



Improving the Common Stock of Knowledge



Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE AUG 2011		2. REPORT TYPE		3. DATES COVERED 00-00-2011 to 00-00-2011	
4. TITLE AND SUBTITLE Research and Development in the U.S. Army Corps of Engineers: Improving the Common Stock of Knowledge				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U. S. Army Corps of Engineers, St. Louis District, 1222 Spruce Street, St. Louis, MO, 63103-2833				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 424	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

**Research and Development
in the
U.S. Army Corps of Engineers:**

**Improving the
Common Stock
of Knowledge**

by

Damon Manders
Ordnance and Technical Services Branch
U.S. Army Engineer District, St. Louis
U.S. Army Corps of Engineers

August 2011

Cataloging-in-Publication Data

Manders, Damon.

Research and development in the U.S. Army Corps of Engineers : Improving the common stock of knowledge / by Damon Manders.

ix, 413 p. : ill. ; 28 cm.

1. Engineer Research and Development Center (U.S.)—Research--History. 2. United States. Army. Corps of Engineers—Research--History. 3. Engineering—Research--History. 4. Hydraulic engineering—Research--History. 5. Environmental engineering—Research--History. 6. Military topography—Research--History. 7. Computer science—Research--History. 8. Coastal engineering—Research--History. 9. Engineering geology—Research--History. 10. Structural engineering—Research--History. 11. Engineering—Cold weather conditions—Research--History. 12. Information technology—Research--History. 13. Photogrammetry—Research--History. I. Engineer Research and Development Center (U.S.) II. United States. Army. Corps of Engineers.

TA200 E8 2011

Foreword and Author's Acknowledgments

When Charles A. Camillo, the U.S. Army Corps of Engineers Mississippi Valley Division and U.S. Army Engineer Research and Development Center (ERDC) historian, approached me in 2007 about the possibility of working on a history of ERDC, I was excited about the potential of the project. He outlined a volume that would cover scientific research in engineering, hydraulics, computer science, topography, environmental science, and other technical fields. As one raised by an engineer in a town with one of the highest concentrations of physicists, engineers, and computer developers in the country — Huntsville, Alabama — and as someone who had written about computers and technology for years, I saw the project as an opportunity to bring my personal interests and experiences to bear on describing one of the most unique organizations in the country. Discussing the project, he envisioned not just an organizational yearbook that is all too often the tone of Corps of Engineers histories, but a narrative of all research and development activities from the origins of the Corps to the modern day that would place ERDC in historical context. It was a sweeping topic requiring integration of a vast amount of information in a brief time — a little more than a year to meet the objective of the anniversary of the formation of ERDC. The result is the present volume. Although it falls short of a comprehensive history, a task that would have taken many years and many volumes to complete, it briefly treats the many Corps research and development activities that led to the formation of ERDC in the context of U.S. engineering research, focusing primarily on the six fields that fall under ERDC: topography and photogrammetry, hydraulics and coastal engineering, geotechnology and structural engineering, construction research, cold regions research and engineering, environmental science, and information technology.

I am extremely grateful for the opportunity to work on the project for a number of reasons. Aside from my personal interests and technical background, I am thankful for the opportunity to chronicle the histories of these influential research organizations, each with long pedigrees and many accomplishments. I had, as has most anyone familiar with the Corps, heard of the U.S. Army Engineer Waterways Experiment Station (WES) and appreciated its long history of important research. I would soon learn of the diverse activities of the other Corps labs that composed ERDC as my research proceeded. I knew that the Corps had for some years conducted research, though I was surprised to learn of the extent of such activities. I am also grateful for the ability to continue working in the field of the history of technology. The topic of Corps research and development lends itself more easily to a broader history of Corps technology than a simple organizational history would allow. As I described Corps research activities in context of early engineering and technological developments, I was able to comment widely on historiographical issues. Until recently the history of technology has received less attention than its importance to society has warranted. Many debates have surfaced over

the past quarter century addressing the relationship of science and engineering, the professionalization of U.S. engineering, the evolution of engineering education, the place of individuals in corporate entities, synergy between military and civil engineering, the utilization of computers, and other topics. The Corps was deeply involved in many of these issues. The knowledge, technology, and scientific approach the Corps developed to protect the country had vast influence on civil engineering practices. Mr. Camillo encouraged me to explore these issues within the overall historical context of the topic. The result is a different sort of history than most funded by the Corps, one that looks as much at broader historical trends and events as with the creation of the organizations. I greatly appreciate his vision that led to this history, which, I hope, will contribute in some small way to the history of technology by discussing the important but largely undocumented role the Corps played in the development of U.S. engineering science. I wish to thank Col. Richard B. Jenkins, the former ERDC commander, who provided the initial impetus for this project, and Timothy D. Ables and the ERDC Board of Deputy Directors, who had the foresight to support and fund this worthy project.

This volume is primarily a synthesis of existing material. Due to the complexity of the subject, which embraces research accomplishments across a dozen engineering fields for more than two centuries, I relied heavily on those secondary works available to me for descriptions of many issues and especially on histories of the various laboratories. To those who came before me, I am, therefore, particularly indebted. Special mention should be made of Benjamin H. Fatherree, whose extraordinarily detailed histories of the WES hydraulics and geotechnical labs provided the basis for much of the descriptions of their research. The WES histories edited by Joseph Tiffany and authored by Gordon Cotton have also been of enormous help for the period prior to 1980. WES in general kept meticulous records, with annual historical or Lab of the Year reports available nearly every year since 1969. The histories of the Beach Erosion Board and Coastal Engineering Research Center by Mary-Louise Quinn and Jamie and Dorothy Moore cover these organizations through the transfer of coastal research to WES in 1983. The Engineer Topographic Laboratories also had the advantage of detailed histories — edited or written by John Pennington, Edward C. Ezell, Andrew Hamilton, and Robert Hellman — covering the time of its formation to 1988. A brief history by Robert Livingstone discusses the formation and activities of the Engineer Detachment at Wright Field. For the Construction Engineering Research Laboratory (CERL), Louis Torres wrote a well-documented history of that organization through 1988, while for the Cold Regions Research and Engineering Laboratory, Edmund A. Wright completed a brief history of that lab through 1985, and a cursory update published by the lab takes the history through 1990. Also helpful was the important work of Frank Schubert on the topographical engineers, Lisa Mighetto and Wesley Ebel on the Bonneville Dam, Gregory Graves on the Institute of Water Resources, and Lawrence Suid on the Corps nuclear program, as well as the many district and division histories referenced in this text. I am also indebted to the pioneering interpretations of Hunter Rouse and Simon Ince, Todd Shallat, Martin Reuss, Brook Hindle, Silvio Bedini, Edwin Layton, and Terry Reynolds on early American and European science and engineering. These predecessors provided much of

the groundwork without which this history would not have been possible in such a brief time-frame. I am extremely grateful for their efforts even when I disagree with their interpretation.

Because of the dearth of secondary data in some areas or to reconcile conflicting testimony on specific issues, in several cases I conducted primary and archival research. In particular, I tried to review critical junctures, such as the founding of the labs or other events with larger political implications. Further, there were many eras and several organizations about which very little has been written. There is no detailed history of the early days of the Engineer School, of many Corps boards, and of the dozens of research organizations that seemed to keep cropping up in documents or mentioned in other histories. And of course, none of the current ERDC organizational histories cover the modern period; most cut off in the mid-1980s, in fact if not in name. In gathering the primary sources for this history, I must mention the support of Sheila DeVeydt of the St. Louis District, who helped track down documentation at the National Archives related to the founding of WES and early board research in the Corps. Charles Camillo, with the aid of historian Larry Roberts and his assistant Janet Fisher, helped to track down reports and images from the U.S. Army Engineer School at Fort Leonard Wood, Missouri. I wish to extend my appreciation to Matthew Percy, Michael Brodhead, Michelle Tyler, and James Gerber at the Corps of Engineers History Office for help in searching their archives for documents and images, and also to John C. Lonnquest, chief of the History Office, for overall support and guidance. I also wish to thank the many public affairs officers and librarians at the many laboratory sites, including Deborah Quimby, Wayne Stroupe, Jackie Bryant, Marie Darling, and Dana Finney, as well as librarians Nancy Liston, Patricia Lacey, and Allan Wiley. These gave me brief but unfettered access to their holdings, of which I can only claim to have scratched the surface, and they helped track down reports, images, and other data. Special thanks should be extended to Michael Golish and David Lienhart for providing photos and data about the Ohio River Division Laboratories and CERL, without which our description of these organizations would have been incomplete. A great many other sources were available on the Internet. There is still a vast amount of information on the subjects that I did not or could not include because of the limitations of funding, time, and space. For this reason, I must leave it to others or to other occasions to delve deeper into the vast depth and breadth of the many topics this volume covers in brief.

Particularly for the years since 1970, oral interviews with former employees helped to fill in many gaps in the record and identify areas of focus. Of the hundreds of names provided by the individual laboratories for potential interviews, I was only able to speak in detail with a little less than 50 due to unavailability of some personnel or limitations of time and only wish that we had had more time and space to cover their experiences in greater detail. I am grateful for the direction and support of the current laboratory directors or deputy directors: James R. Houston, Jeffery P. Holland, Timothy D. Ables, Robert E. Davis, Lance D. Hansen, Joseph F. Fontanella, Reed L. Mosher, Ilker R. Adiguzel, and Kirankumar V. Topudurti. I wish to thank in particular the lengthy interviews and ongoing consultation with retired directors Robert W. Whalin, Lewis E. "Ed" Link, William E. Roper, Narayanaswamy Radhakrishnan, William F. Marcuson, John W. Harrison, Michael J. O'Connor, William Flathau,

and the many former and current employees who made themselves available to me. I should note that, although the majority of personnel mentioned here and, indeed, throughout the text held Ph.D. degrees, we decided not to use the title “Dr.” in most cases to avoid adding several hundred words to the manuscript. No disrespect is intended, and we hope they understand this was due solely to the constraints of space. I also wish to thank Kelley Crook for transcribing many of the interviews, some of them very lengthy and difficult to understand, and Thomas R. Freeman and the entire staff of the St. Louis District Ordnance and Technical Services Branch, who helped manage the contract and support me in my endeavors.

For development of the final book, I extend my appreciation to the talented ACE-IT employees — Betty Watson for the layout and graphic design of the final book and Chandra “Pat” Caldwell for designing the cover. Charles Camillo was extremely valuable, both in locating and organizing photographs and images, as well as providing guidance about the structure and look of the final product. I also thank public affairs office personnel and others, such as David Lienhart, who tracked down or provided images. Although we considered many additional images for inclusion in the manuscript, we only had space to include a representative sampling. We nevertheless appreciate the input, and encourage those interested in the graphical history of the labs to view the more complete library of images.

The inaccuracies or misstatements possible in a history of this scope cannot be underestimated. I gratefully acknowledge the many reviewers who have contributed to my understanding of the issues, improved my prose, or who helped to correct unfamiliar names, titles, and terminology. We asked former laboratory directors and personnel to review all or part of the manuscript, including Robert Whalin, Ed Link, N. Radhakrishnan, John Harrison, Chester Langway, William McAnally, and many others. Many of these made significant additions to the final text. In some cases, we were unable to answer some questions or verify some data within the time we had to complete the manuscript; these will have to wait for future research. In addition, the review committees — headed by Timothy Ables and including James Houston, Jeffery Holland, Joseph Fontanella, Ric Herrmann, Andrew “Ed” Jackson, Peter Smallidge, Deborah Quimby, Wayne Stroupe, Robert Palermo, Jackie Bryant, Charles Lopez, Robert Pazak, Dana Finney, and Charles Camillo — provided excellent corrections and additional documentation for each chapter and for the manuscript as a whole. I am indebted to them all. Nevertheless, the final interpretation of events is entirely my own, as are any errors of omission or commission. The views expressed in this volume are those of the author and not necessarily those of the U.S. Army Corps of Engineers.

I also wish to thank my wife and children for their enduring long hours of my discussing such topics as paleoclimatology, soil mechanics, and the finite element method before I worked them out in my head and committed them to paper. You helped me more than you know. Finally, I thank God for the opportunity to work on this project.

Damon Manders
November 2009

About the Author

Damon Manders is a contract historian employed by the Ordnance and Technical Services Branch, Engineering Division, St. Louis District, U.S. Army Corps of Engineers. He is the lead author of “Rebuilding Hope: Task Force Hope and the U.S. Army Corps of Engineers, Mississippi Valley Division’s Response to Hurricanes Katrina and Rita,” and “The Bayou Builders: A History of the U.S. Army Corps of Engineers, New Orleans District, 1976-2000.” He is also author or editor of two histories of the U.S. Army Corps of Engineers, Engineering Support Center in Huntsville, Alabama, covering the period 1988-1998. Before joining the Corps, Mr. Manders served as marketing manager and senior editor and writer at Intergraph Corporation, where he researched and wrote widely about military, computing, geoscience, engineering, and business technologies. After serving more than 10 years in network administration roles for the 279th Signal Battalion, he currently serves as an officer in the 115th Enhanced Signal Battalion of the Alabama Army National Guard. He graduated magna cum laude from the University of North Alabama with degrees in English, history, and political science, and he earned his master’s degree in history from the University of Mississippi in 1995. He is married with two children.

Contents

Foreword and Author’s Acknowledgments..... iii

About the Author vii

Contents viii

Introduction..... 1

Chapter One. Where Science and Engineering Meet..... 6
Science or Engineering • Science and Research • Early Engineering Research • Science and Engineering in Early America • The Corps of Engineers and Engineering Science • Early Research by the Corps of Engineers • Professionalization of Engineering

Chapter Two. Toward a National Civil Engineering Laboratory 36
Corps Research to the Early Twentieth Century • Research Boards • Development of Hydraulics Laboratories • Freeman’s Drive • Opposition of the Corps • Foundation of the Waterways Experiment Station

Chapter Three. Early Laboratory Research 66
First Experiments at WES • Support for the Mississippi River Commission • Innovations of the First Decade • Soils Research: The Terzaghi Connection • The Buchanan Era at the WES Soils Laboratory • Some Concrete Developments • Coastal Research and the Beach Erosion Board • The Engineer Board and Photogrammetric Research • Continued Experimentation at the Divisions

Chapter Four. War and Military Research..... 100
The March to War • War Footing at Corps Laboratories • Water Research and the War Effort • Runways and Pavement Research • Trafficability, Mobility, and the Environment • Cold Regions Research to the Cold War • Weapons and Weapons Effects

Chapter Five. Expansion of Corps Research..... 132
Topographical Research Breaks Out • Consolidation of Cold Regions Research • Establishment of the Coastal Engineering Research Center • Growth of WES Laboratories • Focus on Construction Research • Other Corps Research • Research Management

Chapter Six. Green Research 170
Conservation and the Corps • The Military Environment • Greening of the Corps • NEPA and Military Construction • Coastal Ecology and Coastal Zone Management • Evolution of the Environmental Laboratory • Dredging, Wetlands, and Water Quality • Ice Research and Climatology

Chapter Seven. Entering the Information Age 214
Development of Computers • Adopting and Adapting Computers • Numerical Modeling to Visualization • Software Engineering • Geographic Information Systems • Formation of the Information Technology Laboratory • The Limits of Computers

Chapter Eight. Engineering Research Comes of Age..... 258
The Merging of Coastal and Hydraulics Research • Militarization of Geotechnical Research • Growth of Civil Structural Research • Environmental Restoration and Military Installations • Continued Development of Information Technology • Topographical Research and Warfighter Support • Retooling Cold Regions Research • Construction Materials and Technology • Technology Transfer • Doing More with Less • The Fight for ERDC

Chapter Nine. Engineer Research and Development Center	302
Standup of ERDC • Technical Program Development • Continued Organizational Adjustment • Geospatial Research and Engineering • Military Engineering • Environmental Quality/Installations • Civil Works • Information Technology Support • Tradition of Excellence	
End Notes	338
Appendices	
Appendix A. Biographies of Notable Scientists and Engineers	370
Appendix B. Gallery of Distinguished Civilians.....	388
Bibliography.....	390
Index.....	406



Introduction



Benjamin Franklin. *Library of Congress*.

The first drudgery of settling new colonies, which confines the attention of people to mere necessities, is now pretty well over; and there are many in every province in circumstances that set them at ease, and afford leisure to cultivate the finer arts and *improve the common stock of knowledge*. To such of these who are men of speculation, many hints must from time to time arise, many observations occur, which, if well examined, pursued, and improved, might produce discoveries to the advantage of some or all of the British plantations, or to the benefit of mankind in general.¹

– Benjamin Franklin, 1743

In 1743, Benjamin Franklin was trying to establish an American philosophical society. As with many of that age, Franklin believed that science, like statesmanship, was a gentlemanly career pursued individually by those of independent means. What he had in mind was something like the Royal Society of London, to which he and other colonials belonged. Unlike the highly centralized royal academies of France or Sweden, the Royal Society was a loosely connected group of gentlemen scientists, professional and dabblers, who collected information, posed theories, conducted experiments, or advanced technology. The Society provided a forum to coordinate among members, publish findings, distribute funds, provide books or data, and

in other ways support scientific research. Included among such efforts were topics that would clearly be considered engineering at various times in the future – topography and cartography, mining and metallurgy, management of natural forces, development of instruments or other devices, and improvements to methods of everything from sailing ships to building roads and canals. Franklin’s campaign to form a similar society in America was in essence the first attempt to develop a national capability for scientific and engineering research – what would later occur in government laboratories.²

Over the next 250 years, many other attempts were made to harness the scientific drive that was developing in America, including within the engineering profession. Central to the story of the evolution of scientific engineering was the U.S. Army Corps of Engineers, which Franklin played a role in helping to establish. As ambassador to France, he helped recruit highly educated French officers for service in America as engineers, noting to George Washington, “you cannot have too much of that Science in your Army.” Influenced by French engineering theory, the Corps and the U.S. Military Academy at West Point, New York, were early pioneers in engineering science at a time when their mostly mechanic-trained civilian counterparts preferred practice over theory. The Corps routinely collected data, researched ideas, developed technologies and theories, and conducted experiments to support planning and construction of whatever projects for which they were necessary. Yet such activities were inconsistent – limited in scope, rarely funded, and never continuous. Even with these limitations, early Corps research and its scientific approach to engineering in general held great sway over the American engineering profession, prompting the professionalization and scientification of engineering education and practice. Soon, colleges developed engineering research facilities. Cities and states formed academies and labs. Professional societies grew up to promote increasingly specialized interests and develop professional standards. By and large, however, these efforts were decentralized. Other than for educational purposes, there was not a protracted effort to develop federal research laboratories until the end of the nineteenth and early twentieth centuries. Most of these at first primarily served the agency of which they were a part and thus were not national in scope; or else conducted specific tests and did not pursue broader public engineering questions.³

It was not until a series of national disasters heightened the need for greater understanding of civil engineering problems that the drive to develop a national civil engineering laboratory at the federal level culminated in the campaign of John R. Freeman to create a national hydraulics laboratory that could serve multiple agencies as well as the public. It was this event, and the resulting authorization of the Waterways Experiment Station (WES) in the Flood Control Act of 1928, that brought the Corps of Engineers permanently into the research laboratory business, albeit somewhat reluctantly. Although the commitment of the Corps was questionable at times, thanks to early leaders with great vision and talent, WES became the first permanent federal facility to apply modern research methods to large national civil works. A steady stream of reimbursable projects quickly made the laboratory the largest and most active hydraulics research facility in the world. Other facilities quickly followed. The Engineer Board, whose predecessors

had long conducted research on military equipment, developed a permanent research establishment at Fort Belvoir. A small detachment of engineers that had existed since 1920 to test photographic equipment grew to become the Corps' proving ground for topographical and photogrammetric technology. The Beach Erosion Board, founded in 1930, developed an early national coastal research center that housed the world's largest wave generation tank. Concrete and soil laboratories developed for a series of dams on the Muskingum River in 1934 became the foundation of the Corps' construction research. Several agencies that developed during World War II to research cold weather construction merged to become the nation's leading cold climate research center. In 1999, the inheritors of these organizations would find a common home in the U.S. Army Engineer Research and Development Center (ERDC), which became an award-winning research center and storehouse for engineering knowledge in support of civil and military projects throughout the nation. Franklin's dream of an organization to "improve the common stock of knowledge" had come true, though not as he would have envisioned it.

Aiding these efforts was the work of the many men conducting the research. Before the twentieth century, the number of private engineering practitioners lent itself to history focusing on great men. Engineers and inventors such as Henry Miller Shreve, James Eads, Henry Abbott, Andrew Humphreys, James Watt, Alexander Bell, Thomas Edison, and others fill early accounts of the development and advancement of technology. Since the twentieth century, however, because of the changing nature of the engineering enterprise, which has become more and more associated with large corporations and agencies, the work of the individual is often lost in the history of the organizations. However, the evolution of research and development in the Corps of Engineers was often the result of talented leaders who advanced the mission. Men such as Joseph Arthur, Thorndike Saville, Robert W. Gerdel, Arthur Casagrande, Louis Shaffer, and Herbert Vogel were key to developing the labs or establishing their early work. Other great intellects or innovators, such as Garbis Keulegan, Henri Bader, Robert Frost, Bryant Mather, and countless others, developed important concepts, worked on major projects, or introduced new technology that made significant contributions to engineering knowledge. Such men form a key part of the story of the labs.

Although a history of research and development in the Corps of Engineers must include the genesis, evolution, and integration of the research facilities and their employees, the greater story lies with what they accomplished. At the beginning, the only known practice for testing the performance of hydraulic structures came from European laboratories that, in 1928, were of rather limited scope. Although European practice greatly influenced the research teams, WES researchers forged their own way in building grander models, experimenting with scale and materials, and developing new tools for measurement. It was an exciting time, and the work WES conducted proved a useful foundation for future research. The Beach Erosion Board also made significant contributions to knowledge, gathering the most comprehensive coastal data to that time. What would later become the Topographic Engineering Center developed technologies for photogrammetry, surveys, and aerial photography. The Ohio River Division Laboratories (later the Construction Engineering Research Laboratory) and WES experimented

with different construction materials and soils, developing innovative techniques for building under a variety of conditions. World War II established new war-related missions, including the research of new equipment, pavement, mobility, cold weather construction, and weapons effects. After the war, the Corps labs turned to environmental issues such as wetland creation and delineation, or mitigation of hazardous waste contamination. After 1954, the labs entered the computer age and began to regularly apply information technology to their efforts, greatly advancing knowledge of complex mathematical problems such as the behavior of water and waves. Since that time, research has steadily expanded to include a variety of issues critical for military and civil engineers.

It is the history of this research – its growth, expansion, and findings, as well as the history of the men and facilities that engendered it – that this volume describes. The story more or less follows a chronological order, but gradually evolves into overlapping topical discussions on military research, environmental research, and information technology. Chapters One through Three trace the influence of the Corps on the professionalization of engineering during the nineteenth century, through its various project-related research and research boards, to the development of WES and other government-run research laboratories at the Engineer Board, Beach Erosion Board, and Corps divisions and districts. They introduce early research in fields such as photogrammetry, hydraulics, beach erosion, soil mechanics, and concrete led by early Corps pioneers in these fields. Chapter Four focuses on war-driven research in hydraulics, pavements, mobility, permafrost, and weapons effects from World War II to the Cold War and explores the relationship between military and civil engineering. Chapter Five discusses the evolution of the five primary Corps laboratories – WES, the Engineer Topographic Laboratories, the Coastal Engineering Research Center, the Cold Regions Research and Engineering Laboratory, and the Construction Engineering Research Laboratory – and introduces many management issues faced by the Office of the Chief of Engineers as the research program expanded. Chapter Six examines the growth of environmental research from early conservation projects to natural resource management, the National Environmental Policy Act, and climate change, and includes the evolution of the Environmental Laboratory. Chapter Seven discusses the evolution of information technology and the creation of the Information Technology Laboratory. Chapter Eight is an overview of research efforts from 1990 to 1998 and looks at the wide range of missions for Corps of Engineers laboratories as well as discussions and circumstances related to the formation of ERDC. Chapter Nine discusses the merging of Corps laboratories as ERDC in 1999 and the resulting programs through present day.

Today, ERDC stands as a legacy of two centuries of Corps research and development, from the introduction in America of engineering science to its current diverse military and civil research programs. Throughout its history, the Corps has served to “improve the common stock of knowledge,” as Franklin envisioned, by advancing national understanding of engineering issues and promoting the national interest, through greater protection at war and more reliable infrastructure at peace. But it also stands as a promise of a brighter future by demonstrating that

when engineers apply the scientific method to hydraulics, soil mechanics, construction, and the environment, the result is an increase in both general and applied knowledge.



Chapter One

Where Science and Engineering Meet



West Point cadets working with models, 1904. *U.S. Army Engineer School.*

In 1928, Congress approved a plan to create a hydraulic engineering laboratory under the direction of the U.S. Army Corps of Engineers. The nation had just suffered the worst flood damage ever recorded in the Mississippi Valley during the Great Flood of 1927. As a response, the Corps proposed a series of flood control measures known as the Mississippi River and Tributaries Project. Part of the plan included the development of a hydraulics laboratory, which others had suggested, and the Corps had resisted, for many years. Built in 1930, the laboratory was the first such facility at a federal level. Many other engineering research efforts were ongoing, including many within the Corps. However, the facility that became known as the Waterways Experiment Station grew and incorporated additional research programs, eventually eclipsing other labs in size, funding, and status, until, finally, in 1999, the major Corps of Engineers laboratories merged as the U.S. Army Engineer Research and Development Center (ERDC). Since that time, ERDC has become the foremost engineering research and development center in the nation, serving not just the Army but many other agencies and activities. Over the years, the ERDC labs have been integral to the development of civil engineering disciplines such as hydraulics, geotechnology, and ecology, as well as military technologies related to blast resistance, topography, and even weapons design, which often had a synergistic relationship with civil engineering. The story of the formation, growth, and contributions of these laboratories, as well as that of other parallel efforts within the Corps, is central to understanding not only the technical underpinning of most Corps of Engineers projects but advancement of U.S. engineering in general.

Today, the concept of applying experimental scientific inquiry to engineering may seem self-evident, but in fact was not widely accepted until the twentieth century. On the whole, the evolution of engineering as a science with standardized research practices came rather later than the basic sciences, particularly in the U.S. Unlike fields such as chemistry and physics, which developed standardized methods for research as early as the seventeenth century, some engineering fields did not consistently apply similar methods until the nineteenth century or later. This was due in part to long-standing ideologies among scientists and engineers about the proper spheres of their occupations. By the nineteenth century, however, engineers sought greater professionalization and standardization through improved education, the formation of professional societies and ethics, and most of all the scientification of engineering practice. The Corps of Engineers was on the forefront of this movement by establishing the first engineering school at West Point and by emphasizing scientific engineering traditions. It was this drive to professionalize engineering that culminated in the movement to create a national hydraulics engineering laboratory. Therefore, it is only fitting that a history of research and development in the Corps of Engineers should begin with the drive to move engineering deeper into the world of science, a world where research and development are the critical tools for improving and applying knowledge.

Science or Engineering

When people talk about engineering research and development, it raises a host of questions that engineers as well as historians have grappled with over the years. Foremost of these is the

relationship of science and engineering.⁴ The popular sense of engineering as applied science lends credence to the view that laboratory research belongs to science not engineering. Scientists develop theories in laboratories; engineers apply theories in the field through technology. Experimentation, categorization, and research form the basis for the scientific method. Engineering grew out of practical endeavors such as mining, building, and designing. Over time, engineers came to apply scientific theory, but, according to this view, engineers did not originate the theories. Development performed by engineers, such as invention of the steam engine or other devices, was more akin to tinkering than to scientific discovery. Even admitting engineering research, would the research be basic or applied, who would do the research, and what is the relationship between experimentation and technology development?

In many ways, such questions are misleading since the line between science and engineering is not nearly as clear as some believe. Many scientific discoveries resulted from technological development; many scientists delved into application. Application of the scientific method was not as monolithic as some depict, nor was its application to engineering as late as some argue. Nevertheless, encouraged by a popular tradition that sees engineering as a mere offshoot of science, some circles view engineering research with suspicion. As recently as 1988, there have been public disputes among historians over the role of science in engineering. According to historian Edwin T. Layton, at least three ideologies competed in the realm of science and engineering. In the ideology of pure science, basic research leads to new knowledge, and engineering is merely applied science. The view gained a particularly strong impetus with Social Darwinism, in which societal evolution was the result of scientific advances, and scientific practice became linked to status. By the late nineteenth century, many engineers believed in engineering science. Men such as Robert Thurston, the founder of the American Society of Mechanical Engineers, defined engineering as measurement of nature from which scientists derive general laws and theory. Thurston was an early advocate of engineering research. All the while, there remained engineers who embraced the traditional concept of engineering as design. In this view, scientific theories operate in an ideal laboratory world, but do not always work in the real world. While not denying the analytical and systemic nature of engineering, this view stresses its cumulative and practical side and places art above theory. Over time, people variously accepted or rejected these views primarily for ideological reasons. In reality, however, engineering and science are closely tied. As Layton concluded, "While distinct, they are not totally different; there are curious semantics which link the two to a common physical reality and to each other."⁵

U.S. engineers have also struggled whether to emphasize application or science in defining themselves, particularly in the development of engineering education. Before 1830, only about 30 percent of engineers received a formal education. Most learned their trade as apprentices in which practice was paramount. At first, even formal education was more akin to an apprenticeship. Engineer students learned some basic mathematics and science, but the focus was still more on practice or application. Over the next hundred years, education gradually increased in scientific content, with the most dramatic changes after World War II, a conflict in which science and technology played particularly decisive roles. Studies following the war recommended that engineering education stress more basic science and theory, and in 1955, the president

of the American Society of Civil Engineers first talked about “engineering science.” By 1980, only 35 percent of engineers did not have a degree. School content focused mostly on theory, with the assumption that engineers would learn application on the job. Yet in 1986, a National Research Council report noted that engineers showed weaknesses in building systems. There was a need for more practice and less theory in engineering education. The debate had come full circle. Today, engineers continue to debate whether theory or practice is more important.⁶

To best understand the evolution of engineering science, one must look to its origin. In Greece, those who first defined science (*episteme*) placed engineers outside of it. Science was the work of philosophers observing nature and developing theories. Technology was the application of theory by the mechanic (*mechanaomai*) and architect (*architekton*). Much of this view resulted from class distinctions since most Greek artisans were slaves, which is why Aristotle famously observed of artisans that “the best form of state will not admit them to citizenship ... but only to those who are freed from necessary services.” As citizens, philosophers pursued science objectively, but artisans were less objective being tied to practical service. He sometimes listed mechanics as a subfield of mathematics, but generally downplayed it as less empirical. Although mechanics such as Heron of Alexandria and Archimedes of Syracuse achieved a measure of fame, only with the more practical Romans did engineering emerge as a worthy occupation. Expansion of the empire and Pax Romana required good roads and urban centers with all the comforts of “civilization” – public works, indoor plumbing, and water- or animal-powered industry – resulting in greater need for mechanics. Their education stressed, not just practice, but math, writing, astronomy, and other sciences. Typical of Roman ingenuity were patrician engineers such as aqueduct designer Sextus Julius Frontus and water wheel developer Marcus Vitruvius Pollio. Both served in the military, which provided training and recognition for engineers. Each Roman legion included a master builder (*architectus*), a surveyor (*mensa*), a water engineer (*hydraularius*), and an artillery engineer (*ballustarius*). It was from military engineers of the late empire that the term engineer (*ingenieur*) came, as one who employs ingenious siege engines. In the Middle Ages, most mechanics, architects, and artisans were relegated to the lower classes. Even highly respected architects such as William of Sens and John of Gloucester were generally illiterate and uneducated. Most worked in a guild system, in which masters passed their skills manually through a long apprenticeship, and there was little mobility or long-term transfer or retention of knowledge. Because the philosophical nature of science required education, it was mainly churchmen such as Robert Grosseteste, John Duns Scotus, and William of Occam who conducted research. These practices remained relatively unchanged until the Scientific Revolution. While many histories overuse the term revolution by ignoring earlier progress, there can be little doubt that the rapid increase in knowledge resulting from the expansion of science changed engineering greatly.⁷

Science and Research

For ancient Greek philosophers such as Aristotle, scientific inquiry was more a matter of observation and classification than experimentation and demonstration. Although Aristotle believed “truth obtained by demonstrative knowledge will be necessary” to prove some premises,

“not all knowledge is demonstrative.” For these questions, deductive reasoning provided the answers. The Aristotelian methodology was to make observations, draw conclusions using induction, then reason deductively to apply conclusions to new areas – in essence to argue from specific to general, then from general to specific. Relying on logic, this often resulted in erroneous conclusions. Those of the Pythagorean School, such as Ptolemy, believed in ideal forms and looked instead to mathematical theorems to describe reality. However, Middle Age scholars and the Church held that Aristotle was the pinnacle of scientific knowledge and the ideal form of process. The development of the seventeenth century scientific method changed this, eventually having profound influence over engineering science.⁸



Renee Descartes. *Library of Congress.*

Historians generally recognize two figures as establishing the scientific method. Most attribute it to Francis Bacon, although the concepts were not original to him. In the Middle Ages, Muslim scholars and churchmen Robert Grosseteste and Roger Bacon argued for experimentation, a process adapted ironically from the trial and error approach of artisans, but widespread illiteracy prevented popularization of their views. Francis Bacon, in the widely read *Novum Organum*, firmly established experimentation as the core of the scientific method. After rejecting the Aristotelian tradition, writing that the Greeks “have laid their stress upon intense meditation [deduction]” that “tended more to confirm errors than disclose the truth,” he set out a method of guided, iterative experimentation and thorough documentation and publication. “The secrets of nature betray themselves more readily when tormented by art than when left to their own course,” he wrote. While he recognized that mechanics used similar methods, they did not increase knowledge because “the mechanic, little solicitous about the investigation of truth, neither directs his attention, nor applies his hand, to anything that is not of service to his business.” As with classical attitudes, the true scientist was more objective. Soon after, Renee Descartes published *Discourse on Method*. Although most famous today for his philosophical conclusion that cognizance proves existence (“I think, therefore I am”), it greatly influenced scientific thought through four rules for thinking:

The first of these was to accept nothing as true which I did not clearly recognize to be so. . . . The second was to divide up each of the difficulties which I examined into as many parts as possible. . . . The third was to carry on my reflections in due order, commencing with objects that were the most simple and easy to understand. . . . The last was in all cases to make enumerations so complete and reviews so general that I should be certain of having omitted nothing.

This concept of dividing and examining components provided a pattern for scientific problem-solving. Only as an afterthought did he add that experiments “become so much the more necessary the more one is advanced in knowledge.” The *Discourse* stressed the use of deduction and mathematics, in essence starting with a hypothesis, working as far as possible through deduction, and then turning to induction. In *Rules for the Direction of the Mind*, he elaborated on

the importance of mathematics, noting that “no other sciences furnish us with illustrations of such self-evidence and certainty.” For him, “enumeration [induction] obtains surer conclusions than any type of proof except intuition [deduction].”¹⁰

These two sometimes conflicting approaches had a tremendous impact on scientific inquiries. Bacon’s inductive method had greatest influence on what men at the time called natural history – biology, zoology, botany, chemistry, mineralogy, geology, and related fields. Instead of these sciences relying on the ancients or merely making empirical observations of nature as directly experienced, scientists revealed hidden qualities through controlled experiments such as dissection, excavation, or application of heat or cold. Over time, they started using devices such as microscopes and telescopes, both inventions of the seventeenth century. The deductive reasoning of Descartes, meanwhile, provided greater influence on natural philosophy, which included such fields as physics, mechanics, aspects of astronomy, and other physical sciences in which mathematics held greater sway. Rather than merely developing mathematical truths, natural philosophers such as Blaise Pascal, John Hershal, and Isaac Newton applied increasingly complex mathematical theorems to the natural world, unfolding what many considered the mysteries of the universe. But it was the combination of these methods – observation, experimentation, and inductive reasoning on one side and problem-solving and deduction on the other – that held the greatest influence. Men such as Galileo Galilei, Robert Stevin, and Robert Boyle combined experimentation and algebra to convincing effect, overturning many long-held views on multiple fields, with the result that many consider Galileo the true father of modern science.¹¹

The resulting method as traditionally understood more or less includes four steps. Typically, scientific inquiry begins with collection of data through observation and experimentation, which should be directed, repeatable, and controlled. The second step – systemization – is correlation of data into patterns that allow drawing conclusions. Researchers then form a hypothesis by fitting patterns into existing knowledge and explaining discrepancies. Finally, the researcher must test the hypothesis through further experimentation, and either confirm or discard the view. Thus, the method is actually a repeated cycle of conclusions, data gathering, and systemization. While historians generalize this method, it was not this monolithic nor its development this sudden. For example, John Herschel and William Whewell developed alternative methodologies that provided varying approaches for induction and deduction, differentiated between facts and ideas, and described in greater detail the transition from hypothesis to law. Debates between those stressing induction, such as John Stuart Mill, and those stressing deduction, such as William Stanley Jevons, continued to be prominent. Later scientists such as Karl Popper, Carl Hempel, and Thomas Kuhn discussed verification of hypotheses and theories and standard criteria for acceptance, while post-modern scientists have questioned the objectivity of scientists and theories. Scientists disputed nuances, but the basic methodology remained more or less intact. Its wide publication made it better known, so that, not only did scientific inquiry become more consistent, it changed the way people saw the world. The era became known as the Age of Reason, an age when faith in science became central to people’s world view. It was in this environment that engineering science was born.¹²

Early Engineering Research



Leonardo da Vinci.

By the late Renaissance, some began to apply the scientific method to engineering. It was by no means consistent, and there quickly developed a divergence between practice in Continental Europe and Great Britain, where engineers retained medieval traditions far longer. By the time of Leonardo da Vinci, engineering in Europe was blossoming. Although best known as a painter, Da Vinci investigated many fields. Noting that 30 of 36 skills he exhibited were technical in nature, one history called him an “engineer who occasionally painted a picture.” A century later, many scientists experimented with engineering. Galileo studied mechanics, experimented in metallurgy, and designed his own telescope. Benedetto Castelli defended Galileo’s hydraulic theories and advanced the law of continuity for steady flow. Vincenzo Viviani experimented with inclines, pendulums, and sound and developed clocks and other technology, and Evangelisto Toricelli experimented with air pressure and developed the first barometer. Another contemporary, Flemish mathematician Simon Stevin, applied mathematics to designing drainage works and ships. In France, Maximillian de Bethune, duc de Sulley, who managed reclamation projects and designed bridges and canals, was an early proponent of studies that explained projects in scientific terms. Domenico Guglielmini, founder of the Italian hydraulics school, developed theories on water velocity and efflux, applying them to civil works. By this time, though still mostly middle class, mechanics were increasingly educated and scientifically astute. The rule of thumb still prevailed, but application of the scientific method to engineering was becoming more prominent.¹³

In France, engineering achieved a clearly superior status due to sponsorship of Bourbon kings, who saw it as a modernizing power that increased the influence of the state. In 1675, the gifted military engineer Sebastian Le Prestre de Vauban founded the *Corps des Ingenieurs du Genie Militaire* (Corps of Military Engineers), the first state-run engineer agency, to build forts needed for the campaigns of Louis XIV. Engineers such as Languedoc Canal designer Pierre-Paul de Riquet de Bonrepos quickly became the darling of Jean-Baptiste Colbert, the king’s minister of finance, who set out on an aggressive plan for civil works. These were so extensive, another corps – the *Corps des Ingenieurs des Ponts et Chausses* (Corps of Engineers of Bridges and Roads), founded in 1720 – became necessary. To help train engineers, the state established the *Ecole des Ponts et Chausses* in 1744 and *Ecole Royale du Genie* in 1748. The schools produced a generation of the brightest scientifically educated engineers, including Henri de Pitot, who conducted experiments on the Seine River; Charles Augustin Coulomb, who developed theories of earth pressure; and Charles Bossut, who applied physics to the study of waterways. By and large, the theories developed were of little use to builders, yet as historian Todd Shallat argued, “The outlook of science – its positivism, its need for verification, its indifference to chivalry and noble obligations – was a professional orientation that rebuilt the French civil service, inspiring the savants who transformed public works.” Under Napoleon Bonaparte, the two schools combined in 1794 as the *Ecole Polytechnique*, which later had strong ties to the U.S. Military Academy at



Sebastian Le Prestre de Vauban.
Library of Congress.

West Point. The centralized model of civil engineering established by France soon found favor throughout Europe.¹⁴

In Great Britain, development of engineering took a different route. Instead of centralized schools and agencies, individual practitioners and decentralized organizations were more characteristic. Partly due to the less autocratic nature of government and partly to continuation of apprenticeship, English engineers remained civilian and mechanic-oriented with varying education. Typical is James Brindley. Raised as a craftsman and apprenticed to a mill, he went on to design several canals and experiment with pumps. Also born of a poor family, John Metcalf became a great road designer. Perhaps the most influential engineer of the era was John Smeaton, a middle class lawyer and instrument maker, who experimented with cement and built lighthouses, bridges, and canals. He was the first person to use the term “civil engineer” in founding the Society of Civil Engineers in 1771. He developed many theories and wrote an influential text on water and wind power, but mostly used science to explain discoveries rather than as a means of discovery. Many engineers were members of the Royal Society of London, a decentralized organization of scientists that provided a forum for sharing knowledge and supporting research. The only British engineering school of the time, the Royal Military Academy at Woolwich, was small and not concerned with civil engineering. Support for engineering education came only with the Industrial Revolution, with its focus on mechanization, power, and progress. Engineers began to become more professionalized, leading one historian to call it the “era of the engineer.” With increased capital and resources, government and businesses could invest in larger construction projects, aided by the steam engine, improved metallurgy, and better building materials.¹⁵

Demand for educated engineers grew, and soon universities began to oblige. From 1826 to 1907, University College, King’s College, the University of Glasgow, Cambridge University, and Oxford University offered engineering courses, then engineering degrees, then departments. While France had the *Ecole Polytechnique*, Germany established the Technical Institutes of Munich and Berlin in 1868 and 1879. Although such facilities included standard chemistry and physics laboratories, most engineering experimentation occurred in the field. For example, Guglielmini developed mathematical theories in the lab to explain erosion and siltation, leading to experiments with grass to reduce erosion. Smeaton, sometimes considered the father of hydraulic modeling, often experimented with models and tested soils and materials prior to building water wheels or mills, but only applied theory later if at all. By the end of the eighteenth century, laboratory work was becoming more common. In 1775, the Marquis de Condorcet and Charles Bossut began hundreds of laboratory experiments to prove Guglielmini’s theories. By the end of the nineteenth century, development of engineering theory by experimentation was fairly standard. In the field of soil mechanics, the papers of Alexandre Collin, William Rankine, and Benjamin Baker led to field studies on landslides and construction that greatly influenced the work of Karl Terzaghi, who is generally accepted as the father of modern

geotechnology. Development of movable hydraulic models in 1875 started a trend toward hydraulics laboratories, starting with Hubert Engles at Dresden. These labs were the direct inspiration to create an American national hydraulics laboratory. The scientification of engineering, which had been ongoing in Europe for two centuries, was starting to take hold in the U.S.¹⁶

Science and Engineering in Early America

While French and English engineering traditions each influenced America, engineering and science in the U.S. were much more connected. Lines often blurred between scientists and surveyors, experimentation and invention, and mathematicians and mechanics, what historian Silvio Bedini calls “Thinkers and Tinkers.” Much of this was the result of lower population and fewer class divisions than existed in Europe. Exploration created demand for mathematically trained surveyors, navigators, and map-makers. Surveyors accompanying expeditions were also responsible for recording new species, requiring talents as natural historians. A demand for precision instruments led to experimentation with metallurgy, optics, astronomy, and physics needed for building telescopes, orreries, barometers, sextants or octants, and other devices. The inventors of these instruments were usually more educated mathematical practitioners – school teachers, college-educated amateurs, physicians, and philomaths or math-lovers – who invented or experimented in their spare time. Many, such as Benjamin Franklin, were retired businessmen. Some studied meteorology and astronomy to produce almanacs, for which there was a great demand. More than date books, these included observations or predictions and calculated sunrises, tides, and navigation data. The most popular of these – Franklin’s *Poor Richard’s Almanac* – combined scientific data and philosophy in a homespun wit. More educated colonists experimented in physical sciences, astronomy, geology, and mathematics. Metallurgist John Winth became world famous for discovering the fifth moon of Jupiter. Prolific Puritan writer Cotton Mather discussed many scientific issues, including inoculation. Philadelphia mathematician Thomas Godfrey invented a widely used octant. John Bartram, John Wintrop, and John Griscom contributed to knowledge of optics, magnetism, and chemistry. Perhaps most typical of early American engineers were David Rittenhouse and Andrew Ellicott. Born a farmer, Rittenhouse was a gifted surveyor and instrument maker who constructed clocks, orreries, and the first telescope in the U.S., which incorporated the use of spider webs as a reticule. Ellicott was perhaps the best known surveyor in the U.S., working with Rittenhouse to complete the survey of the Mason-Dixon Line between Maryland and Pennsylvania and completing the first survey of Washington, D.C. He later went on to teach mathematics at West Point. Both men served in the American Revolution and in early government. These were self-taught men who moved back and forth from surveyor to mathematician or scientist without much distinction between them. In other fields, such as manufacturing, mechanics followed more traditional English models.¹⁷

With no developed infrastructure in America, there was a need for engineers to build wharfs, roads, and canals, which often fell to surveyors. Due to the abundance of timber, most works were of wood, requiring less complex engineering. This was less the case with hydraulics. Canal-building in England influenced a series of projects in America after 1765. Thomas Gilpen led a

campaign to connect the Delaware River and Chesapeake Bay, surveying the route from 1766 to 1769. Rittenhouse and Samuel Rhodes surveyed the Susquehanna for a canal design, but admittedly lacked the civil engineering experience to build it, delaying the project another 50 years. Other men such as Hugh Williamson, John Fitch, and James Rumsey built numerous canals, bridges, and boats. Yet, there was a wide divergence between surveyors and experienced civil engineers. Most American engineers lacked a scientific and theoretical background, giving rise to the sense that theirs was foremost a practical rather than theoretical art. Attitudes remained unchanged for many decades. As late as 1840, Alexis de Tocqueville observed,

In America the purely practical part of science is admirably understood, and careful attention is paid to the theoretical portion which is immediately requisite to application. On this head the Americans always display a clear, free, original, and inventive power of the mind. But hardly anyone in the United States devotes himself to the essentially theoretical and abstract portion of human knowledge.¹⁸

Most American mechanics followed the English model of engineering education. They learned their trade as apprentices or were self-taught, and thus lacked a formally educated scientific background. This was due, in part, to the dearth of schools in colonial America. Public schools tended to be church-run, and the few universities that existed focused on divinity, law, and a classical education rather than science or mathematics. Early philomaths led the way in establishing preparatory and night schools that taught science and mathematics, such as the Philadelphia and Baltimore academies, and would sponsor lecturers to teach mathematics and mechanical arts. Early colonial scientists helped establish libraries, research facilities, and museums, such as the Library of Philadelphia and the Charleston Museum. Most American scientists preferred to advance science and technology through voluntary associations, such as the Royal Society. By 1783, there were 53 American members. Several states or cities developed their own societies, such as the Boston Philosophical Society, the Virginia Society for Promoting Useful Knowledge, or the Philadelphia Junto. Other states supported formation of museums, botanical gardens, general surveys, and scientific expeditions. While naturalists and physicians had already formed small intercolony clubs and meetings, it was physicist Cadwallader Colden who first suggested a general scientific society. Soon after, amateur botanist John Bartram convinced Franklin to support the formation of the American Philosophical Society in 1743, but despite publication of several papers, poor local support kept its membership very small until the coming of the American Revolution.¹⁹

The Revolution impacted U.S. engineering tremendously. Inasmuch as the Revolution included societal change, beneficiaries included lower class artisans and mechanics that suddenly found greater independence and social mobility. Many were on the forefront of opposing British taxation, which impacted their manufacture employers. As Bedini noted, “One of the most conspicuous effects of the successful end of the war was the emergence of the craftsman ... as part of a new class of American society.” Long-term, occupational identities shifted to engineering separate from more gentlemanly scientific pursuits, setting the stage for professionalization of engineering occupations in the nineteenth century. Short-term, the changes were

Benjamin Franklin and Hydraulic Modeling

While best known for his experiments in electricity and his invention of the lightning rod, bifocals, and the Franklin stove, Benjamin Franklin had an early and enduring interest in hydraulics. As a boy, he had experimented with resistance and invented early flippers and hand paddles to improve swimming speeds and used a kite to pull him across the water. Later in life, while traveling to and from England, he conducted experiments with water temperature, enabling him to produce the first chart of the Gulf Stream. NASA continues to use his data, which the agency finds highly meticulous.



Benjamin Franklin, the philosopher and his kite. *Library of Congress.*

One experiment in 1768 involved the building of a hydraulic model, possibly the first by an American. When traveling by canal in Holland with Sir John Pringle, Franklin and Pringle noticed that the boat was moving slower than usual. On asking the boatman the reason, he replied that it had been a dry year and the water was low. When Franklin further inquired if the boat was dragging on the bottom, the boatman said no, but that it was a phenomena with which all boat operators were familiar – that the lower the water, the slower horses towed the boat. On returning to England, Franklin confirmed with boatmen on the Thames that they had the same experience.

Franklin hypothesized that the reason was that since the boat displaced a certain amount of water that must be forced around it, if the canal was too shallow, it forced more of the water to the sides and slowed the boat. Alternately, he hypothesized that it was due to water elevation differentials created by the wake. To test his hypotheses, he developed a model experiment.

Franklin built a wooden trough 14 feet long and six inches wide with a board the same dimensions on the bottom that he could adjust to a depth of one to six inches. Using a model boat that was six inches long, two and a quarter wide, and an inch and a quarter deep with a one-inch draft, he attached to it a string, which ran through a pulley with a shilling weight on the end. This allowed him to draw the boat and still make close observations. He then ran the boat the length of the flume at different depths, counting the time it took to reach the end. Afterwards, he averaged the number of seconds the trip took at each depth.

Through these and many other experiments he conducted using the trough, he was able to confirm that, indeed, the speed of the boat was nearly one-fifth longer at the most shallow depth than at the deepest. Based on these calculations, he determined that for a four-horse tow, it would take an additional horse to maintain the same speed on shallow canals as deep ones.

“Whether this difference is of consequence enough to justify a greater expense in deepening canals, is a matter of calculation, which our ingenious engineers in that way will readily determine,” he wrote to Pringle. Though Franklin was at the same time in correspondence with canal builder Thomas Gilpen about the American Philosophical Society, it is doubtful that this experiment had any major impact on canal construction.



Benjamin Franklin directing the construction of a stockade fort. *Library of Congress.*

more abrupt and immediate. As with all wars, the Revolution spurred considerable invention, with new devices such as the submarine and technical improvements to shipping, artillery, and construction. There was an almost immediate increase in demand for mechanics. Shortages of military maps led to employment of surveyors on both sides of the conflict. The lack of good roads and bridges to move troops and supplies created a demand for civil engineers. Perhaps the biggest shortage was military engineers to design and build artillery emplacements, forts, and camps. While the British had a ready supply of formally and informally trained engineers capable of these tasks, the Americans lacked native talent. Consequently, the Americans turned to the French, who quickly infused the U.S. Army with its own militaristic and scientifically trained engineers. It was the beginning of the Army Corps of Engineers and the scientification of American engineering.²⁰

The Corps of Engineers and Engineering Science

When the Continental Congress created the first U.S. Army in 1775, it included the establishment of a Chief Engineer to serve under George Washington. The first Chief Engineer, Richard Gridley of Massachusetts, was an artillerist who had, like Washington, served in the British Army during the French and Indian War. His replacement, Rufus Putnam, served as Gridley's assistant. But, while the top engineer positions found experienced combat engineers, Washington had great difficulty in finding trained engineers to fill rank and file positions. Congress requested that the French provide trained engineers, and Benjamin Franklin and Silas Deane succeeded in obtaining 16 specialists in engineering and artillery by 1776. By 1782, of the 14 trained engineers serving in the Army, only one was an American. Many of the French engineers served with distinction, including Francois de Fleury, Pierre L'Enfant, Michel du Chesnoy, Etienne de Rochefontaine, Jean de Villeranche, and Jean Baptiste de Gourion. One of them, Louis L. Duportail, became Chief Engineer in 1777 with the promotion to brigadier general. At his, Putnam's, and Washington's insistence that the Army needed a separate Corps of Engineers, Congress created three companies of Sappers and Miners and later approved a separate division within the Army, although it would take many years to recruit men to fill the positions. During the war, engineers provided innumerable services, including reconnoitering enemy positions, drawing detailed maps, and overseeing the construction of fortifications.²¹

At the end of the war, engineers returned to their civilian occupations along with the rest of the Army. Although Washington, Duportail, and others argued that the difficulties of raising units of trained engineers favored training and keeping engineers on staff, Congress in general philosophically opposed maintaining a standing army during peacetime other than what was necessary to enforce treaty provisions. When war with Britain threatened again after 1794, Congress approved the appointment of a small number of engineers to restore fortifications, and President George Washington appointed Maj. Pierre L'Enfant and Maj. Stephen Rochefontaine. L'Enfant would later argue the need for improvement, not only to fortifications, but also to roads and waterways since they aided the transportation of troops, and he personally helped to lay out the streets for Washington, D.C. At approximately the same time, Secretary of War Henry Knox won approval for the creation of a Corps of Artillerists and Engineers, although

the unit would exist only as long as the threat continued. With the continuing shortage of native engineers, Knox chose Rochefontaine to head the corps in 1795, and several French officers served under him. French engineers continued to be the only educated military engineers available in the U.S. As a result, Knox, L'Enfant, and Rochefontaine argued repeatedly for the need of a school to train engineers. From 1794 to 1798, the corps set up temporary instructional facilities for 32 cadets at the fort at West Point, New York, where an unofficial military school briefly had existed from 1781 to 1783 under the leadership of Lewis Nicola and the Corps of Invalids – a troop of injured veterans. Interrupted by a fire in 1796, the new school's impact was minimal. Finally, after pleas from Benjamin Rush, Benjamin Latrobe, John Adams, and others, Alexander Hamilton and Secretary of War James McHenry submitted a plan, and in 1802 Congress created a separate and permanent Corps of Engineers and established an engineering school to train them, the U.S. Military Academy at West Point.²²

West Point eventually became one of the most influential engineering schools in the country. At first, it was fairly small, both in terms of students and faculty. “For a decade after 1802, West Point was a military academy more in name than in fact,” historian Forest Hill wrote. In July 1802, there were nine cadets and fewer professors, standards were low, and instruction was irregular due to other cadet duties. By 1812, only 71 cadets had graduated. The Chief Engineer, Col. Jonathan Williams, nephew of Benjamin Franklin, served as the superintendent of the school from 1805 to 1812. A scholar in his own right, having studied military construction while an envoy in France and written on water temperature in *Thermometrical Navigation*, Williams pushed for increased scientific content as well as for French instructors, which did not sit well with Federalists in the War Department. He also started the Military Philosophical Society with other scholars as a means to instill cadets with a “spirit of scientific curiosity,” as one history of West Point observed. The first curriculum offered was mostly basic mathematics and science; only after 1808 did it include engineering content, and not until 1812 did the school have an engineering professor. It did, however, have a strong topographical content with brilliant surveyors such as Andrew Ellicott and Jared Mansfield serving as instructors. Aside from a library of 50 books started by Louis de Toussard in the days of the Corps of Artillerists and Engineers, there were few engineering texts available. Williams donated many from Franklin's library, including a few English volumes on engineering, and began translating French ones (about a third of the library was in French).²³

One can see in Shallat the development of West Point in three overlapping stages. First, there was the European stage, in which the Americans, lacking engineering expertise, imported faculty members and texts mainly from France. This period reached its peak with the hiring as professor of engineering of the brilliant Claudius Crozet, who trained at the *Ecole Polytechnique* and served under Napoleon Bonaparte. At the time of his arrival in 1816, four of the seven faculty members were French, and one was German. Most of the books of this era were European in origin, often requiring translation. Crozet introduced many French texts, such as *Architecture Hydraulique*, and wrote several texts himself. Next came a borrowing stage, in which American engineers such as Col. Sylvanus Thayer and later Dennis Mahan visited the French *Ecole Polytechnique* and borrowed methods and content while purchasing additional

books and instruments. Thayer had joined the faculty in 1812 and became superintendent in 1817, at which time he redesigned the course of study based on the French model. His student, Mahan, took over the professorship of engineering in 1832, writing the first American text on civil engineering in 1837. After 1830, the school entered into a period of worldwide respect as a producer of the nation's greatest engineers.²⁴

With the shifting of faculty during the War of 1812 and with the introduction of the Thayer method, West Point became much more rigorous and effective. In 1812, Congress set the number of cadets at 250, greatly enlarging the school. Even many of those who disagreed with the scientific approach to engineering or who questioned its elitism admitted that the school was the nation's finest facility of its kind. By 1822, the rapidly expanding library had reached 942 titles, and by 1853, it had 15,000 volumes, comparable to other American universities. It remained the largest U.S. library of technical volumes throughout the nineteenth century. Its staff produced several volumes in engineering, surveying, and other fields, a feat not reproduced by competing schools even to a lesser degree until after 1830. For example, William Bartlett, professor of natural and experimental philosophy, wrote a popular text on analytical mechanics, and Albert Church, professor of mathematics, wrote multiple texts used throughout the country. The school had excellent chemistry and mineralogy laboratories and the latest scientific instruments, such as telescopes, microscopes, and survey equipment. Crozet introduced the use of the blackboard, which was unknown in America at the time, allowing on-the-fly development of engineering drawings based on geometric formulas. Bartlett built the first observatory at the school in 1840. Instruction at West Point was about 70 percent mathematics and science, and included, not only theory, but also experimentation and modeling. The application of the scientific approach and experimentation was a vast departure both from the classical education in civilian schools and less theoretical civil engineering practice of the day. West Point was also from the beginning concerned with more than just fortifications, but with civil works ranging from roads to canals to locks and dams. Although it had taken a generation for L'Enfant's vision to come to pass, the West Point-trained Corps of Engineers took the lead in the largest building projects in the nation.²⁵

By the Civil War, West Point had become not just the nation's leading engineering school, but also the sometime location for engineering research by the Corps. Several faculty members conducted extensive research in topics taught at the school. In 1838, Jacob Bailey, the professor of chemistry, mineralogy, and geology, pioneered the use of microscopes in the study of botany and published findings on fossilized algae and other discoveries. Several of Bartlett's astronomical observations were published by the American Philosophical Society, though his primary occupation was the development of mathematic and mechanical theory. Later, Brevet Brig. Gen. Peter Michie, as Mahan's assistant, conducted research into wave motion, astronomy, and coastal defense, writing widely read texts on each. In 1830, West Point's foundry at Cold Spring was the site of construction of the first two railroad engines built in the U.S., influencing several former students, including Lt. George Whistler, Capt. William McNeill, and Capt. William Swift, sometimes considered three of the most important engineers of the era. Whistler, the father of the famous painter, became one of the leading experts on railroads in America. In 1846,

with the Mexican War threatening, Congress established the first permanent company of engineers stationed at West Point. Other than when accompanying the Army, the company assisted students in instruction and conducted experimental research on combat engineering equipment. The company provided surveys of the Great Lakes and for railroad lines and conducted research into bridge trains and rubber pontoons, which proved particularly valuable during the Civil War. Later, with the expansion of West Point to a general military education and with the establishment of the Engineer Battalion at Willets Point, New York, in 1867, the Engineer School of Application took the place of West Point as the unrecognized research center within the Corps and maintained several laboratories. Although the status of the school was unofficial for 20 years and the battalion was concerned primarily with providing practical experience and training to new engineer officers, Chief of Engineers Brig. Gen. Andrew Humphreys used it to conduct research into fields such as coastal fortifications, undersea mines, pontoons, photographic mapping, and other areas.²⁶

The establishment of West Point marked a milestone in the history of U.S. engineering. It was the first technical college in the U.S., the first offering an engineering curriculum, the first to have a professor of engineering, and the first to house a technical library. Further, it was the only engineering college for more than 20 years. At a time when most schools offered a classical education, West Point was highly innovative. As historian James Morrison noted, “By virtue of its stress on science and engineering, West Point, without intending to do so, placed itself in the vanguard of educational reform in the antebellum era.” When other engineering schools formed in the years that followed, West Point served as both an inspiration and a resource – West Point engineers or instructors (including Thayer) went on to serve in at least five other schools. The influence West Point had on civil engineering was enormous. Most graduates completed their agreed commission in the Corps of Engineers and then went immediately into civilian service; thus, West Point provided a steady stream of educated engineers into private practice. By 1838, more than 100 West Pointers had become civil engineers, compared to only seven from the Rensselaer Polytechnic Institute. As late as 1850, 15 percent of all practicing engineers in the U.S. were West Point-trained, near half of all college-trained engineers at the time. Among these were men such as McNeill, Whistler, Hermann Haupt, and former Chief Engineer Joseph Swift. Not surprisingly, as a military school run by French-trained engineers, West Point closely followed the French engineering model. Graduates read the classic engineering theories of Coloumb, Condorcet, and others. They believed in science, measurement, and theory, and learned to experiment at the school’s laboratories. Many maintained lifelong correspondence with scientists, and dozens of officers made trips to Europe. Like their French counterparts, officers in the Corps of Engineers tended to believe in societal progress through civil works. When they entered civilian practice, they carried these beliefs with them. For example, Whistler served as a railroad adviser to czarist Russia in 1849 and experimented with railroad gauges. In 1857, Haupt conducted soil experiments and developed models when building a bridge as a civilian. Although engineers continued to build the majority of civil works using more practical methods, these men made science in engineering respectable, even desirable. As

Experimentation at the Engineer School of Application

When the Army of the Potomac mustered out of service at the end of the Civil War, three companies of the Engineer Battalion formed a new post at Willets Point, New York. Now at peace, the unit would concentrate on standard engineering training. However, Chief of Engineers Brig. Gen. Andrew Humphreys had grander plans. With West Point no longer exclusively an engineering school and with experience-building assignments surveying the Great Lakes, state boundaries, and railroad routes declining, he envisioned an Engineer School of Application that would provide practical experience for new officers. The plan included using the school as a laboratory to conduct experimental research.

Under the direction of battalion commander Brevet Brig. Gen. Henry Abbot, the unit organized a regimen of drills and daily classes. Facilities built for the school included

barracks, classrooms, laboratories, an observatory, and a circular building with molding sand for constructing scale models of bridges, batteries, and siege works. Lacking funds for more elaborate instruction for the officers, Abbot and the post commander



Students at Willets Point building a pontoon bridge, 1899. *U.S. Army Engineer School.*

started the Essayons Club, in which engineer officers would present scientific papers on research topics in physics and engineering or on experiments conducted. The club met weekly to read and discuss the papers in turn, and later published and disseminated the collected papers. The club ended in 1882 as the technical work of the school increased.

Over several years, the battalion became involved in a series of research projects. In 1868, 11 officers participated in a meteorological study for the Pacific Railroad, in which they collected and published hourly observations of barometric pressure, temperature, and humidity at various elevations. From 1868 to 1872, the battalion reconnoitered and prepared maps of invasion routes for the Army with potential plans for repulsion. After borrowing instruments from West Point and building a field observatory in 1869 (replaced by a permanent facility in 1879), the school regularly made and recorded astronomical occurrences, including valuable data collected in conjunction with the U.S. Naval Observatory, the Lawrence Observatory, and observatories in Europe. In 1871, the school started regular collection of tidal and current measurements.

In addition to collecting scientific data, the Engineering School of Application also conducted a series of experiments to advance technology. In 1868, the battalion tested bridge equipment to help prepare a pontoon manual, and in 1870 developed a system for drying damp powder magazines using calcium chloride. Although the first use of photography in map-making occurred just prior to the Civil War, the school began a study in 1873 to perfect the technique, opening the first photographic laboratory in the Corps in 1875. In 1867, the school undertook research of explosives to counter more heavily armored and armed ships, and collected shock and velocity data, including from detonation of more than 50,000 pounds of explosives at Hallets Point in 1876 and Flood Rock in 1885. The school developed new seismic instrumentation to collect the data.

Perhaps the most important studies, however, were related to developing a coastal defense system of submarine mines. Humphreys assigned the mission to the battalion in May 1869 to explore the relative intensity of explosions, discover laws governing shock waves, test various forms of anchorage, and determine grouping and placement methods for mines. The school conducted, recorded, and photographed explosive experiments with various charges and depths under different weather conditions. In the end, it was able to recommend the size and type of charge, fuses, shapes, buoyancy, velocity, and housing. It even conducted the first tests of the Smith movable torpedo and experimented with electric light mine detection systems. When Congress made the Corps responsible for protection of the coast by submarine mines, the school developed curriculum in 1882.

Although some educational experiments continued, with official War Department recognition of the school in 1885, its re-designation as the U.S. Engineer School in 1890,

and its relocation to Washington, D.C., in 1901, the school adopted more regular courses of study. However, for nearly two decades, it served as the primary test ground for Corps technology.



Officer's Mess at Willets Point. U.S. Army Engineer School.



Willets Point Torpedo Laboratory. U.S. Army Engineer School.

Layton concluded, “West Point engineering did much to establish a tradition of the scientific study of engineering in America.”²⁷

Early Research by the Corps of Engineers

The Corps of Engineers and its sister organization, the Corps of Topographical Engineers, established as a separate corps from 1838 to 1863, quickly became the home of scientifically trained engineers and surveyors. At times exchanging members and sharing responsibilities, the majority of both corps received their education at West Point and held a similar propensity for scientific research. While military engineers primarily focused on surveys and construction of fortifications, roads, canals, lighthouses, and waterway improvements, topographical engineers served as surveyors, explorers, geographers, and cartographers, eventually assuming responsibility for civil works. Most construction projects were fairly straight-forward, requiring only the usual trial and error methodology of civil engineers. Nevertheless, Army engineer officers often experimented with new methods, materials, or equipment, including some basic research. Reference to much of this research was indirect, often earning nothing more than footnotes among participants. With only limited laboratory facilities at West Point and later Willets Point and only limited numbers of personnel (22 engineer officers and 10 topographical engineers in 1824), the vast majority of this research occurred in the field, sometimes through the civilians that executed the projects. By 1837, in addition to Army officers, the Corps employed more than 50 civil engineers and 30 civilian topographical engineers. Each officer typically managed many local superintendents or civil engineers working on half a dozen or so projects at any given time. Boards of scientists and engineers then oversaw and inspected this work, and though some officers questioned the capabilities of civil engineers, several proved highly inventive.²⁸

For the first 20 years, the majority of work in the Corps concerned conducting coastal surveys and building fortifications. To support this task, the Corps enlisted the aid of Brig. Gen. Simon

Bernard, who had served under Napoleon, to oversee construction of fortifications until Corps engineers gained experience. Based on European theory, early construction was standard, though it sometimes involved development of sand or clay models. Only later was there much innovation, as with John Sanders’ cement mixing machine or Chief of Engineers Brig. Gen. Joseph G. Totten’s experimentation with limes, cements, and concretes at Fort Adams, Rhode Island, whose findings the Franklin Institute published in 1838. Totten, who served on the Board of Engineers for Fortifications with Bernard from 1816 to 1826, continued work on fortifications for 30 years, developing iron gun embrasures protected by shutters, new masonry, and other innovations. The engineers he



Brig. Gen. Joseph G. Totten.

trained during this work applied his innovations in forts and sea walls built through the Civil War. In 1867, the Corps established a new Board of Engineers for Fortifications at Fort Totten, New York, under the leadership of Col. John G. Barnard. The board conducted experiments on building materials and designs, including iron armoring, at Fort Delaware and other locations.

Some of this research occurred at the Engineer School of Application. Equally important, as Shallat notes, are the highly technical reports typified by Alexander Bache's coastal studies. The Army engineers conducted considerable research on explosives and military engineering technology such as pontoons, photography, and explosives; in particular, engineer companies at West Point and Willets Point conducted research and development in support of the Board of Engineers or for the Chief of Engineers. In 1872, following a cannon exploding on the *USS Princeton*, experiments on the material led to a congressional board involving the Corps to perform tests on iron and steel.²⁹

The War of 1812 proved the need for improved transportation to protect the nation, and the Corps soon became involved in civil works. In 1820, Congress authorized the first survey of the Ohio and Mississippi rivers to determine navigational improvements, which Bernard and Totten completed. Bernard's report described sand bars and "snags" or downed trees, envisioned experiments with dikes, and recommended improvements. Largely due to the urging of Secretary of War John C. Calhoun that improved transportation routes would aid defense, in 1824 Congress appropriated the first funds to improve the Ohio and Mississippi rivers and Lake Erie, passed the General Survey Act authorizing new surveys with an eye toward planning internal improvements, and passed the first Rivers and Harbors Act in 1826. By 1825, Maj. Stephen Long was conducting experiments with wing-dams to remove sand bars in the Ohio River near Henderson Island. In 1826, Secretary of War John H. Eaton appointed civilian steamboat captain Henry Shreve as Superintendent for Western River Improvements. Shreve developed and patented a special snag-removing steamboat, the *Heliopolis*, with which he removed the large raft of trees blocking the Red River. He also engineered the first manmade cutoffs on the Mississippi River at Turnbull's Bend in 1831 and Raccourci in 1848. In 1829, George Dutton developed the first successful ladder-type steam dredge for a Corps project at Oracoke Inlet, North Carolina, and the Corps later developed other dredge technology, such as the first ocean-going hopper dredge in 1857. By 1828, the Corps had examined, surveyed, or started nearly 100 projects, which continued through 1838 when the newly formed Corps of Topographical Engineers assumed responsibility for civil works projects, including roads, bridges, canals, lighthouses, and railroads. For these, the Corps often adapted European technologies such as levee mats and slack water dams. The research trip of McNeill, Whistler, and Lt. Jonathon Knight made Corps officers railroad experts, and from 1828 to 1834, the Corps became heavily involved in railroad surveys and construction. Similarly, Capt. William Swift and George Hughes studied European lighthouses for adaptation in America, leading to the experimental construction of the first U.S. iron lighthouse built in Boston in 1847 and the adaption of the iron screw-pile foundation by Hartman Bache at Brandwine Shoal, Delaware, in 1854.³⁰



Henry Miller Shreve.

However, the primary responsibility of the topographical engineers, or "topogs," was gathering scientific data in their duties as surveyors and geographers. Like earlier surveyors, topogs

often served as natural historians, biologists, zoologists, botanists, and even early anthropologists in their capacity as explorers. The young nation was expanding, and one of the first duties of engineer officers was to gather data to further exploration and settlement. After the Lewis and Clark expedition to the Louisiana territory in 1804, military engineers led the way into the continental interior: Lt. Zebulon Pike explored to the Rio Grande River in 1808, Long led an expedition up the Missouri in 1819 in a self-designed steamboat, Capt. David Douglass led expeditions to the Great Lakes in 1820 and 1823, and Jedediah Smith and Maj. Benjamin Bonneville led expeditions to California in 1826 and 1832. Accompanying the teams were scientists to help prepare the data. Throughout their explorations, they drew maps and made important discoveries, such as Pike's Peak, the Great Plains, the headwaters of the Mississippi River, the Great Salt Lake, and a variety of natural observations that found their way into scientific journals. In the 1840s, the Topographical Corps turned to a detailed survey of the Great Lakes for the Board of Engineers for Lake Harbors and Western Rivers, a mammoth project worked on by multiple graduating classes of West Point that greatly improved navigation and internal commerce. In 1838, Lt. John C. Fremont blazed the Oregon Trail and in 1842 led the first of his famous expeditions into the Rocky Mountains, but much of the exploration activity of the topogs was cut short by the Mexican War in 1845.³¹

After the war, the topogs received a new mission with the signing of the Treaty of Guadalupe-Hidalgo in 1848 – the U.S.-Mexican border survey, which opened the way for further western exploration and for surveying the route for a Pacific Railroad. Even while border surveys were ongoing, in 1849, Lt. William Emory, Lt. James Simpson, and Capt. Randolph Marcy explored New Mexico, and Lt. George Derby explored Colorado. The same year, Lt. John Gunnison and Capt. Howard Stansbury conducted the first detailed survey of the Great Salt Lake and the Cheyenne Pass, later the route of the Overland Stage, Pony Express, and Union Pacific Railroad. Further exploration into Texas, California, and as far south as the Grand Canyon helped fill in knowledge about the new regions as well as provide detailed scientific data. The descriptions of these explorations were widely published, particularly Gunnison's description of the Mormon settlements in Utah. By 1850, the topogs turned to the other pressing need catalyzed by the Mexican War – railroad routes to the West Coast. Although actually choosing a route proved highly political, the series of surveys conducted from 1852 to 1855 were some of the largest scientific endeavors of the nineteenth century. As historian William Goetzmann characterized it, "Not since Napoleon had taken his company of savants into Egypt had the world seen such an assemblage of scientists and technicians marshaled under one banner." Some 160 scientists accompanied by laborers, field collectors, classifiers, and soldiers took part in the surveys. The data collected were so extensive, it took five years to categorize and publish in 17 volumes of reports and 23 scientific papers. These contained a full volume of maps, hundreds of drawings of animals and Native Americans, 147 lithographs mostly of landscapes, observations of new species, and almanac data. For the next 40 years, scientists classified the findings and developed new theories in fields ranging from geological history and mineralogy to zoology and botany.³²

Although the railroad survey was the largest scientific endeavor, the Mississippi Delta Survey has proved the more influential. After Mississippi River floods in 1847 and 1848, in 1850 Congress authorized a detailed survey and scientific study of the Mississippi River to determine ways to reduce flooding. The Secretary of War initiated two surveys – one by the French-trained civil engineer, Charles Ellet, Jr., and one by West Pointers Long and Capt. Andrew Humphreys. Ellet completed his study in 1852, but Humphreys and Lt. Henry Abbot spent more than a decade gathering an immense amount of data, completing the report in 1861. It was, as a contemporary scientific journal described, “one of the most profoundly scientific publications ever published by the U.S. government.” The topogs conducted several other surveys up to the Civil War, including one of the Canadian border from 1857 to 1861, one of the Isthmus of Panama in 1857, and expeditions into the northern plains by Lt. Gouverneur Warren and others from 1855 to 1860. However, the accomplishments of the railroad surveys and the Mississippi Delta Survey, the amount of scientific data collected, and the influence on scientific and engineering theory inspired their reputation as the most scientific government studies in the nineteenth century. After the Civil War, the Corps of Engineers, reunited with the Corps of Topographical Engineers, continued the tradition of scientific studies, often in cooperation with civilians. For example, in 1867, geologist Clarence King led a Corps expedition to Washington State, publishing seven volumes of data on his return in 1872; in 1871, Lt. George Wheeler organized several civilian expeditions into California, New Mexico, and Colorado; in 1897, Capt. Hiram Chittenden made a scientific study of reservoirs in Wyoming and Colorado. By this time, however, civilian engineering practice was becoming much more standardized and scientific, which influenced perception of the Corps.³³

There was, of course, great value in the scientific data collected by the Corps of Engineers. Knowledge in multiple fields grew exponentially over the course of the nineteenth century. Perhaps of even greater value was the influence that such studies had on other professionals, particularly civil engineers. On the one hand, government studies provided an opportunity for university scientists, who had limited funding available for such expeditions, to rapidly collect data useful for the entire scientific community. Imminent scientists such as Henry Schoolcraft, George Houghton, Joseph Nicolette, George Featherstone, and Charles Geyer accompanied the Corps on its missions, enabling them to significantly expand knowledge in geology, botany, and zoology. On the other hand, inclusion of civil engineers helped to expose them to theory and scientific engineering when most remained bench-trained. As early as 1828, Secretary of War Peter Porter recognized the potential cooperation with civil engineers would have on the profession as a whole, stating that “the interchange of the theoretical science of this national school [West Point] and the practical skill and judgment of our civilian engineers . . . will soon furnish every part of the country with the most accomplished professors in every branch of civil engineering.” Over the next 50 years, the Corps greatly contributed to the engineering profession if, in no other way, by encouraging greater professionalism and scientific engineering practice.³⁴

Topogs and Early Documentation of Native American Culture

By Michael Brodhead, Corps of Engineers History Office

When President Thomas Jefferson sent Capts. Meriwether Lewis and William Clark into the newly acquired territory of Louisiana in 1804, he gave them detailed instructions on what they were to report on. In addition to data on plants, animals, meteorology, geology, and much more, Jefferson instructed the explorers to gather information on the Native Americans of the region. With their customary astuteness and zeal, Lewis and

Clark amassed an impressive body of facts on the many tribes they came upon.

The Corps of Topographical Engineers, the mapping and surveying branch of the Army that existed independently of the Corps of Engineers from 1838 to 1863, continued the Army's exploration of the west. Sometimes instructions from their superiors required the Topographical Engineers, or "topogs" to gather information on the Native American groups they encountered; mostly, however, their own intellectual curiosity guided them. Topographical Engineers such as Maj. Stephen H. Long, Lt. John C. Frémont, and Capt. Howard Stansbury described the cultural attributes of the tribes: religion, family life, food and clothing, dwellings, agricultural practices, burial customs, and weaponry. Social and political life also were areas of interest discussed in the reports: tribal government, relations with other tribes and with whites, and population figures. Many reports also provided Indian vocabularies and Indian names for geographical features.

Two topographical officers made notable contributions to archeology. Lt. William H. Emory's 1846 reconnaissance of the Southwest included his discovery and examination of ruins of ancient towns, such as Casa Grande, in Arizona. In 1849, Lt. James H. Simpson made similar investigations in Chaco Canyon, New Mexico, and Canyon de Chelly, Arizona. Many of their reports included illustrations depicting Native Americans, usually drawn by the artists accompanying the expeditions; however, Lt. James W. Abert, who taught drawing at West Point, furnished his own illustrations.

Like most of their fellow Anglo-Americans, the explorers were generally biased against Native American cultures. However, their observations often were objective or even sympathetic to native peoples. James H. Simpson's report on his survey for an emigrant road across the Great Basin to California included an essay by an Indian agent



William H. Emory as a general officer. *Office of History, U.S. Army Corps of Engineers.*



James H. Simpson. *Mississippi River Commission.*

in Utah who expressed the belief that his charges were incapable of becoming civilized. Simpson wrote a stout refutation of the agent's assertions.

In an age before the emergence of professional anthropologists, the versatile officers of the Corps of Topographical Engineers contributed significantly to a fuller understanding of the Native Americans and their diverse cultures. Their published descriptions proved to be of lasting scientific value and still form the foundation of research by historians, anthropologists, and archeologists.



Engravings of petroglyphs from Maj. William Emory's 1847 report. *Office of History, U.S. Army Corps of Engineers.*

Sketch of Native Americans by Lt. James W. Abert. *Office of History, U.S. Army Corps of Engineers.*



Pimos and Coco Maricopas. *Office of History, U.S. Army Corps of Engineers.*

Researching Muddy Waters

In 1850, Congress authorized the first detailed topographical and hydrological studies of the Mississippi River. The Secretary of War eventually authorized two studies. The first, completed by civil engineer Charles Ellet, Jr., in 1852, was a terse summary of observations and focused primarily on methods of flood prevention. The second, the 1861 *Report upon the Physics and Hydraulics of the Mississippi* (or Mississippi Delta Report) by Capt. Andrew Humphreys and Lt. Henry Abbot, was the most thorough scientific study of the Mississippi before the modern era, resulting in significant advancement of hydraulic physics. As author John Barry wrote, it was also “one of the most influential single engineering reports ever written on any subject.”

After receiving instructions to start the study, Humphreys and Lt. Col. Stephen Long organized three parties in December 1850 to conduct the topographical, hydrographical, and hydrometric surveys, led by James Ford, Castor Smith, and C.G. Forshey respectively. The teams set to work. The topographical team surveyed the river from Routh’s Point to just above New Orleans, in the Delta collecting information on crevasses, flood marks, levee construction, dimension of levees, changes in banks, and related data ending in a

detailed map of the river. The hydrographical team took measurements of cross sections of the river, measured velocity, and sampled the bottom. The hydrometric party took constant measurement of depths, velocity at varying



Bvt. Maj. Gen. Andrew Atkinson Humphreys. Office of History, U.S. Army Corps of Engineers.



Charles Ellet, Jr. Office of History, U.S. Army Corps of Engineers.

depths, wind speed, and sedimentation. The result was a series of comprehensive maps, charts, profiles, sections, diagrams, plots, and drawings included in the report.

Because of illness, Humphreys left the project in 1851 for convalescence in Europe and did not resume the study until 1857. He assigned Abbot to complete the field work. Abbot established gauges at eight locations along the river from New Orleans to Illinois and had parties take velocity and sedimentation observations at four locations from Mississippi to Kentucky. Teams took measurements of prominent crevasses, surveyed the Yazoo Swamp, took detailed observations of the Southwest Pass, and collected miscellaneous data about levees and swamps in the region. Adding to the routine collection of data was the unique opportunity to collect data during the Flood of 1858.

In 1859, Humphreys and Abbot, along with mathematician F.W. Vaughan, sat down to compile, digest, and analyze the data. Because previous hydraulic mathematical analysis relied upon little data, Humphreys found existing formulas to be unreliable. As a result, he developed new theories on river mechanics, including his attempt to develop a universal equation. He commented extensively on existing studies, paying particularly close attention to Ellet's brief and less data-intensive survey. They completed the report in 1861, only months after the start of the Civil War. However, its main influence was not felt until later with the formation of the Mississippi River Commission in 1879.

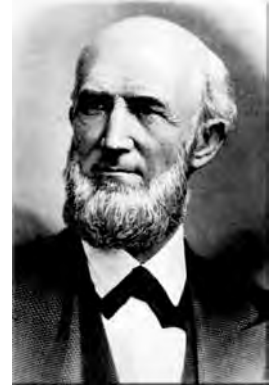
Some recent histories have portrayed the report as riddled with error. There can be little doubt that the Humphreys and Abbot Report contained errors, nearly all concerning its conclusions. Its rejection of outlets and cutoffs as dangerous in favor of primarily using levees to prevent flooding later proved incorrect. Yet the science behind the report and the thoroughness of the data collected were highly influential. The level of data and scientific nature of the report set the standard for engineering reports that had previously often lacked such details. Although its universal hydraulics equation also proved inaccurate, it inspired efforts to establish a universal theory, and within 30 years a more reliable and lasting equation was in use. The fact that for more than 65 years the report formed the basis of Mississippi River policy – right and wrong – is due to its comprehensive scientific nature.



Henry L. Abbot as a general officer.
Office of History, U.S. Army Corps of Engineers.

Professionalization of Engineering

While the Corps of Engineers was developing a more scientific mentality concerned with measurement, theory, and experimentation, most U.S. civil engineers still approached engineering as more of an art that placed greater value on practice than theory. These approaches often clashed, and debates over the value of theory or practice frequently united with political causes. In the Early Republic, Federalists were suspicious of the French, and Federalist engineers were suspicious of French engineering methods. Later, the more populist Jacksonian Democrats were suspicious of the aristocratic West Point and its highfalutin engineering methods. Perhaps best epitomizing competition between methods is the well-known dispute between Chief of Engineers Brig. Gen. Andrew Humphreys and James Eads over the Mississippi River passes – the channels at the river’s mouth. Humphreys was a West Pointer, a scholar, and a firm believer in science. Based on his now famous study of the Mississippi, he believed that jetties could not permanently clear the passes and instead favored dredging or, when that failed, construction of a bypass channel. A self-taught civil engineer, Eads believed that jetties would constrict the channel, increase its speed, and force scouring of the bottom. Then famous for building a bridge across the Mississippi in St. Louis and developing a diving bell and iron-clad ship, he had learned his trade through practical experience, and it was on this that he based his theories. So confident was he on the outcome that he proposed that Congress only pay him if he succeeded. He did succeed, proving for some the triumph of practical over theoretical engineering and leading to the inclusion of civilians in shaping engineering policy for the Mississippi River. Yet the subtle societal changes of the nineteenth century – the technological improvements of industrialization, the belief in the destiny of the U.S. to conquer the continent, the tremendous advances in science, and the growth of populations and urban centers – combined to increase demands on the engineering profession that quickly altered mechanic tendencies.³⁵



James B. Eads. *Mississippi River Commission.*

One of the earliest changes in engineering came in education. Even though many still believed in practical engineering and training through apprenticeship, it was a particularly slow method of producing trained engineers, and the demand outpaced production. By 1840, there were at least three engineering schools – West Point, founded in 1802; Norwich University, Vermont, founded in 1820, which offered its first engineering course in 1825; and the Rensselaer Polytechnic Institute at Troy, New York, founded in 1824, which started offering an engineering degree in 1835. Although most engineering courses still tended to emphasize practice, these schools also provided instruction in mathematics and the sciences. By the Civil War, other mainstream universities started offering engineering courses, including Union College in 1845, Brown University in 1847, and Harvard University in 1854. By 1861, Yale University offered the first Ph.D. in engineering, and the Massachusetts Institute of Technology was founded. The following year, with the passage of the Merrill Land Grant Act, Congress provided aid for the founding of state-operated colleges that taught mechanic and agricultural sciences. By 1870,

there were 21 new schools, with eight offering degrees in engineering. By 1872, more than 70 offered courses in engineering, which grew to 110 by 1890. Estimates are that by 1900, there were more than 10,000 engineering students in the U.S. Through sheer multiplication, the number of university-educated had overtaken bench-trained engineers by 1880, with the result that engineering education and practice became much more standardized. Teaching engineering alongside science and higher math introduced concepts and standards of thought that helped establish scientific engineering practice. Increased educational facilities rapidly increased the number of engineers. Starting at 30 in 1816, the number of engineers grew to 2,000 in 1850, 7,000 in 1880, and 136,000 in 1920. It quickly became impossible to provide experience to the number of students, leading to an increase in teaching theory over practice. Thus, engineering education changed both in quantity and quality.³⁶

Another element in professionalizing the engineering profession was formation of societies that standardized practice, introduced professional ethics and standards, and promoted higher status and pay for their members. Although scientific societies existed in America since the eighteenth century, the first society created specifically for engineers was the Franklin Institute in 1824 in Pennsylvania. In addition to providing members a professional forum, the institute included a laboratory for the development of new technology. With contributions by scientists and artisans, the institute played an important role in the development and standardization of technologies from screw threading to boilers. One of the most influential societies was the American Society of Civil Engineers (ASCE), which formed in 1854 to promote engineering standards, initially for all engineering professions. By the end of the century, there were dozens of such organizations, such as the American Institute of Mining and Metallurgical Engineers formed in 1871, the American Society of Mechanical Engineers (ASME) formed in 1880, and the American Institute of Electrical Engineers (AIEE) formed in 1884. These sometimes also played a role in setting standards and developing new theories, as with ASCE's participation in the 1872 congressional study of iron. Although there were attempts to form broader engineering associations, such as a short-lived confederation of ASCE, ASME, and AIEE in 1903, the societies mostly remained driven by the issues of interest in each field. Nevertheless, their influence on standards of practice cannot be overstated in introducing a scientific ethos if not always scientific practice. Particularly as engineers became overwhelmed with corporate requirements at odds with good engineering, the societies helped balance commercial delivery demands with concerns for professional standards.³⁷

By the end of the nineteenth century, it was this transition to large organizations that set the tone for professional engineering in the modern era. Before 1870, most factories or mills consisted of fewer than 100 employees. Many companies did not have engineers on staff or had to make do with blacksmiths or uneducated mechanics. Most civil engineers operated as private practitioners, similar to lawyers or doctors. By 1900, there were 443 factories with more than 1,000 employees. The size of these organizations allowed hiring of resident mechanical or electrical engineers, with many large companies having entire departments of engineers. Very few engineers worked in the federal government, other than in the Corps. By 1925, about 25 percent of engineers were independent practitioners; by 1965, only about five percent were,

leaving nearly all engineers as members of a large corporation or agency. This resulted in considerable changes in the way engineers operated. Rather than independent engineers making decisions based on practice, corporations pressured engineers to meet schedules and market demands. As Layton and others have noted, this often produced ethical conflicts. Because corporate engineering was much more standardized and impersonal, many found strength in professional organizations, which could act as unions by improving the lot and authority of ordinary engineers. However, the primary escape from being a cog in the corporate machine was through advancement into management. Aside from the rewards of better pay and status, many engineers believed their scientific training as problem solvers could help remake business. Frederick Taylor even attempted to reduce management to a science through the development of principles of Scientific Management.³⁸

Ongoing with changes in the engineering occupation was the scientification of engineering practice. Although the Corps of Engineers and others long stressed engineering theory, in America the rule of thumb was still predominant. However, professionalization created a special niche for engineering, and the primary means of doing so, as with many nineteenth-century professions, was through the application of science. The new engineering societies stressed the need for scientific standards for engineering work. The Franklin Institute and ASCE, among others, participated in scientific studies and experiments. Universities became much more scientific in engineering instruction. Most universities had chemistry or physics labs; by the 1880s several had invested in small hydraulics labs, including Cornell, the University of California, Lehigh, and Worcester Polytechnic. By the 1920s, MIT and other schools had geotechnical labs. This trend extended to business. Large companies such as IBM, Bell Telephone, Kodak, Dupont, General Motors, and General Electric developed research and development laboratories responsible for creating new products. Following in the tradition of Thomas Edison's Menlo Park, these corporate labs included scientists and engineers working together to experiment with materials and devices. A professional, scientifically educated background was a job requirement. With the discovery of microorganisms and the development of pasteurization in 1862, cities began hiring chemists and engineers to plan water treatment, reengineer water supplies and sewerage, and develop sanitation plans. This resulted in the scientification of city planning in general. Even the federal government had started to embrace scientific engineering. By the early twentieth century, the U.S. Reclamation Service was conducting studies into soils classification; the U.S. Army Signal Corps was working with contractors on the development of the wireless telegraph and radio; and in 1901 Congress established the National Bureau of Standards, which operated the first national physical sciences and materials laboratory. In addition to establishing national measurements and weights, the latter conducted experiments on materials and technologies such as fire hoses, railroad rails, and electricity.³⁹

Yet despite the advances in science and engineering that accompanied the professionalization of U.S. engineering, there remained no federal military or civil engineering research facility with national influence. This was not from lack of interest or scientific aptitude, as some Corps critics have proposed – far from it. Throughout its history, the Corps of Engineers had been a constant advocate of engineering science and had long promoted scientific studies across a

range of disciplines. It continued to do so in the years before the creation of the Waterways Experiment Station. It had from time to time used research facilities, but these were temporary, unofficial, and narrow in application, as were those of other agencies. The reason there was no national laboratory was primarily political, and though Congress sometimes debated the need for civil engineering research facilities, it did not act for many years. With the scientification of engineering, and particularly with a series of disasters related to the most engineered body of water in the U.S. – the Mississippi River, the need for a laboratory to examine civil engineering problems became noticeably acute. Times were changing, and soon leading U.S. engineers would seek for the establishment of a national hydraulics laboratory if not within the Corps then outside it.⁴⁰

The history of U.S. engineering was leading to this moment. Since the early development of science, engineers had disputed and sometimes adopted the use of scientific methods. Europe itself had been divided on the matter, with French engineers tending to favor theoretical engineering and English civil engineers tending to favor experience and practice. From the beginning, American experience gravitated toward more practical endeavors. Because of the Revolutionary Army borrowing French engineers and adopting the more scientific French engineering tradition, it was primarily the Corps of Engineers that pushed to make engineering more scientific. Long before American engineers had embraced professionalization, the Corps was developing an engineering school to teach scientific engineering theory. The result was a national engineering organization that gathered and categorized data about the American landscape while steadfastly improving means of controlling it. Yet despite the Corps' progressive view of science, it had always pursued science within its assigned mission, whether military or civil. It was only later, with the scientification of engineering practice for the nation as a whole, that Congress was ready to make research and development a Corps mission in itself.

Chapter Two Toward a National Civil Engineering Laboratory



Early laboratory facilities at the Waterways Experiment Station.

By the twentieth century, research and development within the Corps of Engineers was fairly advanced. The scientific studies at West Point had produced a corps of officers engrossed with scientific inquiry and theoretical explanation. There was regular experimentation with construction of fortifications and underwater mines for coastal protection. This required an advanced knowledge of masonry, wood, and building techniques. As the civil works responsibility of the Corps increased, research increasingly sought to address navigation and flood control issues, including such areas as river training and control of water plants. Yet there remained no national civil engineering research facility, nor the drive to create one. Given the views still prominent among members of Congress that internal improvements were a local issue, the Corps seemed satisfied with conducting most research in the field as part of projects. After a series of disastrous floods in the early twentieth century, there was increased demand for answers on how to control the Mississippi River. In light of advances in European laboratory research into hydraulics using scale models, the field research conducted by the Corps no longer seemed sufficient, with the result that Congress considered for the first time establishing a national laboratory to investigate such questions. At first, the Corps opposed a lab, primarily for nonengineering reasons, but it eventually embraced the idea after the Flood of 1927. Although Corps support for the lab at its founding was lukewarm at best, ultimately the concept of hydraulic modeling had an immense influence on research and development in the Corps, first and foremost through the creation of a hydraulics laboratory whose success inspired additional labs in other fields. By establishing a small research facility at the Waterways Experiment Station, the Corps set in motion the genesis of what would become the leading engineering research center in the nation.⁴¹

Corps Research to the Early Twentieth Century

The passage of time had in no way quelled the scientific inquiry exhibited during the early years of the Corps, and there was considerable research with materials, methods, and equipment. Most of this experimentation occurred at the local level by way of ordinary trial-and-error engineering for ongoing projects. For example, in construction of the Ohio River locks and dams, Maj. William Merrill conducted extensive research on European dam designs in 1871, adopted a French movable dam design with retractable wicket gates, developed a 110-foot rolling truss gate for the Louisville and Portland Canal lock in 1872, and experimented with concrete in 1879 for the Davis Island Dam, one of the earliest U.S. concrete dams. In 1871, Brevet Maj. Gen. Quincy Gillmore developed the first hopper type hydraulic dredge for river use based on a French model developed by Henri-Emile Bazin in 1867. To help clear bars at the mouth of St. John's River, Florida, Gillmore purchased and then converted the side-wheel steamer *Henry Burden* by adding a 26-horsepower, nine-inch centrifugal pump and suction tubes. In 1882, William Gunn Price invented a new cup-type current meter to help measure the velocity of the Ohio River for the Mississippi River Commission (MRC). The Price meter would become the most popular selling velocity meter well into the twentieth century. Brevet Brig. Gen. Cyrus B. Comstock of the MRC, in 1894, directed the Third MRC District to experiment with burnt clay and low-grade concrete as revetment to prevent the caving of banks. In 1901, Maj. George Goethals experimented with using manganese oxide in concrete to reduce the glare of coastal

fortifications. In many cases, contractors tried to persuade the Corps to use their inventions, as with use of SPF Carbolineum by Bruno Grosche and Company to protect woodwork in 1903 or a process for treating clay by Audenried and Bowker in 1906. Such technological development was routine in the execution of both civil and military engineering projects.⁴²

For longer duration or higher profile projects, the Chief of Engineers had, since the nineteenth century, sometimes appointed boards of engineers and scientists to review issues, manage projects, or conduct research, often at the request of Congress. As noted in Chapter One, such boards had overseen work for Western improvements, development of coastal fortifications, the railroad and Great Lake surveys, and other issues. The vast majority of engineer boards focused on specific projects involving ordinary examinations, surveys, and design, such as building a bridge across the Kanahwa River in 1884 or removing obstructions in the Columbia River in 1893. Some boards conducted extensive research in line with project goals. In one 1897 project, Congress authorized the formation of a board to investigate deepwater waterways between the Great Lakes and the Atlantic Ocean to improve commerce. The board met initially on August 11, 1897, and set out on a vigorous series of investigations. Work focused on reviewing plans proposed since 1835, as well as conducting surveys of the Hudson and St. Lawrence valleys and canals in New York and Canada. This included collecting discharge and stage data for Lake Erie and the St. Lawrence and Niagara rivers. Given the varying depths of the lakes, the size of the structures proposed, and the lack of hydraulic formulas for deepwater channels, the board spent about half of its time researching these matters and developing designs. Most interesting was the work on calculating the flow of water over dams in deep water. An article by Bazin had only recently become available in the U.S. discussing his experiments from 1888 to 1898 with flow over weirs having a crest of only 1.5 feet. Needing to develop a working equation for deeper water, the board worked with professors E.A. Fuertes and Gardner Williams of Cornell University to develop new formulas by conducting experiments in wooden flumes with weirs having crests of up to five feet and varying slopes and cross-sections. The board followed this laboratory research with outdoor experiments at Rexford Flats, New York.⁴³

Considerable research prior to World War I concerned building fortifications, which fell under oversight of the Board of Engineers for Fortifications or later just Board of Engineers established at Fort Totten, New York, (Willeys Point) in 1867. After the Civil War, ordnance improved dramatically with the introduction of rifled cannons and armored ships, making U.S. coastal fortifications quickly obsolete. In 1883, Congress established the joint Gun Foundry Board to review the state of armaments. When it established that coastal defense had greatly weakened, Congress authorized formation of a new board to determine what defensive technologies the country needed. In 1885, President Grover Cleveland established the Board on Fortifications and Other Defenses, headed by Secretary of War William Endicott. The Endicott Board reviewed the status of commerce and established which ports required protection, where to place fortifications, how to armor them, and what types of cannons and mines to use based mostly on European weaponry. Although improved weapon ranges, ammunition effectiveness, and ship designs quickly outpaced the board's 1886 technical recommendations, for many years its report informed congressional appropriation and provided basic principles

that guided the Corps to improve fortifications under the auspices of the Board of Engineers. In 1905, Congress authorized a new Board on Coast Defense, and President Theodore Roosevelt appointed Secretary of War William H. Taft to head it. It mostly reported on the status of Endicott Board improvements, but it also reviewed technology changes – advances in communications and transportation, heavier armor on ships, availability of better gunpowder and higher caliber weaponry, electrical lighting, and range-finding devices. Its major departure from the Endicott Board was replacement of floating harbor defenses with longer range weapons and greater naval support. In 1915, after further inquiries by Congress, the Secretary of War established the Board of Review on Seacoast Defenses to review the status of the Taft Board's recommendations. The Corps participated in all three boards.⁴⁴

As a result of the work of these boards, the Corps spent considerable time developing and testing defensive technology. The Chief of Ordnance frequently involved the Corps in testing materials or housing for weaponry. In 1896, Brig. Gen. D.W. Taylor requested aid from the Corps in testing the carriages of new 10-inch guns at Fort Point, California. Col. Charles Suter built housing for them and for 12-inch guns at nearby Lime Point and the Presidio, and after installation of the 10-inchers in February 1897, Lt. Charles L. Potter conducted the tests. In 1901, Maj. Solomon W. Roessler conducted firing tests on mortar pits at Fort Preble, Maine, resulting in recommendations for improving construction of the pits and operation of the weapons – mainly reinforced doors, reinforcing the slopes outside the pits, and telephone lines to position finding stations. When officers witnessed unique construction techniques, they would from time to time make recommendations for trials, as Capt. William E. Craighill did after noticing Chinese defensive walls during the siege of Peking – they had used parallel brick walls with earth filling to absorb the impact of mortars. Some of the research concerned the development of search lights for target spotting at coastal fortifications. From 1900 to 1904, Roessler and others conducted experiments with 36- and 60-inch lights, housing, elevating gears and motors, controls, and generators under different combat conditions. By 1911, because of delays in commercial supply of replacement parts for the lights, the Corps turned to using engineer depots to maintain electrical and motor parts, even while experiments continued with the lights. During World War I, the Corps began to give more thought to defenses against aircraft, primarily through searchlights and microphones to detect the approach of planes. This work eventually brought the Corps in 1917 into cooperation with the Navy, which had contracted Edison Laboratories to aid in tuning microphones to detect the sounds of aircraft. As late as 1896, fortifications were so weak that national security required keeping foreign powers from seeing them. By 1908, the Corps had already increased the number of heavy guns from 92 to 683, plus 514 rapid-fire and rifled light weapons, mines, searchlights, and other improvements.⁴⁵

Not all boards originated for the purpose of overseeing construction projects. The Rivers and Harbors Act of 1902 established the Board of Engineers for Rivers and Harbors to review Corps projects for cost-effectiveness and recommend projects for authorization by Congress. It would become one of the most prominent institutions of the Corps for 90 years. However, it, too, conducted research, although it was usually of the nature of reviewing and compiling data,

The Richardson Highway and Permafrost Research

When members of a U.S. Senate delegation visited the Alaskan territory in 1902, they were appalled that no public roads existed for use in summer or winter. During their 100 years of occupation, the Russians had built only short stretches of road and railroad at Sitka and Kodiak, usually less than five miles long. Since U.S. purchase of Alaska in 1867, Americans had added only a 15-mile road in Skagway in 1867 and a 93-mile dog trail from Valdez to Fairbanks in 1899. As a result, Congress created the Board of Road Commissioners for Alaska in 1904 headed by Col. Wilds P. Richardson. One of its priorities was the expansion of the dog trail from Valdez, and in 1905 the board started conducting surveys and making preparations for construction.



Capt. George B. Pillsbury.
*Office of History, U.S. Army
Corps of Engineers.*

From 1905 to 1906, under direction of Engineer Officer Capt. George B. Pillsbury, the board completed 475 miles of surveys, 46.5 miles of 24-foot wide wagon roads, 272 miles of trails of varying widths, a bridge over the Tazlina River, and it maintained or improved another 40 miles of road. Throughout this preliminary period, the difficulties of building in cold weather terrain led Pillsbury to experiment with a variety of construction techniques. While experiencing some problems with weather-induced time limitations and higher costs resulting from transportation and availability of labor and materials, the largest problem, Pillsbury explained, was “the permanently frozen ground,” which often made traditional construction impracticable.



Engineers constructing a corduroy road as part of a training exercise at Camp Humphreys, Va., 1918. *U.S. Army Engineer School.*

Much depended on the terrain. Where the soil was mostly clay or gravel and not badly glaciated, as at Rampart, the board could strip and grade the road bed as usual. Where the soil contained a mica schist or peaty muck, as at Tanana Valley or Seward Peninsula, stripping the moss or turf covering caused thawing of the surface soil into “an impassible quagmire.” In such locations, the traditional solution developed by the Canadians was to build a “corduroy,” in which engineers would level the ground, place a

protective layer of spruce poles covered with earth, and then build the road. The problem came in areas like Seward Peninsula where no vegetation to build corduroys was available or along the coast where moisture prevented their use. In these cases, the board laid a thick layer of gravel. When thawing revealed that the muck would work its way into the gravel, Pillsbury experimented with empty coal sacks, corrugated iron strips, and other materials to prevent this seepage.

Pillsbury further discovered that, given the thawing soil, ditches were an absolute necessity to prevent sinking of the road, yet often ditches worked under the corduroy, destabilizing the roads. As a solution, he built berms next to the roads to prevent erosion, then built the ditch. In addition, he added culverts to carry off water, although in frozen ground, culverts had to have a floor of wood to prevent water from cutting under or around them. Other than the expense of the materials, the only major difficulty in building the truss bridge over the Tazlina was protecting piles with rock-filled piers.

Once the board settled on methods, construction proceeded fairly quickly. By 1907, the entire 370-mile road from Valdez to Fairbanks was open to sleds. By 1910, continued widening of the road enabled it to open to horse-drawn wagons. That year, the Alaska Department of Public Works reported that 3,500 persons carrying 2,480 tons of freight used the road, a significant uptick in traffic. In 1913, the Army tested the road with a $\frac{3}{4}$ -ton truck, which made 50 miles per day, proving the road’s suitability for automobiles. Continued grading and addition of gravel to the road from 1916 to 1918 made it suitable for stage vehicles. By 1919, more than 90 percent of the traffic was automotive on the road, which Congress renamed the Richardson Highway after the board’s first president. It remained the most developed road in Alaska until construction of the Alaskan Highway in 1942.



World War I Army engineers building a corduroy road. *Office of History, U.S. Army Corps of Engineers.*

not experimentation. The Chief of Engineers, who appointed the board, from time to time requested data to support specific projects or as requested by Congress. In January 1919, the Chief of Engineers assigned the board the duty of designing dredges, barges, and other floating plant for use in river and harbor work. The Rivers and Harbors Act of 1918 requested annual reports on terminal facilities, and the Office of the Chief of Engineers assigned the work to the board, which gathered port data and produced annual Port Series Reports. As a result of the 1920 Transportation Act, the board started to collect and compile statistics on waterborne commerce for the chief, which it published in 1953. From 1936 until its disestablishment in 1992, the board maintained all data for the Corps on ports, waterways, and waterborne commerce.⁴⁶

Research Boards

While the Corps created most boards to oversee particular projects, several boards evolved specifically for the purpose of research and development. For example, in 1897, Congress authorized the Secretary of War to research the removal of water hyacinth from navigable streams in Florida. Chief of Engineers Brig. Gen. John W. Wilson established a Board of Engineers on Water Hyacinth Obstructions in 1898, which included Gilmore and Lt. Col. William H.H. Benyaard, who then obtained the services of J.W. Sackett, an engineer from the Corps' St. Augustine office. The board examined natural controls, mechanical removal using ships dragging nets and log booms, and the use of various acids and a lime and salt mixture developed by engineer P.H. Thompson of Plaquemines Parish, Louisiana. After establishing the lack of effective natural controls and the expense of chemical controls, the board recommended the construction of vessels for management of the plants, admitting that complete removal was impossible. The following year, Congress authorized the construction of ships for removal of the plants. Although research continued on and off for many years to test the effect of various poisons, derricks with grapples, attempts to contain the plants in unused waterways, and methods to dispose of the removed plants, the recommendations of this board remained the method of choice well into the 1920s.⁴⁷

Another prominent research board in the pre-war era was the Board of Engineers on Experimental Towboats. Up to World War I, the majority of towboats in use on the Mississippi River and by the Corps were stern- or side-wheel steam boats. In Europe and in the Western U.S., however, narrower tunnel boats with screw propellers were noticeably more efficient. Observation had suggested that paddlewheel boats used twice the fuel, requiring additional loads, and had one-third more displacement than European models. However, there had been no major experiments with different boat types to confirm the best design. After a boat manufacturer brought this to the attention of the Chief of Engineers, in the Rivers and Harbors Act of 1910 Congress authorized the Corps to design and construct two experimental tow boats. Soon after passage of the act, the Chief of Engineers formed a board in August 1910 headed by Lt. Col. Lansing Beach, which included Lt. Col. Henry C. Newcomer, Maj. Charles Potter, and Maj. Charles Keller. Meeting initially on November 14, 1910, the board's first task was to assemble known data on ship designs and liquid fuels from the MRC and the Navy Bureau of Steam Engineering. In February 1911, it held public meetings in St. Louis, Missouri, to collect various

designs developed by engineers and shipbuilders. It held a test of Ward Engineering Work's twin-screw tunnel boat, the *A.M. Scott*, at Charleston, West Virginia, on March 4, 1911, and arranged a tour of Europe over the summer of 1911 to investigate ship designs. This was particularly helpful as it made the board aware of Italian and German research on the use of steel hulls. A major part of the board's work was the development of model tests of various boat designs. In April 1911, Beach sent blueprints to Professor Herbert Sadler of the University of Michigan to develop the models and conduct tests at the university's Ann Arbor laboratory, and in May the board went to witness the preliminary tests. The board sent new designs with different drafts and curves and made additional model tests in 1912 and 1915. The board published its preliminary report in February 1914, in which it recommended construction of two designs using steel hulls and made specific recommendations on their propulsion, engine, and steering.⁴⁸

Congress further requested in the Rivers and Harbors Act of 1916 that the Corps test the experimental towboats pushing actual barges. Unfortunately, World War I interrupted the planned construction of the towboats due to a lack of available materials and funding. Instead, a reorganized board led by Potter made field tests with steel barges in St. Louis, Missouri, from 1916 to 1920, using various towboats owned by the MRC – the stern-wheel towboat *Nokomis*, the twin-screw tunnel boat *Inspector*, and the stern-wheel dredge *H.S. Tabor*, all steam-driven. The board made its final report in March 1921, in which it concluded that model experiments were consistent with field tests; recommended the loading, engine, propulsion, and horsepower of the tows among those tested; and established that six-barge tows in a single line were most efficient. It is unclear how much impact the report had since the second board was limited in its tests by the vessels available. Also, as the board observed, “commercial service” would ultimately dictate designs, and the government had already favored tunnel boats in recent purchases. At the same time, the early tests of the board did influence the process of designing ships in the Corps using experimental modeling. In 1917, the Chief of Engineers requested tests of barges by Capt. William McEntee at the model tank at the Navy Yard in Washington, D.C., similar to tests conducted for the New York Harbor Line Board. In 1921, the New York District of the Corps requested tests on a drill boat at the yard. The following year, then Chief of Engineers Maj. Gen. Beach requested tests of a new hopper dredges. In short, the work of the board established the usefulness of model testing of boats to the point where, in a final supplemental report published in 1929, the board noted that “the greatest service which it could perform was not in the actual construction, or even design, of towboats and barges, but rather in a systematic and thorough study of the best modern practice,” focusing mostly on model studies.⁴⁹

A major research area involved equipment development. From 1870 to 1922, the Board of Engineers at Fort Totten oversaw equipment experimentation, along with design of fortifications and other issues assigned by the Chief of Engineers, such as submarine mines. The board, which by the twentieth century had assumed more of an advisory capacity, had three permanent members and other rotating members as necessary. With Brig. Gen. Henry Abbot serving as a member for more than 20 years, the board worked closely with the Engineer School of Application, or after its reorganization, with the Engineer Depot at Schenectady, New York, and with field units, which often tinkered with equipment and methods. A good example of

the latter was the assignment in 1902 by Chief of Engineers Brig. Gen. George Gillespie of Maj. William M. Black and the 3rd Engineer Battalion at the Engineer Depot to conduct experiments with entrenching tools, pontoons, winches, and pile driving machines, and Maj. Smith S. Leach and the 1st Engineer Battalion at Fort Leavenworth, Kansas, to develop pack and wagon transportation of equipment. Some equipment research came from necessity, such as the Corps hiring Thomas Edison to help develop barbed wire erection and removal equipment during World War I. The board also became involved in mapping equipment with the development of cartographic photography. Prior to the Civil War, most maps were either hand-drawn or reproduced from plates of hand-drawn maps, both slow and laborious processes. The development of photography after 1839 started to change this, but it was not until the invention of the airplane in 1903 that photographs could easily capture reliable cartographic data. With Germany and Austria greatly advancing the field during World War I, in 1917, the Corps commissioned Maj. James Bagley, a famous camera developer working for the U.S. Geological Survey, to develop an aerial camera, work he continued after the war in cooperation with the newly formed Army Air Service.⁵⁰

With the realization during the war that most field engineers were still using nineteenth century engineer equipment, with the transfer of responsibility for coastal fortifications to the Board of Review, and with the difficulties of coordinating with the distant engineer depot after the Board of Engineers had relocated to the Washington Barracks, D.C., in 1910, the Corps established a Board on Engineer Equipment in 1921 at Camp Humphreys, Virginia, with responsibility to design, fabricate, and test new equipment. By 1922, most activities of the former board had transferred to the new location other than continuation of work on search lights and towers and an underwater targeting system. Testing of pontoons, portable pile drivers, water purification kits, and Lampert portable foot bridges developed during and after World War I continued at Camp Humphreys, and investigations started on areas such as sandbags, demolition equipment, and lithographic printing in cooperation with the depot, the Engineer School at Washington Barracks, field units, and the Bureau of Standards. The board also coordinated with the Engineer Detachment at Wright Field on developing photomapping and topographical technologies, where Bagley continued work on aerial cameras. Developmental work occurred mostly at these facilities or at various test sites; not until late 1928 did the board begin planning laboratory and test facilities at the Engineer School, which had by then relocated to Fort Humphreys. In 1933, the Corps replaced this board with a new Engineer Board, which oversaw the design of engineer equipment over the next decade.⁵¹

By the 1920s, the Corps was also becoming involved in researching the causes of coastal erosion, beginning with the coast of New Jersey. A vacation spot for New York and Pennsylvania since the eighteenth century, coastal areas in New Jersey had exploded in population after the Civil War. Atlantic City became a vacation spot for the wealthy, while Long Branch was a popular religious campground. With the development of railroads and then automobiles, more and more people could escape to the coast. The coast naturally changes and moves as part of the ebb and flow of the ocean, but once development of these lands occurred, investors made the loss of beach property a political concern. Unfortunately, the mechanics and causes of coastal

erosion were not well understood. Most seemed to blame it on severe storms or on subsidence, although leading researchers, such as geologist Douglas W. Johnson of Columbia University, looked instead at multiple causes. In 1922, New Jersey formed an Engineering Advisory Board on Coast Erosion to begin more thorough investigations. On the recommendation of this board, the state legislature funded a formal study and requested aid from the U.S. Department of Commerce and the War Department, both of which maintained various coastal data. The U.S. Coast and Geodetic Survey authorized Cdr. Raymond S. Patton to serve on the board, and the Corps provided Col. Earl I.



Example of beach erosion.

Brown, Col. Eveleth Winslow, and later Col. Newcomer to serve as advisers. The board issued its first report in 1924. In the meantime, Johnson lobbied the National Research Council to form a Committee on Shoreline Studies in 1922, which in 1926 conducted a survey of Atlantic and Gulf of Mexico coastal areas about interest in a cooperative study. In October of that year, 85 delegates from 16 states met in New Jersey to form the American Shore and Beach Preservation Association (ASBPA).⁵²

National opinion was moving in the direction of attempting to solve the beach erosion problem, and though the Corps had provided data and advice on the issue, it had not been heavily involved. That changed by 1929. As lobbying and educational campaigns from ASBPA increased, congressional members began requesting more data. In January 1929, Chief of Engineers Maj. Gen. Edgar Jadwin formed the Board on Sand Movement and Beach Erosion. Permanent members included Col. William Barden, Col. George Pillsbury, Lt. Col. Elliott Dent, and Maj. Brehon Somervell, who involved other Corps officers as needed to discuss problems in their districts. It also appointed civilian advisers, including Johnson and Thorndike Saville, then at the University of North Carolina. During its brief life, this board examined a number of coastal problems, most relating to coastal navigational works or federally owned property. Because of a lack of field data, the board authorized a series of studies. Johnson planned some 30 experiments at two field sites in New Jersey in which lead researchers Morrrough P. O'Brien of the University of California at Berkeley and 1st Lt. Leland H. Hewitt collected measurements of wind, waves, currents, tides, beach profiles, sand samples, and tracer studies. George Pegram of Columbia University designed a current velocity meter first used in these experiments. Using engineering students as summer interns, the board also managed a number of surveys on the New Jersey coast and contracted R.J. Colony of Columbia to conduct a study of New Jersey sand origins. The reports of the board were numerous and formed the first thorough

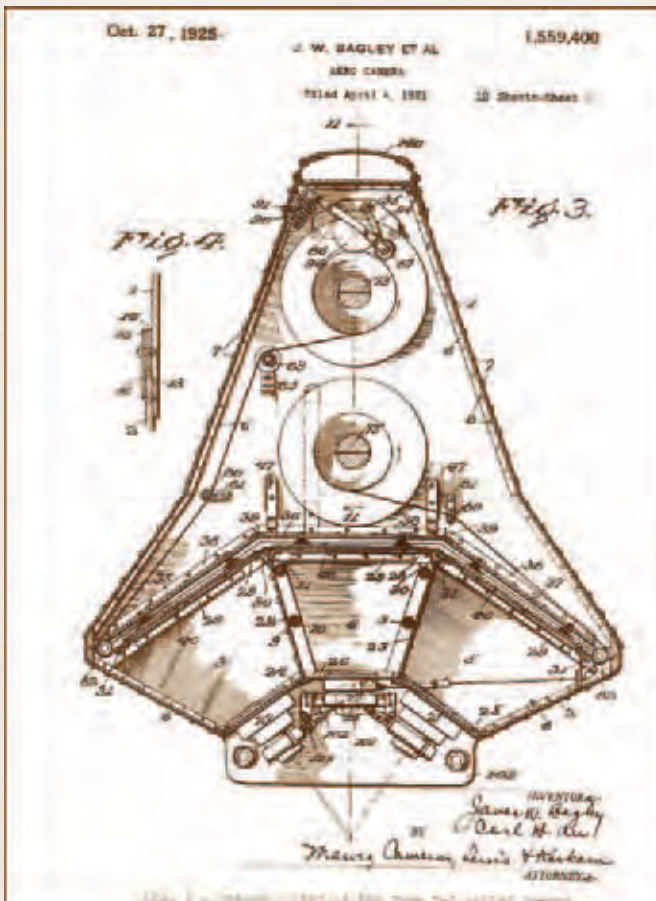
Engineer Pilots and the Development of the Aerial Camera

When you think of the Corps of Engineers, the last thing you think of is airplanes, but in fact the Corps played a crucial role in the development of aerial mapping cameras. Before World War I, the Army had not realized the full potential of the airplane to warfare. Although the Army had used balloons since the Civil War for reconnaissance and signaling, when the Wright brothers developed the first heavier-than-air flying machine in 1903, the Army was not interested. It was not until the aeronautically minded Col. James Allen became Chief Signal Officer in 1906 that the Army created its first Aeronautical Department and purchased its first airplane in 1908. With only limited investment, however, the U.S. soon fell behind European powers in military aviation, including photography-based mapping technologies.

As America entered the war in 1917, the Signal Corps ramped up airplane production, while the Corps of Engineers sought to quickly develop an aerial photographic mapping capability to support cartographic missions. The Engineers commissioned Maj. James W. Bagley, who had developed an improved panoramic camera for the U.S.

Geological Survey in 1910, to develop an aerial camera. Bagley tracked the development of German and Austrian photography throughout the war, and quickly produced an improved three-lens camera, the Type T-1. The T-1 was much faster than European models and provided a simple capability for overlapping photography needed for mosaicing. Although the American Expeditionary Force's Air Service was only able to use airplanes during the last months of the war, the T-1 formed the prototype American aerial mapping camera.

Following the war, in 1920 the Corps assigned Bagley, eventually promoted to Lieutenant Colonel, to head the Aerial Mapping Detachment at the Army Air Service's largest testing facility at McCook Air Field in Dayton, Ohio, later relocated to



Sketch of type T-1 aerial camera developed by Maj. James Bagley.



Maj. James W. Bagley.

Wright Air Field outside of town. The five-man detachment, which included several pilots, conducted research, development, procurement, and funding of aerial cameras and supporting equipment such as reducers, elevation calculators, and plotting instruments. The main contractor during this era was Bausch and Lomb Optical Company.

From 1920 to 1926, the detachment started development of the T-1 through T-3A prototype mapping cameras, the T-4 and T-4A spotting cameras, and the K-3B reconnaissance camera. In an era before wide-angle lenses, these initial prototypes used multiple lenses to increase the coverage area.

The T-5 camera, introduced in 1938, first used a wide-angle lens. Because aerial mapping of the day still used ground surveyors as controls, the cameras did not contain horizontal controls, only an altimeter. More important was the stability of the housing, which included gyroscopically stabilized mounts, cones fabricated with strong alloys, and near-optic quality glass.

In 1926, the Army Air Corps assumed responsibility for developing mapping cameras in accordance with specifications submitted by the Corps of Engineers Board on Engineer Equipment. The detachment remained at Wright-Patterson Air Base to coordinate development until 1943, when it became the Aerial Photographic



Army aerial photography unit with a T-1 three-lens camera, c. 1920. *National Oceanic and Atmospheric Administration Photo Library.*

Branch of the Engineer Board, later a field office under the Geodesy, Intelligence, and Mapping Research and Development Agency and the Engineer Topographic Laboratories.

Bagley, who left the service in 1926 for a lecturing post at Harvard University, later wrote in his textbook, *Aerophotography and Aerosurveying*, that “the pioneer work of aerophotography in the United States has been done chiefly by the Army..., not only to improve military information gathering, but also for making contoured maps and mosaics.”

examination of coastal problems by the federal government. Although the Board ended only a little more than 18 months later, “these early investigators were true pioneers seeking knowledge on a new frontier,” historian Mary-Louise Quinn wrote.⁵³

Despite extensive research in a variety of fields, the Corps had not maintained a permanent laboratory facility other than a handful mostly for educational purposes. A survey of military labs by Secretary Taft in 1908 revealed that, in fact, laboratories were relatively scarce throughout the War Department. Within the Corps, they amounted to an incomplete electrical laboratory at the Engineer School, which Commandant Maj. W.C. Langfitt hoped to use for the entire Corps, and a water testing lab at the Washington, D.C., Engineer Office to support the filtration plant at the Washington Aqueduct. As for construction or hydraulics laboratories, Langfitt noted that “no Civil Engineering Laboratory has ever been started.” In his summary to Taft, Chief of Engineers Brig. Gen. Alexander Mackenzie added that “field laboratories for making acceptance tests of cement and other materials to be used in work of construction are maintained as may be required from time to time in connection with works in progress. No special account of the cost of such testing is kept.” In other words, most Corps labs were part of project expense and were maintained temporarily on project sites, just as research on engineer equipment occurred mostly in the field. The Corps had from time to time considered developing experiment stations, but the obstacle was always financial justification. Later inquiries by the Bureau of Standards in 1926 and 1928 showed similar results. Although the Engineer School briefly maintained a photographic lab and planned facilities for the Board on Engineer Equipment specific to its mission, there was no general construction or civil works laboratory. Most experimentation continued to occur in the field, at the Bureau of Standards, at universities, or at contracted commercial laboratories. This would change with a movement to establish a hydraulics laboratory to study Mississippi River flooding.⁵⁴

Development of Hydraulics Laboratories

It is no surprise that the battleground to establish a national civil engineering laboratory occurred in the field of hydraulic engineering. By 1920, research into hydrology was at the same time one of the most advanced and the least understood of engineering fields. The management of water has always been critical for society, whether for protection, transportation, provision, or cleanliness. Because of this importance, hydraulics became one of the earliest engineering sciences. The early work of Toricelli and Guglielmini in Italy and of Pitot, Bossut, and de Belidor at the French *Ecole Polytechnique* (see Chapter One) had laid the foundation for theoretical studies in hydraulics, yet it remained one of the most difficult fields. These early theorists tried to quantify the behavior of water through calculus, but with only limited success. There were simply too many factors to contend with – velocity, volume, temperature, consistency, direction, tides, and regional factors such as geology, elevation, sedimentation, bed material, vegetation, and air and water quality – making it impossible to precisely calculate all of them before the age of computers. The result was a sense of randomness, which most engineers addressed through continual observation and a good deal of artful estimation. There were some issues that engineers could verify, and Antoine de Chezy and Pierre Dubuat – considered by

some as the fathers of hydraulics laboratories – worked out some solutions in the laboratory, although most experimentation remained field research at project sites. Engineering sciences such as electronics, mechanics, and even civil fields such as road construction were able to significantly advance technology in the laboratory, the result being that engineering laboratories were becoming widespread, particularly in private businesses. However, hydraulics laboratories remained limited in use, with the largest number for educational application.⁵⁵

The difficulty was that, unlike research into electricity or water quality, there was a limited set of thorough hydraulics examinations possible in the laboratory. Testing water for microbes and developing filtering mechanisms were possible in the late nineteenth century because scientists could place water under a microscope. But to test river hydrology as one would test chemicals over a Bunsen burner with repeatable, controlled experiments required being able to take nature into the laboratory. Other than with a few limited areas, such as the behavior of water pouring over weirs or running through pipes, this was impossible for the simple reason of scale. One could not bring a river into a laboratory unless able to reduce it greatly in size, relegating hydraulics research mostly to field experimentation until the advent of scale river models. The building of models has occurred since the beginnings of technology for the same reason people use models today – it was cheaper and easier to work out problems using some type of analogy before building in reality. Reflecting the role of engineering prior to the seventeenth century, early models were primarily for aid in design of structures, not in discovery of scientific principles such as the properties of rivers. Although Euclid had introduced the use of similarity in geometric theory in ancient Greece, Isaac Newton was perhaps first to put into words how the principle worked in the motion of fluids, stating that “like bodies in like situations are said to be moved among themselves with like motions and in proportional times.” This law of similitude had an enormous impact on engineering because of the recognition that the behavior of water or structures in geometrically proportionate models would be the same as the original, allowing greater testing of theory.⁵⁶

Eighteenth century hydraulic engineers, particularly Dubuat and Chezy, obviously understood the principles of similitude, which they applied when developing theories applicable to a variety of dimensions. Yet, other than very limited experiments with pipes and ship models, mainly by Dubuat, few laboratories made the leap to scale models, and many, the Corps included, believed such models less accurate than observations taken in nature. This began to change in 1855 with the experiments of Julius Wiesbach (1806-1871), who made similar but much more comprehensive experiments than Dubuat. In 1865, Henry Darcy and Henri-Emile Bazin conducted a series of experiments on rivers and canals in Paris using a fixed, straight, wooden flume. Most historians recognize Louis Fargue as being the first to build a movable river model – a model with a bottom that could be shaped by the water and thus reflect erosion and bed load movement – in 1875 of the Garonne River. At approximately the same time, William Froude and his son developed an innovative model tank to test the twin-screw sloop, the *HMS Greyhound*, for the British Navy in 1874 and 1883. In 1885, Osborne Reynolds built models of the Mersey Estuary in Great Britain using a wave generator to show silting over time, resulting in recommended channel training works. M.L.F. Vernon-Harcourt, who



Hubert Engels.

worked on the Mersey model, repeated the experiment for the Seine in 1886, which the French government adopted for the Seine Estuary at Rouen from 1890 to 1895. This and glass flume models at the University of Michigan greatly influenced Hubert Engels, who founded an early hydraulics laboratory at the University of Dresden in Germany. Engels brought Gustav Zeuner, a pupil of Wiesbach, to help him begin experimentation in 1891 in the school's Hydraulic Observatory, although he did not build a permanent, separate laboratory facility until 1898. This was the first hydraulics laboratory to use scale river models on a regular basis. Within 20 years, there were more than 30 laboratories in Europe, several of these conducting fairly advanced river experiments.⁵⁷

In the U.S., while there had been experiments and even model experiments very early, most river research came through extensive field experiments. These were of necessity larger than in Europe and produced far more data and often of greater accuracy. The earliest hydraulics laboratory was private, being the work of the Locks and Canals Company at Lowell, Massachusetts. Starting in 1841, five engineers led by French-educated Charles Storrow and James Francis conducted a series of highly influential experiments on turbines and weirs, using three fixed-bed flumes. Hiram Mills, who worked with Storrow and Francis, started a hydraulics laboratory in 1878 for Lawrence Water Power to test conduits and developed a number of instruments, including a variation of the Pitot tube velocity meter and a piezometer to measure earth pressure. Soon other local laboratories sprang up – by 1880 Joseph Davis founded a lab at Boston Waterworks, and Clemens Hershel founded one at the Holyoke Water Power Company, Massachusetts; in 1886 Hamilton Smith published a book on experiments conducted at a mobile lab in California; and John R. Freeman conducted experiments on nozzles, jets, and pipes at hydraulics labs at Washington Mills, Massachusetts, in 1888 and Indian Head Mills, New Hampshire, in 1893. The first U.S. college with a laboratory was Lehigh University in 1887, followed quickly by Worcester Polytechnic Institute in 1894 and Cornell University in 1899. After the turn of the century, Grove Gilbert of the USGS conducted experiments on soil transportation in 1908, Arthur Morgan formed the Miami Conservancy Board in 1913 to test flood protection structures in Ohio, and in 1915 the Department of Agriculture conducted laboratory experiments on irrigation flume and ditch materials proportions. Of course, few of these experiments used scale models, and many were temporary in nature. Nevertheless, by 1922, the Engineering Foundation found more than 70 U.S. hydraulics labs, of which seven were private companies such as turbine manufacturers S. Morgan Smith Company, Allis-Chalmers Manufacturing, and IP Morris Corporation; three were local (certainly an inaccurate count since Freeman mentions many more); two were national, including one at the National Bureau of Standards used for calibrating instruments; and the rest were at universities such as Iowa, Pennsylvania, MIT, and the U.S. Naval Academy. The latter were mostly very small labs used for instruction, general student research, or special faculty projects.⁵⁸

Despite the rather limited nature of many of these facilities, hydraulic experimentation was by the 1920s increasingly advanced, ranging from simple fixed tanks or flumes of wood, metal, or glass to movable-bed models, showing sedimentation movement and scouring. Many focused mainly on testing devices such as nozzles or pipes in actual size or were simple models to test power plants, turbines, or ships and ship movements. Others were mainly for testing structures, such as flow over or through structures such as dams, weirs, and spillways, including some with working gates. Yet, there was also advanced research on complex river problems such as scouring, the behavior of soil, and sedimentation movement in branching streams. The most complex were coastal models that used wave generating paddles and pumps to test waves, flow and tide, wharves, and harbor protection, for as little as engineers understood rivers, the movement of tides was an even greater mystery. The Corps, while not ignorant of these advances, had not fully embraced their usefulness in resolving the most difficult of river engineering questions, although it used modeling in many occasions. And prior to 1920, no one had suggested the desire or need for any kind of permanent research facility to research civil engineering questions. Two factors changed this; one was a series of floods in the early twentieth century. The Mississippi River in particular flooded in 1911, 1912, 1913, 1916, 1922, and 1927, the latter being one of the worst flood disasters the country had ever seen. The other factor was the influence of John Freeman.⁵⁹

Freeman's Drive

Perhaps more than any other individual, it was civil engineer John R. Freeman who was most instrumental in establishing a national hydraulic engineering laboratory. An engineer consultant, Freeman was a well-known expert on hydraulics issues, having worked primarily on water and sewerage projects in the northeast United States, Canada, Mexico, and China. As he told the story, it had been his habit to take trips to Europe to keep abreast of engineering practice abroad. While traveling in Europe in 1913, he visited the hydraulics laboratory at Dresden, Germany. He later testified, "The idea was not particularly prominent then, but immediately I saw that it was a great idea." Over the next several years, while war raged in Europe, he thought about the need for a national hydraulics laboratory and started to make plans for how such a lab would operate in the U.S. In 1922, the American Society of Civil Engineers (ASCE) elected him its president. In his inaugural address, he discussed the advanced state of hydraulics research in Europe and laid bare his desire to establish a national hydraulics laboratory. He reiterated his call in other speeches and papers throughout the next six years. His opportunity to pursue the laboratory would come later in 1922 when he started his collaboration with Sen. Joseph Ransdell of flood-prone Louisiana, who provided a platform in Congress for Freeman to advance his views.⁶⁰



John R. Freeman.

The Mississippi River Flood of 1922, though it caused a limited number of crevasses, exceeded all previous flood stage records. This greatly alarmed Louisiana residents and their

representatives in Congress, who sometimes questioned the wisdom of MRC policies regarding flood control. L.W. Wallace, the executive secretary of the American Engineering Council, later noted that his council introduced Freeman and Ransdell soon after Freeman returned from a tour of the flood in 1922. With Freeman's emphasis on the need for a more scientific approach to river engineering and Ransdell's work on flood control for Louisiana, the passionate pleas of Freeman quickly impressed Ransdell and convinced him to push for the lab. In fact, Ransdell more or less adopted Freeman's elaborate plans as his own. A national lab was not entirely a novel idea. As early as 1915, Thomas Edison had proposed a general national research laboratory to prepare for war, which resulted in the Naval Research Laboratory in 1923. The Corps started planning for a similar facility by the end of the decade to research equipment. However, the proposed hydraulics lab would be the first focused primarily on civil works. On June 13, 1922, Ransdell introduced Senate Joint Resolution 209 to establish a national hydraulics laboratory in Washington, D.C., to study flood control with an initial budget of \$200,000. On July 29, just prior to holding hearings, Ransdell inquired with Secretary of War John W. Weeks about which agency should operate the proposed lab. On consulting with Chief of Engineers Maj. Gen. Lansing Beach, Weeks responded that although any such lab should be the domain of the Corps, he believed that "the hydraulic laboratory proposed would have no value whatever in solving flood control, and that the government would not be justified in incurring the expense of a laboratory for the investigation of flood problems."⁶¹

On September 8, 1922, Ransdell held a hearing of a subcommittee of the Commerce Committee to consider the resolution. His star witness was, of course, Freeman, who stated that, "I have come here to speak in favor of such a laboratory mainly because of my observations of terribly threatening conditions," during the 1922 Flood, and "my profound belief that such a laboratory would be extremely helpful toward better, cheaper, and broader protection against flood disaster." Although he discussed the hydraulics laboratory concept and its history in Europe and America, he mostly focused on the potential uses of the lab. Not surprisingly, many uses were tests that questioned current MRC policy — its accepted conclusions of the Humphreys and Abbot report, its denial of the expediency of river cutoffs, its "levees-only" policy and opposition to outlets, its assigned proportion of revetment, and its views on levee design and setback — on which opinion was divided. He listed 64 other theoretical uses. He then concluded with detailed floor plans and descriptions. Other testimony, including that of Morris Bien, the Assistant Director of the Reclamation Service; R.H. Dowman, a New Orleans businessman; Wallace of the Federated American Engineering Societies; and a letter from Clemens Hershel, all favored the laboratory. In fact, the only opposition was from John Ockerson of the MRC. An engineer with the commission since its creation in 1879, a member since 1898, and a former president of ASCE in 1912, he was the only one speaking with a reputation that rivaled Freeman's. After taking umbrage that "the impression seemed to prevail that an extended series



**Sen. Joseph Eugene Ransdell
of Louisiana. U.S. Senate
Historical Office.**

of laboratory experiments is needed in order to secure data necessary to arrive at a solution of the problems relative to the regulation and control of the Mississippi River,” he stated, “there is no ‘woeful lack’ of data, as has been charged.” While admitting that the MRC did not have all answers, he argued that regarding the problems then under consideration, it would not “obtain any further useful data regarding the Mississippi River problems by the use of laboratory models,” and that the lab “would not materially modify the plans that are now under way.” The Commerce Committee eventually reported the bill favorably and held additional hearings in January 1923 and May 1924, but the Senate took no action on it, due at least in part to the opposition of the Corps and MRC.⁶²

Over the next several years, Freeman worked tirelessly to get approval of his project. However, the Bureau of Budget found a new resolution introduced in February 1926 to establish a hydraulics lab in conflict with President Calvin Coolidge’s financial priorities. After a long absence from Europe, Freeman traveled once again to visit Dresden and other hydraulics laboratories in 1925 to find that their work and facilities had expanded, and that many new labs had opened. On meeting with Hubert Engels, professor of hydraulics at the Technical University of Dresden, Freeman convinced him to help organize a collection of essays by leading hydraulic and hydrological engineers to discuss the work of their laboratories. Among those contributing were Conrad Matschoss, director of the Verein Deutschcer Ingenieur in Berlin; George Henry de Thierry, professor of harbor and canal engineering at the Technical University at Charlottenburg, Germany; Theodor Rehbock, professor of hydraulics at the Technical University at Karlsruhe; and Antonin Smrcek, professor of hydraulics at the Bohemian Technical University at Brunn. In addition, there were 29 other contributors from Germany, Russia, Austria, Czech, Sweden, Switzerland, Italy, Holland, Hungary, Norway, and America. Engels published the original volume in German in 1926. Over the next two years, mostly students and American engineers visiting Germany translated the essays. Freeman added 400 pages of material, including a lengthy introduction by himself, and forwarded copies to Chief of Engineers Lt. Gen. Edgar Jadwin after trying to meet with him in 1927. He published limited copies of *Hydraulic Laboratory Practice* in English in time to hand out to members of Congress in 1928. The following year, the American Society of Mechanical Engineers (ASME) published a revised version. While having only limited value on the 1928 debate, it had unquestionable influence on hydraulic engineers.⁶³

Freeman also worked to establish fellowships to send engineering students and professors to the leading hydraulics laboratories to expose them to laboratory practices he believed would be helpful in solving river problems. He arranged for financial support from ASCE, ASME, and the Boston Society of Civil Engineers, himself contributing \$100,000 when the other contributions were not enough to pay for travel and a year’s room and board. Eventually six applicants, mostly hydraulics instructors and graduate students, won the scholarships, each choosing to study at one of 10 different labs. Freeman accompanied them to Europe, where he



John A. Ockerson, Member, Mississippi River Commission, 1898-1924. *Mississippi River Commission.*

was continually amazed by the advancement of the hydraulics laboratories and the verification and expansion of their practice. By this point, most were focusing not on river problems, but power and irrigation. Nevertheless, the Freeman Fellowships and those that followed in years to come greatly influenced the development of several university labs, and at least five Army officers took part in the scholarships later in the decade, including Blake Van Leer, a captain in the Engineer Reserves and professor at the University of California. At the same time, Freeman also convinced several of his collaborators on *Hydraulic Laboratory Practice* to visit the U.S. as guest speakers. De Theirry, Rehbock, Thoma, and Engels made appearances at MIT in 1927, allowing for greater numbers to hear their views, including three Corps officers attending classes there as well as engineers of the nearby Boston District, which Jadwin sent at the invitation of Freeman.⁶⁴

The Mississippi River Flood of 1927, which made interest in solving flood problems more acute than ever, finally produced results in Congress. In December 1927, Jadwin included in his plan for Mississippi River flood control works a recommendation for a “hydraulic laboratory similar in some respects to such research organizations carried on by certain European governments.” This appeared to be primarily preemptive – Freeman and Secretary of Commerce Herbert Hoover had written Jadwin over the previous year about forming a lab in the Bureau of Standards. In February 1928, Ransdell was preparing to introduce a new bill establishing a national hydraulics laboratory in the bureau, unlike the 1922 resolution, which had left the location open. By this time, Freeman was convinced that the Corps was not the appropriate agency for the lab and wrote that the Corps was still in the “‘phlogiston age’ of applied science,” referring to the ridiculed eighteenth century theory of combustion. When asked by the Bureau of Budget about the proposed bill, Secretary of War Dwight Davis replied March 3 that “studies and experiments pertaining to river and harbor, and flood control, works should be under the direction of the authorities who are charged by law with planning and executing these works.” Shortly thereafter, Ransdell introduced S. 1710, which the Senate Commerce Committee reported favorably by April 6 and the Senate passed a few days later. The House Committee on Rivers and Harbors held hearings on the bill on April 26 and 27, with Freeman; Ransdell; Dr. G.K. Burgess, the director of the Bureau of Standards; Gano Dunn, chairman of the National Research Council; as well as past presidents and current members of ASME, ASCE, and other organizations, all favoring the bill. At the last minute, Jadwin cancelled his appearance, but testified before the committee on May 15. Noting first that he recommended a Corps laboratory to investigate flood control problems, he argued that any such laboratory must be “located on the Mississippi, where experiments can be carried on with the types of alluvium and sediment characteristic of the valley and where a laboratory force can be in immediate contact with the field forces which are executing the actual river work.” He followed this with a point-by-point refutation of reasons provided by Ransdell for placing the lab at the bureau. Although Burgess and Freeman later provided counterarguments, the House rejected the bill. At the time of Jadwin’s testimony, Congress had already passed the Flood Control Act of 1928 authorizing a lab within the Corps of Engineers.⁶⁵



The 1927 Mississippi River Flood.

Opposition of the Corps

Given the propensity of the Corps toward scientific research, its opposition to a hydraulics laboratory may seem oddly schizophrenic. Corps critics have made much of the opposition of Beach, Jadwin, Ockerson, and others to a proposed hydraulics laboratory as proof of a Corps policy opposed to laboratory work and a general spurning of modern scientific approaches. Yet there appears to have been no formulated policy, only the opinion of specific engineers as to the value and political expediency of the work of such labs to answer specific policy questions. Opinions were much divided on the subject, and, though the Chief of Engineers spoke for the Corps, the opposition to the lab was not representative of the whole organization. Soon after the hearings on Resolution 209 on September 8, 1922, Beach, though he had already privately expressed his own doubts on the matter, nevertheless requested input from other Corps officers, both active and retired. The result, as one would expect, was a range of opinions. A few were enthusiastically for it. Retired Brig. Gen. Henry Jervey responded that it would be a “vast benefit” and “practically and scientifically useful.” In an earlier letter, Philadelphia District Engineer Maj. L.E. Lyon had informed Beach of his own use of hydraulic modeling on

the Delaware River in 1921. With the concurrence of Northeast Division Engineer Colonel Newcomer, Lyon believed it “desirable to place the Corps of Engineers on record as among the pioneers in applying experimental methods on river models to the improvement of rivers.” In 1927, Newcomer himself would, after attending lectures on hydraulic modeling, write that “it was worthy of consideration by our Engineer Department.” Others were definitely opposed. MRC member Col. George M. Hoffman wrote that “such a laboratory would not only be enormously expensive but might be dangerous in encouraging the substituting of unreliable determinations from small-scale models from those far more accurate deductions that heretofore have been based on the action of the river itself.” Other opinions were mixed. Former MRC President Col. Curtis Townsend, recognized as a river authority even outside the Corps, argued that modeling was extremely valuable for education, but that “when an engineer has learned these fundamental principles, the river itself affords a much better means for testing them than any laboratory can create.”⁶⁶

As a whole, the Corps was not ideologically opposed to engineering research. It had emphasized scientific and theoretical engineering methods since its founding, it had often conducted research on a variety of topics, and it had long experimented with modeling and even hydraulic modeling. Since the days of Smeaton, it was common engineering practice to build mock-ups or scale models of waterwheels, bridges, or other devices. The Corps used such models frequently, both in engineering instruction and in actual practice. After seeing British Royal Engineers use scale models at Chatham in 1873 to design fortifications and siege works, Brevet Brig. Gen. Henry Abbot had included a building with modeling sand for similar use at the Engineer School of Application. According to Ockerson, civil engineer Robert E. McMath had conducted hydraulic model experiments on bed load movement for the Corps as early as 1880, only five years after Fargue’s moveable model, though apparently McMath met with limited success and abandoned the models shortly thereafter. Nevertheless, he did use data gathered at the Lowell hydraulics lab in developing his theories. Experimental ship model basins, developed initially by the Navy in 1898 at the Washington Navy Yards, figured greatly into Beach’s research on towboats from 1910 to 1915. Lyon, in his research on the Delaware River, built a concrete river model in 1921 at an old barracks at Fort Mifflin, Pennsylvania. “It is believed that the model of the Delaware River referred to is the first of its kind to be constructed in this country,” he wrote to Beach. He was mistaken, however, as U.S. civil engineers, including those in the Corps, had used fixed-bed river models for decades. The Corps had modeled the Mississippi River at New Orleans, and Jadwin testified that he had himself been involved with Caleb M. Seville in experimental modeling of the Gatun Dam in Panama and that modeling played a role in the construction of the Ohio River moveable dams and Wilson Dam at Muscle Shoals, Alabama. Most of these hydraulics experiments did not involve scale models, and the majority using models applied more to testing structure or vessel designs than to understanding river behavior. They were also temporary and project-specific, leading to no lasting knowledge or facilities. The Corps’ conservatism in the application of river modeling certainly put it behind Europe in laboratory research, but it was not for a lack of familiarization with the concepts.⁶⁷

Rather, Corps opposition to establishing a permanent laboratory facility seems to have been primarily personal and political. For some, a negative experience with modeling was the guiding force. As an engineer for the MRC, Ockerson was aware of the failure of McMath's model experiments in deriving data as accurate as the river itself, and hence lacked confidence in the results of modeling for some problems. Townsend and Beach both doubted some of the conclusions that Freeman had reached using modeling of the Yellow River in China. Similarly, according to Brig. Gen. Herbert Vogel, Jadwin became predisposed against submitting the Corps to the results of a national hydraulics laboratory during design of the spillway at Bonnet Carre, Louisiana, in June 1928, when Tulane University professors tried to impose modeling results on him. The influence of civil engineers favoring practical experience over theory undoubtedly led to inclinations about the limitations of modeling. Beach, Hoffman, Townsend, and other officers who served on the MRC worked closely with reputable civil engineers such as Ockerson, Henry Richardson, Charles West, and Edward Glenn with long experience on the Mississippi. Thus, Townsend believed "the volume of discharge and the character of the river bed are controlling [sic] influences which cannot be reproduced in a laboratory," while Hoffman argued that, unlike with ships or small streams of uniform flow, "when it comes to such a stream as the Missouri or Mississippi, it can positively be stated that the variable elements affecting the flow will so vitiate deductions from model results as to render them valueless."⁶⁸



**Maj. Gen. Edgar Jadwin,
Chief of Engineers, 1926-
1929.**

In such views, the Corps, as with other large agencies, tended toward conservatism. Given the ideological constraints on federal spending, which remained relatively small by today's standards, many leaders did not want to recommend spending money on untested techniques, and many within the Corps believed that Congress would balk at public expenditures on a permanent research facility. It was one thing to build a model using project funds, such as the Delaware River model, or to build a laboratory at existing facilities such as the Engineer School where operating costs would be low, as Beach suggested in his letter to Jervey. It was another to recommend construction of a large, expensive facility that would have only limited application, which Hoffman believed was "money wasted" and Secretary Weeks opposed as an expense not justified. Better that such a laboratory should be housed at a private institution such as MIT, as Chief of Engineers Maj. Gen. Harry Taylor suggested to Freeman. This attitude did not change until after the Flood of 1927, but even Jadwin's arguments in favor of a small lab on the Mississippi River as opposed to in Washington, D.C., hinged on the lower cost of land and utilities on the river, the availability of water, and the higher costs of coordinating with the MRC from Washington.⁶⁹

Ultimately, however, the decision was political. The heart of the issue was really the MRC policies over which there had been a long-running dispute. Established in 1879 after a series of Mississippi River floods to improve navigation and reduce flooding, the MRC had espoused river works primarily composed of raising levee heights, closing outlets, constricting

the channel, and prevention of caving banks through revetment. The MRC also opposed works endorsed by various other prominent civil engineers, such as floodways and cutoffs, which Freeman had argued for in his testimony in 1922. In his response, Ockerson noted that, "It is the general impression existing among some people in New Orleans to the effect that what we need is the results that we might get from laboratory experiments." Questioned by the sub-committee on Freeman's points in contradiction to MRC policy, he argued against cutoffs and testified that no amount of laboratory research would improve MRC understanding of revetment or jetties, about which experiments were ongoing on the river. When Ransdell suggested that, in the view of the MRC, "it is a question of money and not of engineering," Ockerson noted that even with limited funding, it reduced the number of breaches during flooding from more than 700 in 1884 to a mere handful in 1922. When Ransdell complained of the \$75 million price tag, Ockerson introduced figures showing an increase in the value of farmland by \$30 an acre. In short, the MRC policies had reduced flooding and provided greater benefit than cost. After the Flood of 1927, some of these policies changed, yet Jadwin still argued that "so-called hydraulics experts" have proposed larger levees, cutoffs, and even new revetment, and he questioned "the soundness of any new suggestions from the same sources."⁷⁰

As with most political questions, the main issue was always one of control. In the nineteenth century, Humphreys had tried to keep the Engineer School of Application in an unofficial capacity so he could control it and the experiments it conducted. In debating the 1922 lab resolution, Townsend had written Beach that, "I am very strongly in favor of intelligent experiments on rivers, and believe that the Engineer Corps has been too conservative in this matter. What I object to is the trifling with scientific subjects by the Departments in Washington, which is called Scientific Investigation." When Jervey had suggested that the Bureau of Standards might be an appropriate home for the lab, Beach hoped that, "your view of work done by the different departments will induce you to take another think on the laboratory," in light of the responsibilities and experience of the Corps. His own argument was the same as that forwarded by Weeks to Congress; while not recommending the laboratory, if it should be established, "its administration should be with the Corps of Engineers," which "has charge of our river and harbor works" and "has had for generations past." In proposing his own laboratory, Jadwin argued strenuously for keeping it near the Mississippi River under Corps control since, "they have been the leading hydraulic scientists of the country for over a century." Notwithstanding his seeming ill-informed comments about transporting water and sediment to Washington, which seem more an excuse to maintain local control, his main arguments against a lab in Washington under bureau control were the cost, its potential lack of responsiveness to Corps requirements, and that, "Laboratory experts isolated from contact with field experts often come to grossly erroneous conclusions." Despite questions by Sen. Harold Hawes and others that he exceeded his authority by going "outside the question of engineering entirely" in addressing questions of economics and administration, in the end, Jadwin's arguments carried the day.⁷¹

Foundation of the Waterways Experiment Station

In response to the Flood Control Act of 1928, on June 18, 1929, Jadwin ordered MRC President Brig. Gen. Thomas H. Jackson to establish the authorized laboratory near Memphis, Tennessee, which was roughly halfway between New Orleans and St. Louis, where the headquarters for the MRC then lay. Jadwin's approval was less than enthusiastic, and he waited for more than a year after passage of the act despite encouragement from several quarters. While believing the lab would eventually "develop into a central place for scientific investigation with respect to the Mississippi Valley," he ordered that it be "constructed gradually as information develops as to the needs of such a laboratory," which may be "continuously or intermittently." He also budgeted only the meager amount of \$50,000 for the lab, which barely provided enough funding to get the lab started, but not enough to operate it. At Jackson's request, Col. Francis B. Wilby, the Memphis District commander, located a site and all but completed plans for a small facility, expandable to no more than 200 square feet due to the limitations of space. In the interim, Jackson's deputy, Maj. Paul S. Reinecke, questioned Wilby about potential directors for the lab, noting the difficulty they were having in finding a reputable civilian. In August, he wrote, "Do you know anything about Lt. Vogel who is detailed for duty in your district? Has he had sufficient training to undertake this work?" A West Point graduate of 1924, Lt. Herbert D. Vogel had, after completing his Master's Degree at the University of California at Berkeley in 1928, received permission to study at the *Berliner Technische Hochschule* (Berlin Technical Institute) in Charlottenburg, Germany, and at the hydraulics laboratory there. At Jadwin's instructions, he also toured hydraulics laboratories in Germany, France, Italy, and Austria. Soon after graduating with his Ph.D., Vogel received orders to assume command of the new lab, arriving in Memphis in October 1929. However, only weeks after Vogel arrived, with the assumption of Maj. Gen. Lytle Brown as the Chief of Engineers in November 1929, a November 16 telegram instructed Wilby to "suspend all construction." Verbal orders followed that the station would move to Vicksburg, Mississippi, where the MRC headquarters was relocating. Wilby passed on the verbal orders for Vogel to prepare for relocation pending formal change of station orders. Vogel made several trips to Vicksburg over the coming weeks to locate a site for the lab.⁷²



Lt. Herbert D. Vogel.

Not knowing the level of activity required but encouraged by Reinecke and Jackson, Vogel believed the key requirement was flexibility. Anticipating the need for multiple models of various sizes, he sought a large area supporting an open floor plan with adjacent land to allow expansion or pursuit of outdoor activities. After conducting a search within a 10-mile area around Vicksburg, Vogel identified a 147-acre site near Halls Ferry Road about 4.5 miles from Vicksburg near Durden Creek, which flowed via Hatcher Bayou into the Mississippi about two miles away. With the purchase of the property finalized in August 1930, Vogel proceeded with construction. First, he built a 400-foot long, 19-foot high dam across the creek to create a 40-acre artificial lake just above the laboratory. A concrete sluiceway with a steel conduit and

Herbert Vogel and Weimar Germany

The man who became the first commander of the Waterways Experiment Station (WES), Lt. Herbert D. Vogel, lived for more than a year in Weimar Germany prior to the rise of Adolph Hitler, providing unique insights into the country before World War II. While pursuing his Master's Degree in Engineering at the University of California at Berkeley, he became interested in fellowships being offered for study in Germany. After clearing his application with the Chief of Engineers, who was interested in German hydraulic labs then in vogue, Vogel applied for and received tuition support to study in Germany.

Vogel and his wife arrived in Berlin in October 1928, and after finding quarters in a house shared with an assistant military attaché and a young woman working at the American Consulate, he started classes at the Berliner Technische Hochschule in nearby Charlottenburg. Once he received certification in the German language, he started work on his Ph.D. in hydraulic engineering, with oral examinations set in August 1929. He also spent considerable time at the Prussian Research Institute for Hydraulic and Marine Engineering learning about hydraulic modeling from Rudolf Siefert, Baurat Kurner, and Sigmund Eisner. In March, he toured other hydraulic laboratories across Europe.

Vogel's overall experience was positive. "Those were happy times for us as the winter ran its course," he later wrote. The German people were friendly and generous. At Christmas, German friends opened their home to the Vogels, feasting them sumptuously. He was invited to numerous parties. When Loraine Vogel became pregnant, the landlady

arranged to provide them with a first floor suite with a separate bedroom and private access to the gardens. "This was but one example of the generosity afforded us by the Germans we came to know. Everyone was always kind, making us feel his interest in us, and trying in dozens of ways to make us at home in a foreign country."

At the same time, Vogel also experienced the high prices that accompanied the post-war depression in Weimar Germany. "It was necessary to apply the principles of frugality," he wrote. After



Lt. Herbert D. Vogel, second from right, in Germany.

paying for their room, the family lived on about \$40 per month, which limited transportation and entertainment. "We enjoyed walking great distances and getting acquainted with the city by underground, street car and bus. The lack of money made these things necessary, and we learned they could be pleasant." There was a lot of window-shopping instead of the real thing, and when it came time for his orals, Vogel had to borrow the required formal attire.

He saw very little of the political situation, other than glimpsing Reichschancellor Hindenburg once at a horse show and hearing occasional whispers of dissatisfaction. "Even though dimly from the background came murmurs about the 'war guilt lie,' rumors of a little man down south named Hitler, worries about the growing strength of the communists in the Reichstag, a fear of singing 'Deutschland Uber Alles' in communist localities; in spite of this, life was good."

When Vogel visited Germany again in 1934, the Nazis were in control and much of this had changed. "The whereabouts of most people who touched our lives in those days are unknown," he noted. His landlady had disappeared, her house turned into an art school. All of the students and professors he knew at Charlottenburg were gone. Eisner, a Jew, was arrested and eventually liquidated. Munitions plants had popped up; everywhere were signs about how to protect against bombs. "Berlin has changed....Everywhere there was fear, and from the background came the sound of marching feet."

"Perhaps it was too good to last, and perhaps that is true of all good things. We do not realize how good they are until it is too late," Vogel concluded.



Outdoor hydraulic river model in Dresden, Germany.

vertical gate provided an outlet for the reservoir and allowed supply of water for experiments downstream. Outdoor models could obtain from the reservoir a controlled flow of up to 1,500 feet per second. The laboratory building was 209-feet long with two, two-story 33- by 51-foot wings on the east and west ends of the building for offices and a 49-foot wide experiment hall, which could accommodate a 175-foot flume and electric pumps. Within the facility was a computing and drafting room, an instrumentation room, a carpenter shop, a photographic dark room, a library, and a sediment laboratory. Some 20 feet above the level of the laboratory building on a cliff face was the director's house, which Vogel himself designed with the look of a European cottage. The design of the facilities was both very simple, with minimal facilities, space for a relatively small staff, and use of natural resources to power models, yet was large and incomplete enough to allow easy expansion if needed. Design of the dam by local contractors started in May 1930, and construction was complete by October. Construction on the entire site was complete in December 1930, although the lab started its first project earlier in June. After some debate on the name of the new lab, the Corps settled on the U.S. Waterways Experiment Station (WES), which in light of continued controversy with Freeman contained neither the word hydraulic nor laboratory.⁷³



Willingham Wood, James Jobes, and Herbert Vogel at the Waterways Experiment Station with the director's house in the background.

Despite initial obstacles, the lab quickly grew. Staffing was extraordinarily difficult in the shadow of the stock market crash of 1929 and resulting federal hiring freezes. The Corps of Engineers prohibited new civil servant appointments, which meant Vogel could only hire temporary laborers. Further, all federal employees received a 15 percent cut in pay, which

made enticing experienced personnel from the private sector difficult. To fill the immediate needs of WES, Vogel arranged for loan of James Jobes, Isham Patty, and Willingham Wood and a few laborers from the Corps' Vicksburg District. Over the next several months, Vogel worked to bring on a staff of highly talented and enthusiastic, if inexperienced, engineers and scientists, mostly recent graduates or students. Although Vogel initially had a very limited budget, Reinecke gave him carte blanche to sign his own travel vouchers, which enabled him to take recruiting trips to leading engineering schools, including the University of Illinois, University of Michigan, Cornell University, and MIT. Among these hirees were Illinois graduates Joseph B. Tiffany and Frederick R. Brown, who became technical directors at WES. Yet despite the initial limitations on hiring, Vogel later found the staff forced upon him to be a strength. As he observed in 1970:

We got the staff we needed, though it wasn't the staff I wanted. I am certain that with unlimited funds and no restrictions on employments I would have gone out to find people who had already made names for themselves. That would have been a great mistake, for such people would have pursued their activities along conventional and accepted lines. The young men that I had to take were energetic, daring and innovative.

By the summer of 1931, the Office of the Chief of Engineers began to send new officers to WES to study until they attended the Engineer School at Fort Belvoir. Among the young officers visiting WES were Lieutenants Paul W. Thompson, K. D. Nichols, C. D. Curran, Francis H. Falkner, Ward T. Abbott, Thomas A. Lane, and J. L. Person. Of these, Thompson and Falkner later became directors of WES. In this



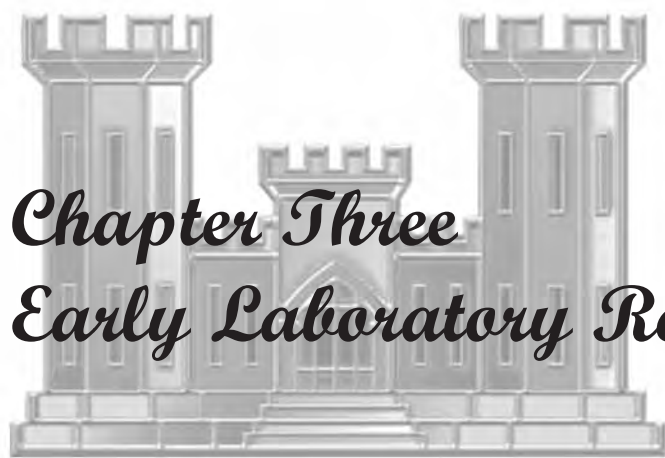
Early experiment at the Waterways Experiment Station.

way, although the permanent staff of WES initially remained relatively small, Vogel had a steady stream of personnel. With the rapid growth of work, WES staff grew to about 20 employees in 1931, 32 employees in 1932, 185 in 1933, and 215 in 1934. Although only a dozen or so held positions as professional engineers, many of the laborers were engineers by education.⁷⁴

Ironically, while WES was being established and starting to grow, the hydraulics laboratory in the Bureau of Standards, finally established in 1930, "was not a success," as one lab proponent later admitted. Soon after General Brown's appointment by President Herbert Hoover, he testified before the House Committee on Rivers and Harbors, February 4, 1930, that he had no opposition to another hydraulics lab. Congress quickly approved the act and Hoover signed it on May 14. Although Freeman was at first elated, he soon butted heads with Bureau of Standards Director George Burgess over the scale of the initial facilities, and eventually they parted ways, Freeman dying soon after. Freeman had always considered the initial appropriation a down payment on starting the program, not the maximum the lab could initially spend. As a result of the financial limitations imposed by its management, the lab lacked an effective organization and competent staff. This much Jadwin had foreseen. In his testimony in 1928, Jadwin had predicted that the director of the lab's "time will be divided." With many other agencies pressing for an answer, "we will go on when we get our turn, and our problem will be handled in a way that he wants to handle it." With WES under the direct control of the MRC,

it proved vastly more responsive and effective than the Bureau of Standards lab would have been under these circumstances. As for Freeman's role in the creation of WES, there can be no doubt that, despite his disagreement with the Corps on the lab, had it not been for his continuous pushing, no lab would have emerged. In this, and in promotion of laboratory research in general, "The great influence of Freeman on American—if not world—hydraulics can never be fully appraised," Hunter Rouse and Simon Ince concluded.⁷⁵

After more than six years of debate and resistance, the Corps of Engineers finally established the first national, permanent hydraulics laboratory at the Waterways Experiment Station to examine the civil engineering questions that were framing national debates on flood control and navigation. In the end, although political considerations played a major role in the decision to finally press for a lab within the Corps, the creation of WES was also an acceptance of a national desire to conduct greater research on river flooding and the changing direction of hydraulics studies. As Jadwin argued, "The proposal for a hydraulic laboratory ... is nothing in any way revolutionary. It is simply a further step in systematizing one particular branch of the theoretical researches which the Corps of Engineers has been carrying on for many years," through, "laboratory tests at the site of the works in question." Once Congress made clear its desire to support increased investigation into river flooding, the Corps embraced the creation of a national hydraulics lab, which it formerly resisted. It had also started to embrace the trend in hydraulics research, which increasingly "emphasized the experimental approach to the almost complete exclusion of the analytical," as Rouse and Ince observed of early twentieth century hydraulics. Laboratory studies soon became the focus of engineering research across many fields, a trend the Corps finally accepted. Over the next 50 years, the Corps established other laboratories in support of other agencies and the nation to examine engineering questions related to topography, coastal erosion, soils, concrete, and other areas. It marked the beginning of a new era in Corps research and development.⁷⁶



Chapter Three

Early Laboratory Research



Measuring current velocity during model tests at the Waterways Experiment Station.

With the Waterways Experiment Station (WES) established *du jure* in May 1928 and *de facto* in June 1929, the Corps of Engineers began its first era of laboratory research. It was a highly innovative time. Although WES engineers initially used the established procedures of hydraulics laboratories in Europe, the scale and timeline for many of their projects were such that they had to experiment widely with distortion ratios, materials, and methods, pushing the bounds of Newton's principle of similitude to new extremes. Yet in experiment after experiment, they showed that the models were helpful, not only to test new projects on the Mississippi and other rivers, but also in demonstrating general hydrological principles. As they successfully proved these methods during the decade before World War II, WES grew tangentially in size and influence until it was unquestionably the largest facility of its kind in the world. Soils research, which in the beginning merely supported the hydraulics lab at WES, soon came into its own. Concrete research in the North Atlantic Division expanded beyond regional concerns, eventually requiring relocation to WES. At the same time, Corps research in several other areas began to congeal and grow. The preliminary attempts to coordinate with states on coastal research gained national impetus with the formation of the Beach Erosion Board in 1930, and that board began working on gathering coastal data and conducting experiments on building materials in a coastal environment. Topographical research, particularly in photogrammetry and aerial mapping, developed considerably under the direction of the Engineer Board, which established facilities at Camp Humphreys, Virginia. These researches portended eventual consolidation of these areas into the large research centers or laboratories they would become.

First Experiments at WES

After receiving approval from Chief of Engineers Maj. Gen. Lytle Brown and Mississippi River Commission (MRC) President Brig. Gen. Thomas H. Jackson, the newly assigned director of WES, 1st Lt. Herbert Vogel, selected a site in Vicksburg, Mississippi, and began drawing up plans for the lab (see Chapter Two). Even while Vogel was working to purchase the property, start construction, and employ personnel, WES received its first mission in June 1930, a survey of Mississippi River sediment readings. Because this task did not involve modeling or other laboratory work, the small number of employees working for WES at the time could accomplish it without active facilities, which were still under construction. The team collected the required data, and in July, Vogel published the first report from WES, "Paper H," describing the results. Another report on sedimentation followed in August, for which WES analyzed 26 samples in its still incomplete soil laboratory.⁷⁷

In late 1930, General Jackson approached Vogel about the possibility of building a model for the Chicago District showing how far floodwaters from the Mississippi River backed up into the Illinois River. The circumstances were still less than ideal – there were still no complete facilities or materials, only Vogel and Freeman Scholar Clarence Bardsley (on loan from the Missouri School of Mines) had ever built a model, and the project deadline was 30 days. Yet Vogel believed that "if refused, the entire approach might be discredited." WES started working on the model on December 20, 1930, which, because of the constrained time, required

considerable innovation. Using cut sheet steel as an elevation template, Bardsley carved a miniature river channel directly into the soil between the building site and Halls Ferry Road, while the rest of the team built and calibrated a weir to control the water from the reservoir on Durden Creek. Due to problems with soil erosion that would result from its use, they believed they had one shot at using the model, from which they determined the limit of the backwater to be 120 miles. This was the first successful test of an outdoor model at WES.⁷⁸

The first indoor model at WES actually started earlier. In October 1930, the Cincinnati District requested a model of the Ohio River Lock and Dam No. 27; however, the team was unable to begin work on it until completion of the laboratory building in early December. With great fanfare, WES started work on the 30- by 12-foot fixed-bed model, which, due to the smaller section of river under investigation, was much smaller than the Illinois model. The team established the navigation stages and, using creosote-soaked sawdust floating in the water, was able to determine current direction and scouring effects. Vogel completed the study and reported the results in May 1931. In January 1931, WES began work on the first movable-bed model of the Bonnet Carre Spillway just north of New Orleans to test erosion around railroad trestles based on railroad company concerns. The small, 30- by 12-foot outdoor model of the entire stretch from the spillway on the Mississippi River to Lake Pontchartrain was part fixed, part movable. Tests with model trestles showed that erosion was not an issue. A related study of erosion of railroad embankments later that year included both an outdoor and a smaller indoor model in which WES conducted repeated trials. WES engineers took gauge readings and dozens of photographs, quantifying the effects of various water levels and velocities on the embankments.



The Illinois River backwater model—the first outdoor model at the Waterways Experiment Station, 1931.



Bonnet Carré Floodway model.

This was, perhaps, the earliest of those rare occasions when WES conducted basic research not related to a specific construction project. These early experiments received considerable attention in engineering journals, as did WES in general in the years after its founding.⁷⁹

Soon, many other projects followed, to the point where work levels required rapid increase of employees. In 1932, WES started work on a model of the St. Andrews Bay, Florida, ship canal – the first tidal model. For the Louisville District, it modeled contraction works on the Ohio River to remove a well-known obstruction – Walkers Bar near Paducah, Kentucky – in order to reduce dredging costs. For the Jacksonville District, WES modeled designs for a spillway in the St. Lucie Canal, Florida. The majority of such work involved structures such as dams and spillways, and from 1933 to 1940, WES modeled no less than eight structures, including dams at Fort Peck, Montana, and Sardis, Mississippi. Whatever reluctance that had existed in using scale river models among Corps engineers prior to 1930 quickly faded with the opportunity for the districts to check hydraulic problems before beginning construction, in some cases significantly reducing costs or level of risk – WES saved the St. Lucie Spillway \$25,000 in concrete alone. Yet, while work for other districts increased steadily after 1932, the mainstay for WES remained projects for the MRC or its districts, particularly New Orleans, Memphis, Vicksburg, and St. Louis.⁸⁰

Support for the Mississippi River Commission

Chief of Engineers Maj. Gen. Edgar Jadwin had placed WES under the authority of the MRC, where it would remain until after World War II. As a result, WES directors maintained a close relationship with MRC personnel. The MRC president gave many orders orally in face-to-face meetings, often in social settings, and was able to resolve many issues in daily conversations. Particularly during the early years, General Jackson gave Vogel a free hand in recruiting, construction, expansion, and operation, and was very supportive of growing the lab. “Almost anything I wanted to do was alright with him,” Vogel recalled. Later MRC presidents took a close interest and held considerable influence in the development of facilities, in budgeting issues, in organizational changes, and in specific experiments, and the MRC as a whole provided considerable support over the years, for example, by supplementing WES resources from the Vicksburg District.⁸¹

At least through 1936, the majority of WES projects were for the MRC or districts in the Lower Mississippi Valley Division specifically for the purpose of solving problems with the river. Many of these concerned the placement of river works. For example, in 1933 WES modeled nine different Mississippi River locations to determine the proper placement and effectiveness of dikes, including replacement of a dike system at Point Pleasant, Missouri. Other experiments helped to analyze failure of works. WES ran tests on various levee sections to determine seepage rates, and its soils laboratory examined foundational causes of levee collapses. WES conducted two major backwater studies, which ordinarily would have taken years of observation on the river. The first of these, the Illinois River Backwater Model discussed previously, proved the capability of WES in January 1931. Quickly following it was another backwater model of the Yazoo River near Eagle Lake, Mississippi, in early March 1931. This one was much larger – 13,000 square feet – and WES had more time to build a fixed-bed concrete model that allowed more extensive trials. Perhaps the most ambitious of these early tests concerned a plan of cutoffs proposed by then Col. Harley Ferguson in 1930. Many engineers, including in the Corps, had rejected cutting across loops of the meandering river to shorten it as too dangerous and likely to increase flooding. A model of the Greenville Bends – a particularly meandering section of river below the Arkansas River – conducted in 1931 demonstrated that this was not the case. Outdoor models in 1932 of cutoffs at seven locations from the Greenville Bends to Natchez, Mississippi, showed varying effectiveness of proposed cutoffs. However, despite the mixed results of site-specific studies, WES models removed many objections to them, opening the door for Ferguson to pursue his cutoff plan when he became MRC president in 1932.⁸²

A significant amount of the work concerned the Mississippi River and Tributaries (MR&T) Project that had its origins with the Jadwin Plan of 1928. In addition to continued river works such as revetment and levees, key components of the project were the five planned floodways or spillways at Bonnet Carre, Louisiana; East and West Atchafalaya Basin, Louisiana; Birds Point-New Madrid, Missouri; and Boeuf or Eudora, Arkansas; the latter of which were later dropped as unnecessary. As already noted, in January 1931, WES helped to model railroad placement in the Bonnet Carre Spillway, although most major construction at that site was already nearing

completion. Construction on the Bird's Point-New Madrid Floodway was also under way when the MRC requested WES to model the floodway to determine the impact of the diversion on the Mississippi River. To better test the MR&T Project, the MRC authorized the Mississippi River Flood Control Model in 1935, the first of the giant models at WES. Representative of a 600-mile stretch of river from Helena, Arkansas, to Donaldsonville, Louisiana, the model was 1,065-feet long, requiring engineers to make allowance for curvature of the earth's surface. WES had to purchase an additional plot of land to house the model. Using 42 personnel to reproduce the floods of 1927, 1929, and 1935 in the model, WES determined that improvements made to the river since 1929 would have held back these floods. It also allowed tests on levees to contain the Yazoo backwater, examination of distribution down Old River to the Atchafalaya Basin, and experiments on operation of the Morganza Floodway, which replaced the East Atchafalaya Floodway into the Atchafalaya Basin. Only a few years later, in 1941, Chief of Engineers Lt. Gen. Eugene Reybold initiated a model of the entire river valley – the Mississippi Basin Model – based on concepts he developed in 1937. WES built the 200-acre model in nearby Clinton, Mississippi, and would run multiple tests on the river model in part or in total from 1952 to 1973,⁸³ and again in 1993.

Initially, as a lab created to conduct Mississippi River research, WES operated mostly out of MRC overhead. General Jadwin had originally allotted \$50,000 for the lab, of which Memphis District Engineer Col. Francis B. Wilby had used about \$1,800 on plans for construction in Memphis. This, added to the \$81,000 that General Brown provided in 1930 to finance construction, left a total of approximately \$129,000 out of direct appropriations to purchase property and equipment for the lab. These were the only direct appropriations for the lab until 1934, yet by the end of 1930 construction costs exceeded \$122,000, not including purchase of equipment or salaries, which all came from MRC overhead funds. From 1930 to 1932, the MRC paid all of the overhead and operating costs for WES, amounting to more than \$110,000. By 1933, however, the level of work for other districts had grown to the point where it became more difficult to pay for operation of WES out of overhead. That year, WES began operating on a reimbursable basis for other districts, although 83 percent of work and funding still came from the MRC. More commonplace today, the concept of a government agency competing for work was fairly new and required WES to sell its services and keep customers satisfied as would a commercial business. Finally, in 1934 the MRC established a revolving fund of \$100,000 – reallocated from the MR&T Project appropriations for Memphis, Vicksburg, and New Orleans districts – to pay for expenditures, which the MRC billed to the districts on a quarterly basis. As the workload changed over the next several years, this fund varied in size from \$200,000 to \$850,000. By 1934, WES business for other districts had increased to more than 25 percent, which paid for 17 percent of its overhead. In other words, within five years, WES could partially pay for itself. By 1940, only a little less than a third of WES project funds came from the MRC, which was paying for less than half of WES overhead. MRC funding remained more or less at this level until WES began reporting to the Office of the Chief of Engineers in 1949.⁸⁴

The Greenville Bends Model and Mississippi River Cutoffs

Since the Humphreys and Abbot *Mississippi Delta Report* in 1861, it was the policy of the U.S. Army Corps of Engineers to studiously avoid cutoffs – cuts across meandering loops of the river to shorten it. Although there had been three natural cutoffs in 1876, 1886, and 1913, the Corps and the Mississippi River Commission (MRC) attempted to prevent these and other cutoffs from occurring through bank protection and revetment and banned man-made cutoffs altogether as a danger to navigation and flooding.

After 1929, several factors worked to change this. One was the occurrence of a natural cutoff at Yucatan Bend where the Big Black River intercepted the Mississippi south of Vicksburg. The bank had been caving there for several years, and when the low water inspection in September 1929 revealed that only a narrow ridge remained of the bend, MRC President Brig. Gen. Thomas H. Jackson ended attempts to prevent it and instead closely monitored its progress. These observations suggested that cutoffs might be beneficial. A second factor was a plan of cutoffs put forward in November 1930 by Col. Harley Ferguson, the South Atlantic Division Engineer serving on the Board of Engineers for Rivers and Harbors. As a result of board approval of this plan, the Chief of Engineers assigned him as president of the MRC in 1932 to pursue the plan. A third factor was the formation of the Waterways Experiment Station (WES).

With the capability of modeling river behavior in the laboratory, engineers could now test the concept of cutoffs without subjecting residents near the river to potential flooding. In November 1930, at the request of the Chief of Engineers, Jackson ordered a study of the Greenville Bends, a particularly meandering span of river between Memphis and Vicksburg running 98 miles over a 45 mile distance. WES started work on the fixed-bed model of Tarpley Neck in December, ran more than 100 tests, and in April 1931, WES Director 1st Lt. Herbert Vogel submitted the final report. In it, he presented the



Col. Harley B. Ferguson.
Mississippi River Commission.



Outdoor Greenville Bends model at the Waterways Experiment Station, 1932.

“irrefutable” results: a lowering of stages by 2.2 feet for 45 miles above the cutoff and no change below it. Further, the model showed “no indication of detrimental effects due to the cut-off,” directly contradicting earlier theories. He published the results widely.

Vogel followed this report with another on cutoffs on the remaining necks in the Greenville Bends in August. After repeating the experiment with multiple scenarios and getting similar results, WES created a moveable-bed model of the same region to test scouring to get a better understanding of the mechanics of a cutoff. The following year, to test additional sites WES expanded the existing outdoor Yazoo Backwater Model to include even more of the river. Although the results of a report in April 1932 were mixed, with a cutoff at Diamond Point showing positive results, a cutoff at Ashbrook showing negative results, and most of the others showing no great benefit or detriment, it did help with deciding which projects would prove most valuable.

In June 1932, only days after he became MRC president, Brig. Gen. Harley Ferguson started work on the Diamond Point cutoff, which opened in January 1933. The MRC quickly completed additional cutoffs in March, May, July, and December 1933. By 1942, the MRC had completed 10 more, for a total of 16 cutoffs since 1930. These shortened the Mississippi by 151.8 miles, which, along with other improvements, lowered flood stages in Vicksburg by seven to eight feet and even more in other locations. Although Gerard Matthes later questioned any direct influence that WES had on Ferguson’s program, which proceeded regardless of model results, there can be little doubt that early tests by WES increased understanding of cutoff mechanics and helped convince many of their benefit, thereby opening the door for Ferguson to pursue an even bolder plan of action.



Brig. Gen. Harley Ferguson, second from left, at the Diamond Point Cutoff. *Mississippi River Commission.*



Yucatan Cutoff. *Mississippi River Commission.*

The Largest Hydraulic Model Ever Built

The Waterways Experiment Station (WES) built many models during its day, but none is more famous than the Mississippi Basin Model (MBM), the largest and most complex hydraulic model ever built. The MBM was the brainchild of Lt. Gen. Eugene Reybold, who served as Chief of Engineers from 1941 to 1943. He came up with the idea in 1937 while serving as the Memphis District Engineer. The smaller models of the many reaches of the Mississippi River had proved their worth for examining the effect of individual projects, but did not provide a view of the entire system. He believed that only a model of the entire 1.25 million-square-mile basin could accurately test behavior of the Mississippi River and Tributaries Project and its levees, floodways, cutoffs, and reservoirs.

When he became Chief of Engineers in 1941, Reybold contacted Joseph Tiffany and Gerard Matthes at WES to initiate a preliminary study. WES completed that study in October 1942 and a detailed project report in April 1943. A site selection committee chose an 822-acre site outside of Clinton, Mississippi, 35 miles east of Vicksburg.

WES acquired the property in November 1942 and started construction in January 1943. Due to manpower shortages resulting from employees serving in World War II, Reybold arranged for the use of German prisoner-of-war laborers, with construction of an internment camp to hold prisoners from the elite Afrika Korps.

By August 1943, the POW camp was in full operation, commanded by Col. James McIlhenny. There were 2,432 prisoners, which grew to 2,912 by 1944. In 1943, around 400 able-bodied POWs worked at the camp or on local farms picking cotton, with the remainder working at the model. There were only a few security issues: one case of sabotage for a POW placing gravel in the oil box of a freight car, a tunneling plot resembling *The Great Escape*, and a single escaped



Aerial view of the completed Mississippi Basin Model.

POW, who authorities captured after two days buying a bus ticket to New Orleans. There were complaints about mail, the use of American clergy, and treatment of 29 generals, who a Swiss representative inspecting the camp, described by reports as “anything but an anti-Nazi,” saw merely as upper class Germans. Authorities believed correction of these issues would bear fruit in post-war



German prisoners of war digging a drainage ditch at the site of the model.

Germany. The work day ran from 0800 to 1600. For their work, the POWs received 80 cents per day. By 1944, more than 1,800 were employed on the model (64 percent of the camp). By 1945, about 1,178 of the 1,651 remaining prisoners worked outside the camp, nearly all on the model. The number continued to decline after the war until the camp's closure in March 1946.

From 1943 to 1946, while WES personnel collected the necessary surveys for design of the model, the prisoners cleared nearly a square mile of ground, dug drainage ditches for 85,000 feet of sewers, and shaped the model. Construction of the hydraulic portions of the model began in 1947 using cross-section templates and later using 100-square-foot contour sections. The model took more than one million cubic yards of cut and fill, and included all levees and floodways and relevant highways and railroads in the basin, with removable sections that allowed tests on smaller projects. The MBM required about 1,000 gallons of water per second to operate. Two



Individual model section prior to assembly.

2,500-gallon-per-minute pumps recirculated the water, stored in an elevated 50,000-gallon tank and fed into the model through 30,500 linear feet of pipelines. It came into operation in part in 1952 and in whole in 1959 – more than 15 years after construction began. It was complete in 1966.

One of the MBM's greatest innovations was its automatic controls and instrumentation. Since it required 250 personnel to operate the model manually, WES researchers spent four years developing the controls. More than 125

commercial companies contributed parts and designs, but many of them the WES engineers had to design themselves. There were inflow controllers, outflow programs and regulators, a system of control valves, staging transmitters and recorders to make sure the proper amount of water was released, and a timing device that synchronized the operation of the model. A control house managed the entire operation.

The MBM quickly proved its worth. In April 1952, the Missouri River Division used the model to forecast the progression of the great Missouri River Flood of 1952. The completed section of the model operated for 15 straight days to provide data on the flood. Estimates are that the data provided by the model helped avoid \$62 million in damages. The model also helped prevent failure of the Old River Control Structure during the Mississippi River Flood of 1973. With the structure experiencing severe scouring, WES used the MBM to test use of the Morganza Floodway to relieve pressure at Old River. As a result, the floodway came into operation for the first and only time. In addition, WES operated portions of the model to test more than 70 local projects.

For many years, the MBM attracted visitors from all over the world to see the largest hydraulic model, which WES maintained for self-guided tours. It transferred custody of the model to the city of Jackson, Mississippi, early in 1973, but leased it back for another 20 years with the Flood of 1973. With MBM's eventual decline and deterioration from lack of use, WES closed the project, and turned it over to the city in 1993.



Interior view of the control room at the model.

Innovations of the First Decade

During the early years of WES, lab workers made a number of discoveries and innovations, including several in the field of hydraulic modeling itself. WES made major improvements to instruments to use in models – those sensitive to smaller velocities and scales – and began to experiment widely with sizes and distortion. European hydraulic models rarely exceeded a 1:300 ratio, and most were proportionate with little or no distortion between vertical and horizontal scales. To some degree, this was due to the scale and size of European rivers, which tend to be narrower and deeper than in the U.S. For example, the Rhine River in Germany ranges from 500 feet wide and 75 feet deep in the Rhine Gorge to 2,100 feet wide and 30 feet deep in the Netherlands. The Mississippi River, by comparison, is at times more than a mile wide but on average only about 30 feet deep. The reason for this, as Vogel explained to his doctoral board, was that Europe was shaped like an inverted saucer with the rivers running off the edges, cutting through rock. In America, major rivers run to the middle of the continent and down the Mississippi, which is hence wilder and more alluvial. Because of the scale of the river, Vogel often faced having to model portions of the river that, if proportionate, would have been hundreds of feet long to be of sufficient depth. “We had problems with size that had never been encountered before and that took us to greater distortions of scale than had been believed practicable,” Vogel said. He routinely fell to using a 1:10 or even 1:20 distortion, “where it’s either that or no model study at all,” Capt. Paul Thompson would later recall. The first model built at WES – the Illinois Backwater Model – had the largest distortion of the early models because of its immense length. It used a horizontal scale of 1:1,200 and vertical scale of 1:48 (due to the English measurement graph paper used at the time, most early models were in units of 12), with a distortion of 1:25. At that size, it was the largest model ever built at the time. The Greenville Bends Model had a 1:4,800 horizontal scale and a 1:360 vertical scale, with a distortion of 1:13. Needless to say, no one was sure if it was possible to get reliable results with that amount of distortion, but in test after test, as Vogel dutifully reported in scientific journals, he did get results, proving that one could play loosely with similitude, depending on what one was trying to test. As Thompson wrote in 1938, “in getting a model to ACT like its prototype, it frequently is necessary to take steps which preclude the model LOOKING like that prototype.”⁸⁵

The level of distortion in WES models eventually became a point of concern with Capt. Francis Falkner, who served as director after Vogel. With the huge increase in the number of experiments, Falkner worried that field engineers had developed “unwarranted expectations” of model tests. He ordered an extensive study of the effectiveness of models, while simultaneously lowering the number of active projects from 45 to 34 in order to verify model accuracy. The study included three components. First, he requested a survey of the effectiveness of other hydraulics laboratories. Of the 50 labs he contacted, however, only 17 provided any data at all, and only four of these involved open channels – the rest being tests of weirs or siphons. These four were favorable, but were too few to draw any conclusions.



Lt. Francis H. Falkner.

Next, he requested a comparison of all available data on projects that WES had modeled that the districts later built. A review of 14 projects through 1937 verified the success of the models – only a single project did not behave as modeled, a tidal model of St. Andrew’s Bay, Florida. Last, he ordered tests performed with nine existing movable models. These showed significant discrepancies between model behavior and actual waterway behavior. For the most part, research indicated this was due to poor operational techniques or maintenance – algae or corrosion or the like – and Falkner issued a number of memoranda standardizing construction and operational methods. For example, he promoted the use of alternative model materials that behaved closer to real sediment, including coal, resin, gilsonite, and haydite. He also ordered his assistant director, 1st Lt. Kenneth D. Nichols, to prepare a study on the theories of hydraulic similitude. After reviewing studies by Cornell University, the University of Iowa, and European labs, and after a series of experiments, Nichols and Joseph Tiffany concluded that the distortion in early WES models was greater than accepted norms. Future models would include less distortion, among other improvements. Although unable to fully verify the effect of these improvements prior to the end of his tour, Falkner made lasting contributions to the reputation and reliability of WES work.⁸⁶

Ultimately, however, Vogel and most of those who followed him understood that a model was a subjective engineering tool, not an objective calculator to produce a final mathematical result. There were too many unknowns and too many aspects of models that the builder could manipulate to vary results. Vogel later explained:

We must be careful not to regard experimentation, or work with models, as an end to itself. Experimentation is not a substitute for thought, it’s an aid to thought. People who are engaged in scientific pursuit must always keep that in mind. It’s the reason that in working with hydraulic models, it’s so necessary to test and adjust until the model is made to simulate the action of the natural stream.

“The model, in fact, represents a series of compromises,” Thompson also concluded. “It is,” he wrote, “only a semi-scientific instrument,” concerned more with solving a specific problem than finding abstract truth. In this, they found modeling to be more akin to engineering theories of hydraulics. A great deal of experience and artistic design filled in gaps where scientific exactitude was lacking.⁸⁷

Most of the research conducted by WES was applied research focusing on specific projects. However, as already noted, WES engineers did from time to time investigate basic scientific or engineering questions, although even these had some object or application in mind. Occasionally, WES engineers would try to play with the models to determine basic laws, but applied projects often intervened. Greater opportunity came with assigned research projects. One of these was the investigation of bed load movement. The MRC was interested in diverting sediment from the Mississippi River to improve navigation. However, the movement of bed load was not well enough understood to propose solutions. The MRC requested that Vogel investigate the movement of bed load around river bends. The only guiding theory was James Thompson’s helicoidal theory of 1876 that currents move materials from outer to inner bends

Pioneering Instrumentation at WES

Throughout the history of the Engineer Research and Development Center, many employees have received recognition for their scientific contributions, several projects earned prizes, and several of the center's various laboratories have won awards. However, few people know that even the instruments developed at the Waterways Experiment Station (WES) made unique contributions to science. In 1986, the American Society of Civil Engineers designated WES facilities as a landmark, resulting in a historical study of WES instruments by the Historic American Engineering Record.

From the beginning, the lack of commercial availability of precise instruments to measure results of model and field tests left WES engineers to design many unique devices. Several of these the lab later licensed to instrument makers or else similar devices later appeared on the market. Particularly from the lab's founding to 1950, engineers designed a number of historically important instruments.

The earliest devices developed measured velocity and flow. Although devices to measure water velocity existed since development of the Pitot tube in 1732, these were less accurate when measuring low velocities. In 1932, Carl E. Bentzel, a research assistant at WES and graduate of the Chalmers Institute of Technology in Sweden, modified these using floats and weights in a tapered tube. The Bentzel tube was able to more accurately measure low velocities. In 1944,



Carl E. Bentzel demonstrating the use of the Bentzel tube.

WES developed a small cup-type current meter to use in models – the WES Midget Velocity Meter or Miniature Current Meter – based on the Price model developed in 1885. In 1946, WES developed velocity meters for relief wells to check seepage levels.

Another problem tackled by the WES Instrumentation Services Division was the creation of pressure transducers. The lab found piezometers or other devices to measure earth or concrete pressure to be unsatisfactory when measuring pressures over extended periods or near moisture. From 1947 to 1954, WES developed a water-proof transducer that recorded readings on an oscillograph. Another device developed after 1952 – the Hawser-pull device – measured strain and pressure on boats within locks.

With WES turning to coastal modeling after 1935, the need for tide and wave generators and gauges became apparent. At first, the lab used a simple drum-controlled tide gate with floating indicators. Later, it used a system of pumps driven by a tidal clock. After 1950, correlation of the inflow and outflow lines allowed greater automatic control,



Leupold and Stevens midge current meter, above, and three variations of miniature Price current meters below.

as well as improving recording and error-correction. WES also developed sophisticated wave generators to create waves of specific height, length, period, and angle. These included plunger or paddle types to create the waves, which gauges carefully monitored and automated devices or computers controlled. Creation of hurricane surge models required an additional tank to hold extra water, which the tide generator controlled.

Perhaps the most sophisticated instruments developed were those for the Mississippi Basin Model, which, because of its sheer size, required greater automation than models used theretofore. After researching devices for four years and receiving bids from multiple commercial firms, WES purchased 160 instruments but still had to design many others, including the complicated controller that had to coordinate inflow and outflow for the whole model based on automated elevation measurements, synchronized with a single timer. A control house with automated controls and later computers managed the sequence of events from a single location.

Of the more than 150 instruments that the Historic American Engineering Record found at WES, researchers identified half as significant enough to record for posterity based on categories such as scarcity, age, originality, and overall contribution to advancements in research. Of these, eight were considered highly significant, and another 20 made considerable contributions. In a facility where making contributions to science was widespread, even the instruments had their day in the sun.



Multiple variations of Pitot tubes used at the Waterways Experiment Station.



Bifurcated flume at the Waterways Experiment Station.

to create deposits. Vogel spent considerable time modeling the problem using the Greenville model. Part of the problem was how to measure current at different water levels. Floats could show direction on the surface, and dropping dyes in the water showed movement of current, but neither showed movement on the bottom. The answer came one day when Vogel was boiling oatmeal and noticed that raw oatmeal floats on the bottom with the kernel pointing up toward the current. To demonstrate the effect, one evening he and Thompson actually placed a jar of water with oatmeal in it on his new Victrola phonograph to spin it around, earning a rebuke from Vogel's wife. Further model experiments demonstrated that in wide rivers bed load moves to areas of low velocity. To test diversion of bed load, WES developed a new type of bifurcated flume in which Vogel experimented with various sediment types taken from 75 samples in the lower Mississippi Valley until he determined the velocity needed.⁸⁸

Another study producing highly innovative basic research involved the meandering of alluvial streams. In 1932, the MRC requested studies on the distance the Mississippi River would maintain its channel under normal conditions. The resulting studies improved a basic understanding of the causes of river meandering. WES engineers built a 50-foot by 15-foot flume, filled it with 9-inches of sand, and ran a single channel of water down the middle. Then, by varying slope, the rate of discharge, and the amount of sediment introduced in the water, they measured how quickly bends formed. In doing so, they discovered that the bends increased with the amount of bed load. With the success of the cutoff program, in 1940 the MRC ordered a more extensive study. After making some preliminary preparations and studies, WES had to suspend the project due to engineers being transferred to military projects in 1941, but resumed

work on it the following year, completing it in 1944. WES experimenters made a number of improvements in the study. First, they built the model larger – 120 by 38 feet – to allow for a larger 5-foot wide, 4-inch deep river. Then they introduced the use of more realistic-performing sediment – crushed coal and gravel versus sand. Last, they captured the results of the study with time-lapse photography, which dramatically showed the formation of bends. The resulting report, Capt. J.F. Friedkin's *Laboratory Study of the Meandering of Alluvial Rivers*, which largely confirmed the earlier results, quickly became a classic of hydraulics studies. Although such basic research was rare, it proved the value of the lab, not just to Corps of Engineers projects, but to the scientific community as a whole.⁸⁹

Soils Research: The Terzaghi Connection

By 1940, WES also saw the tremendous growth of research in soil mechanics with the formation and growth of a separate soils laboratory. Particularly influential on the direction of this research was the pioneering work of Austrian Karl von Terzaghi. Prior to the twentieth century, the impact of soils on engineering was, if anything, less understood than hydraulic engineering, despite the existence of workable general theories still in use today that account for the behavior of some soil conditions. Augustin Coulomb developed the first theories of earth pressure on lateral supports as early as 1773 as a starting point for further inquiry, but, as Terzaghi concluded, “Practising engineers discovered very soon that the theory was insufficient in giving a satisfactory solution to all the manifold problems involved,” such as soil compaction and hydrostatic pressure. There was often a wide divergence between theory and practice. Collapse of earth works resulting from a lack of understanding of soil problems was frequent, and as late as 1850 explanations by civil engineers of these failures tended to be speculative and absent of any scientific testing. Attempts to further quantify the behavior of some soil types – most notably William Rankine's 1856 theory of static earth pressure – though they improved theoretical explanations also did not account for all soil conditions. Part of the reason for this lack of progress was the inadequate experimental methods. Civil engineer Benjamin Baker lamented in 1881:

Long as the subject has occupied the attention of constructors, there is probably none other regarding which there exists the same lack of exact experimental data. Thousands of pieces of wood have been broken in all parts of the world to determine the transverse strength of timber, whilst the experiments that have been undertaken to ascertain The Actual Lateral Pressure of Earthwork are hardly worth enumerating. One authority after another has simply evaded the task of experimental investigation by assuming that some of the elements affecting the stability of earthwork are so uncertain in their operation as to justify their rejection, and have so relieved themselves from further trouble.

As with hydraulics, because of limited application of principles of similitude, experimental research often occurred while building and testing structures in the field, which, given the size of the structures, was very expensive. Usually structural failures provided the best opportunity to gather new data.⁹⁰

Soon after Baker wrote, George H. Darwin published his account of incomplete experiments conducted in 1877. Using fine-grained sands in a wooden box with a vertical hinge, he weighed the sand at different angles, slopes, and pressures and calculated the specific gravity, which he compared to Coulomb's theory. It was a beginning, which he hoped would induce others "to carry out experiments with other materials and by other methods." By the early twentieth century, experimentation had started to advance. In 1900, Swedish chemist Albert Atterberg developed experiments to classify the liquid limit of different soil types. In 1910, German engineer H.F.B. Muller-Breslau created a laboratory shear device to test sheet-pilings. In 1912, the U.S. Reclamation Service began collecting and classifying soil types. In 1913, independent 10-year efforts began by the ASCE Foundation Committee and the Swedish Railways Geotechnical Commission to test the friction, compressibility, and shearing strength of various soil types. Both commissions published multiple reports on their findings. In 1915, British engineer Arthur L. Bell had developed a testing cylinder in which he could increase pressure on clays by turning a wheel. Diaphragms connected to gauges captured the changes in pressure, which he was able to quantify in a series of formulas. Yet the complexity of the various soil qualities these experiments tested prevented any correlation of phenomena. Terzaghi wrote in 1925, "Lacking a knowledge of the elementary factors, experiments merely build up a collection of unusable data and give no knowledge of relations." He set out to change this.⁹¹

Born in Prague in 1883, Terzaghi graduated from the Technical Institute of Austria in 1904 with a degree in mechanical engineering, soon afterwards launching his teaching career. Traveling throughout the Austrian-Hungarian Empire and Czarist Russia as an engineering consultant, he became aware of the divergence of engineering theory and practice, particularly when it came to earthworks. In 1910, he devoted himself to the new field of soil mechanics. He continued to travel and research, even spending time as a laborer for the Reclamation Service. After brief service in the Austrian army in 1914 during World War I, he took a job as Professor of Foundation Engineering at the Imperial School of Engineering in Constantinople from 1916 to 1918. With the fall of the Ottoman Empire in 1918, he transferred to the American Robert College in Constantinople, where he served from 1918 to 1925.

It was during this 10-year sojourn in Constantinople (renamed Istanbul in 1923) that he began extensive experiments with sand, clay, and other soils to measure load, compressibility, and permeability under laboratory conditions, publishing widely in the U.S. and Europe. In 1925, on taking a leave of absence from Robert College, he received an invitation from MIT to serve as an interim lecturer and researcher. MIT professor Charles Spofford, who was familiar with the work of Terzaghi, had convinced MIT President Samuel Stratton to offer the position and, as an enticement, to build a laboratory for him. Terzaghi, who recognized his limited influence in Istanbul, accepted the position and moved to Cambridge, Massachusetts. Almost immediately, he began a regimen of experiments, publishing his often controversial conclusions in the



Karl Terzaghi. *Massachusetts Institute of Technology Museum.*

Engineering News-Record and other engineering journals. Although he later left for Europe in 1929 to establish a soils laboratory in Vienna, he returned to MIT in 1936.⁹²

The practice developed by Terzaghi, generally referred to as rational earthwork or soil mechanics, was essentially the rigorous application of the scientific method to soils research. As he explained in 1925, “The method which finally led to a considerable degree of success consisted of reducing each problem to its simplest possible terms, and using the result of one test for establishing a tentative hypothesis as to the causes of the phenomena observed, which hypothesis could then be verified or disproved by further tests.” In his own research he reduced soils to four factors that explained most soil issues: friction of soil surfaces, the viscosity and surface tension of capillary water in soil, and the influence of the width of voids. In his view, future work in civil engineering required the development of a theory of models for use in laboratory experiments, classification and quantification of soils at each project location through extensive sampling, and the development of design criteria. Progress in engineering required progress in laboratory research, without which experience is valueless. Later, he also emphasized the need for common sense in engineering, focusing more on practical solutions. “There is no doubt in my mind that the mastering of our youngest science will greatly increase the capacities of the experienced engineer,” he wrote in 1939, yet concerned with the dependence on theory, for which there were always gaps in knowledge, he also noted, “To accomplish its mission in engineering, science must be assigned the role of a partner and not that of a master.” Nevertheless, throughout his career, he was the leading proponent of a rational approach to earthwork design, earning him recognition as the father of modern geotechnical engineering.⁹³

As much influence as Terzaghi had over the development of soil mechanics as a whole, his influence on the development of Corps soil research was just as large. Among his many pupils were a number of engineers that would later work for the Corps or consult on Corps projects. Spencer Buchanan would become the director of the Soils Laboratory at WES, and William Wells and Juul Hvorslev would become researchers. Zanesville District Commander Col. Joseph Arthur would start a soils laboratory that would become the core of the Ohio River Division Laboratories and would bring in fellow MIT student Robert Philippe to run it. Thomas A. “Dad” Middlebrooks became the Terzaghi methods champion in the Office of the Chief of Engineers. Glennon Gilboy, who worked as Terzaghi’s assistant and remained as a professor at MIT, consulted on the Muskingum River dams and other Corps projects. Arthur Casagrande, who worked as a research assistant and assistant professor at MIT and then moved to Harvard in 1932, consulted for the Corps’ Boston District on many projects and greatly helped to shape soils research Corps-wide. The Terzaghi disciples – particularly Buchanan, Gilboy, and Casagrande – remained constantly in touch, discussing research efforts and coordinating on educational exchanges. In 1936, Harvard hosted the First International Conference on Soils Mechanics, and in 1938, the Corps hosted the Boston Conference to discuss Corps soils research, both of which all three soil researchers attended. In this way, even while Terzaghi was absent, his influence on the Corps continued for a generation.⁹⁴

The Buchanan Era at the WES Soils Laboratory



Spencer J. Buchanan.

The laboratory at WES designed by Vogel and built in 1930 included a small soils laboratory to conduct sediment research as required for the hydraulic models. As noted previously, the first two projects at WES conducted prior to construction of its facilities were, in fact, related to sedimentation, resulting in the publication of “Paper H,” the first report by WES. By the following year, growth in personnel working on soils issues warranted creation of the Soils Group, renamed the Soils Section in 1933, to work specifically on soils issues. A new Sedimentation Group assumed responsibility for supporting the Hydraulics Group with the development of movable-bed models. By this time, the Soils Group had its own projects – including some model studies – independent of the Hydraulics Group, requiring expansion of the soils lab to an entire wing of the WES laboratory building. By 1934, the Soils Section was working on more than 20 active projects, covering a range of interests: sediment analysis and classification, seepage studies, sampling, and soil model studies. However, what coalesced soils research and brought it consistency and authority was the hiring in 1933 of Terzaghi disciple Spencer Buchanan, who quickly introduced standardized methods of soil mechanics research. According to Vogel, Buchanan stopped at WES on the way back to his home state of Texas from his graduate studies at MIT in 1933. After learning that Buchanan had studied with Terzaghi and was unemployed, he offered him a job on the spot.⁹⁵

Buchanan had a fairly free hand in developing soils research into more than a sideline. He started by hiring two key employees, Frederick Harris and Bres Eustis. Later hires would include fellow Terzaghi student William Wells. Next, he pushed for and received approval to build a larger laboratory facility. The 40- by 60-foot Soils Laboratory opened in 1934. As the program grew, he would add a second story addition in 1939. He next set to purchase or build instrumentation used in the soil lab at MIT. These included an Atterberg liquid limits tester, a consolidometer, a shear box, and a triaxial compression chamber based on Casagrande’s design, as well as more common devices such as piezometers. These were



Technicians at work in the original Soils Laboratory.

the standard devices to test, respectively, saturation, permeability, shear, stress, and pressure. In 1938, WES would design a larger triaxial device suitable for the larger samples the lab had to handle. As there were no textbooks on soil mechanics or soil laboratories at the time, Buchanan set out to write one, publishing the *Manual for the Personnel of the Soil Mechanics Laboratory on Laboratory Procedure in Testing Soils and Sediment* in 1935. In 1936, as part of a plan to develop research centers for gathering and publishing data, WES Director Capt. Francis Falkner created the Soils Mechanics Research Center, which Buchanan also led. In this capacity, Buchanan participated in the First International Conference on Soils Mechanics in 1936 and a Corps Soils Conference in Boston in 1938. Organized by the Boston District and endorsed by the Office of the Chief of Engineers, the latter conference and follow-on meetings sought to establish soils research goals for the Corps. Input from Casagrande, Gilboy, Buchanan, and others helped direct research into cohesive materials, underseepage, pressure cells, and triaxial devices, and established WES as the research center for clay and cohesive soils and the Boston District as the research center for cohesionless soils.⁹⁶

Other than the work established by the Boston Conference, soils research during this formative period focused mainly on fairly standard civil works projects – testing of levee foundations in Illinois, construction tests for Sardis Dam in North Mississippi, resistivity tests at dam sites in Arkansas, soils investigations for the Tennessee-Tombigbee Waterway in Alabama and Mississippi, and mining debris studies for the California Debris Commission. Some projects arose through failure of structures, most notably a major slide at Fort Peck Dam, Montana, in 1938. Although its projects were, for the most part, straightforward, there were moments of brilliance – for example, intentional foundational failure tests of a levee near Pendleton, Arkansas, received national attention for its use of the wedge method of stability analysis – and the lab as a whole became much more productive and reliable. Despite the advances of the era, there was, evidently, some conflict between traditional engineers and the Terzaghi disciples. Buchanan at times privately questioned the ability of Vogel, while at the end of his term Falkner openly questioned adherence to a single method and noted a division among some in the department. “There has been a very definite tendency to accept blindly the teachings of Charles Terzaghi and of his followers, and to look with disfavor upon any idea not produced by this group. Such blind devotion to any school of thought is extremely dangerous,” Falkner wrote in his end-of-term report. Nevertheless, the leadership, organization, standardization, and more scientific processes that Buchanan introduced to the lab unquestionably increased its reputation and helped orient it toward future growth. Buchanan himself, however, would not see the fruits of his labor. In October 1940, he accepted a job at the MRC, and soon afterwards entered active military service, eventually serving with distinction in the Pacific theater during World War II. Yet under his watch, soil mechanics research became an independent focus for WES.⁹⁷

Some Concrete Developments

For the most part, research into structural solutions occurred at the district and division level in 1930. As noted in earlier chapters, the Corps had experimented in the field with concrete and other building materials throughout its existence for the construction of fortifications and

dams, but it had by and large not pursued laboratory research other than the testing of materials for consistency and strength. In part, this was because until the early twentieth century, concrete construction remained fairly limited. The use of concrete dated to Greek use of volcanic ash in 500 B.C.E., which the Romans perfected in the construction of the Coliseum and Pantheon. However, limited knowledge and access to materials made masonry the preferred construction material well into the industrial age. Though eighteenth century concretes relied mostly on ancient mixtures with a few notable exceptions, such as John Smeaton's new concrete mixture used at the Eddystone lighthouse in 1756, Faujas de Saint-Fond's 1778 concrete research for the port of Toulon in France, and development of new materials in Holland over the previous century, the first revolutionary advancement in cement technology did not occur until 1824, when Joseph Aspdin developed Portland cement, a mixture of burnt limestone, mortar, and pozzolan ash that resulted in material as strong as "the best Portland stone." Portland cement remained the most used type for 90 years. Four developments soon made concrete the builder's choice. Chemists in France, Sweden, and elsewhere began experimenting with different crystalline components to strengthen cement. The Danes and others began to export vast amounts of chalk and clay, which greatly increased the availability of materials and reduced costs. The British developed and widely publicized the simple concrete-mixing techniques with cement, sand, gravel, and water, which civil engineer H. Reid called in 1869 the "ABC of the process of concrete making." Last, experiments led to the independent development of iron-reinforced concrete by Frenchman Louis Joseph Lambot in 1854, W.B. Wilkinson and Thaddeus Hyatt in Great Britain by 1877, and A. Ostenfeld in Denmark in 1888, which allowed the construction of larger and more stable concrete structures. Throughout these developments, the Corps was involved in experimentation with concrete and occasionally forayed into scientific debates, but with limited impact on the field.⁹⁸

In the U.S., development of concrete engineering began to significantly increase after the Civil War, with structures becoming ever larger and more ambitious. In 1871, engineers began the first known concrete bridge, the Cleft Bridge at Prospect Park, New York. Rather than construction of a solid concrete mass, builders cast ornate concrete blocks and built the bridge using traditional stone construction methods. The Alvord Bridge in San Francisco, built in 1889, was the first using reinforced concrete. In 1872, construction ended on the first concrete dam at Boyds Corner, New York. In 1873, construction began on the first known concrete building in the U.S. – Ward House in Port Chester, New York. Other buildings followed, focusing at first on those requiring greater fire protection, such as garages. By the turn of the century, engineers were using concrete on very large buildings, such as the first concrete skyscraper, the Ingalls Building in Cincinnati, Ohio, in 1903. The same year, the Harvard University Stadium became the first concrete stadium. In 1904, several concrete contractors and Charles C. Brown, the editor of *Municipal Engineering*, established the American Concrete Institute to provide a forum to discuss concrete issues and development of technology. Within 30 years, concrete projects were exceeding all bounds. In 1910, engineers completed the 325-foot tall Buffalo Bill Dam on the Shoshone River in Wyoming. In 1922, Arthur Davis, the head of the Reclamation Service, proposed a dam on the Colorado River in Boulder Canyon. Championed by Herbert

Hoover, the dam received authorization when Congress passed the Boulder Canyon Act in 1928 (PL 70-642) and appropriated \$175 million. Completed in 1936, the Boulder Dam (later renamed Hoover Dam) was the largest concrete structure built to that time, standing 746 feet tall and 420 feet wide and supporting 45,000 pounds per square foot of pressure from the reservoir. It required some of the most innovative concrete construction techniques, including the circulation of ice water in pipes throughout the drying concrete to cool it, the inclusion of pressure instruments during construction, injecting cement into the foundation to secure it, the use of grout, and others, many of which are still in use in dam construction today. Byram Steele, chief engineer on the Hoover Dam project, would come to have a large impact on early cement research in the Corps.⁹⁹

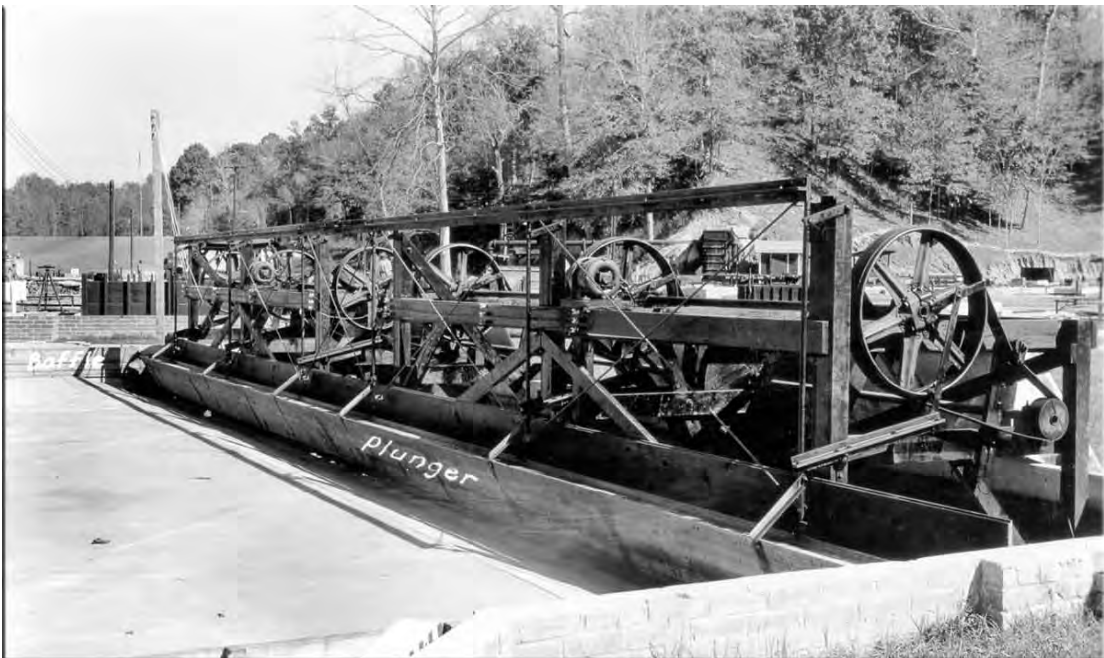
While construction on Hoover Dam was just beginning, the Corps' New England District started a concrete laboratory in support of the Passamaquoddy Tidal Power Project in Eastport, Maine, a particularly difficult project involving constant exposure to saltwater and to cold. Heading the lab was Charles E. Wuerpel, who had previously worked on the Alton Lock and Dam, Illinois, and Bonnet Carre Spillway, Louisiana, before moving on to Maine. With the completion of research for the Passamaquoddy project, the North Atlantic Division moved Wuerpel and the Eastport laboratory to West Point in 1936 to create a Central Concrete Laboratory. The laboratory's primary responsibility was to conduct concrete testing for division projects. Nearly every major federal construction project in New England over the next 10 years had its concrete tested at the lab. In 1938, the Office of the Chief of Engineers hired Byram Steele as the chief of the Engineering Division in the Directorate of Civil Works. By this time, Steele's fame for his work on Hoover Dam and publication of the U.S. Bureau of Reclamation Concrete Manual made him one of the leading national experts on large concrete construction. On learning of the Central Concrete Laboratory's potential, he took a personal interest in it, involving it in a number of projects Corps-wide and using it to conduct experiments on a variety of concrete issues. Among these were studies on the impact of concrete variability on durability, the effects of air entrapment in concrete, and alkali-aggregate reactions in 1939. He also worked to expand the staffing of the lab to include chemists, engineers, and the first petrographer in the Corps, E.P. Rexford. Other employees to serve in the laboratory included Albert D. Weiner, who later served in the Directorate of Civil Works and North Atlantic Division; E.C. Shuman, who became a professor at Pennsylvania State University; Brig. Gen. Howard Eggleston; and Bryant Mather, Herbert Cook, and Thomas Kennedy, who all later moved to WES.¹⁰⁰

The laboratory continued its work throughout World War II. After the bombing of Pearl Harbor, the North Atlantic Division decided to move the lab to a safer location, choosing a site in Mount Vernon, New York, in 1942. While there, the laboratory began work with the Ohio River Division Laboratories on research of membrane-forming compounds for curing concrete as part of Corps airfield pavement studies conducted for the war. As the war wound down and testing for civil works projects began to increase, WES was increasingly coordinating with the Central Concrete Laboratory. After Wuerpel visited WES in April 1946, MRC President Brig. Gen. Robert W. Crawford recommended moving the laboratory to Clinton, Mississippi – the site of the Mississippi Basin Model. Crawford had been looking at consolidating WES facilities at

the site because of its additional space and close proximity to transportation hubs. After hammering out the details of the move with WES leadership later that month, the Central Concrete Laboratory and its test facilities at Eastport, Maine, and Saint Augustine, Florida, transferred to WES in 1946. Several notable employees chose to move with the lab, including Wuerpel, Mather, Cook, and Kennedy, all of which eventually served as lab directors. The lab moved initially into facilities at a nearby prisoner-of-war camp in Clinton until completion of the new laboratory facility later that year. The WES Concrete Division then opened for business. In addition to continued research on runways and military structures, the lab pioneered research into new cements and aggregates.¹⁰¹

Coastal Research and the Beach Erosion Board

While WES was quickly gaining expertise on river modeling, research on coastal and tidal problems was getting a slower start. This was due in part to the limited understanding of tidal phenomena and limited use of experimental modeling for tidal studies – from the time of Osbourne Reynolds' experiments in 1885 to 1930, there had been only 14 well known model studies that included tidal forces. WES did not attempt a coastal model until 1932 with the St. Andrews, Florida, Ship Channel Model. The Gulf of Mexico District requested the model to test the construction of a canal from St. Andrews Bay to the Gulf, and WES engineers were able to build the model very quickly – in about two weeks. However, they had to experiment considerably with the manual wave simulation, essentially a hinged gate that repeatedly opened and shut, in order to affect proper frequency and intensity of waves. While effective enough to produce results, it was tedious and could not imitate many tidal elements, such as salinity,



Wave machine used in early harbor studies.

sedimentation, winds, and currents, resulting in failure to accurately predict shoaling. Improvements such as an automatic wave generator and suspension of gilsonite to simulate shoaling resulted in greater accuracy in the Galveston Harbor, Chesapeake and Delaware Canal, and Balladona Creek models. In a model built in 1935 of the U.S. Navy Yard at Mare Island for the San Francisco District, WES engineers were able to include even more complicated tidal phenomena by choosing better sediment types, using an agitator to suspend it in the water, and purchasing an electric tidal simulator that reproduced a normal high- and low-tide cycle. Additional models of the East River and several harbors the following year showed an increase in demand for such studies, and though WES improved results with practice, coastal models – especially estuary models – remained the most difficult to produce accurate results. In addition, such models were by nature project-specific and not created to investigate general tidal issues or to understand erosion or other problems.¹⁰²

Even as WES worked through its learning curve on coastal modeling, the Corps stepped up coastal research in other areas. As discussed previously, the Corps had worked in cooperation with New Jersey in gathering coastal data. In response to growing national concern over the causes of coastal land loss, the Corps had formed the Board of Sand Movement and Beach Erosion in 1929 to conduct a variety of experiments to better understand coastal phenomena. At first, funding for these studies came mostly from local sources, but the American Shore and Beach Preservation Association had been lobbying Congress to help pay for research. On July 3, 1930, Congress authorized the formation of the Beach Erosion Board in PL 71-520 and established that the states would, “contribute to the project such funds and/or services as the Secretary of War may deem appropriate and require,” generally set at 50 percent. On September 18, 1930, Chief of Engineers Maj. Gen. Lytle Brown ordered formation of the board. Among its members were many involved in the former Board on Sand Movement and Beach Erosion, including Col. William Barden, Col. Elliott Dent, and Thorndike Saville. Other members included Richard Hale of the Massachusetts Department of Public Works, Victor Gelineau of the New Jersey State Board of Commerce and Navigation, Col. Earl Brown, Maj. Gordon Young, and 1st Lt. Leland Hewitt. The former board discontinued, although the Beach Erosion Board assumed responsibility for its ongoing experiments and contracts. Brown also created the Shore Protection Board, which was to focus more on reviewing engineering problems versus general investigation of coastal phenomena. However, since it had the same officers and staff as the Beach Erosion Board, often met at the same times, and eventually merged with it in 1946, discussions that follow do not differentiate among their activities.¹⁰³

The Beach Erosion Board first met in December 1930 in New York City. Over the next nine years, it met 55 times or roughly six times per year. Research expanded gradually, mostly because of funding constraints. Through 1937, the board received only \$161,000 in appropriations, not including local contributions for specific projects. These projects were, by law, restricted to coastal studies only and not review of construction projects, and due to the high cost-sharing requirements set by the Chief of Engineers, participation was limited. From these funds, the board had to pay travel, provide staff salaries, fund experiments or investigations not otherwise appropriated by Congress, and purchase facilities. In 1932, the board built laboratory

and office facilities at Fort Belvoir, Virginia, including a 12- by 24-foot wave tank to conduct experiments, which cost \$1,500. In 1937, it built a larger experimental wave tank, 14 by 85 feet, at the Dalecarlia Reservation near Washington, D.C. By comparison, WES had by 1937 received \$129,000 in direct funding, but had received nearly \$700,000 in overhead funding from the MRC and had conducted nearly a million dollars in reimbursable work. After the passage of PL 74-834 in 1936 expanded the role of the Beach Erosion Board to include construction studies for federal property, review of shore protection projects, and publication of coastal research, the activities of the board increased somewhat. However, funding was never very high, and unlike river problems, in which flooding impacted millions of people and motivated them to invest in research, fewer people were aware of coastal problems, which impacted a much smaller percent of the population.¹⁰⁴

Despite such limitations, the board was able to significantly advance understanding of coastal problems during its preliminary years. Other than completing the work of the Board of Sand Movement and Beach Erosion, which had focused primarily on the North Atlantic coast, a major task involved completion of a series of studies on the Pacific coast. In 1930 and 1931, Morrough O'Brien of the University of California completed an inventory of all beaches, inlets, and harbors the entire length of the U.S. Pacific coast. The result was the monolithic seven-volume report, *A Report on Sand Movement and Beach Erosion Along the Pacific Coast of the United States*, published in 1931. Among the many discoveries discussed were the relationship between tidal prism and flow area within inlets and estuaries and the so-called "river of sand," a littoral drift of sand running in a narrow belt parallel to the shore, which O'Brien documented off the coast of Santa Barbara, California. By 1935, the board had resumed studies of construction materials with a study of steel sheet piling conducted by Ralph Rhodes of Savannah District. After observing conditions at 11 test construction sites along the east and west coasts of Florida, Rhodes published his report in 1936. However, the mainstay of the board were cooperative studies, which usually involved studying beach conditions at specific sites where states were planning construction or where existing structures had problems. On these, the board served as something like an engineer consultant, analyzing problems and recommending solutions. The first of these cooperative studies, or at least the first resulting in publication as a House Document, was the study of Fort Fisher, North Carolina. There had been considerable coastal erosion near the fort, and the board investigated the area and provided advice on the placement of an experimental groin. Other examples include an examination of a jetty at Cape May Harbor, New Jersey, and a seawall at Old Orchard Beach, Maine, in 1935. From 1931 to 1936, the board averaged fewer than three cooperative studies per year. With the passage of PL 74-834, the level of work eventually increased, peaking after 1950 with an average of more than six publications per year for 25 different states.¹⁰⁵

The Engineer Board and Photogrammetric Research

The work of the Engineer Detachment at Wright Field on developing aerial photographic mapping equipment had continued unabated since its formation in 1920 in the Air Corps Photographic Laboratory. Led by Lt. Col. James Bagley through 1926, Capt. Ed Plank from

1926 to 1930, and Capt. Fritz Phillips from 1930 to 1935, the detachment had developed increasingly sophisticated cameras and mounts, including spotting and reconnaissance cameras. It was also during this era that the detachment appointed German national Heinz Gruner, one of the co-founders of the American Society of Photogrammetry in 1934, as its first civilian research director from 1931 to 1936. The Board on Engineer Equipment, formed in 1922, had coordinated with the detachment on its research program, but more or less left it alone. On January 26, 1933, the Corps established the Engineer Board and made it responsible for all future equipment development, including topographical equipment, bringing into question the position of the Engineer Detachment. A conference held that spring with the detachment, the board, and officials from the Office of the Chief of Engineers hashed out the concerns. Primary among these were conflicts with Air Corps reconnaissance and charting research and growing complaints from the Air Corps and the U.S. Geological Service that the detachment was intruding into their work by actually running photographic missions as opposed to merely developing equipment. The upshot of the conference was that the Engineer Board assumed oversight of all research, suggested missions, and developed doctrine, but that the detachment, although greatly restricted in its mission, would remain independent.¹⁰⁶

By the late 1930s, the cameras developed by the detachment were fairly advanced, with the introduction of wide-angle lenses coming in 1938. Prior to that time, most cameras increased perspective through the use of multiple lenses, which provided a schematic print with a mosaic of the images. In 1935, however, Gruner brought word from a trip to Germany that camera maker Carl Zeiss Inc. had produced a wide-angle lens camera that captured a wider area using a single roll of film. The detachment purchased one of the cameras in 1936, but it failed mechanically in tests, and there were problems with photo reduction because of the distortion. In 1938, the detachment began working with Bausch and Lomb to develop a new wide-angle camera. In the interim, the Office of the Chief of Engineers decided after a camera conference in March 1940 to abandon normal-angle mapping cameras and to use the K3B camera with a wide-angle lens – as a multipurpose camera, it worked with any lens type. With the introduction of the T-5 camera, however, the Corps quickly standardized on this wide-angle model. In addition to being extremely precise, the camera included many innovations, such as a viewfinder, an exposure meter, and markers at the focal plane inside the lens cone.¹⁰⁷

Over the next several years, while continuing development of equipment for fuel handling, camouflage, and other areas, the Engineer Board made several other advances in topographical technology. With the development of wide-angle cameras, mappers needed a way to plot the maps without the distortion caused by older plotters. In 1935, the Engineer Board had purchased and tested Zeiss wide-angle multiplex plotters – plotters capable of making multiple exposures at one time. By 1937, the board worked with contractors to manufacture its own and in 1938 standardized on this version. By 1936, the board had also developed a series of stereo equipment used for the analog plotting techniques then in use. These were different plotters and glasses, such as static stereoplotters and portable stereocomparagraphs or viewers, which allowed the viewer to look at two aerial photographs in 3-D. By 1941, the board had developed tri-metrogon equipment for plotting oblique photographs and had worked with

The Origins of American Photogrammetry

Photogrammetry – the science of measuring photographs, primarily for geographical and engineering purposes – has been around almost since the development of cameras. Yet, the United States remained behind Europe in the field until the twentieth century, when Americans became world leaders in digital photogrammetry, due in part to the efforts of the Corps of Engineers.

Within a year after the development of daguerreotype photographs in 1839, Dominique Francois Jean Arago wrote that he believed the new science would be useful for topography. Within 10 years, Aime Laussedat of the French Army began experimenting with photographic mapping, earning him the title of “Father of Photogrammetry,” although the term itself did not originate until 1893. By 1858, he had started experimenting with aerial photography using kites and balloons, assembling the image on a plane table. At the end of the century, France, Germany, and Austria were regularly using aerial photography for mapping and had developed improved cameras and plotting devices to obtain precise measurements from them.

The U.S., however, did not start thinking about photogrammetry until the Civil War in 1862, when the Union Army used photographs to develop maps of the battlefields around Richmond, Manchester, and Chickahominy with limited effect. By 1875, the Engineer Battalion at Willet’s Point was experimenting with photography, and in 1888, West Point professor Lt. Henry A. Reed promoted photogrammetry in his book, *Photography Applied to Surveying*. In 1893, a civilian working for the Army, C. B. Adams, first developed the principles of radial plotting and triangulation and patented his methods for balloon-based photography. By this time, the U.S. Coast and Geodetic Survey and



Amphibian airplane used during early photogrammetry projects, 1925. *National Oceanic and Atmospheric Administration Photo Library.*

several states had started using aerial photographic mapping.

Development of aerial photography continued using airplanes starting with Wilbur Wright in 1909 and matured by Austria during World War I. Maj. James Bagley of the Corps of Engineers developed the first airplane-based camera for the U.S. in 1917, and by 1926 had developed increasingly

sophisticated cameras through his work with the Engineer Detachment at Wright Field. Over the next 10 years, the detachment greatly advanced photogrammetry through the development of wide-angle lens cameras and other instruments. Two members of the detachment – Heinz Gruner and Russell Bean – were founders of the American Society of Photogrammetry in 1934.

By World War II, the detachment and its contractors had produced some of the most advanced photogrammetric equipment of the time, improving on European models developed during World War I. It developed a multiplex to quickly perform detailed compilation of aerotriangulation data, including the first in the U.S. designed for the wide-angle camera. It developed the first stereoplotters in the U.S. for viewing two photographs in 3-D and experimented with a variety of mobile stereoscopic devices, such as anaglyphs, comparagraphs, and plotters.

With the introduction of computers during the era of the Geodesy and Intelligence Research and Development Agency and Engineer Topographic Laboratories, the Corps pioneered analytical photogrammetry by introducing software for measuring and marking coordinates, error-correction, and multi-photo-processing. It also developed newer, more compact hardware for triangulation analysis, point transfer and marking, high-altitude photograph stereoplotters, and mosaicing. From the origins of photogrammetry to its entrance in the computer age, the Corps has been on the forefront of U.S. photogrammetry.



World War I aircraft with side-mounted camera. *National Oceanic and Atmospheric Administration Photo Library,*



Using a stereoscope to bring images on adjacent photographs into coincidence. *National Oceanic and Atmospheric Administration Photo Library.*

Raytheon Corporation to develop photorectifiers that could correct angles during development. Following was a series of devices for tri-metrogon equipment, including multiplex equipment, sketchmasters, and related devices to correct these angles. Another major development was the use of radio to determine positioning. Before 1930, ground controls or surveyors were necessary to determine the precise horizontal positioning of a plane, since vertical position was determinable using barometric altimeters, in order to map aerial photographs to a precise location. The increased development of radio, however, allowed one to determine location by calculating distance traveled by radio waves. Once war started in Europe, it became critical to reduce the need for ground controls, and Maj. Gilbert Lorenze of the Engineer Board worked with the Army Air Force in developing Short-Range Navigation or SHORAN devices in 1943. Although some development work had occurred prior to that time related to using radio altimeters to determine distance to ground versus altitude above sea level, the board developed and tested a working SHORAN device from January to June 1944.¹⁰⁸

Another area of development was related to reproduction of maps, which was traditionally a slow process of hand cranked presses and blueprinting sets, usually at field mapping battalions. From 1928, the 29th Engineer Battalion at Headquarters, aided by Bagley, was responsible for developing reproduction equipment. Among its many advances were the development of a lithographic press in 1934 and the adoption of the Davidson Multilith in 1937. It had also begun development of a mobile reproduction plant for use by field units. This was a train of eight vehicles and trailers that could carry a complete set of press equipment anywhere in the world. In September 1940, the board formed a Reproduction Division to focus on developing methods and equipment for map reproduction, starting with camera-copying reproduction equipment. The division made many innovations in the lithographic process, such as half-tone screens, the use of printing plates, and rapid printers. By this time, the growth of topographical research at Fort Belvoir had grown considerably and intensified because of the war. It was largely because of this rapid growth that the Engineer Detachment recommended in 1941 that it be transferred to Fort Belvoir and replaced at Wright Field by a liaison from the Engineer Board's Aerial Photographic Branch. Approved in December 1942, this arrangement went into effect in February 1943, ending the independent existence of the detachment.¹⁰⁹

Continued Experimentation at the Divisions

Although the activities of WES and other national labs became the focus of most major research efforts in the Corps, and hence form the core of this history, scientific experimentation continued at multiple levels throughout the Corps. At the division and district level, research into river attributes, structural integrity, and dozens of other issues of interest to the Corps intensified. Most of the research at the division level was field work, frequently related to river training. For instance, throughout the 1920s, the Kansas City District conducted multiple experiments with revetment designs – underwater bank protection, traditionally mattresses of woven willow branches weighted by ballast and covered with sediment. Because of the increasing unavailability of willow bushes, the Corps experimented with various revetment designs, such as lumber mattresses, Jacoby mattress made of brush and galvanized cables, Pittman mattress

made of wire springs and poles, Parker mattress made of wire and brush, and even concrete. Memphis District conducted experiments with underwater groins for bank protection – submerged rock walls perpendicular to the bank at intervals along stretches susceptible to bank erosion. From 1930 to 1931, the Corps installed 22 groins at New Madrid Bend, Missouri, and 12 at Happy Valley Bend, Arkansas, though the results were unsuccessful. Later, such research often preceded or followed laboratory experiments, as when the MRC conducted tests with semi-permeable sills to reduce bed load movement or scouring on concave banks of the Mississippi. After WES tested the concept in 1944, the MRC went on to test it in the field at Barfield Bend, Arkansas, as well as conducting related experiments with similar sills or low elevation dikes to deepen the channel at Walter Bend, Tennessee, in 1946. Some experiments, such as testing the effects of dredge fill on revetment at Profit Island, could take years to complete. Given the great expense of such experiments (the Walter Bend experiment exceeded \$1.5 million in costs), the use of cheaper model experiments first became normal practice. There were even experiments conducted in cooperation with other agencies. In 1935, the St. Louis District conducted experiments with velocity meters with the U.S. Geological Survey – teams tested USGS-developed meters against Price meters at observation points at the Municipal Bridge, St. George Street, and on barges and recommended changes. In short, the activities of division engineers were often experimental, reflecting the trial-and-error nature of civil engineering as well as the scientific bent within the Corps.¹¹⁰

Soon after the formation of WES, other hydraulics and construction laboratories began to appear at the division and district level. Prior to World War I, local Corps offices used private contractors to conduct research work on specific projects, such as testing water quality or concrete mixtures, often paying thousands of dollars for such services. In cases where onsite testing was not possible, construction offices would send samples off to private or university laboratories for testing. Many opened offices at universities to conduct hydraulic or other experiments. Starting in 1930, the Corps operated a tidal laboratory at the University of California at Berkeley and conducted modeling at MIT; the Pittsburg District opened an office at the Carnegie Institute of Technology to support testing for construction of Lock No. 9; and the St. Paul District maintained an office at the University of Iowa until 1948. According to one estimate, some 29 investigations for the Corps were ongoing at universities in 1936.¹¹¹

By the 1930s, it was becoming more usual for the divisions and districts to maintain their own laboratories for these purposes. In 1936, there were at least six hydraulics laboratories operating in the Corps, including in the St. Paul District, Milwaukee District, Portland District, and North Pacific Division. Perhaps the most prominent examples of successful district laboratories are the Portland District's Bonneville Hydraulic Laboratories, which supported construction of the Bonneville Dam on the Columbia River in 1933, and the Zanesville District laboratories, established in 1934 for the Muskingum River dams that became the core of the Ohio River Division Laboratories (ORDL). Both of these started as district laboratories but eventually went on to conduct research on a reimbursable basis for other Corps divisions and federal agencies. Some of these laboratories eventually merged with Corps-wide laboratories – for example, ORDL formed the genesis of the Construction Engineering Research Laboratory, while the

Construction Research at the Ohio River Division Laboratories

Construction of the Muskingum River dams in Ohio, 1934-1938, was a particularly complex project, consisting of one concrete and 13 earthfill dams and several earthen levees. Having studied at MIT under Karl Terzaghi, the famed Austrian geotechnical engineer, Zanesville District Commander Maj. Joseph Arthur was aware of the soil issues that could impact the project. To help test soils and experiment with construction techniques, he established soils and concrete laboratories in May 1934 at the project site and brought in Robert Philippe, another Terzaghi disciple and fellow MIT schoolmate, to head the labs. The labs conducted tests to determine the best soils to use, their proper compaction and treatment, and to analyze concrete, which together saved hundreds of thousands of dollars. As historian Leland Johnson noted, this “removed earth construction from the realm of trial and error and permitted rational structural design to achieve the greatest safety and economy.”

The lab ran its final tests in 1937, and construction ended in June 1938, at which time the Ohio River Division transferred the work and employees to the Huntington District and turned the dams over to the Muskingum Conservancy District for operations and maintenance. The question remained what to do with the labs? With construction of earthen dams just starting in the Pittsburg District, the division moved the soils lab there to support the project. It moved the concrete lab to the Fernbank Repair Station (Dam 37) near Cincinnati under the direction of Sidney Emery. The five-man staff conducted all concrete testing for the division and began research into various classes of concrete, temperature controls, vibration techniques, placement methods, and related technologies. Within two years, with requests from other Corps divisions, state highway agencies, the Tennessee Valley Authority, the Bureau of Reclamation, and MIT, the lab had grown to more than a dozen personnel, and Ohio River Division Commander Brig. Gen. Edwin Marks decided the time had come to invest in a larger facility.

Marks negotiated with Cincinnati



Concrete laboratory at the Ohio River Division Laboratories.

University to lease land and use laboratory space, and he sought permission to move the soils laboratory, still under the direction of Philippe, and the concrete lab to the university. However, William McAlpine, a senior engineer at the Office of the Chief of Engineers, believed the concrete labs at West Point and Fort Peck Dam met the needs of the Corps and did not approve construction of new facilities. After renewing the request several times, and with research for the Army and Air Corps increasing as World War II geared up, Marks finally won approval to build a facility on government land at Mariemont after McAlpine retired.

Renamed the Ohio River Division Laboratories in 1945, the labs focused primarily on defense work through the war, particularly runway studies, returning to civil works research on floodwalls and other structures after the war. By 1950, the laboratories had expanded to more than 40,000-square-foot facilities and expenditures exceeding \$390,000 – half of the entire division. About two-thirds of its work originated outside the division. By 1960, only about a quarter of its million-dollar workload came from the division. With an average of 130 employees, it was working on high-profile projects such as experimental construction techniques and moon dust simulation for NASA. In short, it had outgrown the division.

In 1964, when the division requested new facilities for the laboratories, Harry Zackrisson of the Office of the Chief of Engineers recommended formation of a construction lab under its control. With a plan approved in 1966, the Corps signed an agreement with the University of Illinois in 1967, started construction in 1968, and opened the Construction Engineering Research Laboratory (CERL) in 1969. With the transfer of more than half of its personnel to CERL and another 18 to the Waterways Experiment Station along with its concrete laboratory, ORDL deactivated soon afterwards, although a greatly reduced Laboratory Section continued division testing and other work at ORD. For more than 20 years, ORDL had served as one of the premier concrete and soils laboratories in the Corps.



Laboratory facilities at the Ohio River Division Laboratories.

Fisheries Engineering Research Laboratory, also in Portland District, became part of WES. Most, however, were project-specific and declined upon completion of the projects. Eventually, all divisions and districts maintained some test facilities and employed scientists to support field activities in water quality and other fields, but by 1940, WES had easily outgrown them all to become the preeminent civil engineering laboratory in the Corps and in the federal government.¹¹²

By World War II, WES had become a permanent establishment within the Corps. Vogel completed his tour at WES in 1934, moving on eventually to decorated service in the Pacific Theater in World War II, Southwest Division Engineer, member of the Mississippi River Commission, Assistant Director of the Panama Canal, and President of the Tennessee Valley Authority. His successor, Falkner, left in 1937, being replaced by Capt. Paul Thomson, then in 1939 by Capt. Kenneth E. Fields. By 1940, total work conducted by WES was nearly \$700,000 per year, with an overhead cost of \$300,000. Much of this work was now for Corps districts outside the Mississippi Valley. From a handful of employees in 1930, it had expanded to more than 130. In short, WES had grown to the point where it was difficult for a junior officer to manage the laboratory. In 1940, Fields recommended that MRC President Brig. Gen. Max G. Tyler establish a civilian organization to manage WES in case war required service from its officers, including a civilian assistant or technical director. With the transfer of Buchanan, the senior civilian, to the MRC in October, Fields selected Joseph B. Tiffany to serve as assistant to the director, essentially the first technical director, although Gerard Matthes was the first to hold that title during World War II. After World War II, only colonels would serve as directors at WES, but it was the technical director who led the research program, a tradition that continued at WES and at other Corps laboratories until the 1990s.¹¹³

Research had advanced considerably at WES during its first decade. The lab worked on a steady stream of hydraulics and soil problems of increasing complexity, including some basic research. Even in the midst of this seeming success and despite the popularity of the lab, the age-old debate continued between the rule of thumb and more theoretical studies. Particularly with movable-bed models, estuary and tidal models, and soil studies, in which it was difficult to simulate the wide range of characteristics needed, such as soil roughness, turbulence, and sedimentation, the usefulness of laboratory study repeatedly came into question. Reflecting the rift between engineering and scientific or mathematical studies that was occurring across the industry, some engineers, such as Falkner, were slow to adopt tools based on theory and, assuming the realities of engineering irrationality, pressed for greater verification of model studies. Others, such as Vogel and Thompson, noted that the use of scientific or theoretical tools did not negate the need for guesswork and often played with model parameters to achieve reliable results. The key, however, was that they did achieve results and thus proved the usefulness of laboratory research for engineering studies. In this, the influence of research at WES on other fields was undeniable. The Beach Erosion Board and the Engineer Board soon established permanent research facilities, while multiple districts and divisions established their own hydraulics, soils, and concrete labs. Most of these efforts, including at WES, were rather limited compared to the

accomplishments to follow. What changed this was the growth of the industrial and research complex during World War II.¹¹⁴



Chapter Four

War and Military Research



Portable runways — a great contribution and achievement in aviation.

In 1949, Vannevar Bush reflected on the war years in his book, *Modern Arms and Free Men*. As the chairman of the National Defense Research Committee (NDRC) and director of Office of Scientific Research and Development that oversaw the Manhattan Project and other research efforts during World War II, he wrote, "I was in a position to see as much as any single man could see what science has done and can still do to the art of warfare." The president of the Carnegie Institution, one-time vice president of MIT, and an early developer of analog computers, Bush directly participated in the development of new technologies. With his office overseeing more than \$500 million in funding and 30,000 scientists and engineers nationwide working on technologies such as the atomic bomb, guided missiles, the computer, radar, radio, and submarines, he saw how science was changing the nature of warfare: "Scientists became full and responsible partners for the first time in the conduct of war." It was, as Engineer Board President Brig. Gen. John W.N. Schulz, also noted, "a scientific war, a technical war, an Engineer's war." More than any time in the past, scientific advances provided decisive advantages on the battlefield. In return, Bush wrote, war pushed research into new directions as "applied science . . . pursues the path pointed out to it by authority." Science changed the nature of warfare, but warfare itself drove the direction of science, which in turn impacted civil life. In this observation, Bush joins many others who have noted the role warfare has played in the evolution of technology and ultimately of society.¹¹⁵

Research and development in the U.S. Army Corps of Engineers was no different. The research that the Waterways Experiment Station (WES), Beach Erosion Board (BEB), Engineer Board, and other entities conducted during World War II and the Cold War greatly influenced the outcome of these conflicts. The technologies and knowledge that came from their efforts helped save lives and often provided a decisive advantage to the Allies during the war. At the same time, the war greatly influenced research and development efforts, giving them direction and infusing them with cash. War did have some negative effects on Corps laboratories. Many personnel served in World War II, the Korean War, and the Vietnam War, which reduced the manpower of these facilities during critical periods. Funding for much of the peacetime research going on before the war declined, as did the availability of some facilities. One of the labs came close to suspending activity until after the war. Yet the war also changed the labs in positive ways. Funding increased for wartime research. Military projects increased the capability of the labs and provided employees with considerable experience solving specific problems. Many of these new missions became some of the longest-running projects the labs ever supported, some lasting for decades. In addition, the war caused many internal and social changes. With the absence of men who were serving, more women and temporary labor began working at the labs, as with other businesses and agencies, forcing modernization even in conservative towns such as Vicksburg, Mississippi. The labs had to adapt to the changing circumstances of wartime operation, altering their structures to accommodate new fields and shifting headcounts, whether due to employees leaving to serve or expansion after the war. The war and the changes it brought form a central part of the history of Corps research from 1935 to 1960.¹¹⁶

The March to War

As the march to war in Europe became more precipitous after 1936 with the rise of Adolf Hitler as dictator of Germany, the Corps increasingly became involved in a variety of research programs to prepare the nation for the possibility of war. As noted in Chapter Three, after World War I the Corps spent considerable effort updating the Army's military engineering capability to more modern methods, particularly in topography. The Engineer Board and the Engineer Detachment at Wright Field, Ohio, experimented widely with aerial mapping, correction, and map publication technologies. On the eve of World War II, the board and detachment had developed a wide-angle aerial camera (the T-5), supporting rectifiers and multiplex equipment designed for processing wide-angle film, and a variety of viewers and stereoscopes to aid with photogrammetric analysis. It also greatly advanced field reproduction, reducing the size of the equipment needed from up to 12 full vehicles to less than half that amount. Another major area of research was the development of field engineering and navigational equipment. From 1928 to 1938, the Engineer Board developed three different compasses for the Infantry Board. After the start of the war in Europe in 1939, it turned to survey equipment, working with a contractor to develop a domestically produced theodolite, an instrument used to measure angles for triangulation while conducting surveys. The board worked on the device for several years before perfecting an experimental model. From 1941 to 1942, it developed a new military level. From 1942 to 1943, it developed a survey altimeter. From 1941 to 1943, it developed several models of astrolabes and observatories. From 1942 to 1944, it developed two different slide rules. Some of the devices were very innovative – from 1940 to 1943, the board developed a prototype mechanical survey computer capable of calculating latitudes given a certain azimuth and range, and in 1944, it developed an illuminated plotting board to support nighttime field operations in Europe. Such devices improved the speed and accuracy of surveys and map creation.¹¹⁶

In addition, the Engineer Board oversaw development of equipment supporting the full range of combat engineer responsibilities – construction equipment, pre-fabricated bridges, field fortification supplies, water purification and distribution equipment, fuel storage and distribution equipment, demolition equipment, firefighting equipment, and other supplies. In several instances, it worked in conjunction with Bush and the NDRC, the government's civilian research arm, or with the National Bureau of Standards, the Forest Service, the Naval Research Laboratory, and the Army Signal Corps, Ordnance Department, and Chemical Warfare Service. From its foundation in 1933 to 1945, the Engineer Board worked on 1,663 research projects, 87 percent of which began after 1940. Of these, 885 resulted in equipment the Corps adopted as standard or replacement issue during that period. Among the equipment adopted were tractor-mounted earth augers, portable sawmills, snow removal equipment, pile drivers, tractors, dozers, and many others. Some of the devices that contributed most to the war effort were the Portable SCR-625 Mine Detector, which the Engineer Board and NDRC jointly developed from civilian metal detectors; a bulldozer blade attachment for Sherman tanks, developed jointly by the Engineer Board, the Ordnance Department, the Caterpillar Tractor



American soldiers using the SCR-625 to clear mines in France. *U.S. Army Engineer School.*

Company, and LeTourneau and LaPlante-Choate tractor blade companies; and the British-developed sectional Bailey Bridge, which the Engineer Board and steel product contractors adapted for heavier U.S. tanks and tested for use with pontoons. These three made major contributions to the war – the SCR-625 played a crucial role in removing mines in North Africa, the tank dozer helped clear obstacles at the OMAHA and UTAH beaches in the Normandy Invasion, and the Bailey Bridge was a workhorse device used for temporary bridges over the Varenne River, France; Rhine River, Germany; and Shweli River, China. Less noticed, but equally important, was research into oxygen plants that provided tanks for medicine, high-altitude flying, and welding when none were commercially available.¹¹⁷

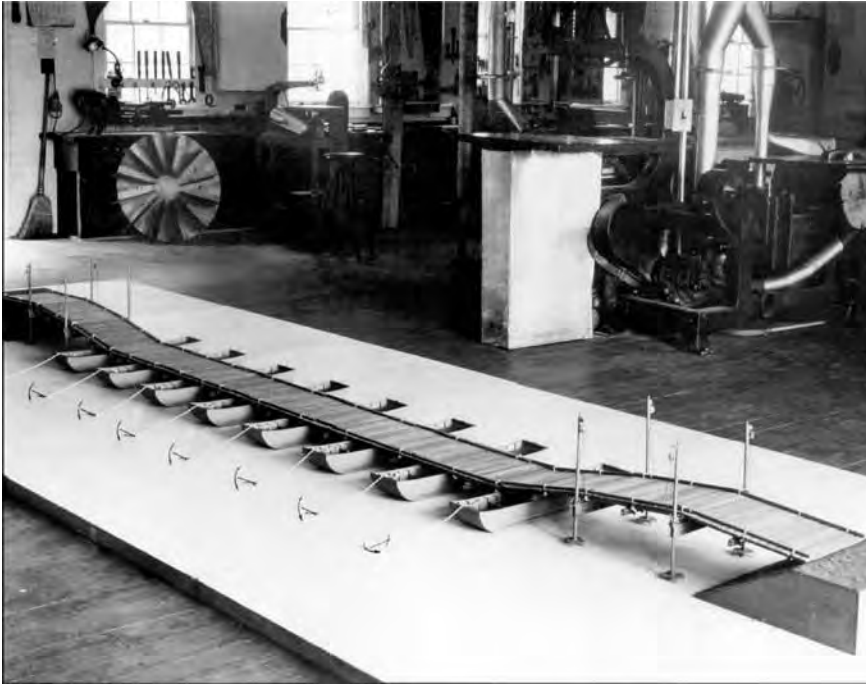
At the behest of the Engineer Board or the Office of the Chief of Engineers (OCE), WES also became involved in developing engineer equipment such as pontoons and landing mats as the war ramped up. In 1939, the Army Air Corps involved the Corps of Engineers in research on portable landing mats under the auspices of providing an emergency landing capability. Also after 1939, WES became involved in developing and testing pontoons. To aid in the instruction of engineer soldiers, WES helped build 100 miniature test pontoons used at the Engineer School and other training centers. As a result of the success of these models, the Army deployed several WES employees to form an Engineer Model Maker Detachment in England, which built scale models to support training and planning. As plans for European invasion developed after the U.S. entered the war, the Corps involved WES in testing pontoons and pneumatic floating bridges to help navigate notoriously treacherous rivers such as the Rhine. From June



Tankdozer in action during World War II. U.S. Army Engineer School.

to November 1943, the lab conducted tests on pontoons, primarily on how to attach them and how to prevent their overtopping. WES built models of four new pontoon designs with varying weights in a four-foot flume, eventually recommending a design that became the Army standard by 1944. It would refine the designs after the war in 1945 and 1946.¹¹⁸

A major issue involving WES was research related to military construction, which increased rapidly as the prospect of war increased. WES had built a reputation in the 1930s for solving tough hydraulic engineering problems at U.S. bases, such as Navy facilities at Mare Island, California, and East River, New York. After 1939, the Corps became increasingly involved in military construction projects, and especially after 1941 when the Corps gained responsibility for all domestic military construction, the amount of military construction grew rapidly, with the Corps eventually managing 27,000 wartime construction projects such as barracks and airfields amounting to \$15 billion in spending. Just for airfield construction in 1941 alone, the Corps spent \$400 million on construction of 42 airfields and expansion of 25 others. To handle this workload, the Corps increased civilian employment from 39,000 to 700,000 employees. WES significantly expanded purchase of testing devices such as pressure cells to support the expected workload. As Corps districts and engineer units proceeded with project construction, the Corps



Pontoon bridge model.



Engineers employing a pneumatic bridge in Europe during World War II. *U.S. Army Engineer School.*

called on WES to help model several difficult coastal and harbor projects. Among these were testing of dry dock pumps at Puget Sound Navy Yard, Washington (1939); modeling of a floating dry dock at Charleston, South Carolina; modeling of the placement of rock breakwaters at San Juan Harbor and Roosevelt Roads Naval Base, Puerto Rico (1940 and 1941); modeling of breakwaters and a seawall and jetty at Alameda Naval Air Station, California, in San Francisco Bay (1942); and a test of potential surge action at Naval Air Station Terminal Island in San Pedro Bay, California, near Los Angeles (1943). These applications of hydraulics expertise by

Robert Y. Hudson, John E. Arnold, and others helped the Corps prepare the national infrastructure for war and the possibility of invasion.¹¹⁹

War Footing at Corps Laboratories

By the time Congress declared war on Japan and Germany on December 8 and 11, 1941, WES and the Engineer Board were already heavily involved in missions related to war preparations. However, the Beach Erosion Board (BEB), whose mission was entirely civilian, found itself in the difficult position of being a lower priority for funding and facilities. With the expansion of the Navy Department as the European war began, it requested in 1939 that BEB vacate the Navy building in Washington, D.C., where the board had maintained office space for several years. The 20 BEB personnel relocated to temporary quarters at 21st Street and Virginia Avenue, and in 1940 moved into a new office it built at the Dalecarlia Reservation, where it already operated an 85-foot wave tank. The board continued to work on civil research, and in fact published major reports on breakwaters and oscillatory waves in 1940 and 1941, but once the war began, its civil functions greatly decreased to the point where employees expected the board to suspend activities. WES, although it also saw a reduction in civil projects during the war, saw a large increase in war-related work. Particularly after 1943, funding took off, reaching more than \$1 million for the first time in 1944. During the same period, WES civil projects for the Mississippi River Commission (MRC) dropped from 45 percent of projects in 1943 to 21 percent in 1946. To remain open, BEB also needed to cultivate war-related work. In June 1942, Senior Board Member Brig. Gen. John J. Kingman, Martin Mason, and Morrough O'Brien proposed to the Corps the capability of providing beach intelligence, which it started to do the following month.¹²⁰

Despite this influx of work, or more appropriately because of it, BEB struggled with personnel losses, as did most of the Corps labs. BEB lost several prominent members to service in the war effort, including Richard Eaton and senior civilian Forrest Byrns. To support the increased work, Kingman arranged to borrow employees from the National Bureau of Standards, among them Garbis H. Keulegan, as well as geologist William Krumbein from the University of Chicago. WES, meanwhile, saw a huge loss of personnel, coming close to closing its doors. Eventually, 631 WES employees served in the war, and those who remained had difficulties making it to work because of gasoline rationing. Some of those who left were reassigned military officers such as Capt. Paul Thompson and Kenneth Fields. After leaving WES in late 1939, Thompson served as a planner in England and eventually landed at Normandy in June 1944. Fields, who left WES in 1941, served as a combat engineer during the invasion of Germany with notable action at the Rhine River campaign. Other employees, including Soil Mechanics Laboratory Chief Spenser Buchanan, Hydraulics Division engineer Eugene Fortson, and Executive Officer Joseph Tiffany transferred or reported for active duty, although newly commissioned Captain Tiffany worked at WES throughout the war. With Tiffany's reassignment and the deployment of Fields, Gerard H. Matthes, the Chief of Engineering at the MRC, assumed the role of technical director through the end of the war, with Tiffany assuming a similar position at the war's

conclusion before being named technical director in 1956. And, of course, Corps labs often turned to commercial or state labs according to OCE policy.¹²¹

While WES and BEB struggled with departing personnel, the Engineer Board was staffing up to support its more extensive military research programs. As late as 1941, the board had seven permanent members, three members from other Army branches, and a staff of 37 personnel. Its peak personnel during the war was 240 officers and 1,170 civilians plus support from more than 1,000 troops at the Engineer School and elsewhere to conduct daily equipment testing. Strength eventually tapered to 150 officers, 251 enlisted, and 783 civilians by the end of the war. For more than a decade, the board had worked out of a handful of cantonment buildings at the Engineer School that were some distance apart and had fairly low security. Its single shop building, used for work ranging from automotive repair to carpentry to photography, and its low funding had prevented work on more than a handful of projects at a time. Testing space was limited, which was a concern given the large numbers of recruits being trained at Fort Belvoir. In February 1941, the board requested and received permission to build modern research facilities consisting of 24 buildings with 368,123 square feet of floor space and labs for temperature testing, electrical testing, searchlights, chemical, hydraulics, and engine testing. This included more than \$2 million in new equipment, such as testing devices, a pontoon basin, fences, communications systems, and access roads. The board also obtained 1,000 acres of land and maintained field installations at Wright Field; Yuma, Arizona; Fort Story, Virginia; Fort Pierce, Florida, and elsewhere to test equipment.¹²²

Because of the absences at WES and BEB, operations at the labs underwent significant social and organizational changes. Perhaps the most dramatic of these was the increased hiring of women. Although women had long worked at the labs, they mostly served in secretarial roles. Now, as in many industries, WES hired women into technical jobs so as to continue to function. Many of these women were wives of departed soldiers who had never previously worked in a co-ed environment, although some, such as Eloise H. Bodron, were hired fresh from school. At BEB, while Josephine Rowzie headed up a large secretarial staff, the more educated Clara Edmunds and Eleanor Tatge, who came with Krumbein from the University of Chicago, were heavily involved in analyzing data and preparing reports. There was also a large influx of temporary laborers, and in one of the more bizarre episodes in WES history, the Chief of Engineers arranged for German prisoner-of-war laborers to work for the lab building the Mississippi Basin Model in Clinton, Mississippi. To support the changing workload, Matthes created a Hydrodynamics Division to focus on military hydraulics projects, expanded the Soil Mechanics Division to include a Flexible Pavement Branch to work on runway tests, and added a Geological Division. After the war, with more than 100 returning employees requiring rehiring, WES reorganized again as the Hydrodynamics and Geological divisions became branches under a reconstituted Hydraulics Division. The Engineer Board, meanwhile, in 1941 and 1942 created a Mapping Branch and Aerial Photographic Branch, the latter of which replaced the Engineer Detachment at Wright Field, ending its existence.¹²³

Similar departures and increases in project load also occurred during the Korean and Vietnam wars, though to lesser degree proportional to the size of the total force serving. More than

The Engineer Board and Fake Weapons

In 1944, the Supreme Headquarters Allied Expeditionary Force under General Dwight D. Eisenhower was preparing for the invasion of Europe. Among its plans were deception and subterfuge activities – Operations Bodyguard, Fortitude, and Quicksilver – designed to deceive German spies and reconnaissance flights about the real aims, units, strength levels, and plans for invasion. The operations included a fake Army division under General George Patton, double agents to feed false plans to German spies, and a series of dummies and decoys developed by the Corps of Engineers to obfuscate troop strengths and locations.



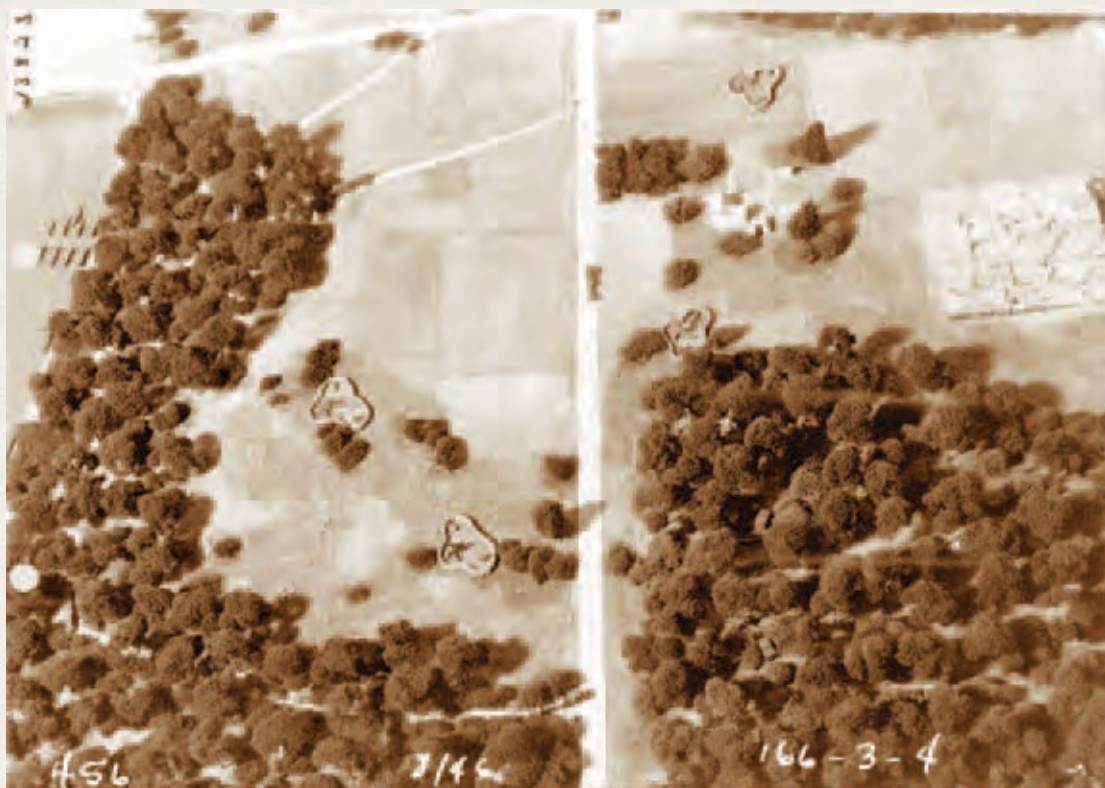
Decoy artillery weapon developed by the Engineer Board.
U.S. Army Engineer School.

Since its founding, the U.S. Army had used camouflage to hide equipment and personnel, dummies

to fool the enemy, and decoys to draw enemy fire from real targets. However, development of specialized technology to meet these ends began only in World War I, when a toy shop in Dijon, France, produced camouflage netting, painted silhouettes, and methods for simulating trenches. The 1932 Engineer Field Manual included many of these techniques. In preparation for the impending war, the Engineer Board began research into new camouflage technology in 1937, and in 1938 partnered with the Air Corps at Fort Eustis, Virginia, to develop aircraft silhouettes. Over the next seven years, the board worked on dozens of projects to develop similar technology.

The experiments at Fort Eustis proved the value of aircraft decoys, but there was still a requirement to create models small and light enough for easy transportation on fully loaded planes. From 1938 to 1942, the Engineer Board developed collapsible, inflatable, and lightweight designs. These included prefabricated and field expedient silhouettes that fooled overhead surveillance and incorporated both flat models and raised or suspended models that cast shadows. After the invasion of Africa in 1943, demand for more realistic dummies resulted in the development of 3-D decoys of various make and model planes made of inflatable rubber or cloth-covered wood or metal frames. Although the board recommended against the rubber models due to easy puncture and problems with valves, they were the most highly demanded because of their light weight.

After 1942, the Engineer Board developed dummies of a variety of equipment, including anti-aircraft guns, tanks, and trucks, but also water-based landing craft and



Aerial view of decoy deception. *U.S. Army Engineer School.*

pontoons. Most of these were 3-D models of rubber or cloth-covered frames with metal pipes to appear as muzzles. Others were wooden, fiber-board, paper, or cardboard panels that unfolded like a box held together with clips, glue, or tabs and slots. Following German lead, the board developed mobile versions that fit over vehicles, as well as envelops or superstructures to fit over tanks and disguise them as cargo trucks. In addition, it developed equipment to mimic smoke, flash, or sound. It even developed fake people, buildings, and airfields using silhouettes, 3-D dummies, and deceptive lighting that gave the appearance of a base at night.

Use of aircraft silhouettes and decoys was widespread, both on an individual basis and en masse in all theaters. Altogether, the Engineer Board procured nearly 4,000 decoy and dummy items, the vast majority of them non-pneumatic. In addition to use prior to the invasions of Italy and France to confuse the enemy as to proposed landing sites, they also found frequent use after invasion, including use by the “Ghost Army” attached to the First Army to provide the appearance of much larger forces than actually landed, for Operation Exploit to hide forces massing to cross the Rhine, and in the Pacific to intimidate the Japanese. In this, as one history noted, “due credit must be given to the Corps of Engineers and the agencies with which it worked.”

230 WES personnel served in these two conflicts through 1969, most of these in the Korean War. A major contributor to active service was the formation of the Army Reserve 434th Engineer Battalion, which WES personnel actively served in and supported. Lt. Col. Ralph King, WES commander from 1947 to 1950, encouraged the formation of the unit in 1948, and a number of engineers joined. When the unit deployed to Korea on January 4, 1951, more than 70 WES personnel deployed with it. Commanding the unit was Lt. Col. Eugene Fortson, chief of the Hydraulics Division. Replacing him as commander was Maj. John Franco, another prominent WES engineer. Other personnel also joined other units that served in the conflict. As in World War II, WES hired women to help fill the gaps, many of whom went on to long and successful careers, including Margaret Peterson, who later served as the first female branch chief at WES. Although fewer personnel served in Vietnam, WES saw a large uptick in the number of military projects, which had grown steadily since the Korean War. At least initially, most of this shift was due to the reassignment of WES from the MRC to the Office of the Chief of Engineers in 1949 and the considerable efforts of Col. Herrol J. Skidmore, commander from 1950 to 1952, and others to find new projects and mission areas. By 1968, 65 percent of WES projects were military in nature. Likewise, after the Korean War there was a renewed focus on military research for BEB, which created a Military Intelligence Branch in 1951 that eventually grew to 42 personnel.¹²⁴

Water Research and the War Effort

WES had been conducting hydraulics research for the War Department even before America's entry into World War II. At first, the majority of its projects were for stateside or territorial military bases in Puerto Rico, California, and elsewhere. Although there were significant reductions in civil works spending, there were increases in projects deemed vital to national defense, such as those that protected or accessed industrial areas. For example, the Mississippi River and its tributaries were critical to war industries, from transportation of oil, fuel, and other supplies to repair of Navy ships in dry dock. To help reduce flooding that could shut down use of the river, WES oversaw construction from 1943 of the Mississippi Basin Model (discussed in Chapter Three) to test flood control works. To aid navigation, WES and several districts analyzed designs for locks and harbors used to transport iron ore, such as the Sault Ste. Marie Lock, Michigan; Two Harbors, Minnesota; the Detroit Dam, Oregon; and St. Mary's River, Michigan. In addition, WES built models of the New Jersey Ship Canal on the Atlantic Intracoastal Waterway from 1943 to 1944. This waterway, though initiated long before the war, was critical for the movement of supplies along the coast without exposing ships to submarine attack because it ran mostly inside the coast through connecting rivers and bays. However, its construction presented a problem by allowing salt water to intrude into fresh water bodies, damaging industry and agriculture and tainting drinking water. In December 1943, the Corps requested that WES model the effects of locks on saltwater intrusion up the deep-draft canal from New York Bay to the Delaware River. Based on similar experiments on saltwater intrusion up the Mississippi River in 1942 by Hudson and Henry B. Simmons, model testing over several years using dyed saltwater helped demonstrate the lock's effectiveness, though war priorities

prevented its construction. After the war, WES continued to model breakwaters and harbors, and, in one unusual case in 1952, determined the range of radioactivity downstream from a Savannah atomic bomb plant by tracing low-level radioactive hydrogen through a model.¹²⁵



M. Juul Hvorslev.

Although not directly related to the war effort, Mississippi River geological and potamological studies initiated during the war for the MRC supported understanding of the river necessary to reduce flooding and maintain safe navigation. After the MRC started to pursue the cutoff plan in 1932, WES had continued to investigate the causes of river bends, culminating in an important study on meandering rivers from 1943 to 1945. Because little was definitively understood of the geological history and nature of the river basin, in 1941 the MRC initiated a geological study of the Lower Mississippi Valley. WES hired renowned geologist Harold Fisk of Louisiana State University and established a new Geological Division with an office in Baton Rouge, Louisiana. The team collected data for several years, resulting in the publication of Fisk's *Geological Investigation of the Alluvial Valley of the Lower Mississippi River* in December 1944. The report revolutionized the understanding of the river's geological composition and showed the river actually consisted of two major substrata layers as deep as 50 feet instead of multiple thin layers of alluvium. It greatly changed understanding of the river's formation and historical course, arguing that the river had changed within the last 2,000 years instead of being relatively stable in the modern era. It also first identified the danger of the Atchafalaya River capturing the Mississippi at the Old River conjunction, which, after further studies in 1947, 1949, and 1953, resulted in the construction of a control structure at Old River. Potamological studies gained increased impetus after the war when revetments failed at Reid-Bedford Bend in 1946. WES proposed a series of soil and hydrological investigations. In 1946 WES hired Danish soil engineer and Terzaghi student Juul Hvorslev as a technical consultant on potamological issues and in 1948 held a Potamology Conference. With the development of a new instrument in 1950 to help measure velocities and current – the hydrodynamic pulsometer – the lab significantly advanced understanding of hydraulics issues contributing to bank erosion.



Drill rig and subsurface sampler designed by Juul Hvorslev.

These efforts eventually bore fruit during the Cold War era in the development of new revetment technologies and an improved ability to predict revetment failure based on hydrological and soil factors.¹²⁶

With American entry into the war, Corps labs increasingly turned to research related to the theaters of operations. The program of beach intelligence research proposed by BEB, approved in 1942, quickly took off as the board began to analyze troop landing sites in North Africa in 1942 and Southern Europe and Pacific Islands after 1943. It would continue similar work in the Korean War and would, through 1962, provide beach landing chapters for the National Intelligence Survey for the Joint Chiefs of Staff. It also tested a variety of equipment during and after the war, including landing craft, submarines, buoy antennas, underwater mines, and portable breakwaters or harbors. These devices included some that were highly unusual, such as seadromes (floating landing fields) and searafts (floating beaches). The board helped WES model and test breakwaters and caisson designs planned



"Mulberry" caisson model used in D-Day preparations.

for the Normandy Beach landing. Although some dispute the impact of Corps research, model testing of caissons from October 1943 to January 1944 at least confirmed if not improved British designs, which aided in calming coastal waters until storms destroyed them 13 days into the invasion. WES, meanwhile, supported modeling of coasts, rivers, and fortifications at numerous locations. It helped model coasts for potential invasion sites in North Africa, Sicily, Italy, Calais, and Cherbourg. For the Army Air Force, WES personnel made scale models of target territories, including factory and weapon sites (mainly V-1 and V-2 missile launch sites) at Eder, Sorpe, Moehne, and Schweinfurt, Germany; Ploesti, Romania; Pantelleria Peninsula, Italy; and sites in Norway and other locations. The models helped bombers visualize locations to supplement radar or aerial photography. After the June 1944 invasion, WES pieced together data from available sources and modeled the Rhine River to predict river stages and help the Army plan the best location for crossings in 1944. The models also helped to plan an assault on the fortress at Merz. By November 1944, hazardous navigational conditions in a canal and deepwater lagoon at the Midway Naval Operating Base led WES to model the impact of surge action on the base, which resulted in construction of a breakwater in 1946 to prevent ero-

sion. These models and research provided the U.S. military a critical service, both in planning combat operations and maintaining reliable facilities and equipment.¹²⁷

Runways and Pavement Research

In 1941, Corps labs became involved in a new mission that would greatly expand soil and concrete research and lead to some of their most fruitful investigations. As the Corps began construction of runways and airfields, one of the problems it encountered was the cracking of runway pavements under the strain of larger and heavier planes. Before the war, most aircraft were lighter than 25 tons, or a wheel load of 12,500 lbs. Most runway designs used ordinary highway asphalt pavement standards. After the war began, however, the Allies developed increasingly heavier aircraft. Most bombers had a wheel load greater than 37 tons, more than triple the weight of earlier planes. When in 1941 the Air Corps tested the XB-19 prototype bomber, which had a 212-foot wingspan and weighed 160 tons, the plane actually broke the runway at Clover Field, California, damaging the plane as it taxied. Even the concrete runway laid after this incident cracked under the weight of the massive plane. Concrete runways, of course, could handle more weight and thus avoid many problems, but concrete was expensive, labor-intensive, and time consuming to lay compared to asphalt. To accommodate the heavier planes, the Air Corps requested that the Corps of Engineers build runways to handle a wheel load of 100 tons and a stress load of 500 lbs. per square inch, while providing greater durability, skid and dust resistance, and low friction. To help solve these problems, the Corps split pavement research among its various labs in early 1941. The Soil Mechanics Laboratory at WES would investigate flexible pavement issues, significantly expanding its mission. The Central Concrete Laboratory and Ohio River Division Laboratories (ORDL) would investigate concrete issues. The divisions and districts would continue to experiment with various paving materials with the support of WES personnel and test equipment.¹²⁸

Unfortunately, understanding of pavement surfaces was still fairly limited. Much like concrete technology, road pavement changed little from Roman times until the nineteenth century and typically consisted of multiple layers of rock, silt, and cobblestones. In the eighteenth century, Pierre-Marie-Jerome Tresaguet and Thomas Telford experimented with different materials, but it was not until John McAdams, who stressed using smaller broken stones in his 1816 book, *The Present System of Road Making With Observations Deduced from Practice and Experience*, that any major advance in road technology occurred. His method allowed the first modernization of roads in London in 1824, and the Corps adopted it for the National Road in 1828 and Washington, D.C., streets in 1832. Experimentation with road materials such as wood blocks, Brussels stone blocks, brick, and even steel followed, including the use of tar to even and protect road surfaces. Although the Swiss discovered asphalt in its natural state in 1720, the first application to road surfaces did not occur until Leon Malo paved roads in Paris in 1854. By 1880, Paris, London, Berlin, New York, Boston, New Orleans, and Washington, D.C., were all experimenting with asphalt roads. Asphalt in an unprocessed state tended to be powdery and dusty until Edward J. DeSmedt developed a mixture of asphalt, sand, and coal waste (culm)

Where to Start an Invasion

The U.S. Army Corps of Engineers Beach Erosion Board was facing near shut-down. Like many federal research departments during World War II, personnel shortages and cuts in peaceful research funding had put the board into difficult times. Since its establishment in 1930, the board had conducted research on coastal erosion problems in the continental United States. Martin Mason, the senior civilian working for the board, and others at the agency debated whether to become dormant or find a way to contribute to the war effort. Mason argued that with the agency's knowledge of shore processes, it might supply useful knowledge about foreign beaches slated for amphibious landings. Senior Board Member Brig. Gen. John Kingman agreed.

At a conference called in June 1942, Kingman suggested the idea to Lt. Col. Joseph McCaffrey and Mark Connaughton of the Strategic Intelligence Branch, Military Intelligence Division, of the Office of the Chief of Engineers. With their approval, the staff completed a preliminary investigation of the coast of France along the English Channel most appropriate for use as a beachhead for a landing. The board published the "Landing Area Report:



Brig. Gen. John Kingman, Martin Mason, and William Krumbein examine potential landing sites.

Cherbourg to Dunkirk" in July 1942. The report quickly came to the attention of the Joint Chiefs of Staff, which promptly classified the study and applied security restrictions to the entire Beach Erosion Board staff and all future beach intelligence work.

Over several years, the board completed a host of landing site studies, usually on short notice – most within a month, some in less than 24 to 72 hours. The reports typically contained facts such as beach slope, sand characteristics, tidal fluctuations, coral reef locations, and wave and surf conditions. They were often accompanied by maps, photographs, and charts. One set of fast turn-around studies known by the staff as "quick-ies" provided the terrain layout of large areas such as islands or peninsulas. Leading the research efforts were William C. Krumbein, a noted geologist from the University of Chicago, and his assistants, Eleanor Tatge and Clara Edmunds.

From 1942 to 1945, the board completed several important beach studies. In September 1942, it completed a study of the coast of North Africa from Casablanca to Tangiers for the Allied landing that took place in November of that year. Later that fall, it studied landing sites on Sicily and the southern half of Italy. In 1943, the board turned to Pacific islands, from New Guinea to the Solomons, the Carolines, and the Philippines. Several studies were included in the Joint Army Navy Intelligence Study reports.

Eventually, the reports turned out to be more than academic. The board helped train personnel from the U.S. Geological Survey, who deployed with troops in the Pacific theater and had responsibilities, among other areas, to study a beachhead before a landing to verify the accuracy of landing site reports.

Over the course of the war, 30 to 35 members of the Beach Erosion Board completed more than 50 important reports on landing sites and other topics related to beach intelligence. For this work, in March 1945 the War Department awarded Mason the Exceptional Civilian Service Award and Krumbein the Meritorious Civilian Service Award.



Normandy beach landing site, June 6, 1944. *U.S. Army Engineer School.*

in 1870. There were also limited natural sources of asphalt, which made it expensive until the Union Oil Company learned to separate it while refining oil in 1890. As a result of these and other technological developments, by 1920 half the streets in the U.S. were asphalt, and paving highways had begun. The introduction of automobiles revealed new problems because asphalt mixtures could not bear the weight. After World War I, the Army and state highway departments worked to increase the load bearing of asphalt roads, but introduction of even heavier planes and vehicles during World War II pushed existing pavement technology to its limit.¹²⁹

In January 1941, WES began experiments on airfield drainage that resulted in new designs for subsurface pipe and filtration systems. By the end of 1941, WES joined ORDL in runway tests at Langley Airfield, Virginia, where early investigations indicated the role of soil stability on pavements. At the same time, Lt. Col. James Stratton, the new chief of the Engineering Division at OCE, became aware of work since 1920 by O.J. Porter of the California Department of Transportation, who had developed a paving method building thin asphalt over a compacted base. Key to the method was determining the bearing ratio of the base. He had developed a new method to determine soil strengths, the California Bearing Ratio (CBR), but the method was somewhat controversial. There



Arthur Casagrande.

were several methods of calculating weight bearing, including a widely used method promoted by the American Association of State Highway Officials (AASHO). The Corps primarily used Arthur Casagrande's triaxial compression chamber to test soil strengths in the laboratory. The advantage of CBR was that it was simpler and faster. Engineers could calculate the strength of pavement foundations on-site using a simple device that measured soil resistance to penetration compared to resistance against a standard high load-bearing soil type. A chart related bearing ratios with pavement thickness. Although Florida and North Dakota had also adopted CBR, many questioned the method's accuracy, including the Asphalt Institute and the Highway Research Board. Within the Corps, Robert Philippe of ORDL also opposed it because it lacked theoretical underpinning. In 1942, at the request of Stratton, Thomas A. Middlebrooks at OCE asked Porter to meet to discuss the method, which promised to save considerable testing time, but found himself questioning its capability after the meeting. Only after Casagrande arranged a demonstration, in which Porter was able to quickly calculate nearly the same results as Middlebrooks, did Corps leaders decide to adopt the method.¹³⁰

At the end of 1942, OCE requested that WES help thoroughly test the method through CBR analysis of existing runways. WES established the Flexible Pavements Branch under Keith Boyd, brought on Phillip Rutledge of Northwestern University as its chief consultant, and expanded its staff to include, among others, Bruce Marshall of the Mississippi Highway Department. OCE established an Airfields Group in the Engineering Division in 1941 that included Gayle McFadden, who had built La Guardia Airport in New York and the National Airport in Washington. In 1943, WES completed construction of a Flexible Pavements Laboratory to support the mission. Working with the districts, WES started field investigations in 1942 and

1943 at Army and civilian airstrip sites throughout the U.S., including Dothan, Alabama, Municipal Airport; Corpus Christi, Texas, Municipal Airport; Fargo, North Dakota, Municipal Airport; Eglin Field, Florida; Barksdale Field, Louisiana; Langley Field, Virginia; and Stockton Field, California; with Porter and the California Highway Department supporting the latter. The result of these tests were mixed, with the CBR method generally proven reliable on non-military sites, but also with a recognition that thicker bases than CBR tests indicated would be necessary on some soil types for heavier aircraft. As a result, the Corps adjusted the CBR chart and modified the tests to include more and deeper soil samples similar to the AASHTO method. It also adopted a new method and equipment developed by Marshall for testing asphalt materials that were much faster, cheaper, and could handle heavier weights than the standard Hveem Test and Hubbard-Field Test, which were expensive or limited in application.¹³¹



Field in-place CBR apparatus set up for a test.

In 1942, the Corps updated its field manual, which received peer recognition for its contributions on airfield drainage. By the end of the year, Casagrande developed a new soil classification system for airfield construction, and he and Karl Terzaghi volunteered to teach classes to new Army engineer officers and recruits. When CBR tests came in, the Corps updated the manual in 1943. By this time, WES had become involved in conducting field tests for new airfields or runway improvements. With Stratton's emphasis on using indigenous materials, WES took the lead on testing alternative materials. By the end of 1943, the Army had constructed 1,100 airfields well in advance of the 1944 roll-out of the heavy B-29 bomber. WES conducted additional tests for this plane and in 1944 provided new blueprints and sent soil experts to the Pacific to advise on airfield construction. In the Pacific, the Naval Mobile Construction Battalions (CBs or Seabees), who had responsibility for airfield construction in that theater, built 111 airfields with Corps of Engineers support, including on Tinian Island, from which the *Enola Gay* took off to drop the first atom bomb on Hiroshima, Japan. In 1944, as part of its research into portable landing surfaces, WES also conducted experiments on prefabricated bituminous surfaces based on Hessian mats – burlap sacks coated in asphalt or tar – developed by German immigrants in Scotland and Canada. These mats helped supplement and weatherproof other landing surfaces. In 1945, WES and division or district laboratories began research into other areas related to airfield construction, including soil compaction, moisture content, water repellants, fuel spillage, subsurface drainage, frost, and turf bases. Some of this research continued after the war. In 1948, Charles Foster of the Flexible Pavement Branch deployed to Berlin to develop a method for making pavement out of rubble in support of the Berlin Airlift. In 1954,

WES began studies of channelization – the creation of ruts when aircraft landed. When the Air Force introduced jets in 1954, the Corps tested the corrosive effects of jet fuel on asphalt, eventually leading to the development of tar-rubber pavements. After the war, many of the runway engineers went on to become leaders in various state highway agencies, transferring their experience and knowledge of asphalt technology to the construction of President Dwight D. Eisenhower's new U.S. interstate system.¹³²

Concrete research, meanwhile, also advanced to support rigid pavement development. The Central Concrete Laboratory, then located in Mount Vernon, New York, continued exposure tests at its Treat Island facility in Maine, where concrete mixtures received exposure to the elements over several years. The lab also conducted a range of studies on various concrete types, including x-ray, thermal, chemical, physical, and microscopic. Over the course of the war, the lab examined 169 concrete mixtures and tested 16 different concrete replacement materials. Among its major discoveries was the effect of air bubbles in concrete mixtures on reducing strains due to freezing. From 1941, ORDL tested concrete design principles for airfields. In experiments at Wright Field, Ohio, using seven-inch reinforced concrete built on clay, and at Langley Field, Virginia, using six-inch concrete slab over sandy silt, researchers placed 60-ton weights on various locations on the slabs to determine the effect. It also collected aircraft tire imprints on lime-coated runways. Based on these tests, the division was able to develop curve charts that helped engineers quickly determine the thickness of concrete required for a given subgrade to support wheel loads of up to 30 tons. After repeated near-crash landings in Dayton, ORDL showed that cracking occurred when planes slowed after landing, in essence that “the greater the speed, the lighter the load on paved surfaces,” as one history stated. Although the speed and lower cost of installing flexible pavement ultimately won out during World War II, the Defense Department remained deeply divided on runway surfacing, with the Air Force continuing to prefer “luxury” concrete runways. Because of asphalt deterioration when exposed to jet fuel, in 1954 Lt. Gen. Curtis LeMay, commander of the Strategic Air Command, ruled in favor of concrete runways in locations where spillage was most likely, using asphalt only where planes taxied. In 1955, the Air Force ruled in favor of all-concrete runways. However, cost overruns eventually led to further Air Force and Corps experimentation with asphalt in 1957 and 1958, and its gradual acceptance over concrete.¹³³

Trafficability, Mobility, and the Environment

As the Corps became more involved in soil studies related to military construction, new problems presented themselves, one of which was the impact of soil conditions on the mobility of troops and equipment. Some soils could prevent or slow movement, as the deserts of North Africa, the beaches of Italy, and the volcanic ash on Iwo Jima demonstrated. The U.S. Navy Beach Trafficability Unit and Army Ordnance Department, the British, and the Canadians had conducted limited research into trafficability, mostly based on pioneering work in the 1930s by Polish scientist Mieczylsaw G. Bekker, who immigrated to the U.S. soon after the war began. In the U.S., most research focused on trafficability of agricultural equipment. When preparation for the invasion of Japan began in 1944, tanks or other heavy equipment getting stuck in

rice patties was a major concern. Planners needed to know how much traffic soils could bear to avoid obstacles and delays in routing troops and equipment. In July 1945, OCE directed WES to develop field trafficability tests by September for use in the invasion. Running tests practically non-stop for weeks, WES engineers drove 14 vehicle types in tracks at four locations using various soil types and moisture contents. Through these tests, they developed data about using penetrometers to measure trafficability. Invented in 1917 and perfected by the Dutch in 1934 for agricultural uses, these devices consisted of a shaft inserted into soil that pressed against a spring attached to a sensor that detected resistance. The cone penetrometer used by the Corps was a smaller, more mobile version of this device that scouts could use to test soils before the invasion. Although Japan's surrender precluded the use of the penetrometer, the Corps would work to refine this preliminary research over the next 20 years.¹³⁴

By 1948, WES had conducted more than 950 tests to improve its testing methods. It established the standard of making 50 passes with a vehicle before determining the effects of soil on mobility. It also improved the quality of testing lanes and identified various soil types and mobility problems related to each. As a result of these tests, engineers were able to significantly improve the penetrometer and develop a new device, the dynameter, to test the pull of vehicles. Beginning in 1949 and continuing through 1961, WES worked to prove the method through field tests by driving various vehicles in undisturbed locations. In 1954, it added tests of snow and ice through several experiments at Thule, Greenland, and the Arctic. Again, as a result of these tests, it was able to refine its soil and vehicle classifications and develop new technologies, such as an aerial cone penetrometer – a device dropped from a plane that could remotely provide trafficability data. After 1948, remote prediction of trafficability became increasingly important to Cold War planning efforts. In addition to remote penetrometers, WES helped study the effects of weather, vegetation, and terrain physiology to aid in predicting trafficability, often using nothing more than aerial photographs. From 1950 to 1961, the Soils Division participated in studies with the U.S. Forest Service to collect data at 650 sites in order to refine this capability.¹³⁵

By the late 1950s, this research expanded beyond the trafficability of soil to include vehicle mobility and other environmental impacts on combat troops. In 1955, WES established a Mobility Board of Consultants to advise on future trafficability research. The board included leading experts from MIT, New York University, University of California at Berkeley, Purdue University, as well as Robert Philippe at OCE, formerly of ORDL. On their recommendation, WES formed the Aerial Mobility Research Center within the Flexible Pavement Branch in 1956 to continue examining the relation of vehicles and soil and built a new laboratory to support research efforts. As research into mobility continued to grow, the center became a separate entity within the WES Soils Division in 1958. During this period, the center worked to develop laboratory methods of testing mobility, primarily through the use of vehicle simulators that could produce various weight loads without the need for having the vehicles on-site. Over several years, the center worked to verify this equipment against field data. It also developed modeling and soil testing equipment, improving on equipment developed by other mobility labs, and soon recorded a mass of data to support its investigations. Despite the development

Portable Runways

With the growth of air power during World War II, one of the little known problems faced by Allied forces was the construction of landing areas. Runways were time-consuming and expensive to build and subject to repeated Axis air attack, while use of unpaved airfields caused mobility and related problems during inclement weather, especially in cultivated areas. Both France and England experimented with types of temporary landing surfaces such as rigid bar mats and tracks of flexible square mesh. On finding previous designs unsuitable, the U.S. Army Air Corps engaged the Corps of Engineers to research landings mats for emergency surfacing of runways in 1939, before the U.S. entered the war.



A section of portable runway in Alaska undergoing expansion. *U.S. Army Engineer School.*

Investigations began at Langley Field, Virginia, in May 1940, under direction of the Engineer Board, which brought in the Waterways Experiment Station (WES) to conduct research. The Air Corps requested two designs – a light design for pursuit and observation planes and a heavy design for bombers. At a meeting with G.G. Greulich of Carnegie-Illinois Steel Corporation, Engineer Board representatives described what they needed, and by the end of

the meeting Greulich had already sketched a design that Lt. Gen. Henry Arnold later described as “the year’s greatest contribution and achievement in aviation.” Initial designs included a wire mesh mat for the lightweight and a pierced steel plank for the heavy. Sliding interlocking projections held by spring clips locked the mats together.

Other companies submitted designs over the next several months, which WES put through engineering and service tests. If mat designs withstood repeated stress under an 18,000-lbs truck, the mats then faced tests under airplane traffic. In December 1941, the Army selected the Greulich design for the heavy mat and four designs for the lightweight, which, in 1943, it reduced to two after observing field performance. Throughout the war, 39 companies produced 798 million square feet of heavy mats and 45 million of lightweight. Change of design criteria in 1944 to a single weight mat led to the development of lighter pierced aluminum plank. The Corps also experimented with prefabricated bituminous surfacing – a waterproof fabric adhered to soil – but did not use it for portable runways because it punctured too easily.

After the war, the Air Force requested continued studies for dual weight requirements, and the Corps experimented with steel, aluminum, magnesium, and plastic mats and developed

improved connecting mechanisms. The Engineer Research and Development Laboratories, which replaced the Engineer Board in 1947, worked with WES to design and test the mats. The M6 and M8 light and heavy mat based on earlier steel models became the standard mats used through the Korean War. The Corps added the M9 aluminum mat in 1952. However, jet planes, introduced in 1952, made the perforated designs obsolete because jet blasts contributed to soil erosion. As a result, the Corps began developing mats to meet the need of jet planes in 1958.



Close-up view of M8 steel landing mat. *U.S. Army Engineer School.*

After 1957, WES assumed future responsibility for development of mat designs. These included the development of small tactical airfields for use in amphibious operations for the Naval Air Materiel Command in 1961, the development of stronger aluminum and magnesium mats for the Army Materiel Command after 1962, and testing of standardized Tri-Service landing mats from 1964 to 1966. The latter resulted in standardizing on high-strength alloy mats developed by Dow Chemical Corporation in 1967. Waterproof designs by Kaiser Aluminum and Chemical Sales became the standard in Southeast Asia, while WES developed the Truss Web heavy duty mat for heavy C-5 planes.



M8 landing mat undergoing testing at the Waterways Experiment Station.

By 1975, the landing mat development mission was complete. Over 35 years, WES and the Engineer Research and Development Laboratories developed and tested hundreds of mat designs prior to implementation in the field. The mats made a significant contribution to national defense from World War II to Vietnam. As one author noted, the mats were “largely responsible for the growth and maintenance of Allied air power.”



Riverine Utility Craft.

of laboratory equipment, a major part of its mission included testing of vehicles or vehicle components such as wheel or tire designs. For example, the center participated in field testing of vehicles designed to operate in marshy or soft soil conditions such as the Marsh Screw, Weasel Track Vehicle, XM759 Marginal Terrain Vehicle, and Riverine Utility Craft amphibious vehicles and Mule small ammunition carrier. Another project, the Tire Research Program from 1960 to 1962, tested the performance of different tire designs in various soil conditions.¹³⁶

Related to the mobility research was WES' involvement in researching the impact of the environment on Army operations. Paul Siple of the Army Research and Development Division had argued strongly for the need to understand the impact of environmental factors such as vegetation, wildlife, moisture, terrain, and climate on combat operations. In 1952, his office enlisted WES to support the Environmental Analogs and Evaluation and Presentation of Changing Environmental Factors initiatives to research environmental issues faced by the Army. In 1954, OCE combined these programs as the Military Evaluation of Geographic Areas study. The WES Soils Division created an Area Evaluation Section in the Flexible Pavements Branch to support the new mission. Over the course of the next eight years, WES and consultants from George Washington University, the University of North Carolina, and Cornell analyzed 9,200 incidents of environmental factors impacting combat operations and compared various environments, even going so far as to live and conduct experiments in Greenland. The result was the identification of six factors that could affect troops: surface geometry, surface composition, hydrological geometry, vegetation, animal life, and weather and climate. Although researchers found it nearly impossible to quantify these factors, their understanding and ability to describe

and classify regions improved considerably and allowed the development of highly informative regional maps. Because of the success of the program, in 1962, OCE requested that WES support the Mobility Environmental Research Study of Southeast Asia to support U.S. efforts in Vietnam. With the growth of the program, in 1963 WES formed the Mobility and Environmental Division to handle future research efforts. It was, as historian Benjamin H. Fatherree observed, an inauspicious start for environmental studies, which eventually became one of the largest research areas for the Corps of Engineers (see Chapter Six).¹³⁷

By the end of the war, soil mechanics research had advanced considerably, at WES, ORDL, district and division labs, headquarters, and various contracted universities such as MIT. Leading experts in the field had provided guidance to the program, for example, through the Board of Consultants for Airfield Pavements. In addition to research of pavement designs and trafficability of military equipment, the Corps supported a number of research areas in military and civil fields, such as evaluation of soil bearing capacity under gun placements, draining filters used in slope protection, improved methods for measuring soil stress, and general research on earth pressure cell development and measurement of their stress in soils. Despite the fact that such research in the Corps was decentralized and uncoordinated, which Thomas Middlebrooks called a “fundamental weakness” that “should be de-emphasized,” it was “invaluable” to the war effort. “The Department should be proud of its record in the application of soil mechanics, since it is now recognized the world over as leaders in this field.”¹³⁸

Cold Regions Research to the Cold War

Another research area coming out of World War II that eventually became a major Corps focus was inquiry into the effects of cold climate on construction. Some of the most intense military construction occurred in cold regions, which were mostly undeveloped prior to the war. The so-called North Atlantic Road – a series of air bases in Newfoundland, Greenland, Iceland, and Northern Europe – provided transit stops for refueling aircraft during the war. Likewise, the Alaskan Territory, for which the Corps gained sole responsibility for military construction in 1941, was critical due to its strategic access to the Pacific Ocean. Over a two year period, the Corps built more than two million square miles of runway at bases on the Atlantic coast, while planning and building Alaskan facilities at Ladd Airfield, Annette Air Base, Yakutat Landing Field, Fort Richardson, Fort Ray, and other locations. It also helped build an Alaskan-Canadian Highway in 1942. Construction of these facilities faced almost continual problems due to cold climate issues, primarily permanently frozen ground – permafrost – and the continual cycle of freezing and thawing. In cold regions, there are multiple soil layers, including seven or eight feet that go through seasonal, annual, or cyclical thaws and often 30 feet or more of permafrost. The cause of most construction problems was the movement of groundwater above the permafrost layer, which caused mudflows, landslides, gullies, cracks, and fissures that quickly eroded pavement and destabilized structures. Heated buildings or hot asphalt contributed to problems because of melting permafrost, as did driving piling without insulation. In addition, cold weather caused problems with mobility, entrenchment, and even waste disposal for troops. Other than limited construction in Alaska since 1890, the Corps lacked experience with these issues.

Often relying on the expertise of Canada, Sweden, Russia, and other allies, the Corps was able to resolve some issues through trial and error; for example, using sand and gravel to stabilize structures, using plank runways, diverting groundwater, and investigating construction sites over several months before selection to determine the location of permafrost.¹³⁹

After a warehouse at Northway Airfield sank into eroded soil, the Army Air Transport Command (ATC) initiated research with the U.S. Geological Survey (USGS) and Siemon Muller of Stanford University, who had coined the word permafrost. Their research mostly related to groundwater, not permafrost per se. In 1943, the Corps began new investigations, which General Henry Arnold of the Army Air Force (AAF) called “most important and urgent,” including investigations of freezing pavement by the Missouri River Division. In 1944, OCE tasked William Sherman of the Boston District Soils Laboratory to oversee tests of frozen soil in what became the Arctic Construction and Frost Effects Laboratory (ACFEL). It also tasked the Engineer Board to review existing research and literature, starting with Russian research on “vechnaya merzlota” or permanently frozen ground. The board held several conferences that spring with the AAF, ATC, USGS, the Northwest Division, the Greenland District, and private industry, which revealed construction difficulties – pockets of frozen and unfrozen ground, annual variances in permafrost location, and the effect of construction on thawing. In December 1944, the AAF called a conference with OCE, ATC, and Canadian units to settle how to proceed. While Muller provided advice on building techniques and argued for multi-year experiments to ensure reliable construction, the U.S. military could not wait that long. Instead, the team developed short-term goals supporting immediate construction and maintenance, and long-term goals for collecting data over several years and conducting laboratory and field experiments. A flurry of activity followed. OCE tasked Lt. Col. Lynn C. Barnes of the St. Paul District to organize a task force to study permafrost. Barnes created a Permafrost Division, established a field station at Northway Field, and started additional studies with the USGS and Muller. The station started aerial reconnaissance and collected meteorological and soil samples from various locations to identify permafrost, the extent of groundwater, and temperature ranges. The Corps published a permafrost manual compiled by the Engineer Board and developed training courses. In addition to reviewing Russian research, the board reviewed research by Canada, Purdue University, the University of Minnesota, the University of Nevada, and other institutions. Construction teams began to experiment with construction techniques, sampling drills, and other equipment.¹⁴⁰

In the summer of 1945, with the war nearly at an end, the Corps entered into cooperative snow investigations with the Weather Bureau, the USGS, and the Bureau of Reclamation to conduct basic research into snow issues such as compaction, accumulation, depletion, and runoff. Robert W. Gerdel, then with the Weather Bureau, served as the technical director, Forrest Rhodes was the Corps administrator, and about 20 personnel from the South Pacific Division helped collect data. The team purchased a four-square-mile basin near Soda Springs, California, in the Sierra Nevada Mountains as a micro-climatic project, set out instruments, and built the Central Sierra Laboratory. It later built additional labs at Glacier Park, Montana, and Blue River, Oregon. Meanwhile, work continued at the Permafrost Division, which

opened a new field station at Ladd Field in 1946, while ACFEL published *Pavement Design for Frost Conditions* and conducted experiments in Greenland the next year. By 1947, as the Cold War began to heat up, the importance of the northern frontier in Alaska, which shared multiple borders with the Soviet Union, became evident, yet little improvement in construction techniques in the region had occurred. That spring, the War Department sent Henri Bader, a Swiss-born American scientist teaching at Rutgers University, to Europe to determine the progress of snow and ice research. His report prompted a conference on August 12, 1947, which stressed the need for increased basic research. Chief of Engineers Lt. Gen. Raymond A. Wheeler recommended in October and again in May 1948 the establishment of a Snow and Ice Mechanics Laboratory. The following year, the Army Research and Development Board approved the lab and on March 15, 1949, the incoming chief, Lt. Gen. Lewis

A. Pick, ordered the establishment of the Snow, Ice, and Permafrost Research Establishment (SIPRE), further ordering that St. Paul District locate facilities, recruit personnel, and establish a board of consultants. In June 1949, the Research and Development Board gave the Corps the lead in conducting snow, ice, and permafrost research and related cryological, meteorological, and environmental research.¹⁴¹

At the preliminary SIPRE conference in 1949, Phillip Rutledge of Northwestern Technical Institute, Edwin Bucher from Switzerland, Morrough O'Brien of the University of California, and representatives from the St. Paul and Sacramento districts and South Pacific Division agreed that the Central Sierra Lab should become part of SIPRE. With its transfer and the closing of the Montana and Oregon facilities, the Weather Bureau Cooperative Program came to an end. However, the bureau agreed to loan out Gerdel, who joined Bader and others at St. Paul. He eventually transferred to SIPRE. At first, Henry Manger of the Permafrost Division managed SIPRE out of the district, but OCE made it clear it was to operate independently. The team moved to offices at the University of Minnesota until other facilities were located. Bucher, Rutledge, and Commander Col. A.H. Lahlum eventually settled on a three-story dry cleaning plant in Wilmette, Illinois, near Northwestern University, and SIPRE moved into the facilities in July 1951. In the interim, SIPRE started its work. The lab's first missions were to survey existing



Robert W. Gerdel at Central Sierra Snow Laboratory.
Mark McLaughlin/Gerdel Collection.

research and coordinate with other agencies on research needs. SIPRE spent considerable time gathering data in coordination with OCE and the Library of Congress, and it held a series of conferences starting in 1950 on snow compaction and related topics. It also started its basic research program by letting contracts for experiments on snow compaction, snow classification, ice crystals, and ice mechanics. Over the winter, Gerdel and Lahlum started the first field research to determine the effects of cold on pathogens for a Canadian medical unit. By early 1951, SIPRE established a research program and budget for the Central Sierra Lab, focusing on issues ranging from radiation penetration of snow to permeability, evaporation, vegetation, and snow cover. It also determined the need for a field station and established the Keweenaw Field Station in the Upper Peninsula, Michigan, in 1953. With the support of the 1st Engineer Arctic Task Force and in coordination with ERDL and WES, over the next several years SIPRE participated in snow trafficability tests in inland Greenland and elsewhere, developed subsurface roadways, tested ice runways to support supplying the Distant Early Warning radar stations, and established subsurface research stations, first at Camp Fistclench (Site Two) in 1955 and then Camp Century in 1959. These were 218 and 138 miles, respectively, east of Camp TUTO (Thule Take-Off) near Thule Air Force Base, Greenland, on the edge of the ice sheet.¹⁴²

Weapons and Weapons Effects

Since the nineteenth century, through the Engineer School, the Board of Engineers, and the Endicott and Taft Boards, the Corps had gathered data and conducted experiments related to weapons such as torpedoes and mines and their effect on fortifications. World War II and the Cold War were no exception, although the Corps mostly worked for the Ordnance Department or other agencies. For example, the Engineer Board tested various combat vehicles, and after the war BEB worked with the Navy on studying submarine motion in a confused sea and helped develop methods for sweeping and neutralizing mines in coastal waters. Perhaps the biggest weapon project entrusted to the Corps was work on the atomic bomb through the Manhattan Project. As early as 1939, several German immigrant scientists led by Albert Einstein made President Franklin D. Roosevelt aware of work being conducted in Germany on subatomic physics and its destructive potential. After Germany invaded Belgium, whose colony, the Congo, was a prime source of uranium ore best suited for atomic weapons, the president initiated a secret project overseen by the NDRC, which tasked the Corps of Engineers to manage it. In August 1942, the Corps established a covert district office headed by Col. James C. Marshall and later Col. Kenneth D. Nichols. Since early work occurred in Manhattan, New York, including purchasing uranium ore from the Congo, the Corps established the Manhattan District headquarters on Broadway near the Corps' North Atlantic Division. Brig. Gen. Leslie Groves, the no nonsense project manager assigned in September 1942, quickly enlisted leading physicists such as Robert Oppenheimer of the University of California and established laboratories in Oak Ridge, Tennessee; Los Alamos, New Mexico; and elsewhere. The headquarters moved to Oak Ridge in August 1943, while Groves established his office in Washington, DC. Although not a physicist, Groves not only managed facilities and materials, he oversaw design, development, and testing of the first bomb in July 1945, as well as planning and developing policy for

its deployment. A major feat was maintaining strict secrecy, which he accomplished by compartmentalizing research. After the war, both he and Nichols went on to serve in the Armed Forces Special Weapons Project, which carried on nuclear research for peaceful purposes.¹⁴³

Soon after the end of World War II, the Corps requested that WES support research into the effects of explosions on various infrastructures. With the development of the atomic bomb and the ensuing arms race, concern about



Maj. Gen. Leslie R. Groves considering potential targets. Office of History, U.S. Army Corps of Engineers.

the impact of nuclear weapons on structures gave weapons effects research a new impetus. No one knew exactly how these new weapons would affect U.S. infrastructure such as dams or waterways, and there was a particular fear that a nuclear bomb detonated off the U.S. coast would cause a tidal wave. In early 1950, during the absence of WES Commander Col. Herrol Skidmore, Executive Officer Maj. G.L.C. Scott received a call from OCE about the lab's capability to conduct a secret research program on underwater explosion effects for the Armed Forces Special Weapons Project, which later fell under the Atomic Energy Commission. It would come to be known merely as Study 2178, the project number assigned by WES. Skidmore directed the formation of a task force under the leadership of Guy L. Arbuthnot. In mid-December, WES set off the first of several conventional explosions at varying depths in a test basin, with explosion sizes ranging from fire crackers to several pounds of TNT. Engineers then recorded the results using cameras, air gauges, and seismic equipment. While Skidmore alerted the public to the ongoing explosions for defense-related research, it was not until later in 1951 that the public learned that the explosions tested the impact of nuclear weapons on harbors such as New York, San Francisco, New Orleans, and Philadelphia. Simultaneously, team members visited other laboratories, including the Army Ballistics Research Laboratory and Naval Ordnance Laboratory, to collect data on weapons tests. OCE also tapped BEB to conduct research into wave refraction from nuclear and conventional explosions and the spread of radioactivity in beach materials.¹⁴⁴

After a conference with consultants on February 5 and 6, 1951, and other conferences throughout the year to review progress of the preliminary tests, the scope of WES research expanded considerably to include air blast, water shock, cratering, and effects on structures. With work now extending past a year and with multiple projects lined up for the future, Hydrodynamics Branch Chief Fredrick R. Brown created a Special Investigations Section to handle the work in June 1951. Project funding increased from about \$100,000 in 1951 to \$900,000 in

Positive Uses of Nuclear Technology?

In 1962, President John F. Kennedy requested an investigation into the construction of an Isthmian Canal to supplement the Panama Canal, including exploration of potential construction methods. In response, Glenn T. Seaborg, chairman of the Atomic Energy Commission (AEC), directed a study of nuclear excavation under Operation Plowshare, the 1957 program to explore peaceful uses of nuclear technology. In May 1962, Seaborg arranged the support of the Corps of Engineers in a joint study. The Office of the Chief of Engineers established the U.S. Army Engineer Nuclear Cratering Group (NCG) a few months later.



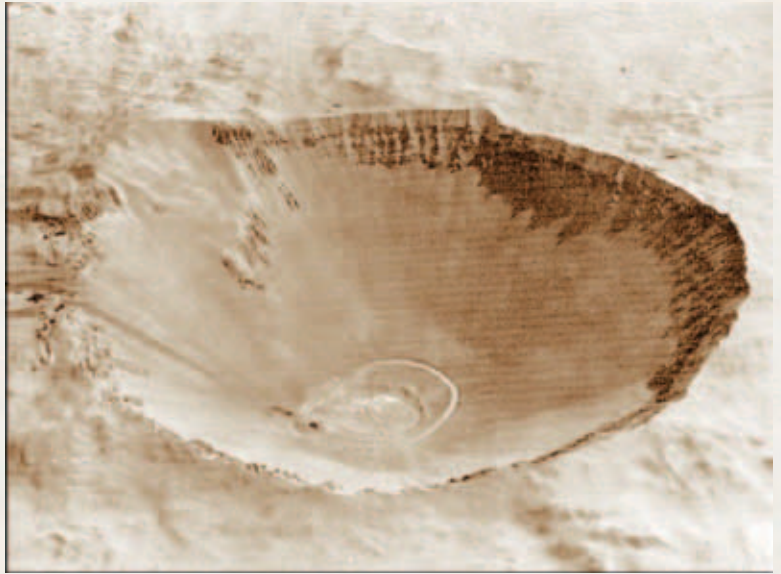
Ernest Graves, Jr., the first director of the Nuclear Cratering Group, as a general officer. *Office of History, U.S. Army Corps of Engineers.*

Headquartered at the Lawrence Radiation Laboratory in Livermore, California, where it could work closely with the AEC, NCG initially included six officers and one civilian. The first director was Col. Ernest Graves, Jr., who held a Ph.D. in Physics from MIT and worked on the Manhattan Project during World War II. Later directors included Col. Walter Slazak, who also worked on the Manhattan Project; Lt. Col. Maurice Kurtz, formerly from the Engineer Research and Development Laboratories; and Lt. Col. Bernard Hughes, who previously served as assistant director under Graves. By 1969, the group grew to 11 officers, 24 civilians, and six enlisted personnel. NCG also involved the Waterways Experiment Station (WES) and Corps districts in several experiments.

Per joint agreements, the AEC provided nuclear devices and carried out experiments, while NCG conducted non-nuclear experiments, developed engineering data, and conducted construction, technical, and engineering studies. In 1962, NCG began non-nuclear investigations at the Nevada Test Site and Fort Peck and Glasgow, Montana, to test various TNT charges with different soils and to collect data on crater geometry. These eventually resulted in scale laboratory experiments in 1965 to study craters and distribution of ejecta. Also starting in 1962, NCG participated in AEC nuclear detonation experiments at the Nevada Test Site to collect data on scaling explosions, row cratering, and radiation distribution, concentration, and decay. With names like Operation Pre-Gondola, Zulu, Danny Boy, Sedan, and Sulky, the projects were highly secretive.

While conducting tests to get a better understanding of cratering behavior, NCG also participated in 12 Corps feasibility studies involving the use of nuclear explosives for excavation and quarrying and another 22 studies for state agencies or the Bureau of Reclamation. These included studies of spillways, canals, quarrying, dams, and harbor improvement, mostly in the Northwest United States. Although NCG found in the majority of these that using nuclear explosives was cheaper than conventional explosives,

safety concerns such as proximity to population centers, impact area reentry time, and geological instability often outweighed any savings. Perhaps the most productive study involved formation of ejecta dams, where explosions create rockfill dams in a canyon. In 1966, NCG published a technical manual on using nuclear explosions for excavation and quarrying.



The Sedan crater measured 320 feet deep and had a 1,200 foot diameter.

With the passage of Public Law 88-609 in 1965, NCG also gained responsibility to support the Atlantic-Pacific InterOceanic Canal Study Commission (A-PIANC). NCG helped A-PIANC analyze potential Isthmian Canal routes, including ones through Columbia, Nicaragua, and Costa Rica that used nuclear explosives for excavation.

By the end of the decade, safety concerns and related costs made using nuclear technology for construction unrealistic. Further, the Strategic Arms Limitation Treaties (SALT), which the U.S. began negotiating in 1969, restricted testing or use of nuclear explosives, eliminating all but the non-nuclear investigations of NCG. By 1971, the group's activities had slowed greatly, and the Corps redesignated it the Explosive Excavation Research Laboratory under management of WES until its eventual closure and transfer to Vicksburg in 1975. Although use of nuclear cratering in construction proved



Danny Boy crater, view from the inside of the crater.

untenable, the program increased understanding of nuclear explosions, such as terrain impacts and prediction of effects, while also advancing knowledge of excavation techniques.

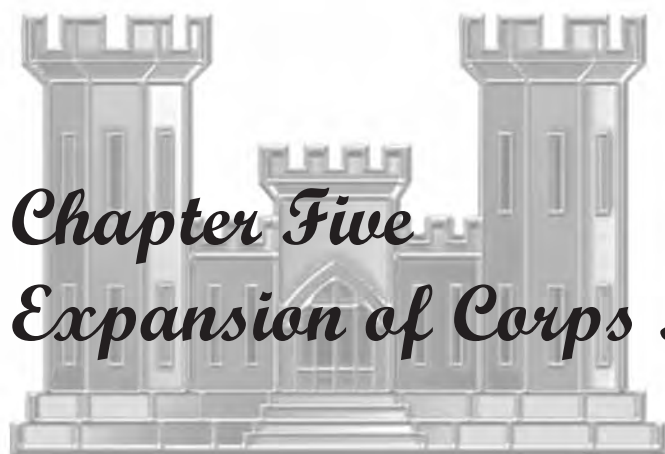
1962, when a total of 38 personnel were supporting research efforts. With continued growth of the program, the section became the Nuclear Weapons Effects Branch within the Hydraulics Division in 1962 and became a separate division in 1963, which formed the basis for the Weapons Effects Laboratory in 1972, renamed because of its later emphasis on conventional weapons. The first division chief was Eugene P. Fortson, then Brown in 1964, Arburthnot in 1966, and William Flathau in 1972. By 1968, the Nuclear Weapons Effects Division included 88 personnel and had an annual budget of \$4.5 million.¹⁴⁵

At first, the primary research area was underwater effects of explosions. By 1953, the size of explosions needed to simulate nuclear weapons required tests away from WES, which was too close to residential neighborhoods. That year, WES detonated 50 tons of TNT at Sevier Bridge Reservoir, Utah, the largest underwater conventional explosion to that date. In 1957 and 1958, WES conducted several explosive experiments at a site in the nearby Big Black River swamps, where modelers built a concrete mock-up of a dam and reservoir. Some of these experiments produced very novel results, as with the 1965 10,000-pound explosion tests at Mono Lake, California, in which WES collected detailed data on the generation, propagation, and runup of waves generated by underwater explosions. As early as 1952, WES became involved in under- and above-ground explosions related to collection of cratering data. While conducting conventional detonation experiments of up to 600 tons at test sites in Amchitka Island in the Aleutians, the Greenland icecap, Canada, the Rocky Mountains, and the Ozarks to measure effects in various terrains, WES also participated in numerous nuclear tests at the Nevada Test Site, the salt dome in New Mexico, and Eniwetok Proving Grounds in the Pacific. In 1962, WES became involved with excavation tests in support of the U.S. Army Engineer Nuclear Cratering Group, including several experiments in 1962 of excavation in Panama using cratering, a 1965 study of an interoceanic canal, and a series of 23 test projects using nuclear excavation by local Corps districts or state organizations. By 1956, WES also became involved in testing the effect of nuclear explosions on structures with its participation in Operation Plumbob at the Nevada Test Site. Following this test of buried arches, WES went on to test other underground structures of various shapes and sizes to determine the effects of explosions on their stability. The WES Soil and Concrete laboratories and other Corps entities participated in many of these tests to investigate stress wave and impulse propagation, conduct subsurface exploration experiments, and test construction technologies such as grout, while BEB consulted on erosion issues related to a NIKE launch site on Kwajelin Island. In the late 1960s, WES turned to tests of the effect of conventional weapons on above-ground structures such as barracks, and during the Vietnam Conflict helped in developing methods of locating tunnels or other cavities, testing tunnel-busting bombs, and measuring the penetration of projectiles through soils or structures.¹⁴⁶

The weapons effects research led to significant advances in understanding a range of issues related to explosives and structural integrity. For example, through the only shallow-water tests of underwater shock propagation to that time, WES was able to develop shock attenuation rates for various depths and thus predict underwater pressures and wave heights at various distances from an explosion. Similarly, cratering tests allowed prediction of explosion effects such as stress propagation or soil arching in various terrains, improving its ability to predict strain on

structures. As a result, WES was able to develop technologies and strategies to protect against explosions or projectiles that found use in civilian as well as military designs. Among the technological developments accompanying this research were improvements in the ability to record and simulate explosive effects. From the days of Study 2178, WES instrumentation researchers such as Eugene Woodman, Francis Hanes, L.H. Daniels, and Leo F. Ingram developed instruments ranging from high-speed cameras to blast or shock gauges, such as transducers and earth stress gauges. Many of these devices were not commercially available. A major breakthrough in laboratory blast testing occurred with the installation of the Large Blast Load Generator in 1963, which could place loads up to 500 pounds per square inch (psi) on soils and structures. WES also installed ram-type loaders and a smaller blast load generator from 1966 to 1968, the latter of which could place up to 13,000 psi on samples. Paul F. Hadala, Darryl Hale, and others led efforts to perfect the use of these devices by placing samples in metal cylinders or using greased liners to reduce sidewall friction. This enabled WES to test many weapons effects in the laboratory, saving valuable time and lowering project costs.¹⁴⁷

The history of research and development from 1935 to 1960 proved Vannevar Bush almost prophetic in the influence science had during the Cold War era and beyond. Certainly, research within the Corps of Engineers proved this true as the technologies and knowledge created by the Corps helped save lives and achieve victory from World War II to Vietnam. In Bush's conceptualization, humanity in the post-war world faced a choice between democracy and dictatorship, a choice in which science increasingly had a role. While science could help one or the other be victorious through improved methods of warfare, it also helped mold world view: "Science has altered war. But it has also molded the thinking of men." In this more subtle competition, according to Bush, democracy would always be the clear winner because it created an atmosphere of freedom in which scientists could flourish, whereas dictatorship or totalitarianism stifled science by controlling and politicizing it. The results of science in the free world were beneficial not only to armed conflict but to peaceful prosperity: higher standards of living, longer life, improved health, etc. Corps research also found extensive peacetime application in civil works and other fields. Its research into runway pavements improved asphalt and concrete technology, leading to the development of the most advanced highway system in the world. Its mobility studies eventually led to the Army's entry into environmental research. Study of permafrost to support wartime construction in cold regions expanded to include far-reaching investigations of engineering in cold climates. Weapons effects research improved overall structural understanding. As with other areas of scientific research after the war, "the application of science yet to come are manifold and far-reaching."¹⁴⁸



Chapter Five

Expansion of Corps Research



Research in a permafrost tunnel at the Snow, Ice, and Permafrost and Permafrost Research Establishment.

After World War II, the federal government recognized the need to continue scientific and engineering research to remain competitive in military and peacetime activities, but attracting the brightest minds to less publicized, lower paid jobs became increasingly difficult. To improve government research, many federal departments created government-operated or privately operated but government-funded research centers. These laboratories, research centers, and think tanks often were associated with universities, which helped attract leading scientists, provide an independent atmosphere, and allow continuity of research with a constant stream of new ideas. The level of investment increased from \$100 million before the war to \$10 billion annually by 1962. It is no surprise that, given the incredible growth of these research centers, their impact on regional industry, and the growing level of federal funding involved, Congress soon became concerned with their effectiveness and long-term impact on the private and government workforce. Largely as a result of these concerns, President John F. Kennedy requested an investigation of federally funded research. The resulting report, known as the Bell Report after Bureau of Budget Director Robert Bell, evaluated both contracted and in-house research. While noting the value of contracted research facilities, it also warned of the need to improve in-house research, simplify management, and increase salaries and education levels of government researchers, and it called on the government to develop plans of action. “No matter how heavily the government relies on private contractors, it should never lose a strong internal competence in research and development.”¹⁴⁹

The Corps of Engineers, which had accepted the need for national engineering research centers a decade before the war, started to improve and simplify its research capability even before the Bell Report. By 1960, Corps research had grown to where there were multiple laboratories with overlapping missions serving the entire Corps community. There were at least two central laboratories for coastal engineering, two focusing on river hydrology, three researching construction issues such as concrete or soils, and three examining climatic issues, not to mention division and district laboratories that duplicated these areas. The research conducted was valuable, but often redundant. Further, research in several laboratories expanded well beyond traditional missions of the Corps, such as testing vehicles used for non-military purposes. To address these issues, the Corps started the first of several efforts to organize its laboratories into a coordinated system. Over the next 10 years, it merged research activities into seven major areas at five labs: topographical engineering at the Engineer Topographic Laboratories; cold climate science and engineering at the Cold Regions Research and Engineering Laboratory; coastal engineering at the Coastal Engineering Research Center; hydraulic engineering, geotechnical engineering, and concrete technology and structural engineering at the Waterways Experiment Station (WES); and construction research at the Construction Engineering Research Laboratory. At the same time, it introduced several research organizations at headquarters and developed a structure to coordinate among the different laboratories within the decentralized nature of the Corps. These efforts greatly improved research, but the Corps did not fully address the mission conflicts that continued until the modern era.

Topographical Research Breaks Out

Through World War II, the Engineer Board had developed military equipment ranging from mine detectors and tank bulldozers to military theodolites and astrolabes. As part of an overall trend within the Corps away from research or examination boards toward permanent laboratories, in 1947 the Office of the Chief of Engineers (OCE) redesignated it as the Engineer Research and Development Laboratories (ERDL). However, its mission at Fort Belvoir, Virginia,



Instruction in aerial photo topography. *U.S. Army Engineer School.*

ia, continued more or less without change. While funding remained flat and even decreased slightly from the war years, the number of projects it processed increased rapidly from 192 in 1945 to 314 in 1950, handled by fewer than 1,300 personnel. In addition to its headquarters, it operated a Materials Laboratory, Motion Picture Laboratory, Compressed Gas Testing Facility, Mine Detection Laboratory, Petroleum Distribution Test Facilities, a

test area at Eebee Field at Fort Belvoir, and a field facility at Yuma Test Station that closed in 1950. It also coordinated with other Corps agencies and districts, such as the Arctic Construction and Frost Effects Laboratory (ACFEL) in the Boston District or WES in Vicksburg, Mississippi. After 1945, research shifted from short-term research of equipment needed for the war effort to long-term investigations and training support of equipment. Research into airfields, protective structures, mine detection, and bridging decreased, due in part to transfer of some of these activities to other laboratories. However, funding of research on camouflage, petroleum and water distribution, and mechanical and electric engineering equipment increased sharply. The majority of this research focused on development of technology concepts related to actual equipment – of 1,515 projects processed from 1945 to 1950, more than 130 resulted in standard equipment, more than 800 were in various stages of testing, and 376 were in the prototype stage.¹⁵⁰

One of the high-growth areas at ERDL was the development of topographical and mapping equipment in the Mapping Branch of the Technical Department. With the introduction of electronic and automated survey tools, the topographical area had grown to the point where, in 1951, ERDL introduced a Topographical Engineering Department, which included Surveying, Map Compilation, Map Reproduction, and later Topographic Systems branches. By

1959, the department had grown to 108 personnel. There was by this time recognition that topographical and mapping technology was gaining importance for both combat and non-combat purposes. The availability and use of more geographic data, the potential of using newly developed artificial satellites to capture data, the need for faster and more precise survey equipment, and the development of methods to improve data collection were of interest to local and state agencies, such as highway departments, as well as federal agencies. To address this trend, in 1960 OCE formed the U.S. Geodesy, Intelligence, and Mapping Research and Development Agency (GIMRADA), which combined all topographical research being conducted by ERDL, the Engineer School, and the Army Map Service. The first commander, Col. L.L. Haseman, served briefly while the agency stood up, and it quickly expanded in mission and funding under his replacement, Col. W.H. Van Atta. By 1965, GIMRADA had nearly doubled its personnel to 200 and was receiving \$12 million in funding annually. As the non-combat-related research of the agency grew, the name of the agency became a problem because the intelligence function and its security requirements sometimes intimidated civilian agencies. In 1967, GIMRADA changed its name to the Engineer Topographic Laboratories (ETL), a name it would retain for more than 20 years.¹⁵¹

Military equipment research under ERDL, meanwhile, continued. Among its many achievements was the development of an early prototype nuclear power plant, the SM-1. Although the Nuclear Power Division at OCE was responsible for the overall Nuclear Power Program in the Corps, the Nuclear Power Branch at ERDL managed construction, oversaw operation of the SM-1 at Fort Belvoir from 1957 to 1973, monitored radiation, and provided expertise on other nuclear power construction projects. The Engineer School trained on nuclear power operation using this plant for many years. ERDL continued research into landing mats and portable bridges, conducted investigations into hydrogen fuel cells, and developed heavy drills and other engineer equipment. After 1960, ERDL research turned increasingly to development of vehicles such as bulldozers or equipment shelters for the Signal Corps, with more and more equipment being developed for non-engineering purposes. With the creation of the Army Materiel Command (AMC) in 1962 to oversee supply and logistics issues at the recommendation of the 1961 Hoelscher Committee, Secretary of Defense Robert McNamara moved most equipment research under its direction. In 1962, the Army Chief of Staff ordered that ERDL be moved under the AMC. Although the Deputy Chief of Engineers for Military Operations continued to head the lab for several years, from this point ERDL was an AMC asset. In 1967, AMC renamed ERDL the Mobility Equipment Research and Development Center, and it soon after became a separate command under the AMC, the Army Mobility Equipment Command. The Corps continued to support testing equipment related to engineering activities, but it no longer had the lead for developing military equipment and vehicles.¹⁵²

However, the Corps argued that, while the AMC was responsible for “materiel” research, the Chief of Engineers had “implied responsibility for research in support of his other missions.” Among this research was development of topographical equipment by GIMRADA and ETL. Work continued on rectifiers, projectors, stereoscopes, and plotters to adapt them to new technology. With the advent of high-altitude spy planes, such as the U2, researchers had

to adjust equipment to handle wider collection areas and angles, for example, through supplemental camera coverage and new triangulation formulas. Larger collection areas eventually led researchers in 1955 to develop devices for converging photographs into a single image or mosaicing data from multiple images. The dynamic nature of military photography and restricted access to surveillance subjects led the lab to develop techniques to take measurements without a ground control, using radar or other remote sensing. It developed analytical methods for triangulation, relying on mathematical or computer models instead of instrument measurements. In the reproduction field, GIMRADA continued work with lithographic printing and copy cameras. By 1958, experimentation with modern electrostatic printing methods began. This method, which most major reproduction vendors adopted, used static electrical charges, heat, or pressure to force or attract dry ink toner onto the printing drum, allowing a faster and cleaner process. The development in 1955 of the color separation process, which uses four ink colors to provide nearly any shade of color, enabled simpler, higher quality color maps. With the advance of electronics, the lab developed a series of electrical devices to automate survey tasks. ETL developed theodolites, tellumeters, altimeters, time comparators, and other devices to automatically measure distances or aid in surveying, using radar or microwave signals. Perhaps the most significant development was short-range, long-range, and geodetic ranging or positioning systems that calculated positions by triangulating among ground stations, airplanes, or later satellites – essentially predecessors to modern global positioning systems (GPS). Of these, the most advanced was the Sequential Collation of Range (SECOR) System, which functioned conversely to GPS – instead of a single station and multiple satellites, it calculated position using a single satellite and multiple ground stations within a 1,500-mile radius of the unknown point.¹⁵³

Although the majority of research under GIMRADA and ETL was applied research to develop new equipment, there was a significant expansion of basic research related primarily to mathematical and geometric issues involved in use of satellites. ETL contracted leading experts from the U.S. and abroad to help develop a general knowledge in photogrammetric issues; its list of employees and consultants reads like a list of who's who in geodesy and photogrammetry. For example, Angel Baldini of ETL developed the Baldini Theory, a working theory of a geocentric geodetic system that allowed triangulation using satellites against the fixed position of stars. Using data collected after 1966, Hellmut Schmid of the National Geodetic Survey and a Corps adviser corrected the data to within 4.5 meters based on 3,672 field observations, while Erich Rutscheidt and others from ETL used test data from SECOR from 1965 to 1970 to correct its computational procedures to an accuracy of 10 meters. Karl Rinner of the Technical University of Graz, Austria, furthered efforts to correct error propagation in space triangulation from 1964 to 1967. Additional research addressed methods for determining the geoid, or the gravitational surface of the earth coinciding with global mean sea level, which was necessary for determining precise location. E.A. Bjerhammar, formerly of the Royal Institute of Technology, Sweden, worked in 1960 on methods of gravity data reduction that allowed him to develop a figure of the earth based only on horizontal observation points, gravity, and differences. After further refinement of gravity anomaly computations by Carlo Morrelli of Bari University, Italy,

through 1965, Armando Mancini of ETL developed a refined gravitational model of the earth. Others, such as Emmanuel Sodano of ETL and Karl Ledersteger of the Technical University of Vienna, Austria, sought alternate methods of calculating triangulation or the earth ellipsoid. The majority of research, however, was related to photogrammetry. Schmid, Sandor Veres of Purdue, H.M. Karara of the University of Illinois, and Bertil Hallert of the Royal Institute of Technology, Sweden, were among those who researched limitations and error-correcting methods for stereo photogrammetry, while Schmid and Hallert helped pioneer analytical methods. Growth of basic research led to the formation of a Research Institute after 1965 in ETL to house these functions.¹⁶⁴

Consolidation of Cold Regions Research

By the mid-1950s, cold regions research at the Arctic Construction and Frost Effects Laboratory (ACFEL) and the Snow, Ice, and Permafrost Research Establishment (SIPRE) had advanced considerably. Both organizations, along with ERDL, WES, and others, supported applied research into cold regions operations through the examination of technology and issues such as mobility, water supply, erection of structures, and snow compaction. A significant amount of this research centered in Greenland. A colony of Denmark, Greenland had remained largely unsettled until the war, but became a strategic location for airfields and missile systems. As noted in Chapter Four, SIPRE had helped develop methods for supplying the Distant Early Warning (DEW) line in Greenland, while ACFEL, which merged with the Permafrost Division in 1953, continued construction research. In 1952 and 1953, WES participated in mobility research with the Transportation Corps in Greenland. SIPRE became involved in this research in 1954, and by 1957 the Corps maintained a permanent presence in Greenland with a station at Thule and field locations, including Camp TUTO and Fistclench. By the end of the decade, SIPRE had 100 active projects researching surface snow, permafrost, crevasse location, snow drifts, glaciology, and blasting. In 1959, at Camp Century, SIPRE built an ice tunnel occupied year-round and experimented with various technologies. ACFEL had more than 50 projects focusing on construction issues, such as building roads near Camp TUTO. ERDL tested a variety of equipment in cold climates, such as snow plows, sanitation systems, pipelines, power plants, shelters, and path-finding and -marking systems. Additional research was ongoing at SIPRE's Keweenaw Field Station, Michigan, to which it had transferred research and equipment from the defunct Central Sierra Laboratory in 1954. ACFEL continued research in Northway, Alaska; ERDL conducted some cold weather research at Manitoba, Canada; and SIPRE aided the Navy with sea ice research at Point Barrow, Alaska. According to one estimate, about 550 personnel in the Corps had cold regions experience by the mid-1950s.¹⁵⁵

While ACFEL worked mostly on specific projects and researched the impact of permafrost on construction, SIPRE launched a program of basic research primarily of ice, snow, and snow compaction. In fact, the majority of the research at SIPRE was basic research, led by the Basic Research Branch, which included engineers and scientists holding six doctorates, four master's, and four bachelor's degrees in physics, geology, chemistry, and various engineering fields. Prior to the war, scientific knowledge of ice and snow was slight. In 1960, only two countries



Inside the ice tunnel at Camp TUTO, Greenland.

were pursuing major research into cold regions construction – the U.S. and the Soviet Union. Roughly 70 percent of the reports published by SIPRE were in the basic area, a fact in which employees prided themselves. As one 1960 branch summary noted, Lt. Gen. Arthur Trudeau, then director of Army Research and Development, had observed, “Basic research is crucial! It is the chief determinant of progress in the weapon art for this decade, and beyond. The Army clearly comprehends the need constantly to expand the horizons of basic research, to out-manuever and outdistance the Communists in this critical area.” Employees saw providing a general understanding of cold regions as well as SIPRE’s contributions toward the DEW line and developing under-snow camps as furthering these goals. The research conducted by SIPRE to improve understanding of the qualities of ice and snow, including molecular structure, density, conductivity, hardness, adhesion, elasticity, permeability, shear strength, and influence on soils, helped to firmly establish snow and ice mechanics as fields of engineering study. As with soil mechanics at WES, SIPRE engineers believed that thoroughly understanding snow, ice, and permafrost properties, and taking extensive samples and observations could improve the safety of designs and reduce the number of structural failures.¹⁵⁶

Although research was advancing, there were ongoing complaints about the adequacy of the research programs. In fact, SIPRE had hardly formed when its leaders began to question the lab and direction of research. Some of this originated with the unavoidable complaints about facilities. During the first few years at SIPRE, when it was located at St. Paul, Minnesota, there was not enough office space for all researchers, and the organization lacked suitable soil, chemical, and physics laboratories. Even after it relocated, SIPRE quickly outgrew the old dry cleaning building at Wilmette, Illinois, and leased additional buildings in Wilmette and nearby Evanston. ACFEL, meanwhile, moved some four times in 10 years, each time interrupting research efforts, until finally landing in crowded space at a hospital near Boston. Yet there were also complaints about the organization and research efforts. In his two-year review of SIPRE, Commander Lt. Col. Richard Flint noted that, while SIPRE had made progress, it had difficulties in attracting sufficient scientific personnel, particularly a chief scientist; it lacked guidance due to the infrequent meetings of the Board of Consultants; and it had not been aggressive in pursuing research programs. He recommended moving closer to a university, coordinating more with OCE, and doing more than manage research contracts. Days later, Edwin Bucher proposed the creation of an American Institute of Snow and Ice. He found SIPRE too loosely organized with poor communications among its elements. He complained that it was focused more on project management than research and that there should be separation between snow and ice research on one hand, and permafrost research – which he saw as merely soil research – on the other. In late 1959, F.J. Sanger, assistant to the director of SIPRE, identified several needed research projects, such as adfreeze bond, cooling systems for heated structures on permafrost, and studying the lateral pressure of footings on snow, ice, and permafrost, all of which SIPRE could not pursue because of the shortage of qualified personnel. By 1960, the Board of Consultants, which admitted it met too infrequently to have a good grasp of SIPRE’s activities, likewise stressed the need for more basic research, more scientific employees, and greater collaboration with local universities. Some kind of reorganization or move to another locale was unavoidable.¹⁵⁷

Voyage of the *Manhattan*

It was the dream of explorers for hundreds of years. Find the Northwest Passage – a channel providing a shortcut to Northwest America – and win acclaim and wealth by discovering a new trade route. Beginning with John Cabot in 1497 and continuing with Martin Frobisher in 1560, Henry Hudson in 1607, Robert Bylot in 1615, William Baffin in 1616, and others, the search for the passage continued until discovery of a route through the Arctic Ocean by William Parry in 1819, its overland navigation by Robert McClure in 1856, and its sea navigation by Roald Admundson in 1907. Unfortunately, harsh conditions and low profits rendered the passage commercially useless.

That did not change until the discovery of the largest oil field in North America in 1967 at Prudhoe Bay, Alaska (the North Slope). Transporting the oil would require either an expensive investment in pipelines or a revival of the Northwest Passage. However, no one knew if it was possible to navigate the passage year-round, whether ice-breaking ships and tankers could make it through the thick sheets of ice, or what the cost would be.

In March 1969, M.A. Wright, the chairman of Humble Oil and Refining Company, contacted



S.S. Manhattan in the Northwest Passage, 1969.

Secretary of the Army Stanley R. Resor about possible collaboration on a proposed expedition by their prototype ice-breaking tanker, the *S.S. Manhattan*. Charles Poor, the Assistant Secretary of Research and Development, put Wright in contact with Lt. Col. John Wagner, commander of the Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL). After reaching an agreement on funding, protection of the company's proprietary data, and release of other scientific data, CRREL agreed to rotate senior research personnel to supervise experiments on the vessel, including Donald Nevel, W.F. Weeks, Guenther Frankenstein, and Andrew A. Assur.

Captained by Roger Steward, the *Manhattan*, its crew of 55, and 71 guests departed in July and, accompanied by the icebreakers Canadian *H.M.S. John A. MacDonald* and U.S. Coast Guard *U.S.S. Northwind*, proceeded through the passage, making only a brief stop at Resolute Bay. Although the *Northwind* turned back at



Andrew A. Assur.

Viscount Melville Sound due to engine trouble and the *Manhattan* became temporarily stuck in ice in McClure Strait, they successfully arrived in Alaska on September 17. Joined on the return trip by the icebreakers *U.S.S. Staten Island* and *H.M.S. Louis St. Laurent*, the expedition paused in Viscount Melville Sound for three weeks to conduct extensive experiments.

During the trip to Alaska, CRREL took ice core samples and collected measurements on the salinity, temperature, strength, stiffness, and friction of sea ice, while the Coast Guard tested protective wet suits through dives in the freezing water. On the return trip, the team focused on testing the ability of the *Manhattan* to break through the ice. Humble Oil had designed the 1,005-foot vessel – the largest ever to navigate the passage or to fly the U.S. flag – with a reinforced hull. Each day, helicopters located large ice floes, then the vessel tried to break through them while scientists observed its thrust and velocity, how the ice cracked and wedged, and stresses on the hull. While they were able to develop data regarding the impact of ice depth, salinity, and rigidity on its ability to bend, further research would be necessary to determine the ice content that tankers could handle, whether annual or multi-year, and what thickness or consistency the designs needed to address.

The tests proved so successful, Humble Oil requested support on a second voyage leaving April 1, 1970. In addition, the company requested support from CRREL on selecting potential terminal facilities. However, by October, reduced cost estimates for a Trans-Alaskan Pipeline prompted it to suspend plans for using the Northwest Passage. Although the company chose not to use the passage, the expedition was “a chance to make history,” whether or not useful data resulted, as Humble project manager Stanley Haas said. “Let’s throw the facts and figures out the damn porthole and make a name for ourselves.”



Icebreaker *Northwind*.

As early as 1953, Robert Philippe and others at OCE had discussed merging SIPRE and ACFEL. A search for potential sites ensued with an emphasis on collocation with a major university to facilitate research. Several schools were under consideration, but from the beginning, OCE favored the Boston area, with Dartmouth College, New Hampshire, being the leading contender. In 1956, OCE directed SIPRE engineers to develop facility designs, for which it submitted a request for \$2.5 million in 1956, and which Congress authorized in 1957. Unfortunately, revision of the designs to increase refrigerated laboratory space required more funds. When OCE submitted a request in 1958 for an additional \$1.2 million, members of the House Appropriations Committee balked and initiated an investigation to determine if the lab was necessary and its cost estimate accurate. Work of the Cold Regions Engineering Laboratory Planning Committee, headed by Keith Boyd, demonstrated that given overlapping cold regions research missions of WES, SIPRE, ACFEL, and ERDL, creating a single cold regions lab would avoid duplication, be more cost-effective, and improve coordination. By 1959, congressional inquiries with Philippe and others at OCE shifted to the chosen location at Hanover, New Hampshire, with the primary concern that the Corps had not more strongly considered the federal building in Denver, Colorado. OCE completed an additional survey, and once it became clear that existing facilities in the five cold weather regions SIPRE identified as potential locations were not sufficient and that cost estimates for the new lab were accurate, Congress funded it for 1960. Construction on the new lab began in June 1960, and in January 1961, the Army officially established the Cold Regions Research and Engineering Laboratory (CRREL) with Boyd as technical director and Col. William Nungesser as commander. Although a 1962 fire delayed its full operation until 1963, CRREL moved its headquarters to Hanover in July 1961 while skeleton crews maintained a presence at the previous lab facilities until the new building opened. Altogether, 114 slots moved from SIPRE, 36 from ACFEL, and 60 from ERDL for a total of 210, not including maintenance staff. Actual staffing in 1962 was around 170. The merger reduced cold regions research facilities from 61 to 40.¹⁵⁸

With consolidation finally achieved, CRREL resumed research in 1961. Early research plans included not only continuation of basic research of snow and ice mechanics, but also climatology and environmental studies, which received increasing funding. In 1963, it began to collect data at Byrd Station, Antarctica, and built a tunnel in permafrost at the Fairbanks Project Office to evaluate excavation methods and provide opportunities for basic research on permanently frozen ground. In 1966, a CRREL team at Camp Century, Greenland, headed by B. Lyle Hansen, was the first ever to recover a 1,387-meter glacial core sample using specialized deep drilling and ice core sample retrieval techniques developed by the laboratory. These efforts and later co-development of the Greenland Ice Sheet Program (GISP) provided a wealth of data on thousands of years of climate history detected by isotopic and chemical analyses of the annual accumulation of layers of snow in the ice cores. CRREL followed this with drilling a 2,164-meter sample at Byrd Station in 1968, and in 1978 helped drill through the Ross Ice Shelf, Antarctica. In 1967, Wilford Weeks conducted award-winning research on sea ice, and in 1971 James Hicks developed methods of fog dispersal in cold regions. There were also efforts by the Photographic Interpretation Research Division, headed by Robert Frost, to develop methods

of identifying terrain features through photographs, a precursor to remote sensing. Although CRREL argued for continuing its presence in Greenland to support research into areas such as glaciology, seismology, atmospherics, and geomagnetic and astronomical observation, OCE sought to reduce the presence of the Corps there to offset increased research in Alaska and the Antarctic. The latter in particular promised new possibilities for the investigation of basic research into sea ice, permafrost, and ice core analysis as well as applied research into transportation, drilling, and experimental engineering and construction.¹⁵⁹

CRREL also supported a number of award-winning applied research projects. It continued providing research support for construction and maintenance of DEW facilities. In 1977 Wayne Tobiasson received an Army Research and Development Award for designing a system of scaffolds and rails to move a 10-story, 3,000-ton DEW line DYE-3 radar tower on the Greenland ice cap. Constantly accumulating snow and the shifting of glacial ice had weakened the foundation of the radar, leading the Air Force to consider building a replacement. By moving the existing radar facility across the glacier onto a more stable foundation, the government saved \$1.5 million. CRREL helped Corps districts solve a number of ice-related problems by developing machines and techniques to cut ice from lock walls, testing methods to alleviate ice jams and floods, modeling specific designs in refrigerated hydraulic models, and developing chemical coatings for lock and canal walls to prevent ice build-up. Further, CRREL often collaborated on private scientific expeditions and experiments and supported private industry in developing criteria for ice-based oil platforms in offshore Alaska, evaluating the Northwest Passage for oil transport, and building the Trans-Alaska Pipeline. Drawing on earlier permafrost studies, CRREL engineers served on a multi-agency working group that reviewed criteria and assessed burying the pipeline in areas where permanently frozen terrain posed a construction challenge. CRREL biologists and soil scientists made extensive observations of the pipeline's impact on the Alaska environment. In 1976, a CRREL team won an award for developing subsurface exploration techniques to locate electrical grounding areas. Solving this problem provided an effective ground for the pipeline's cathodic anti-corrosion system and saved more than \$1 million. Fred Crory received an award in 1979 for design and concept testing of permafrost-stable support platforms for elevated sections of the line. The lab also continued to support testing of vehicles such as the Surface Effect Vehicle, although it transferred the Keweenaw Station, where much of this research once occurred, to the Army Mobility Command in 1963. CRREL employees became involved in several remote sensing projects, including the Canadian Bold Survey of snow and ice-covered terrain and reconnaissance of the Zoji La Pass in India. From 1962 to 1969, CRREL operated under management of the AMC, although coordination with OCE continued. With the return of the laboratory to the Corps in 1969, the laboratory experienced tremendous growth, and by 1980 CRREL was receiving \$14 million in funding annually.¹⁶⁰

Establishment of the Coastal Engineering Research Center

At the conclusion of the war, the Beach Erosion Board (BEB) saw a significant increase in peacetime coastal research. Consulting on coastal construction projects – its mainstay before the war – resumed and even grew after 1959 with the passage of PL 86-645 and 87-874,

which allowed increased federal funding of coastal projects. Having gained improved knowledge of beach processes, its approach to projects had changed considerably, as reflected in the groundbreaking 1954 manual, *Shore Protection Planning and Design (TR-4)*. Instead of building stronger structures to stop natural processes, its method was to work with nature to avoid potential erosion, which resulted in a dramatic drop in coastal structure failure. After Congress authorized BEB to pursue general investigations in 1945, basic research was also on the rise. In 1947, BEB established regional Field Research Groups for the Atlantic, Pacific, Gulf of Mexico, and Great Lake shores to collect coastal data. Supported by contracts with New York University, the Scripps Institute of Oceanography, the University of California at Berkeley, and WES, the groups began a comprehensive program of surveying the shoreline, measuring wind and tides, collecting echo data, and sampling the salinity and sedimentation of waves while riding around in DUKW amphibious vehicles. Simultaneously, BEB developed new testing facilities at its Dalecarlia Reservation headquarters. From 1943 to 1953, it built a 300- by 150-foot Shore Process Test Basin, in which 10 wave generators allowed modeling of wave and coastal processes. From 1954 to 1955, it built a 635-foot long wave tank to test larger waves than its existing 85-foot basin. These facilities supported a renewed focus on researching wave properties, beach processes, currents, and other forces affecting littoral zones, as well as the impact of these forces on sheet piling, bulkheads, and other structures. It also enabled BEB to undertake more comprehensive research projects, such as developing methods to allow sand to bypass inlets that interfere with beach development and cause erosion. Perhaps the most important new research was a series of hurricane investigations established by 1955's PL 84-71. Joseph M. Caldwell and Thorndike Saville, Sr., participated in the Hurricane Study Coordinating Committee, which worked with the National Weather Bureau on the research. With BEB modeling waves and surge, the team helped define a standard project hurricane, the maximum probable storm used in designing hurricane protection structures. Another project, the Sand Inventory Program, established after severe 1962 storms obliterated beaches on the northeast coast, consisted of locating sand appropriate for use in beach nourishment projects through which the Corps reversed erosion by placing new sand on beaches.¹⁶¹

Because of the success of these programs and the anticipation of continued growth, OCE initiated a review of BEB functions with a view toward updating or possibly replacing the organization to handle the increasing workload. A 1962 commission that included members of BEB, OCE, and the Board of Engineers for Rivers and Harbors (BERH) found that, although a body was still necessary to review engineering project reports, in general engineers had a better understanding of coastal phenomenon than in the past and that a specialized board was no longer necessary. There was also still need for a center to conduct research in support of congressional imperatives for coastal planning and growing oceanographic research, as well as to consult and coordinate with Corps districts on specific engineering projects. However, the expected workload required a more robust organization than a board or simple laboratory could provide. The plan submitted by Chief of Engineers Lt. Gen. Walter K. Wilson and authorized by Congress in 1963 in PL 88-172 was to establish a Coastal Engineering Research Center (CERC) to focus on coastal engineering research, with oversight provided by a Coastal

Engineering Research Board (CERB), which would include three Corps division commanders and three civilians, with the Director of Civil Works serving as president. Review of coastal project reports would fall to BERH, which already had responsibility to review engineering reports for river and harbor improvements. Standup of the new organizations proceeded rapidly in 1964, headed by Caldwell of the BEB Research Division.¹⁶²

To maintain continuity with BEB, CERB and CERC initially included prominent BEB members, who carried on many of the same projects they had previously. There were, nevertheless, several major shifts in operation. One was in funding. BEB had mostly received direct funding in the General Investigations budget line item, but CERC now received the majority of its funding from the Directorate of Civil Works, which some feared would result in less independence in research objectives. Although CERC had overall responsibility for the coastal research program, it had to share research with the Great Lakes Survey, the Committee on Tidal Hydraulics, and WES, the latter of which had similar test equipment and built similar models. This caused considerable contention over time, which OCE initially resolved by stressing in engineer regulations CERC's basic research mission, making it the Corps' "Office of Naval Research," as one staffer wrote. At the same time, funding increased rapidly. CERC planners expected up to \$16 million in funding from OCE and elsewhere over the next 10 years, and by 1971, annual budgets had increased from \$800,000 to \$3.25 million. Its 1968 budget – \$2.5 million – was 1.5 percent of the total coastal program, a greater investment as a percentage than other research areas. To handle this workload, there was rapid growth in personnel as CERC grew from a staff of 75 in 1964 to 131 by 1970. Another major change was relocation of the lab to Fort Belvoir, Virginia. Beginning in 1957, the Senate District of Columbia Committee pushed for turning over the Dalecarlia Reservation, which contained a reservoir, to the Washington Aqueduct Authority. Because of its investment in facilities there, the Corps resisted and even planned further expansion of the reservation. With continued resistance from the National Capitol Planning Commission and the constraints of space, by 1968 the Corps agreed to the move, which it accomplished in 1973 after completion of the \$3.5 million Kingman Building, the headquarters CERC shared with the BERH and the Institute for Water Resources. Although the Corps spent millions rebuilding wave tanks and test facilities, it did not make many needed upgrades, which some felt constrained CERC's research efforts.¹⁶³



Field Research Facility, Duck, N.C.

Nevertheless, even without major expansion and using old wave generators, the new facilities – which included a 635-foot wave tank, 72- and 96-foot flumes, a covered shore process basin, a circular tank, a tsunami basin, and a water tunnel maintained at the National Bureau of Standards – proved valuable for an enhanced laboratory research program. This research helped advance theory and test specific projects. For example, CERC used the facilities to study wave parameters such as turbulence, velocity, height, and period; develop wave curves to help predict wave run-up; and examine transport rates that resulted in more precise formulas for estimating sediment movement in the dominant wave zone so as to improve calculations for coastal construction. It also used its new facilities to test wave impact on specific shore and inlet contours and engineering works such as dike enclosures on the Great Lakes. Knowledge gained in these tests helped CERC issue a revised *Shore Protection Manual* in 1978, which remained a best seller. Supplementing these facilities was a field facility CERC built to study waves in nature. After environmental groups objected to a plan to build an extended pier at the Assateague Island National Seashore Park, the Corps built its Field Research Facility at an abandoned Navy bombing range at Duck, North Carolina, in 1980, though it was able to use the facility as early as 1977 to test wave-gathering microwave instruments on the SEASAT satellite. After 1970, computer models often aided physical models. Despite improvements in scale modeling, difficulties remained in modeling some problems, such as littoral transport and tidal inlets, which, due to limits in modeling small particles or multiple coastal processes (such as the complicated patterns of Masonboro Inlet, North Carolina), were hard to reproduce. Computer models proved particularly helpful in solving these problems.¹⁶⁴

CERC also set out on a rigorous field research program, including continuation of wave, surf, and sand data collection efforts started under BEB. CERC opened 21 data collection stations on the Atlantic and Gulf of Mexico coasts and by 1977 had established 100 automated data collection points in California on fixed points and buoys. These data, along with those collected by other agencies, proved indispensable for creating wave pattern maps and statistical tables used for purposes as varied as construction planning and weather prediction as well as for other Corps projects. CERC soon became involved in several high-profile research programs. The Sand Inventory Program, initiated in 1962, proceeded rapidly, and by 1967 CERC had collected data along 6,300 miles of shoreline and identified suitable sand deposits. In addition, CERC established profiles of 90 beaches to study storm-initiated erosion. The resulting shore protection and restoration research programs helped develop methods for collecting and placing sand using draglines, scrapers, and pumps. Although CERC tested the use of groins, bulkheads, and various types of breakwaters to trap sand, block waves, and check erosion, it found that beach nourishment and wide beaches were in fact cheaper and more effective than most structural approaches. It nevertheless worked to develop methods for reducing the impact of structures on erosion, for example, through the use of a sand transfer system that moved sand around structures using pipes and pumps to allow continuation of natural littoral processes. With growing national interest in coastal erosion after 1968, CERC became involved in the 1970 National Shoreline Study, which examined 84,000 miles of shoreline for erosion. Soon afterwards, CERC became a member of the Shoreline Erosion Advisory Panel that reviewed

specific construction projects. In this, it drew on its Technical Services Program, which provided consulting services to Corps districts facing difficult coastal construction issues and conducted one- to two-week courses on various engineering topics.¹⁶⁵

Growth of WES Laboratories

WES, meanwhile, saw steady and continuous growth in its research programs. Hydraulic modeling continued unabated, with an increased impetus on testing structures. WES tested many lock designs, starting with Algiers Lock, Louisiana, in 1946 and growing to more than 30 locks by 1962, including Calumet River Lock, Illinois; Barge Canal Lock, California; Holt Lock and Dam, Alabama; and innovative floor culvert systems used in Millers Ferry Lock, Alabama, and Dardanelle Lock, Arkansas. The workload was so heavy that WES created a Structures Branch in 1963 to develop standardized lock criteria. As part of ongoing potamological studies, through 1951 WES modeled revetment technologies such as concrete slabs and asphalt, although tests had proven mostly inconclusive. More successful was work on breakwaters. WES primarily modeled breakwater sites during the war and by 1946 turned to testing designs. Dating to Roman times, breakwaters improved navigation by calming waters in harbors, and the Corps managed more than 600 breakwaters as part of its harbor work. After modeling various designs and materials, including quarried rock, concrete slabs, and molded tetrapods and other shapes, the Water Waves Branch of the Hydraulics Division developed design standards, which the Corps issued in a 1963 manual, *Design of Breakwaters and Jetties*. Formulas developed by Robert Y. Hudson found wide use into the 1990s. WES also built several river models, the largest of which were the 1950 Niagara Falls model used to test the impact of a hydroelectric plant on the famous landmark and an analysis of channel realignment in the St. Lawrence River. Concerns about model distortion, which originally arose under Capt. Frank Falkner, finally resulted in formal studies. A consultant board of leading hydrologists, including Lorenz G. Straub of the University of Minnesota, Hunter Rouse of the University of Iowa, and Arthur T. Ippen of MIT, developed equations to correct distortion, and in 1953 WES tested these in a model with a movable cross-section to adjust river depths to measure changes in velocity, current, and erosion. Engineers integrated the resulting corrections into all future physical models. Despite these concerns, experimental modeling demonstrated a high return on investment. An analysis of 59 projects in late 1950 determined that WES saved \$55 million at a return of nearly 8:1, although it noted that it is not “the primary purpose of hydraulic model studies to reduce the costs of prototype projects, but rather to check, improve, or develop designs which will perform satisfactorily.”¹⁶⁶

However, the largest growth area in the Hydraulics Division was tidal and estuary modeling, which prior to World War II was constrained by the inability to simulate the complexities of waves, salinity, shoaling, and sedimentation, and a general lack of documentation of the behavior of fresh and saltwater when mixed. After the war, WES greatly advanced its modeling



Robert Y. Hudson.

of saltwater bodies, aided by the work of Morrough O'Brien at BEB and Garbis Keulegan at the Bureau of Standards Hydraulics Laboratory on density and salinity. In 1946, WES developed its most complex estuary model to date, the Savannah Harbor model, which saved an estimated \$20 million by demonstrating that the addition of jetties and channel realignment and deepening would increase shoaling. It was, nevertheless, an extremely complex model, and the model team spent considerable time trying to duplicate currents, which it finally accomplished by ensuring a proper mix of salt and fresh water. Because of the difficulties encountered, Joseph Tiffany and Ralph Rhodes of WES proposed that OCE create a Committee on Tidal Hydraulics to further research these issues, which it did in 1947. While this committee gathered and published data on tidal research in a 1954 bibliography, the Rivers and Harbors Branch at WES developed ever more sophisticated and accurate estuary models, including models of the Delaware River in 1948, Charleston Harbor in 1953, and the Hudson River in 1957. It also continued the more straightforward work of testing planned harbor improvements through several smaller models of Memphis, Wilmington, Agate Bay, Port Washington, and Oswego, all before 1950. Growth in estuary and tidal work eventually led to the formation of the Estuaries and Water Waves Branches in 1963.¹⁶⁷

The increased coastal content of WES hydraulics research eventually led to friction with CERC. In establishing CERC, Congress gave it responsibility for all coastal research, and in 1974 OCE re-emphasized CERC's basic research mission versus applied research at WES, but the distinction was never clear. In the 1965 General Investigation Tidal Inlet Studies, CERC tasked WES to build three test basins for basic research and then objected when the Water Waves Branch used them for specific projects. OCE supported CERC, but CERB eventually authorized WES to expand the program. In 1974, the renamed Wave Dynamics Branch, headed by Robert W. Whalin, assumed responsibility for the program. In 1978, CERC Commander Col. John H. Cousins complained that WES was conducting research in seven of eight areas he considered CERC responsibility and requested authority for all coastal research. Col. John L. Cannon of WES rebutted this position, but OCE seemed at first to agree with Cousins. Nevertheless, over the next two years, several decisions made clear that momentum had shifted toward WES. In 1978, Whalin requested permission to buy a multispectral wave generator – a complex machine that could simulate waves from multiple directions. CERC opposed the purchase, but since WES used reimbursable funds, OCE approved it. In 1979, CERC objected to WES developing a wave model for the South Atlantic Division instead of its own team. Based on successful numerical modeling of the Great Lakes by Donald T. Resio and C. Linwood Vincent, WES vigorously disputed CERC's approach, and OCE gave WES the project. In another project, CERC objected to WES conducting a numerical study of sediment transport in Oregon Inlet, North Carolina, despite having earlier approved the study. Although WES later included CERC modeling of the inlet in a 1983 report, a confrontation over the project largely inclined James Choromokos, the director of Corps Research and Development, against CERC. By this time, budget cuts and pressure to move CERC out of the national capitol region prompted Choromokos to propose moving CERC to WES, which would also save 43 positions or \$1.3 million annually. Underlying the financial reasons for the move was

that CERC had proven less effective in meeting new demands than WES. It had always been underfunded and, because of its focus on basic research, had fewer personnel and facilities to respond to reimbursable projects. Approved in February 1983, the move took place in April, although fewer than 24 of the 83 persons offered a transfer agreed to move. About half of the engineers and scientists transferred, and CERC hired about 14 new people for a total of 33.¹⁶⁸

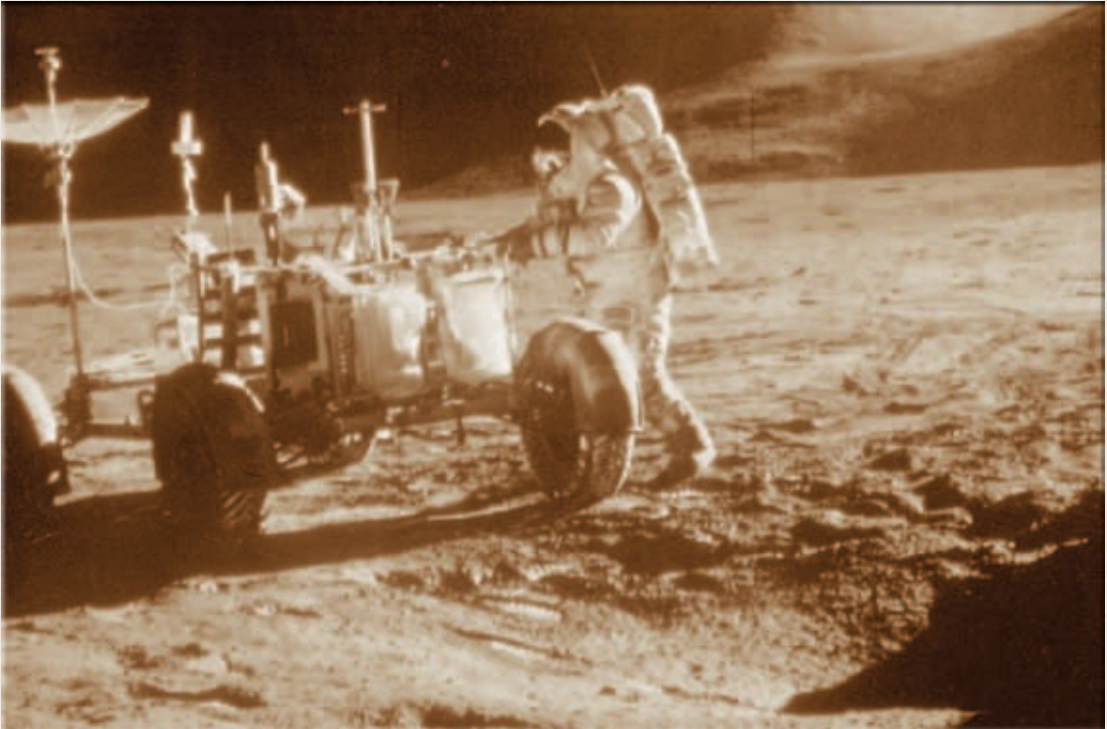
The work of the WES Soils Division also advanced under the leadership of Willard Turnbull. Runway research by the Flexible Pavement Branch had quickly grown into the largest research area in the division, while research into trafficability and mobility expanded until, by 1958, the Army Mobility Center became a separate branch and, by 1963, it had become a separate division. Included in its investigations was support for testing vehicles such as the Gama Goat, the XM-1 Tank, and Tugs for Sea-Land-Service. In 1970, it even helped design and test boots for astronauts and tires for the Lunar Rover for NASA. Foundation research also continued, with the primary project being potamological studies led by Juul Hvorslev. The Soils Division conducted field investigations through 1962 of more than 60 revetment sites on the Mississippi River and developed methods of predicting revetment failure based on soil conditions. As Karl Terzaghi noted in 1960, geological considerations were becoming more important in the successful application of soil mechanics. The geological investigations of the Mississippi River Valley and in particular of Old River continued in the Geology Branch after the war with the students of Harold Fisk. One outgrowth of its investigations and those into explosive cratering was increased interest in the field of rock mechanics. Rock mechanics originated with the work of Austrian engineer Franz von Rziha, who had built the first tunnel through the Alps in the 1870s, and the geological investigations of Zurich University professor Albert Heim, although it was not until 1926 that H. Schmidt developed a workable theory. In the U.S., mining schools and the Bureau of Mines had been involved in rock mechanics research since 1916, but national interest in the field did not take off until after 1950. Some researchers at WES followed developments in the discipline, for example with the participation of Kenneth Saucier in the First International Conference on Rock Mechanics in 1966. In 1968, the Soils Division formed a Rock Mechanics Section and hired several experts. Its primary project in these early years was a five-year study of clay shale led by Don Banks that followed slope analyses of the Panama Canal Zone for the South Atlantic Division. In 1973, the Corps designated WES as the primary Corps research center for rock mechanics and transferred five personnel and research ongoing at the Missouri River Division to Vicksburg.¹⁶⁹

A major challenge to soils research was the so-called “crisis of confidence” soil mechanics faced in the 1950s. With highly publicized failures of structures designed by self-proclaimed adherents of soil mechanics theory, particularly in France, there was sharp criticism of the method, although Karl Terzaghi, Arthur Casagrande, and others argued that such failures were the result of its misapplication, for example, through over-reliance on mathematical theory instead of first-hand observation, through under-sampling, or through poor testing methods. In the 1960s, WES started a decade-long process of reappraising and modernizing its approach. From 1965 through 1971, WES evaluated soil testing machines, eliminating obsolete models in favor of higher-capacity triaxial and shear machines and adding new technology such as an electron

Designing Wheels for the Moon

By Charles A. Camillo, Mississippi Valley Division

On October 4, 1957, radios from around the globe picked up the faint “beeps” emitted from two radio transmitters that circled the planet 150 miles above the earth’s surface. The transmitters were housed on the 184-pound satellite, *Sputnik I*. The successful orbital launch of the Soviet unmanned satellite forever changed humankind’s relationship with the vast universe surrounding the planet, and helped to usher the Corps of Engineers’ research and development mission into the space age.



The lunar rover vehicle.

Nearly 10 months after *Sputnik's* initial 96-minute orbital journey, President Dwight D. Eisenhower signed the law creating the National Aeronautics and Space Administration (NASA). Early in the NASA space program, the agency’s planners recognized the need for vehicles capable of traversing the lunar surface and coping with the lesser gravitational pull of the moon. In the spring of 1969, just months before Neil Armstrong’s successful moon walk with Apollo 11, NASA requested that the Waterways Experiment Station (WES) conduct investigations to determine the best mobility characteristics of wheels for use on lunar rover vehicles (LRV), which the space agency hoped to have on the moon by April 1971. The task for this endeavor came to rest with the station’s Mobility Research Branch of the Mobility and Environmental Division – since incorporated into the Geotechnical and Structures Laboratory – under the leadership of Dean R. Freitag and later Sterling J. Knight. Klaus-Jergen Melzer and A.J. Green were largely responsible for testing design and data interpretation throughout the LRV project.



Model test of the lunar roving vehicle.

NASA had gathered lunar soil samples from the Apollo 11 and Apollo 12 missions, but the quantities were insufficient for the purposes of the proposed trafficability tests. To simulate the actual fine and non-compacted lunar soils, NASA shipped to Vicksburg large quantities of dune sand from the desert near Yuma, Arizona, and crushed basalt from the Napa Valley in California. The WES Mobility Research Branch, in turn, subjected the materials to tests typical of conventional mobility studies, and then placed the samples into test bins to simulate the loose, non-compacted soil conditions on the moon's surface.

Of the various LRV wheel designs sent by NASA to the Mobility Research Branch for testing, the model submitted by Boeing-General Motors showed the most promise. This specific design consisted of woven zinc-coated music wire, with titanium chevrons riveted to the wire mesh to provide enhanced traction. After validation of the general design in early tests at WES, Boeing-General Motors made minor improvements that the Mobility Research Branch continued to evaluate. NASA finally approved the Boeing-General Motors wheel design in early 1971.

In late July, Apollo 15 landed on the moon with the first operational LRV – an event witnessed by Freitag, Melzer, and Green from the control room of the Marshall Space Flight Center in Huntsville, Alabama. The successful performance of the LRV during the mission allowed the astronauts greater mobility on the lunar surface and provided a “geological bonanza” for scientists back on earth.



Lunar roving vehicle wheel undergoing test.

microscope and a radiation laboratory. These expansions led to construction of the \$4.5 million Arthur Casagrande Building in 1978 to house the enlarged Geotechnical Laboratory. With increased application of computers to soils research (discussed in Chapter Seven), the division worked from 1966 to institute information centers in both soil mechanics and mobility to provide up-to-date data and reports to Corps districts and divisions, which it accomplished in 1970. By 1965, WES was beginning to adopt finite element method (FEM) analysis. In this approach, instead of solving complex problems as a single entity, such as analysis involving heterogeneous materials, engineers break problems into subsystems they can analyze separately at multiple levels of granularity, taking advantage of computers to systematically process data. Based in part on numerical methods such as the finite difference and Ritz methods, FEM originated in 1943. After applying FEM to several projects, by 1972 WES had become a recognized leader in the field when it hosted an international symposium on the subject.¹⁷⁰

One area where review of methods was particularly apparent was in response to problems with liquefaction, which posed one of the greatest challenges to the Corps in a generation. Liquefaction occurs when saturated soils lose cohesion and act as a liquid, causing boils, mud spouts, or mud slides, often triggered by vibration. Casagrande had conducted research on liquefaction as early as 1936, and the Corps began its investigations into the phenomenon after an earth slide led to failure of Fort Peck Dam, Montana, in 1938. However, when a 1971 earthquake led to the near failure of the San Fernando Dam, California, doubts arose as to the structural integrity of other hydraulic fill dams – dams built using water jets to place materials by sedimentation – such as those at Fort Peck and San Fernando. In 1971, the Corps authorized WES to conduct a detailed investigation of the Fort Peck Dam with oversight from a board led by Casagrande. It was, as historian Benjamin Fatherree noted, the “most thorough evaluation of a Corps structure ever performed” at that time, and included seismological and geological studies of the site, dynamic tests on the structure, tests of soils taken from 300-foot core samples collected over six months, and standard penetration tests (SPT) of soil density. In 1975, WES proclaimed the dam safe in all possible earthquake conditions. It followed this with an extended study of liquefaction potential of dams and foundations from 1976 to 1979, which included placing loads on various soils. To ensure accurate results, WES conducted a review of SPT devices that confirmed that they were more accurate than triaxial testing for liquefaction, although there were continuing problems with variances in some circumstances between test results of “undisturbed” samples in the laboratory and behavior of soil on site.¹⁷¹

The liquefaction problem reflected a broad shift in soils research after 1950 toward soil dynamics. Soil dynamics examined soil performance under changing loads versus static, such as those that occur from earthquakes, explosions, or heavy equipment use. Although German researchers explored soil dynamics in the 1930s, Casagrande and WES performed the first consistent soil dynamics research in the 1950s to determine how nuclear and conventional explosions would impact structures such as the Panama Canal. In addition to collecting data during nuclear and conventional explosions at White Sands, New Mexico, the Soils Division conducted laboratory experiments on how soil behaved under up to 50,000 pounds of pressure in its ram-loader or when shaken by a mass vibrator purchased from the Navy. In 1963,

growth of this research led to the formation of the Soil Dynamics Branch. Although the majority of its work involved military applications, such as impulse loads on Minuteman missile silos, stress waves from nuclear explosions, and vibrations from radar facilities, it also became involved in earthquake research. Since 1925, the U.S. Coastal and Geodetic Survey had overall responsibility for earthquake research, but a series of damaging 1964 earthquakes led to the creation of a National Academy of Engineers Committee on Earthquake Engineering Research, which included Corps consultants Harold B. Seed and Ralph Peck. In 1969, WES assigned responsibility to the Soil Dynamics Branch to collect earthquake data and research earthquake-resistant dam designs. It participated in Project Rulison, the last Plowshare nuclear detonation, whose location near the Rifle Gap Dam, Colorado, allowed measurement of the impact on the structure of vibrations emanating from the explosion. Using the knowledge gained from this and other research, WES acted as a federal consultant on earthquake engineering. In 1973, WES formed the Earthquake Engineering and Vibrations Division of the Soils and Pavements Laboratory, which helped collect data on dams in seismic zones. With dynamic growth of fields such as earthquake research, rock mechanics, and the return of mobility research to the Soils and Pavements Laboratory, WES renamed it the Geotechnical Laboratory in 1978 to reflect its widened scope.¹⁷²



Bryant Mather.

There was also growth in the Concrete and Nuclear Weapon Effects divisions at WES after 1960. The Concrete Division, now headed by long-time employee Bryant Mather, worked mostly on developing replacement materials for civil and military construction. In some cases, this was to reduce construction costs or the expense of transporting heavy materials to distant sites; at other times, it was to meet specific needs, such as weatherproofing or constrained project timeframes. The division developed several new cements, concretes, and aggregates. It combined cement with plastics, foams, and rubbers to develop lightweight and insulated cements, experimented with mixing cements with fly ash from power plants instead of volcanic pozzolan to lower costs and increase strengths,

and added chemicals to mixtures to control the speed of cement hardening. For example, WES worked with the Pittsburgh District to use the metal-based strengthening agent silica fume in concrete for construction of the Kinzua Dam in 1960, the first public use of this technology. The division experimented with stronger and lower cost aggregate and reinforcing materials such as fiberglass and bamboo rods, iron shards, and even recycled concrete. To support local construction, it routinely conducted tests on local materials to determine suitability. It also gained responsibility for the rigid pavement research program from the Ohio River Division Laboratories in 1970. As with the soil data centers, the lab developed a Concrete Technology and Information Analysis Center to consult on various concrete issues. By 1967, the high volume of work and the difficulties of coordination led WES to build a new, larger laboratory facility in Vicksburg. Completed for \$2.2 million in 1969 and dedicated in June 1970, the new lab consolidated all WES divisions in the same campus.¹⁷³

The Nuclear Weapon Effects Division continued its military research program, particularly investigations of explosions and development of blast- and projectile-resistant structures. Although the Limited Nuclear Test Ban Treaty of 1963 and the Strategic Arms Limitation Treaty of 1970 curtailed and then eliminated nuclear explosions, the division continued experiments with conventional explosions. It helped investigate soil dynamics issues, evaluated wave propagation impacts on SAFEGUARD program radar facilities, tested the McNamara Line of defensive barriers in Vietnam, analyzed Russian missile silos, continued research of cratering through the Explosive Excavation Research Laboratory, California (which merged with the division in 1975), experimented with the impact of explosions on infrastructure such as roads and bridges, and developed hardened structures such as shelters, aircraft hangar designs, and concrete man-holes. In one classified project, known merely as Project 85, the Air Force requested that WES evaluate a triple-box design for an underground bunker near the Pentagon. WES reported that the design would fail under explosive shock waves but that an arch structure would not. Eventually, the similarities of research at the Concrete Laboratory, Weapon Effects Laboratory, and Soil Dynamics Branch of the Soils and Pavements Laboratory – investigation and development of structures that could resist shock, vibration, and erosion – recommended the combination of these activities. WES Technical Director Frederick R. Brown had considered consolidating the labs for several years because the Concrete Laboratory had tested grout at the Plumbob experiment and the Soil Dynamics Branch was heavily involved in weapons-related soils issues. In 1978, these labs merged into a single Structures Laboratory headed by Mather with William Flathau as his assistant.¹⁷⁴

The Structures Laboratory continued its extensive research into concrete, weapons effects, and soil dynamics. Investigation of concrete properties under Mather continued. The lab increasingly focused on developing concrete specifications based on climate to reduce costs and initiation of work related to the 1984 Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program, in which the lab researched and developed guidance on how to decrease the lifecycle costs and extend the life of concrete structures. Mather and others in the lab were leaders in professional societies including the American Concrete Institute, American Society of Testing and Materials, and the Transportation Research Board. The lab continued work on explosives research, for example, modeling ammunition storage sites in Korea, measuring projectile penetration into concrete structures, testing silo doors for the Peacekeeper and Minuteman missile systems, and conducting studies of hardening for railroad-based nuclear missile systems. Some of this work involved very innovative and high-precision experimental measurements, which were often difficult due to the large amount of high explosives used in experiments. Raphael “Ray” Franco, who had received a patent for developing a cableless system in a protected shell to record blast effects, helped develop a similar device housed with an accelerometer inside of a projectile to test the impact of a 30mm GAU-8 round. After the 1983 bombing of the Marine barracks in Beirut, Lebanon, the lab became involved in the investigation of protecting facilities and embassies in foreign countries. Initially, these investigations concerned the “standoff” distance from a building a vehicle bomb would have to be to prevent damage and devising fairly economical means of strengthening a structure, such as through special reinforced

concrete and shatter-proof windows. Such research increased greatly with the increase of terrorist attacks after 1996.¹⁷⁵

By 1980, WES had experienced incredible growth across all of its laboratories. From 1957 to 1965, its workload tripled to \$15.6 million annually, 43 percent for agencies outside the Corps. This grew to more than \$38 million by 1975 and \$62 million by 1980. Its civilian strength increased from 1,127 with 297 scientists and engineers in 1965 to 1,400 with 514 scientists and engineers in 1980. By this point, WES reached a generational gap – most employees that started their careers at the lab in the 1930s had either retired or were near retirement, among them Technical Director Joseph Tiffany in 1968 and Weapons Effects Chief Guy Aburthnot in 1972. A 1967 study noted that within 10 years there would be 442 retirements with 93 in key positions. The loss of experienced researchers could seriously impact the organization. However, unlike the other Corps labs located near universities, there was no inherent mechanism to replace educated personnel. As early as 1964, WES started aggressive recruitment at 20 leading universities, with programs at MIT, the Georgia Institute of Technology, Penn State, and Michigan, California, Wisconsin, Illinois, and Virginia universities to pay for employees getting advanced degrees. It brought in visiting scholars and contracted resident researchers, including Hunter Rouse of the University of Iowa, A.A. Shapiro of MIT, and Arpad Kezdi and John Bogardi from Budapest, Hungary. The same year, WES started a graduate center through Mississippi State University, with courses in engineering, geology, mathematics, and related subjects taught mostly by WES personnel at WES facilities. Within five years, Carl Pace became the first graduate of more than 535 students. Although the program declined to around 50 students after 1980 as WES leadership sought to hire more employees with advanced degrees, WES made several improvements after 1985, including hiring Carlos H. “Jim” Pennington as its director, arranging accreditation from Texas A&M University and Louisiana State University, and adding courses in computer science, ocean engineering, electrical engineering, and other fields. WES Technical Director Robert W. Whalin said, “This on-site graduate program coupled with the Long Term Training Program is the single most important investment WES makes.” As a result of these improvements, WES saw a net increase of 50 percent in employees with doctorate degrees between 1980 and 1987.¹⁷⁶

Focus on Construction Research

A new research focus that emerged after 1960 was construction research. The Corps had conducted laboratory research on construction issues since 1930, but divided the program over multiple facilities. Although WES pursued some construction-related research through the work of its Concrete, Soils, and Nuclear Weapon Effects divisions, this research was often underfunded, uncoordinated, and mostly concerned civil works, not military construction. Most construction research took place at the division laboratories, primarily the Ohio River Division Laboratories (ORDL), which, by 1960, had grown to more than 100 personnel. The work of ORDL had been extremely valuable to the Corps. Since World War II, it had been involved in rigid pavement research, including theoretical studies, load model studies, and field performance tests covering the gamut of issues such as thickness, joint spacing, materials, smoothness,

blast effects, and drainage, with continual adjustments to new plane weights and technologies such as flotation gears and jet engines. It conducted important research in pavement maintenance and rehabilitation, tested the effects of jet exhaust and fuel on pavement, developed standard markings and lightings for heliports, evaluated American Association of State Highway Organizations road standards, and developed launch pad pavements. In the concrete area, it developed Portland cement reinforced with steel fibers to increase tensile strength, created foam-based concretes to resist shock, proposed design criteria for pre-stressed concrete, and gained responsibility for testing concrete for three divisions in 26 states. In the construction area, it developed borehole cameras to view inside rock formations and epoxy grouts to repair fractured foundations, developed indices to predict structural damage and stability requirements for oscillating structures such as radars, and helped to evaluate overseas soils and building materials. By 1960, only about a quarter of ORDL work was for the division, about half was for OCE, and the other quarter was for others, mostly Corps divisions and districts but also agencies such as NASA and the North American Aerospace Defense Command (NORAD). After 1962, it grew tremendously, eventually topping more than 130 personnel in 1966, and was handling more than \$2 million in projects, which it expected to grow to \$3.7 million by 1968. However, due to space limitations at its Mariemont, Ohio, facility, it had to lease space about a mile away. Consequently, in February 1964, ORDL requested permission to build larger facilities.¹⁷⁷

The primary effect of the ORDL request, which OCE denied, was awareness at OCE of the need for a construction research program. Looking at anticipated growth in military construction, the poor state of technology in the conservative construction industry, and the innovative construction requirements to support projects for NASA, the NIKE-X missile, and other programs, Harry B. Zackrison, chief of the Engineering Division in the OCE Military Construction Directorate, initiated several research projects in 1964 to examine military construction techniques. A new Subcommittee on Military Construction Materials and Techniques established in October 1964 under the Corps Technical Committee approved the projects and authorized a staff study to determine the program structure. The study started in December, and by January 1965 the concept of a construction research laboratory outside ORDL started to congeal. At a February 3 meeting, Chief of Engineers Lt. Gen.



Harry Zackrison.

Walter K. Wilson approved the concept and a request by Zackrison that the National Academy of Sciences (NAS) provide guidance on the program's parameters. Within days, OCE started discussing funding. The staff study, completed on March 10, outlined plans for using ORDL to meet immediate research needs while expanding an existing facility near an engineering university using emergency Military Construction, Army funds. In April, OCE drew up site selection criteria, but by August, a review of 28 installations found none that fit the requirements. Construction of new facilities would be necessary, which would require further approval and delay. OCE Chief Scientific Advisor Gilford Quarles had already briefed Lt. Col. DeWitt Cook from

the Army Office of the Chief of Research and Development in January, and Zackrison briefed Assistant Secretary of the Army (ASA) for Installations and Logistics (IL) Daniel M. Luevano in May. OCE briefed Luevano's replacement, Robert A. Brooks, in November and ASA for Research and Development Willis M. Hawkins in December 1965 and January 1966. On April 20 and 21, 1966, Hawkins visited WES and ORDL. Among his observations were that their work was "cookbook type," that WES researchers were underpaid, that ORDL was "lethargic," and that they conducted too little basic research. Nevertheless, he was impressed overall with Corps capabilities and continued to support the proposed lab.¹⁷⁸

On April 20, 1966, OCE received official notification that the Director of Defense Research and Engineering had approved the construction research laboratory. After discussing a letter soliciting university proposals for the lab with Hawkins while returning from ORDL, OCE sent inquiries to 46 universities with strong engineering programs and received 19 responses by July, of which eight were favorable. The site selection committee, advised by the NAS Building Research Advisory Board, selected the University of Illinois at Champaign in October 1966, and negotiations began to lease property and begin construction. In the interim, planning continued to draw up facility designs, staffing plans, and laboratory functions, while OCE briefed stakeholders on progress, including the Office of Science and Technology, the Office of the Chief of Research and Development, and ASA(IL). In January 1967, search for a lab director and military commander commenced, while coordination began with ORDL on a plan to transfer more than 60 spaces. By August 12, however, fast track formation of the lab hit a snag when Rep. Porter Hardy of the Armed Services Committee questioned the lab in an informal meeting with Zackrison, Quarles, and others. He accused the Corps of trying to "circumvent the Committee" by pursuing the lease option and receiving university proposals before ruling out existing facilities. On August 15, Rep. L. Mendel Rivers, chairman of the committee, requested more information. Both Acting Chief of Engineers Maj. Gen. Frederick J. Clarke and Assistant Secretary of Defense (IL) Paul R. Ignatius responded with additional explanations, and on August 24 Clarke testified before the Real Estate Subcommittee, carefully explaining the need for the lab, the lease agreement, and the selection process. After he testified again on October 4, the committee approved his recommendation. On October 9, 1967, Lt. Col. Rodney E. Cox reported to ORDL as the first commander of the Construction Engineering Research Laboratory (CERL), which General Orders dated September 9, 1968, established effective May 1, 1968. On May 23, 1969, the Corps appointed the first technical director – Louis R. Shaffer of the University of Illinois, who had established a construction research program in the early 1960s at its College of Engineering and later served on the NAS advisory board. By this time, personnel were already occupying the new building as needed. The remaining 34 civilians from ORDL transferred over the next few months, although dedication of the CERL headquarters did not occur until July 25, 1969.¹⁷⁹



Louis R. Shaffer.

Shaking Things Up at Champaign, Illinois

In 1970, the Corps of Engineers Huntsville Division approached the newly opened Construction Engineering Research Laboratory (CERL) about constructing facilities to test the impact of vibrations on tactical support equipment for the SAFEGUARD missile program. The shake table built as a result was one of the most advanced testing facilities of its kind in the Department of Defense and was eventually improved to support expanded mission areas.

By October 1970, the Huntsville Division had researched existing U.S. shake table facilities and found none capable of supporting the required weight and shock requirements, but testing the equipment was critical for national security. On determining that none of its existing buildings could tolerate the shock generated by the proposed shake table, CERL requested approval for new facilities to house the system being designed by MTS Systems Corporation.

Completed in November 1973 for \$3 million, the Biaxial Shock Test Machine in-



Biaxial shock test machine ready to shake a transformer.

cluded a 12- by 12-foot test platform capable of holding 12,500 pounds and a control system enabling researchers to generate vertical and horizontal accelerations of 28 and 15 Gs. The operating program delivered a wide range of motion over a programmed or random time history. To prevent its operating frequency of 200 Hz from damaging the housing, it included a unique foundation design occupying 1,000 cubic

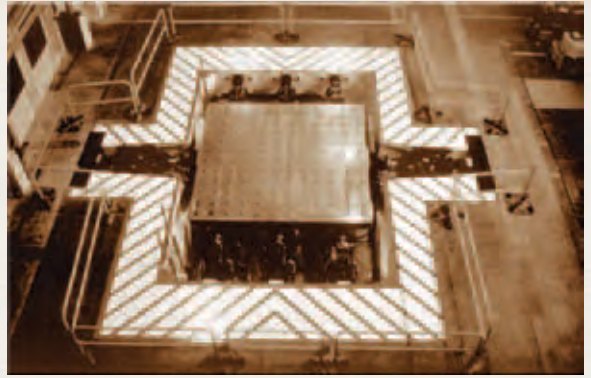
yards and weighing four million pounds with separate foundations for vertical and horizontal reactions.

It remained the only facility of its kind for many years, but focused mostly on military uses with rapid acceleration over a wide frequency. Although CERL was able to conduct some earthquake investigations, its limited payload capacity and range of motion did not provide realistic tests. When President William Clinton established the National Earthquake Hazards Reduction Program through Executive Order 1291, CERL invested \$5 million in 1995 to upgrade the shock table.

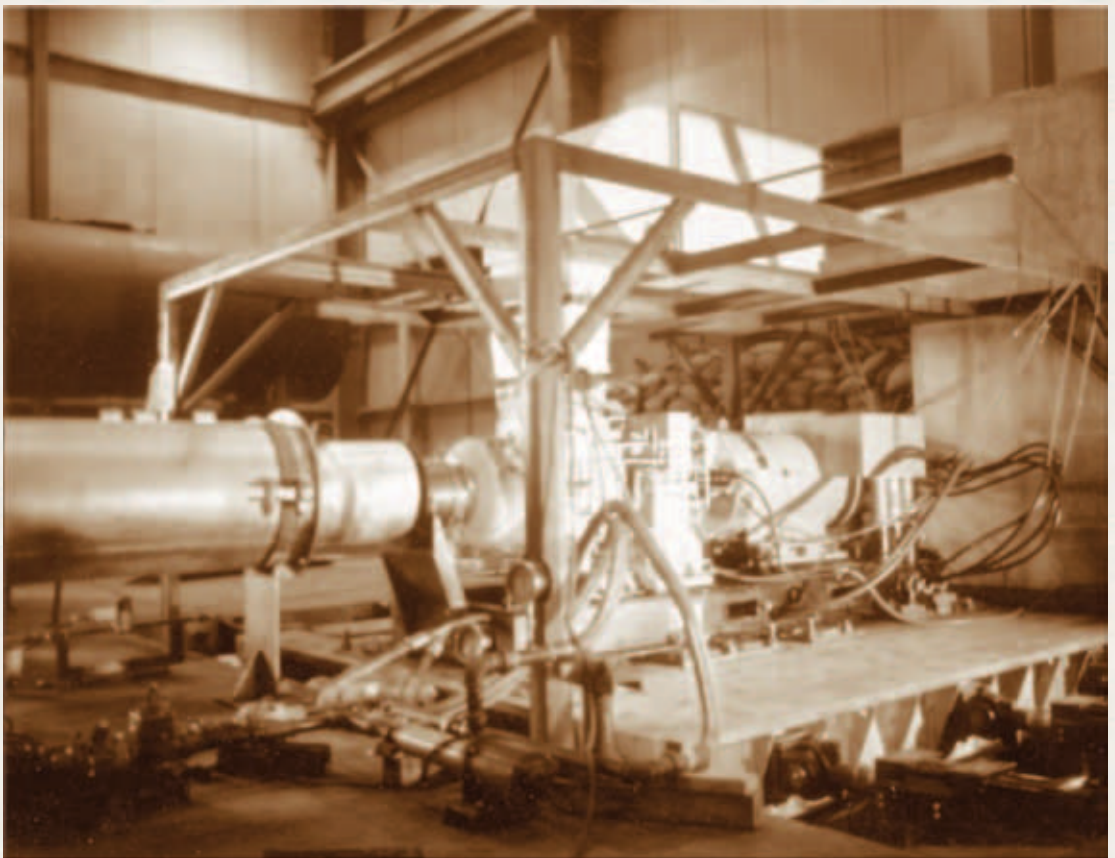
The Triaxial Earthquake and Shock Simulator came on line in January 1996. The addition of a second horizontal axis increased the range of motion and degree of rotation to create a more realistic simulation, with horizontal and vertical velocities of 50 and 30 inches per second respectively. The upgrade also increased the weight limit to 120,000 pounds. A new computer system allowed a greater variety of vibration environments, such as long sweeps similar to most seismic activity.

Since completing the upgrade, CERL has been able to conduct a wide range of research for the Army and for private contractors. Its first use was shock testing of multimillion-dollar computer hardware for IBM Corporation. However, most efforts have focused on working with various universities and the National Institute of Standards and Technology to test materials to improve facility earthquake resistance for the Department of Defense, which owns 75 percent of federal buildings in potential earthquake zones. Replacement of the 24,500 Army buildings alone could cost \$17 billion, and finding new concrete and masonry technology could reduce this number considerably.

“The work that CERL can now do for the Army and others will improve the safety of buildings in America,” said CERL Commander Col. James T. Scott.



Triaxial Earthquake and Shock Simulator after its 1995 upgrade to provide full six-degree-of-freedom capability.



Shake Table-Generator – A 300-kW gas turbo-generator in operation while undergoing simulated nuclear shock tests in the mid-1970s.

In large part, the research program goals were already established. The NAS Building Research Advisory Board, which included members from academia and industry such as John A. Logan, president of Rose Polytechnic Institute, and Edwin L. Harder, a researcher at Westinghouse Electric, had issued its final report in April 1967 outlining its recommendations. While endorsing the Corps plans as “sound and timely,” it argued that they were not “sufficiently broad” and recommended interdisciplinary research using a systems approach that supports each function in the design and construction cycle in meeting user needs. Research also needed to address industry trends such as control of the building process, economic and sociological research, and integration of technology, particularly computers. The program as defined by OCE included long-term research on construction trends, short-term research focusing on immediate needs, and ad hoc reimbursable research to solve district problems, with oversight provided by a Military Construction Board of Directors and program technical monitors. CERL’s primary differentiation from other labs was its emphasis on non-civil works construction, with projects mostly for the Corps, but also for other military branches and agencies such as the Department of Housing and Urban Development and Federal Aviation Administration. By 1973, it was serving 21 federal agencies. Despite this careful positioning, overlap existed with other Corps labs, particularly what became the WES Structures Laboratory. Continuation of the ORDL rigid pavement research, including investigations of alternate construction materials such as fibrous concrete and inflatable concrete foams, and research into shock-resistant facilities for the SAFEGUARD program were often redundant with work at WES.¹⁸⁰

Aside from the short-term testing of district projects and materials development, such as recycled or artificial building materials, ceramic anodes for improved cathodic protection, and shock-resistant materials, most initial research focused on the systems approach to construction. The concept of the system as a scientific paradigm – seeing the interrelationships among components in a system – originated with mathematician Norbert Wiener during the development of computers and gained application to other fields. Although it was biologist Ludwig von Bertalanffy who generalized the theory in 1954, Jay Forrester introduced the concept into management in 1964, and it soon found application in construction. In it, engineers address the functional requirements of a user, such as space, lighting, or energy use, prior to prefabrication and construction of components, so as to cost-effectively ensure use and fitting of components at the beginning of the process instead of making costly adjustments at the end. As Cox explained, the Corps “has built by precedent, doing minimal research on an ad hoc basis. If we’re to . . . start getting ahead on demands, we must use systems” by basing construction on analysis of long-term user needs. For example, CERL conducted the first analysis of barrack architectural designs based on habitability requirements of troops, and its pioneering use of industrialized construction techniques at Fort Knox, Kentucky, which broke building systems into prefabricated subcomponents for easier assembly, cut construction time by one-third. It developed standards, manuals, and computer systems for operating and maintaining facilities from hospitals to pavement, and conducted research to extend the life of roofing systems in 1978. CERL grew rapidly, reaching nearly \$40 million and more than 400 employees by 1986.

Contributing to the latter were the more than 100 students and faculty employees from Purdue, Stanford, and the universities of Texas and Colorado, in addition to Illinois.¹⁸¹

One addition to CERL came with the reassignment of the Paint and Corrosion Laboratory from Rock Island District. The district developed the lab in 1938 to support maintenance of Mississippi River dams. At the time, underwater paints lasted only two to three years, requiring frequent and expensive upkeep. Through meticulous research of paint materials and corrosion, the lab developed the first vinyl paint (V766) for hydraulic structures in 1947, which extended paint wear up to 20 years. After testing it on dams throughout the 1950s, the Corps approved it for general use in 1960, and the lab developed supporting technical manuals. The lab,



Paint testing – Al Beitelman of Construction Engineering Research Laboratory inspecting paint samples exposed to atmospheric conditions.

which included about five personnel at its height, also conducted classes to teach districts how to mix and apply paint, and it helped to perform routine testing of materials. It had been the intention of OCE to merge the lab with CERL, but with Fletcher Shanks and Willard N. Lappin set to retire shortly, they requested a deferral on its transfer. They handed off the paint school to Fort Worth District in 1968, and in 1970 brought on board Alfred D. Beitelman to backfill retiring leaders. In 1973, Beitelman, Thor Olson, and the lab transferred to CERL. The lab continued research into longer lasting vinyl coatings for cathodic protection, developed techniques for metalizing (spraying molten metal), experimented with surface penetration and sand blasting materials, and addressed environmental regulations through environmentally safe lubricants and to reduce air pollution caused by aerosol sprays, using methods such as air atomization. It released dozens of technical reports and helped develop and maintain technical manuals. In addition, it continued providing local districts classes on paint application and on-demand testing services and was the first to integrate computer technology with an electric gas chromatograph to perform paint analysis. It spent about 20 percent of its time helping districts troubleshoot paint and corrosion issues. Although the paint lab formed a miniscule portion of the CERL budget and personnel, rarely exceeding a few hundred thousand dollars or a half dozen personnel, it provided early and continuous return on investment that far exceeded the size of the program. As early as 1968, estimated savings on longer lasting paint exceeded \$1.2 million annually.¹⁸²

Other Corps Research

In addition to Corps-wide research activities that OCE had consolidated since 1960 at five major laboratories – ETL, CRREL, CERC, WES, and CERL – there were many other research activities ongoing at the local level and at headquarters. The five labs received the vast majority of direct-funded research, but several Corps divisions and districts continued to operate labs that conducted work for others on a cost-reimbursable basis. Many of these developed from local projects but had received recognition from the Director of Civil Works (DCW) at OCE as special research areas. Based on its work maintaining aging dams, Rock Island District operated the Corps' only Paint Laboratory until its transfer to CERL in 1973. The Southwestern Division, which required tools to drill through hard rock formations in its geographic area, tested and purchased all diamond tools for the Corps. The North Pacific Division operated the Bonneville Hydraulic Laboratory initially to support construction of Bonneville Dam, but it eventually provided reimbursable services to other Corps facilities, as did the Fisheries Engineering Research Laboratory at Bonneville. The Nebraska Field Laboratory near Mead, Nebraska, also conducted hydraulics research related mainly to design of a navigation channel in the Missouri River. Missouri River Division gained expertise in rock mechanics through several projects for NORAD and from 1968 to the group's transfer to WES in 1973 led research in this field. The South Atlantic Division conducted exposure tests on rock and sediments, work previously conducted mainly at Treat Island, Maine. A further 22 percent of direct-funded Corps research occurred at private or university laboratories.¹⁸³

OCE also assumed responsibility for or initiated several new research programs. Although OCE lost responsibility for equipment research conducted by ERDL in 1962, one program not transferred to AMC was research into nuclear and conventional power. When the Army Research and Development Office established a Nuclear Power Program in 1952 under Corps management to develop a nuclear power plant, OCE created a Nuclear Power Division with a liaison office at the Atomic Energy Commission (AEC). The Engineer Reactors Group at the Engineer Center at Fort Belvoir formed the core staff, while the Nuclear Power Branch at ERDL served as its field office. Working with AEC, the Engineer Reactors Group completed a design and trained operators, and the Nuclear Power Branch managed construction of the SM-1 plant, which came online in 1957. Over the next several years, the Engineer Reactor Group, renamed the Nuclear Power Field Office in 1958, developed several other innovative prototype power plants. In 1971, an Army and Corps review of the program found it to be no longer viable given budget cuts, the availability of low-cost conventional power, and the lack of cost-effective designs that met Army requirements. Although development of nuclear hardware ended, Chief of Engineers Lt. Gen. Frederick Clarke recommended continued operation of the four remaining nuclear plants. With the closure of three of these plants, including the SM-1, by 1973, the office was largely an organization without a mission. When Lt. Gen. William Gribble, Jr., became Chief of Engineers, he moved the office under the newly created Facilities Engineering Directorate in OCE and renamed it the Facilities Engineering Support Agency (FESA) in 1974. In line with the directorate's mission of supporting local installations in planning, maintaining, and operating real property, FESA evaluated technology and provided technical

support related primarily to utilities and power generation. It continued to operate the remaining nuclear power plant – the MH-1A, a mobile nuclear-power plant operating on the vessel *U.S.S. Sturgis* – until its decommissioning in 1978. FESA conducted some minor research into nuclear power, but such activities occupied only about five percent of its time. Its new mission was conventional power, including delivering mid-range conventional power units under the Non-Tactical Generator Program established in 1972, operating the power barge *Andrew Weber*, overseeing operation of all Corps power plants, and developing technologies for energy conservation and alternative power.¹⁸⁴

OCE also assumed management of the Hydrologic Engineering Center (HEC) at Sacramento, California. Established in 1964 as part of the Sacramento District at the urging of Albert Cochran of OCE and announced by Chief of Engineers Lt. Gen. Walter Wilson, HEC initially had three mission areas: accelerate improvement of hydrological engineering by training engineers in more effective techniques and applications, leverage computer modeling to improve hydraulics studies, and evaluate and foster progress in hydraulic engineering by researching new techniques. Most of HEC's research focused on developing computer modeling applications and adapting traditional engineering processes to computers. These applications found use in universities, local government, and in private industry, as well as among federal agencies. Included among its applications were software for dam safety, watershed, river, and reservoir analysis, for example to analyze urban storm runoff and improve predictions of sedimentation in reservoirs. It also worked to adapt new mathematical procedures, such as systems analysis, low-frequency analysis, stochastic processes, and probability-based analysis of flood risk. With the rise of the environmental movement, it helped gain acceptance of environmental uses of hydraulic modeling. From 1965 to 1967, it conducted 12 courses for engineers in these techniques. By 1979, it had trained more than 400 Corps employees and 90 other persons and established a library of computer programs for hydrologic engineering. Led by noted hydrologic engineer Roy Beard and operating out of the district headquarters, it quickly outgrew its facilities and moved to the Davis, California, campus of the University of California in 1969. By 1971, it had grown from its initial six personnel to a total of 26, with an additional 18 personnel assigned from various Corps offices, seven from other federal agencies, 12 university or private lecturers, and 14 international students. In 1972, William Eichert assumed leadership of the lab with the retirement of Beard that year. After a brief period as part of the South Pacific Division, HEC came under management of the Institute for Water Resources (IWR) from 1973 to 1975 before moving to the Engineering Division of the DCW at OCE. In 1979, it became part of the Water Resources Support Center that Chief of Engineers Lt. Gen. John W. Morris established at Fort Belvoir, Virginia.¹⁸⁵

OCE established IWR in 1969 to conduct economic research on civil works projects. Prior to 1960, there were few economists or other social scientists working for the Corps, despite long-standing requirements for performing economic benefit-cost analyses to justify civil works projects. After Arthur Maass, Gilbert White, and others criticized the Corps for its lack of comprehensive planning and reliance on engineering feasibility to develop benefit-cost analyses, Joseph Tofani, chief of the Programs Division and later the Policy and Analysis Division at

Nuclear Power Research and FESA

On April 8, 1957, the Stationary Medium Power Prototype (SM-1) plant at Fort Belvoir, Virginia, started its first nuclear reaction. Although the Atomic Energy Commission (AEC) developed the first nuclear power plant in 1951 and the Navy launched the first nuclear submarine in 1954, the SM-1 developed by the Corps of Engineers was the first nuclear power plant in the U.S. Army. After initial tests and correction of problems, it began continuous power production on April 29, 1957.

As the first atomic bombs ended World War II, President Harry S. Truman expressed interest in peaceful uses of atomic power. Unlike the Navy, the Army did not begin research until 1951 with the appointment of Brig. Gen. Kenneth D. Nichols, former Manhattan District Engineer,

as chief of the new Army Research and Development Office. In 1952, Nichols established the Nuclear Power Program under Corps management, and the Office of the Chief of Engineers created a Nuclear Power Division, headed by Col. James B. Lampert, with a liaison office at AEC and a field office in the Engineer Research and Development Laboratories (ERDL). Lampert's 1953 report, *Army Nuclear Power*, argued that, although nuclear power had a high initial cost, it would reduce fuel delivery requirements at remote sites



The SM-1A nuclear power plant at Fort Belvoir, the Army's first nuclear reactor constructed in 1957. *Office of History, U.S. Army Corps of Engineers.*

such as Distant Early Warning radar sites. Since no commercial plants and few operators were available in the new field, the Corps would have to develop the technology.

Working with AEC's Oak Ridge National Laboratory, Tennessee, the division completed a design and selected a site at Fort Belvoir to allow easier testing with support from ERDL. The design was highly innovative. Due to its location near the capitol, it incorporated the first domed vapor containment shell and burnable poison on the fuel rods to increase safety and reactor control, features that became standard on later plants. While the construction of the plant proceeded under the direction of ERDL's Nuclear Power Branch, the Engineer Reactor Group at the Engineer Center established a program to train operators in time for its opening.

In 1956, the division began planning another plant at Fort Greeley, Alaska. The Alaska District managed the \$4.8 million construction project, and the SM-1A came online in March 1962. In 1958, the division awarded contracts to design and pre-construct a portable prototype (PM-2A) for installation at Camp Century, Greenland. Extraordinarily complicated due to transportation and reassembly in winter conditions, this first field nuclear power plant came online in 1960 and quickly proved the Corps' concept by saving 400,000 gallons of diesel fuel per year.

The Corps completed the PM-1 for the Air Force in 1961 and the PM-3A for Navy use at McMurdo Station, Antarctica, in 1962.

The division examined nuclear-powered trains, trucks, and barges for the Army Transportation Corps, and began development of the gas-cooled, 40-ton mobile light-power prototype (ML-1). After testing at the ERDL Gas Turbine Test Facility in 1959, it operated for the first time in 1962.

Extending the concept of barge-based power plants popularized during World War II, the division developed the mobile high-power prototype (MH-1A), which it installed on the former liberty ship *U.S.S. Sturgis* in 1965. After conducting tests, the Corps sent the *Sturgis* to Panama in 1968 to provide power for the Panama Canal Company.

By this time, the nuclear power program was already in decline. Research into smaller boiling water reactors faced a setback when an explosion at the Idaho SL-1 plant killed three people in 1961 – the only fatal U.S. nuclear accident. The program's later inability to develop a cost-effective plant small enough to meet Army needs, combined with budget cuts and the availability of cheaper conventional generators, led to the program's curtailment in 1971. The Corps continued

to operate its plants until decommissioning of the PM-3A and SM-1A in 1972 and the SM-1 in 1973, the others having closed earlier. The *Sturgis*, which left Panama in 1977 when negotiations began over the future of the canal, sank off the coast of North Carolina. After a dramatic recovery by the Corps, it was decommissioned shortly thereafter, thereby ending the program.



Components of the PM-2A portable nuclear power plant awaiting movement to Camp Century, 1960. *U.S. Army Engineer School.*



The *U.S.S. Sturgis* transporting the MH-1A nuclear power plant to the Panama Canal, 1970. *Office of History, U.S. Army Corps of Engineers.*

OCE, argued for increasing the number of economists in the Corps and creating a long-term planning organization similar to a think tank. In 1968, Chief of Engineers Lt. Gen. William F. Cassidy requested approval from Congress to create an Economic Research Center. At the same time, the Appalachian Regional Development Acts of 1962 and 1965 authorized a study of how public works could stimulate economic growth. The Corps formed the Office of Appalachian Studies in the Ohio River Division. With the completion of this study, the division proposed creation of a Regional Development Group in 1967, which Cassidy saw as potentially forming the core of his research center. Finally, Director of Civil Works Brig. Gen. Charles C. Noble accepted and Cassidy approved Tofani's recommendation to incorporate the group into his thinktank. The new organization, IWR, came together in April 1969 with a staff of 20. The organization initially focused on environmental studies. OCE tasked it to analyze and develop policy guidance for the 1969 National Environmental Policy Act (NEPA). To help promote public involvement, a goal of NEPA, IWR reviewed the Baltimore District's Susquehanna Projects and recommended changes to public participation that became a model for future reports, such as the Puget Sound, Washington, Project that IWR later evaluated. Review of several wastewater projects led to the development of urbanization studies in which IWR proposed social impact statements parallel to environmental impact statements. Simultaneously, it conducted navigational and port analyses, such as the McClellan-Kerr Report, as well as flood control analyses. After a 1975 reorganization, IWR narrowed its focus to support the DCW in developing planning guidance and conducting occasional project reviews as needed.¹⁸⁶

Research Management

By 1970, the difficulties of managing the increasingly complicated research programs within the Corps were becoming apparent, and the Corps sought ways to improve management. The 1962 Bell Report called on government agencies to develop plans of action to improve research. The Department of Defense (DoD), the Army, and the Corps in turn began a review of research activities. The DoD had already subordinated most research under the AMC. As noted previously, CRREL temporarily (1962-1969) and ERDL permanently moved to the AMC. The publication of the Bell Report prompted a flurry of activity. In 1962 and 1968, the Army issued new policies for laboratory management. It formed the Army Research Council, which proposed in the so-called TARC report of 1964 a new centralized research organization and a five-year plan that met strenuous opposition from Lt. Gen. Frank S. Besson, the first AMC commander. Days later, Deputy Director of Defense Research and Engineering Chalmers Sherwin issued his report, "A Plan for the Operation and Management of the Principal DoD In-House Laboratories," which, after criticizing the current status of research activities, made several proposals that embraced Bell Report recommendations, including more discretionary funding and development of DoD organizations to manage all research. All three services voiced opposition to the plan, and the DoD established a Scientific Advisory Board to consider the matter. In March 1965, Gribble, then serving as director of Research and Development at AMC, called a conference of its lab commanders, including CRREL, to discuss the plan. The crux of the criticisms was that Army research had not changed since World War II, that there

were too many labs to manage effectively, and that military lab directors were unqualified. In 1968, at the request of OCE, the DCW completed a review of his laboratories. Although the review did not comment directly on the ongoing controversy, it did note that civil works research spending had grown from \$2.2 million to \$9.3 million over the previous six years in new areas such as oceanography and nuclear explosives, that such research was highly specialized, that most funding went to WES and CERC, and that the directorate closely coordinated with other agencies to avoid duplication of effort. It further found that Corps labs had saved \$126 million from a \$26 million investment – a return on investment of 5:1. This included \$2.6 million saved in concrete, \$2.4 million in locks and gates, and \$4.6 million in fish ladders annually.¹⁸⁷

There was, nevertheless, recognition at OCE that improved management of research was needed. Its responsibilities included research coordination with other commands including the AMC, Army Research and Development Office, Army Chief of Staff, and Office of the Secretary of Army for Civil Works, as well as Congress. Management of research within the Corps generally fell to offices under the DCW, the Director of Military Construction (DMC), and the Director of Military Engineering and Topography (DME&T), although a Chief Scientific Advisor kept the Chief of Engineers apprised of research issues. In 1969, Clarke introduced the Research and Development Office (RDO) to coordinate among the labs, but its function was mostly monitoring, not program review. Management of the individual labs remained fractured. In 1970, he made preliminary attempts to define lab jurisdictions, but without specific instructions on coordination. A 1971 Division Engineers Task Force that included lab directors identified additional problems, but recognizing it did not have authority to change management at OCE, it mostly recommended on reporting and how to present research programs to the Office of Management and Budget, although it did identify the need for a strong RDO that could set future goals and prioritize spending. As a result, Clarke directed several changes in 1972, including moving HEC under IWR, moving the Rock Island Paint Lab under CERL, consolidating Missouri River Division rock mechanics research with WES, and assigning CERL the lead in energy research in coordination with what became FESA. Only months later, he would write, “For some time I have been concerned about the organizational structure and management procedures for our R&D program, in that they are too diverse, fractionated and complex for optimum management. Some improvements have been made over the past few years, but there is still much to be desired.” He requested a thorough review of research, including benefit-cost analysis, and ordered formation of an organization to evaluate research priorities. He also established the Research and Development Review Board in January 1973. Comprising the Deputy Chief of Engineers, DCW, DMC, and DME&T, the board reviewed and evaluated research needs and programs, but it had no management responsibilities and no dedicated staff.¹⁸⁸

In August 1973, soon after the appointment of Gribble as Chief of Engineers, the Army Inspector General conducted a review of Corps research and found that “the decentralization of the R&D efforts to the directorate level within OCE appeared to impair optimum effectiveness and economy.” In response, Gribble ordered a new study by consultant William Taylor. The

Taylor study reviewed management structure, funding, in-house and out-of-house work, and customer needs. Among his findings were that the Corps conducted more in-house research and more work for others than the average for DoD labs and that it had a higher cost per man-year than other agencies. He recommended adoption of several concepts implemented successfully at AMC, including lead labs, in which headquarters delegates each lab as the lead for a research area, and single program element funding, in which headquarters delegates program management to lab directors and focuses on setting goals and assigning programs. He presented two lab management alternatives: continued split management under general headquarters guidance, with civil works labs reporting to the DCW and consolidation of military construction research under the DME&T; or a centralized office in which all eight Corps labs would report directly to the Deputy Chief of Engineers supported by a well-staffed Research and Development Program Office. In commenting on the plan, WES objected to some of the report's findings, arguing that Taylor had not considered reimbursable work or Corps responsibilities to support other agencies and therefore came to wrong conclusions, in particular in calculating operating costs. Both outgoing WES Commander Brig. Gen. Ernest D. Peixotto and his replacement Col. G. H. Hilt favored continued split management mainly because recent changes had not been given a chance to work, although Peixotto believed the lead laboratory concept could help reduce competition among labs. However, Gribble, who had considerable experience with research programs in the Corps, AMC, and the Army, favored more consolidated management. In January 1974, he established a well-staffed Office of Research and Development Management, headed by a civilian Assistant Chief of Engineers, to directly manage the labs except for IWR/HEC and FESA, which continued under the DCW and Facilities Engineering Directorate. The other directorates at OCE would continue to provide research guidance through the review board.¹⁸⁹

Review of lab functions and incremental improvements in operations continued. In 1974, the DoD requested a study of its laboratories to determine overlap and cost improvements, looking closely at overhead and in-house vs. contracted rates. While finding that "the Army laboratories are now, as a result of aggressive improvement programs in recent years, operating in close agreement with ODDR&E management principles," it found a greater need for formal planning and cost control, particularly through lab consolidation and reduced in-house research. Although the report concerned primarily AMC, in 1977, the Deputy Chief of Engineers requested a thorough study of Corps labs. Conducted by the RDO and reviewed by OCE staff, the 1978 Corps Laboratories Study differed from earlier efforts in that it deeply involved lab directors. It generally found that there was little duplication or need for reorienting the labs, but it did set long-term staffing goals and recommended implementing a consistent cost-accounting system, among other changes. A 1979 DoD study found the spread of projects over so many labs as "extreme," which, it noted, made them reactive instead of proactive. Its main recommendation was increasing long-term research. In 1980, IWR completed a research prioritization study that made other recommendations, including establishing a field advisory committee, giving districts greater say, strengthening the Civil Works R&D Review Committee, holding an annual directors conference, improving communications, and developing a

five-year plan. Such improvements, as well as later changes such as the evolution of the RDO into the Directorate of Research and Development and creation of the Research and Development Review Committee, continued to aid with management of the labs.¹⁹⁰

Despite improvements, there continued a desire to strengthen research management. In late 1978, WES Commander Col. John L. Cannon requested that Chief of Engineers Morris allow him to stay an additional year to “work on concepts for improving R&D management within the total R&D community.” The previous year, he had instituted a five-year study group at WES, which had, among other suggestions, recommended reducing WES laboratories from six to four; Cannon now wished to apply these lessons to the larger research community. The RDO asked in January 1979 for ways to reduce manpower, and in February, Cannon circulated a “think piece” to Morris and the other lab directors arguing for a Corps R&D Command. Pointing to his own success in consolidating WES research, he argued that the RDO was “severely understaffed” for managing four laboratories and for “ferreting out undesirable duplications of effort.” In June, a WES panel completed a study of his suggestions and found that a command was feasible, would save 121 spaces (mostly administrative), had strong precedents at other Army commands, and would be ideally placed in Vicksburg. It was also the first study to treat WES laboratories as separate elements in such a command. Acting RDO Chief Col. Maxim Kovel rejected the study out of hand as inaccurate and undocumented, argued that the current organization could address any issues, and noted that “reorganization at this time offers no advantages, and would be disruptive and detrimental to the R&D program.” The irony was also not lost on him that WES, which had earlier and would later resist similar recommendations, had the most to lose by becoming lost in a larger command. Although many of the report’s conclusions would later prove correct and something similar to its recommendation later adopted, it would be almost 20 years until it came to fruition.¹⁹¹

By 1983, the diverse Corps research program had reached a state of maturity. The decentralized labs at ETL, CRREL, WES, and CERL were conducting applied and basic research in their prolific mission areas of photogrammetry and geodesy, cold climate science and engineering, coastal engineering, hydraulics, geotechnical and soil studies, structural engineering and technology, and construction. OCE directed additional research into power generation, hydraulic modeling, and socioeconomic issues involved in civil works. At times, the diversity of the program caused management problems, which the Corps had not fully resolved. Yet despite this complexity, the labs found a single purpose: to support the total mission of the Corps by enabling military and civilian engineers to better execute required tasks through improved technology and knowledge. The research and development mission was complex because the Corps’ mission was complex. With multifaceted responsibilities for planning and managing the nation’s water resources; supporting design, construction, and management of facilities for the Army, Air Force, and other agencies; and aiding combat engineers in mapping and surveying tasks, the Corps had to develop broad knowledge across multiple areas. To continue meeting Corps needs, the research program shifted as missions changed. Of all the changes to Corps research after 1970, none was more dramatic than development of research to support emerging environmental requirements.



Environmental scientists collecting samples.

By 1970, Corps of Engineers laboratories became engaged in a new research topic that evolved into one of the broadest in the modern era – environmental research. As the primary manager of U.S. water resources, the Corps long had an ecological aspect to its mission as directed by Congress. Until the early twentieth century, its emphasis was maintaining rivers and harbors to ensure navigation. Most of its research reflected these concerns by aiding the planning and construction of waterways. After the dawn of the industrial age, with the advent of conservation and scientific resource management, the Corps turned to examining how to best manage waterways to benefit multiple interests through protection of fisheries or agriculture. During World War II, it turned to understanding the impact of the environment on military operations. After passage in the post-war era of multiple environment laws, the Corps worked to balance these requirements with its existing mission by improving knowledge and developing new technologies to address environmental aims. In his 1926 book, *Climate through the Ages*, British meteorologist C.E.P. Brooks, playing off the Rudyard Kipling poem “In the Neolithic Age,” wrote, “There are at least nine and 60 ways of constructing a theory of climate change, and there is probably some truth in quite a number of them.” One could say the same of environmental science in general, which encompasses a wide range of scientific fields seeking often competing objectives under the broad goal of protecting nature. Indeed, what people call the environmental movement is itself a diverse set of interests – fisheries and agriculturists trying to protect their industries, wildlife enthusiasts seeking to restore nature to an idyllic state, health advocates working to reduce air- and water-borne pollution, and government agencies at all levels providing oversight, land use management, and wildlife preservation functions – each taking unique though sometimes allied positions based on its own science. Inasmuch as environmental laws affected nearly every aspect of society, the Corps likewise found itself embroiled through 1990 in researching a wide range of environmental topics – remote sensing, pollution abatement, energy conservation, wildlife management, water quality, coastal and wetland protection and restoration, and even climate change. In each of these areas, it significantly advanced understanding of nature as well as how to effectively protect and manage it under the growing environmental legal framework.¹⁹²

Conservation and the Corps

America's interest in environmental protection came not long after widespread industrialization. With growing populations and social stability after 1850, consumption and production increased, leading to urbanization and agricultural and industrial development. At times, such activities caused great strains on natural resources, denuding farmland, stripping forests, exhausting coal or other minerals, and obstructing waterways. To support orderly economic growth, the federal government began to encourage more efficient use of natural resources through regulation and agency oversight – the Department of Interior, Department of Agriculture, U.S. Geological Survey, Forestry Service, Bureau of Reclamation, Bureau of Fisheries, and National Park Service all originated from 1849 to 1916. The term usually applied to this movement was conservation, which originated with the reservoir movement following the Arid

Land Act of 1888 because it sought to “conserve” water for multiple uses. Reaching its heyday during the Theodore Roosevelt administration, conservation was concerned less with protecting or preserving the environment than with efficient management of resources through the application of science. “Conservation, above all, was a scientific movement,” historian Samuel P. Hays wrote, in which scientific leaders sought to establish progressive government policy. As such, it was largely a top-down movement – not until after 1910 did it include a strong popular element. Nevertheless, it addressed many environmental concerns. The push for reservoirs led to water projects in relief of barren areas and to creation of the Bureau of Reclamation in 1902 to manage these projects. Concern for poor navigation resulted in the Rivers and Harbors Act of 1890 and 1899 to restrict dumping or altering waterways. Demands for efficient land use for agriculture, livestock, and logging, which began with the Homestead Act of 1862, resulted in the General Land Act of 1891, Forest Management Act of 1897, and creation of the Forest Service. Public land ownership grew, particularly under Roosevelt, who tripled public ownership of forest lands. In 1877, Congress created what became the Bureau of Fisheries, which merged with the Bureau of Biological Survey to form the U.S. Fish and Wildlife Service (FWS) in 1940.¹⁹³

Since the time of Brig. Gen. Andrew A. Humphreys, the Corps had questioned the wisdom of reservoirs for flood control purposes and in other ways initially resisted multi-use structures desired by leading conservationists. As with the debate over a national hydraulics lab, this was partly a political response to the threat of losing control of waterways placed in its care. Only as Congress embraced interagency coordination and invested in the Corps greater conservation responsibility did the Corps begin to build and operate facilities for many uses. Limitations on construction and dumping imposed by the Rivers and Harbors acts of 1890 and 1899 – and especially Section 10 of the 1899 act, which required a Corps-issued permit for changes in waterway “course, location, or capacity” – greatly expanded Corps responsibilities. In 1905, Congress gave the Corps power to regulate dumping or transportation of nearly any kind of waterborne refuse. The Oil Pollution Act of 1924 made it illegal to discharge oil into waterways, while the Water Pollution Control Act of 1948 and Water Quality Act of 1965 expanded the definition of pollution. Simultaneously, Congress required greater cooperation from the Corps with other agencies. The Inland Waterways Commission of 1907 and Waterway Commission of 1917 sought to increase coordination among water resources agencies, and although these bodies were temporary and ineffective, Congress required cooperation with the Corps in developing hydroelectric plants in the Water Power Act of 1920. The Wildlife Coordination acts of 1934, 1946, and 1958 required the Corps to coordinate with other federal agencies – primarily the FWS – to consider how waterway changes affect game and wildlife. Congress required coordination in additional areas on a project-by-project basis.¹⁹⁴

In line with these requirements, the Corps researched the impact of its works on industry, wildlife, or other issues. Before 1960, most research occurred locally as part of specific projects. The Waterways Experiment Station (WES) also sometimes conducted research in support of projects. A 1971 analysis of WES projects reported that between 1936 and 1965 WES processed 48 projects and \$8 million in funding for research with environmental content, nearly

half of it after 1960. A good example was continued research and development of methods to control aquatic plants. As discussed in Chapter Two, in 1898 Congress had approved a Corps study on mechanical and chemical methods of controlling water hyacinth and had funded various attempts to eradicate or control it, alligator weed, and other plants. Such plants had spread to several major waterways in the Gulf of Mexico and South Atlantic states, frequently damaging boats, reducing drainage, and increasing insect pests. In 1945, Congress adopted a resolution authorizing a follow-up study in coordination with FWS, Public Health Service, and departments of Interior and Agriculture. Committees in the three affected Corps divisions – Lower Mississippi Valley, Southeast, and Southwest – experimented with chemical controls and developed vessels such as booms, crushers, and saw-boats, but problems continued. In a 1956 interim report, the Board of Engineers for Rivers and Harbors recommended, and the other departments and seven states approved, another five years of experiments. Public Law 85-500 of 1958 authorized a greatly expanded pilot project that ran through 1965. Looking at several surface, bank, and underwater plant species, the team reviewed literature to understand the history of the plants and their impacts, screened and tested 641 herbicides, and experimented with available commercial equipment. The project report concluded that “complete eradication of obnoxious aquatic plants is not feasible,” but that control within critical waterways was possible. It recommended continuation of the program at \$1.5 million per year. By 1968, WES was researching new controls, including high-tech methods developed in conjunction with Athens College and Redstone Arsenal, Alabama, involving infrared light produced by lasers. Although these methods proved ineffective, WES has continued studying traditional control methods to present day.¹⁹⁵

Several districts also conducted wildlife management research, although the concern was more with protecting industry than the species themselves. In the Northwest, the Corps appreciated the need to mitigate the effect of dams and other navigational works on fisheries and fish, particularly anadromous or migratory fish such as salmon. As early as 1917, the Seattle District developed fish ladders, and for the Bonneville Dam and other dams on the Columbia and Snake rivers it initiated an extensive fishways research program with the Bureau of Fisheries. When the Corps developed a comprehensive, multi-purpose plan for the Columbia River Basin in 1946 in cooperation with the Bureau of Reclamation, FWS, and others, protecting salmon was a major concern. The resulting plan incorporated innovations resulting from this research, such as fish runs from lower to upper tributaries, removal of obstructions, fish refuges, screening of diversions, fishways around dams, pollution protections, and artificial proliferation. For some projects, agencies such as the FWS researched and planned wildlife management facilities. The Corps often included FWS-developed wildlife management areas in its project reports as specific project elements, for example, at the Jackson Lock and Dam Project, Alabama, and the Platte River reservoirs, Missouri. Only later did the Corps begin to develop its own capability to analyze wildlife impacts and plan mitigation. By the 1960s, WES was conducting research on wildlife impacts of waterways separate from general project reports, such as a 1967 study of the effect of the James River deep channel on seed oyster beds and 1970 studies to determine estuary impacts on shrimp and clams.¹⁹⁶

Conserving the Salmon

In the 1933 National Recovery Act, Congress authorized the Bonneville Dam on the Columbia River. However, its construction posed a threat to salmon fishing and canning, major industries in Washington and Oregon. Because salmon are anadromous – they migrate upriver from the sea to spawn – obstructions on the river would prevent breeding and depopulate the species, causing economic disaster. To prevent this, the Corps of Engineers researched the fish and methods of bypassing Bonneville and other dams.

Long before the Bonneville Dam, the Corps was aware of the need to protect salmon, having included fish ladders on the Hiram M. Chittenden (Ballard) Locks in Seattle in 1917. A connected series of ascending pools, the ladders allowed fish to bypass the dams. As early as 1929, proposals for a Bonneville Dam stated the need for similar mechanisms, but in order to put people to work, Congress approved the dam before designs were ready. In 1933, the Corps began collaboration with the Bureau of Fisheries to design fishways on a scale never before attempted.

Led by Bureau of Fisheries biologist Harlan B. Holmes, hydraulic engineer Milo C. Bell of the University of Washington, and Portland engineer Henry C. Blood, the research team gradually developed a unique design that included both fish ladders and fish lifts, which operated like locks to move large quantities of fish. Another innovative feature was the fish collection system using a variety of entrances under constant high-velocity water designed to attract fish. Although the cost of the fishways increased from \$2.8 million to more than \$7 million, *Scientific American* called it an “immense experiment,” noting that “the success of these fishways is a matter of worldwide interest.” The dam began operation in 1938.

Despite the success of these efforts and their application to additional projects, there was still much to learn about fish migration. Research continued at the Bonneville Dam under Holmes and Corps biologists Ivan J. Donaldson and Edward M. Mains, including tests of a fish tunnel – essentially an underground ladder – for the McNary Dam, completed in 1953. By 1947, research



Bonneville Dam fish ladder under construction, 1937.



Fish ladder at Bonneville Dam. *U.S. Army Corps of Engineers.*

by Holmes and others revealed that the dams were still killing large numbers of juveniles, which he estimated in a 1952 study at 15 percent, an unacceptable number. Causes included turbines, gas bubble disease, delays in migration, loss of spawning grounds, and other factors.

In 1951, the Corps formalized and funded research efforts with the U.S. Fish and Wildlife Service and Bureau of Reclamation in the Fish Engineering Research Program, later the Fish Passage Development and Evaluation Program (FPDEP). To research areas such as the velocity, lighting, size, grade, and length of fishways, the Corps established the Fisheries Engineering Research Laboratory at Bonneville in 1955. The lab included a flume with two fish pools and underwater sound equipment. Over the next 25 years, the lab experimented with methods of counting and tracking fish, developed a juvenile bypass system to avoid turbines, tested methods of fish collection and transportation, and designed new types of fishways. The research programs were sometimes fraught with conflict among biologists, environmentalists, and engineers, but they greatly advanced understanding and protection of anadromous fish.

Although the FPDEP continued, as did testing at the Bonneville Dam, the Fisheries Engineering Research Laboratory closed in 1980 when a snow storm destroyed the roof of the lab's main facility. Soon after, both it and the Bonneville Hydraulic Laboratory transferred to the Waterways Experiment Station.



A researcher injecting dye into a salmon.



Garbis H. Keulegan.

One area WES addressed as a research pioneer was water quality. Beginning in World War II, it conducted extensive experiments to determine the detrimental effects of navigational works on water salinity and local ecologies. Saltwater intrusion up the Mississippi River due to low freshwater flows and up the Delaware River due to construction of the Intracoastal Waterway threatened agriculture, industry, and drinking water. Tests on intrusion, using dyed saltwater in hydraulic models at WES from 1942 to 1945, helped engineers understand how saltwater acts in freshwater bodies and demonstrated the effectiveness of underwater sills in preventing intrusion. These sills have found use as recently as 1988 to counter

intrusion up the Mississippi River during periods of drought. However, questions arose as to the accuracy or completeness of this research because it seemed to conflict with research by Morrough O'Brien for the Beach Erosion Board. This led to a series of Corps-sponsored experiments at the National Bureau of Standards (NBS) National Hydraulics Laboratory in Washington, D.C., by physicist and mathematician Garbis H. Keulegan, who was widely known for his theory on density currents published in *Laws of Turbulent Flow in Open Channels*. His work helped verify Corps methods, as did WES research on saltwater intrusion throughout the 1950s and 1960s. In 1950, WES conducted tests on intrusion in the Calcasieu River, Louisiana, which later resulted in construction of a barrier structure similar to a lock. Other barriers followed on the Atlantic and Gulf Intracoastal Waterways. In 1956, WES studied saltwater intrusion of Vermillion Bay, Louisiana, which was impacting rice production. It made additional studies of the Delaware River and investigated Narragansett Bay, Rhode Island; New York Harbor; San Francisco Bay, California; Savannah Harbor, Georgia; Lake Pontchartrain, Louisiana; and other bodies. Most of these studies involved determining the impact of structures such as deep draft ship channels, addition or closure of canals, or hurricane protection levees. WES also examined the effect of changing stream flows from hydroelectric plants, city water supplies, or for flood control. Such studies continued for decades at WES with the aid of Keulegan. After retiring from the NBS in 1962 at age 72, Keulegan accepted a consultant position as a retired annuitant at WES and produced landmark work for another 26 years, including continued work on density and saltwater intrusion.¹⁹⁷

It was a natural progression to move from river salinity to pollution studies since both involved measuring the chemical content of water and studying its movement. The first extensive Corps study of water pollution, the Ohio River study completed in 1943, included surveys, sampling, and field and laboratory tests in coordination with the Tennessee Valley Authority and state and local agencies. The Public Health Service conducted most laboratory tests, although the Ohio River Division provided a field laboratory on the quarterboat *Kiski*. After finding high levels of pollution in nearly every tributary, the report recommended a number of remedial measures, none of which specifically involved the Corps, whose primary function was organizing data collection. The first pollution studies at WES were of the Delaware River from 1955 to 1957. After completing salinity studies, the Hydraulics Division used existing models

to test the impact of a proposed Delaware City Plant for Tidewater Oil, then for dispersion of contaminants for DuPont Chemical and the New Jersey Zinc Company. The tests involved the same principle as saltwater models – developing a simulation with the same density, concentration, and temperature as waste effluents were marked with a dye that engineers could trace in the model. WES was able to repeat the experiments on models of Narragansett Bay, New York Harbor, and Charleston Harbor, as well as conducting research on salt disposal and dredged material placement. By the dawn of the environmental era, WES had proven the capability of using hydraulic models to study ecological issues, ranging from pollution to wildlife impacts of Corps works.¹⁹⁸

The Military Environment

Although most conservation research focused on civil works, the effect of military operations on the environment also became a concern after World War II. In 1941, the Army transferred military construction and maintenance responsibility from the Quartermaster Corps to the Corps of Engineers, making natural resource management on Army installations the domain of Army engineers for the first time. There were severe problems with several installations – the “Camp Swampy” jokes later made by cartoonist Mort Walker and others reflected the experience of many wartime trainees. Erosion of drill fields, roads, and training areas created choking dust in the summertime and muddy morasses after rain. Corps districts and offices often lacked experience with such issues and responded by requesting support from the Soil Conservation Service to conduct surveys, develop plans, and provide technical support to installation managers. Many of these professionals transferred to the Corps as war mobilization and installation workloads increased. Eventually, oversight of these activities fell to the Office of the Chief of Engineers (OCE) under the Buildings and Grounds Branch within the Military Construction Directorate. After the war, new issues led bases into greater conservation activities. Large tracts of forest and farm lands required the adoption of land management programs, agricultural leasing, and timber sale. The dangers of fires resulting from pyrotechnics and training with live rounds led to the adoption of fire management practices such as controlled burns. As havens for wildlife escaping urban sprawl, installations had to implement wildlife management policies such as pest control and enforcement of gaming and fishing laws. For the most part, before 1960 the Corps merely adopted standard practices by working with the Forestry Service and other agencies to develop policies, but as legal demands increased, it would need to research new natural resource management methods and technologies.¹⁹⁹

By the end of World War II, it was also apparent that the Army needed to better understand the impact of the environment on military operations. As discussed in Chapter Four, concern about troop and equipment movement through the rice paddies of Japan led the Corps into a series of trafficability studies that formed the basis for its first specific environmental research program. The WES Mobility and Environmental Division, formed in 1963 out of the Army Mobility Research Center in the Soils Division, conducted research on the military rather than civil environment. Most of this research involved testing vehicle mobility through laboratory and field experiments. Scale models of vehicles such as the XM-1 Tank tested performance



March screw amphibian test.

in simulated terrains prior to prototype construction when modifications were more expensive. Laboratory tests of components such as tires, wheels, pistons, and joints helped take the guesswork out of which performed best under multiple soil conditions. By 1971, the lab was pioneering computer models of terrains that could analyze impact on mobility. In cooperation with the Advanced Research Projects Agency and Army Land Locomotion Research Laboratory or Tank-Automotive Research and Development Command, the lab analyzed vehicles through repetitive wear on test tracks or in field conditions complete with simulated combat conditions such as explosives. It assessed vehicles such as the Marine Corps XM759 amphibious logistical carrier, the Navy Marsh Screw and Riverine Utility Craft, and the Army M37 and M113A1 cargo and personnel carriers, among others. Meanwhile, the Snow, Ice, and Permafrost Research Establishment (SIPRE) and the Cold Regions Research and Engineering Laboratory (CRREL) conducted research on arctic vehicles. These included the Surface Effect Vehicle, a hover-craft-like vehicle tested in the early 1970s that used an air cushion to travel over tundra or ice ridges in Alaska and the Arctic Ocean; wheeled vehicles such as Ballistic Missile Office mobile launch vehicles; and blue ice runways or ski landing gear for aircraft to expand airlift logistics capabilities for military and National Science Foundation's Antarctic research programs.²⁰⁰

The WES Mobility and Environmental Division also became involved in terrain analysis studies. The Military Evaluation of Geographical Areas (MEGA) studies, initiated in 1954, analyzed terrain types and their impact on military operations based on factors such as hydrology, vegetation, animal life, topography, and soil conditions. Although MEGA included

attempts to quantify terrain using macrogeometry (surface analysis based on linear or nonlinear and random or parallel patterns) or vegetation structure (leaf and stem pattern analysis), more useful was the classification of specific regions based on literature, maps, and field studies. As early as 1959, WES started experimenting with radar and infrared sensors to remotely identify soil types or terrain features. In 1962, the lab initiated a new study at the request of the Army Materiel Command (AMC) to analyze mobility in Southeast Asia. The Mobility Environmental Research Study (MERS) applied MEGA categories to a specific region: Thailand. Thailand had terrain similar to Vietnam but, as a member of the Southeast Asia Treaty Organization, was friendly to the U.S., allowing combat-free tests. The study ran through 1965 and included a literature study, surveys and maps, vehicle tests, photographs, and 2,400 soil, water, and vegetation samples from seven study areas in the U.S. and Thailand, which WES published in eight volumes from 1966 to 1968. The immense data were not only useful to military planners, they also helped improve the MEGA method and mobility studies in general and provided the basis for later computer simulations.²⁰¹

Terrain analysis was a major concern for intelligence analysts and military planners alike. Well into the Cold War, the Corps provided the Army geographic intelligence through engineer terrain detachments supported by the Army Map Service. In 1963, the Corps reduced the number of detachments and transferred the service to the Defense Intelligence Agency (DIA). Although it retained responsibility for military geographic information, the Corps did not have an official agency performing this function from 1963 to 1975. Instead, a small group from the Army Map Service headed by James D. O'Neal filled in gaps between DIA and the detachments. Because they initially supported the Agency for International Development (AID), they became known as the AID Resources Inventory Center, renamed the Engineer Agency for Resources Inventories (EARI) in 1966. Working out of the Defense Mapping Agency (DMA) Topographic Center, Maryland, but reporting to the Corps, the 30 personnel completed studies of eight Latin American countries; conducted civil studies of soil, vegetation, and hydrology for economic planners; and assembled an atlas of Southeast Asia for the United Nations. With decline of work for AID under President Richard Nixon, in 1969 OCE involved EARI in environmental resources inventories of the Lower Mississippi Valley. EARI performed similar work for Corps districts, the Environmental Protection Agency, Department of Housing and Urban Development, and Department of Health, Education, and Welfare. In 1972, EARI began reporting to the Engineer Topographic Laboratories (ETL) but did not move to Fort Belvoir until 1975. O'Neal and 14 others accepted the transfer.²⁰²

The 1973 Israeli Yom Kippur War demonstrated how lack of terrain cover could increase losses, which renewed Army interest in military geographic information. With no personnel at DIA to support data requests, ETL formed the Terrain Analysis Center (TAC) in 1975 out of the EARI team, and by 1978 it was covered up in work – O'Neal estimated at the time it would work 260 labor years over the next five years. By 1981, DMA was providing standard maps, but it often outsourced specialized analyses to TAC, amounting to about 35 map sheets per year. TAC also supported field units such as the 18th Airborne Corps, the 5th Corps, and 22 Army installations; it completed analyses of urban areas such as Seoul, South Korea; and it

helped update Army Intelligence encyclopedias in 1981. Particularly important were special area maps and overlays showing water locations in Southwest Asia and North Africa for what would later become the U.S. Central Command. Over time, the mission of providing reports to combat units formed the basis for enormous growth in TAC, which became the de facto operational side of ETL. It developed a close relationship with engineer terrain detachments, playing “godfather to topographic units worldwide,” as ETL Commander Col. David F. Maune observed, and it continued to support DMA. Several factors increased demand for terrain data, including the 1983 Grenada Invasion, new military hydrology requests, and an emphasis on analysis of the AirLand Battlefield Environment (ALBE) as part of the Army 21 Concept – how the Army would fight in the next century. ETL developed several new systems and TAC’s workload increased, which resulted in a 1987 Modernization Plan. The new organization included a Products Division to output maps and digital terrain products and a greatly enlarged Military Hydrology Division and Water Detection Response Team. By this time, the unit had tripled in size to handle the workload. In 1988 alone, TAC developed four country geographic studies, 174 terrain data bases, 240 water resources overlays, and 660 tailored digital terrain elevation data.²⁰³

To support terrain analysis, the Corps learned to cull a tremendous amount of information from photographs, radar, and satellite data. Robert Frost first developed a multidiscipline photo-analysis team at Purdue University after World War II. It was still a relatively new concept to bring together engineers, biologists, geologists, and other scientists, and the team produced some novel results. After working on projects for various agencies, the team joined SIPRE to help de-



Robert Frost.

tect permafrost at construction sites such as Thule Air Force Base, Greenland. Working at Keweenaw Field Station, Michigan, and other sites, the team experimented with photographic and thermal imagery to detect camouflaged targets, ice crevasses, or terrain features from the air or later from space. Although scientists had been able to detect ultraviolet and infrared light for many years, it was not until after World War II that instruments to capture the data advanced enough for terrain analysis. After the 1956 application of infrared analysis to agrosience by Robert N. Colwell and the 1960 launch of the TIROS-1 satellite, use of multispectral sensors – those viewing multiple bands of the light spectrum – increased. This allowed easier detection of snow or vegetation with a higher reflectivity or a thermal signature. Even

as SIPRE relocated in 1961 to CRREL, Frost expanded his work to include other climates, including work on MERS; at Yuma Proving Ground, Arizona; Puerto Rico; and Vietnam. The team also worked to further parse light using camera filters to obtain additional color bands and experimented with radar, infrared, and luminescence. Throughout this work, it tested a broad range of equipment, such as film, cameras, sensors, and a mobile measurement tower. In 1968, the AMC planned on greatly expanding this capability in creating a Terrestrial Sciences Center from CRREL, but plans ended when CRREL returned to Corps oversight in 1969.²⁰⁴

In 1970, the Corps transferred the CRREL Photographic Interpretation Research Branch and 25 employees to ETL, which had long worked in remote sensing. ETL had been researching radar mapping since the early Cold War, it had developed photo-interpretation methods for mine detection, and from 1964 to 1967, it supported NASA in experimenting with multispectral and color data capture. As early as 1959, CRREL had become familiar with the work of ETL, as well as of WES, through a working group on remote sensing. In addition, CRREL had periodically conducted research for ETL – on night vision technology and color photo-analysis techniques – so the move came as no surprise. After the move, Frost worked to expand the multidiscipline analytical techniques he developed at CRREL by using stereoscopic devices to create overlays of terrain features such as water sources, vegetation, and mineral locations. He developed three principles that explained the approach:

1. An air photo is composed of pattern elements that indicate conditions, materials and events.
2. Like material and conditions, given a like environment, yield like patterns; conversely, unlike materials and conditions yield unlike patterns.
3. The information gained will mirror the competence of the analyst.

Among those who later transferred to ETL was his fellow Purdue alumnus, Jack Rinker, who carried on Frost's research after he retired. In 1974, to further develop remote sensing methods and technologies, ETL formed the Center for Remote Sensing (CRS) in its Research Institute. In 1979, OCE designated ETL as the principal laboratory for remote sensing.²⁰⁵

CRS pursued several avenues of research related to manual and automated analysis of photos, radar, and satellite images. Continuation of the multidiscipline approach brought the team into close cooperation with agencies such as DMA, NASA, Naval Research Laboratory, U.S. Geological Survey (USGS), Department of Agriculture, and National Oceanic and Atmospheric Administration (NOAA). With the increase in application of computers to photogrammetry and digital imagery, the ETL Digital Image Analysis Laboratory tested methods for automating identification and collection of terrain features from 1979 to 1983. Both Frost and Rinker were doubtful a fully automated system could effectively identify terrain features without human input, and Rinker concluded in 1984 that such techniques were “of little practical use and are not likely to be improved in the foreseeable future.” At the same time, interactive techniques, in which computers aid and speed processes performed by analysts, showed considerable promise. Computers could quickly identify features such as lines and shapes based on mathematical patterns, but analysts still had to classify them. In addition, major advances in hyperspectral imaging allowed isolation of features with specific reflection, absorption, luminescence, and radiation through even greater division of visible and invisible light, as well as with electromagnetic or radio waves. After launch of the LANDSAT Multispectral Scanner in 1972, which offered six bands including infrared, CRS developed a test site in 1976 to determine the effects of time,



Jack Rinker.

season, and weather on thermal sensing of various soils, ground cover, and objects. Another leap occurred after 1985 with the Airborne Imaging Spectrometer, which captured solar energy in 128 channels, and the Airborne Visible and Infrared Imaging Spectrometer, which captured 220 channels. CRS helped develop classification methods and software, developed a series of test sites with the USGS, and collected a large database of measurements. Such research not only helped the Army analyze difficult terrain, it provided data usable by many agencies, for which, as Rinker noted, there was “90 percent overlap.”²⁰⁶

Even after the transfer of Frost’s team to ETL, CRREL continued research in remote sensing, which was critical for measuring ice and snow. Throughout the 1970s, CRREL used LANDSAT data to map permafrost distribution and ocean current patterns in Alaska and elsewhere. Duwayne Anderson, who directed this program, also consulted with NASA on developing sensors to detect water for the NASA Viking mission to Mars. CRREL often applied remote sensing to solve specific problems in support of districts or independently, such as analysis of soil saturation; modeling storms or hydrology; review of dredged material disposal sites; locating the black box from a 1982 airline crash in the Potomac River; 1989 analysis of the Exxon Valdez oil spill in Prince William Sound, Alaska, and identification of damages after 1989’s Hurricane Hugo. As noted previously, WES had experimented with remote sensing technologies as early as 1959. By 1974, it had fully integrated remote sensing into its mobility, soil, and hydrology studies; developed LANDSAT overlays and computer programs for change detection; and used remote sensing to aid in the Survey and General Design Memorandum Flood Protection Studies. By the early 1980s, WES assumed responsibility for research into using remote sensing for the detection of mines and targets, was conducting work amounting to more than \$3 million per year, and even taught classes and released a Remote Sensing Application Guide. In 1983, WES Commander Col. Tilford C. Creel requested that WES be made lead laboratory in this field, but in 1985 OCE made CRREL manager for civil works remote sensing with responsibility for coordinating among Corps entities on military applications and hydraulics-related sensing. Soon after, Harlan “Ike” McKim proposed creation of a Remote Sensing/GIS Center at CRREL to support the districts. After lengthy consideration, OCE approved the concept in 1990, and McKim became its first chief in 1992. Over several years, CRREL developed faster processing techniques, such as conversion of raster images to vector lines, and helped to map and monitor shoreline changes, snowmelt runoff, dredged material placement, and other issues.²⁰⁷

Greening of the Corps

Although conservation brought awareness of ecological issues that advanced federal regulation, most historians date the modern environmental movement to the 1960s. Improved living standards and easier access to wilderness areas engendered in the post-war generation an appreciation of nature and a desire to maintain what Samuel Hays called “beauty, health, and permanence;” that is, they sought to preserve wilderness areas, protect health from pollution, and maintain balance with nature. Unlike conservation, this new movement organized from the bottom up as diverse local groups cooperated and demanded change. The Sierra Club, the National Wildlife Federation, the Audubon Society, Greenpeace, the National Resources

Defense Council, and other organizations protested the environmentally harmful behavior of government and industry. Colored by a suspicion of the establishment that permeated the counterculture, the movement often saw collusion between industry and government, typified by what some saw as a cozy relationship among Congress, the Corps, and shipping interests. As historian Richard Andrews argued in 1987, “the civilian agencies ... came to be perceived no longer as the neutral, expert voices of a general public interest, but as a patchwork of powerful and self-interested sub-governments, each acting as a mouthpiece for powerful client constituents.” Books, articles, and newsletters publicized problems such as a 1965 Mississippi River fish kill, damming of the Grand Canyon, and a 1969 oil spill. Many saw Rachel Carson’s 1962 *Silent Spring* as the beginning of the movement because it catalyzed concern about pollution for the first time. Later, Paul Ehrlich’s *Population Bomb* and Dennis Meadows’ *Limits to Growth* blamed environmental problems on the population explosion. The groups organized protests, lobbied for changes in laws, and brought suit against environmentally destructive activities.²⁰⁸

The result was a series of piecemeal and sometimes inconsistent laws addressing a broad range of environmental issues. In a short space, Congress passed the Clean Water Acts of 1960, 1965, and 1972, the Clean Air Acts of 1963 and 1967, and the Endangered Species Acts of 1964, 1968, 1973, and 1976. In 1970 it created the Environmental Protection Agency (EPA), in 1976 it established principles for cradle-to-grave handling of wastes in the Resource Conservation and Recovery Act, and in 1980 it established a Superfund to pay for pollution cleanup in the Comprehensive Environmental Response, Compensation, and Liability Act. At the local level, city and state agencies developed zoning laws to control industrialization. Although litigation of these laws provided incremental improvements, they did not produce sweeping change or establish a single systematic strategy. The closest thing to a comprehensive law was the 1969 National Environmental Policy Act (NEPA), which greatly changed the way federal agencies operated. In particular, Section 102 required that an environmental impact assessment (EIA) and statement (EIS) be included “on proposals for legislation and other major federal actions significantly affecting the quality of the environment,” and that each EIS be subject to public review. NEPA also required that agencies take an “interdisciplinary approach” to including environmental science in planning all “resource-oriented projects.” Over the next decade, court cases made it clear that NEPA applied to federal regulatory responsibilities and all civil works projects, including large, multi-region programs such as those managed by the Corps.²⁰⁹

The environmental movement also influenced science, research, and technology. As Samuel Hays explains, soon after scientists began considering the environment after World War II,

Environmental science became a driving force as each new piece of research revealed not only more understanding but more yet to be discovered. The enterprise generated a potential new field of knowledge that could absorb an enormous amount of human energy and resources. A huge environmental world, now barely known but with almost unlimited dimensions for discovery, became a major field of scientific exploration.

As environmental groups began to investigate issues, they relied on science to better understand the impact of human activities. They turned to chemists to track the spread and content of

pollution; to physicians to measure impact on health; to biologists, zoologists, and botanists to see changes in habitat; to meteorologists, geologists, and climatologists to discern changes in the earth and atmosphere; and to sociologists and economists to understand the influence of society. Hays breaks environmental research into three impulses – exploratory research seeking to answer questions about environmental impacts by pushing into unknown fields, defensive research seeking to debunk or balance extreme or incorrect positions taken during exploration, and administrative research seeking ways to implement solutions within the legal framework. For the most part, environmental advocates, including new agencies such as the EPA, were exploratory researchers who sought primarily to collect data, identify problems, and establish acceptable standards, leaving it up to administrative researchers such as the Corps and defensive researchers in industry to develop workable technological solutions. Although the conflict between exploratory and defensive research was often the result of the give and take that occurs in all scientific advances, both sides often found themselves as tools of political positioning, whether it was environmental opponents blasting “junk science” or advocates painting “doom-and-gloom” scenarios.²¹⁰

As the environmental movement grew and Congress acted, the Corps had to change many of its activities in response to new mandates. As early as 1962, under direction of President John F. Kennedy, the secretaries of Army, Interior, Agriculture, and Health, Education, and Welfare published “Policies, Standards, and Procedures in the Formation, Evaluation, and Review of Plans for Use and Development of Water and Related Land Resources.” This document set goals for multi-purpose planning that considered preservation and health, provided review policies, and included recreation and wildlife as benefits of projects. Each law that followed required action to bring the Corps into conformance, none more than NEPA, which carved out a whole new set of responsibilities for the Corps. Within months of its passage, OCE sent out engineer circulars making divisions and districts aware of the new requirements. In June 1970, Chief of Engineers Lt. Gen. Frederick J. Clarke issued the first memorandum on environmental policy, which sought mainly to increase ecological knowledge while balancing development and the environment, in order to bring the Corps “‘up to speed’ with the new national environmental awareness,” as Lt. Gen. John W. Morris later observed. A study by the Institute for Water Resources in October 1970 argued that, given the Corps’ history in water quality and its administrative capabilities, it should take responsibility for water quality planning at the federal level, which it saw as an “unexploited opportunity.” The report reviewed several options for structuring a water quality program, all of which included extensive research. Among research identified were continued investigation into dredging and development of water quality technology, which the Corps could test on military bases.²¹¹

Corps laboratories were already preparing plans for increased ecological research. The nascent Construction Engineering Research Laboratory (CERL) included an environmental lab in its preliminary plans, and CRREL increasingly reviewed environmental issues as part of its climate-related research. Based on its authority over coastal ecology research, the Coastal Engineering Research Center (CERC) expressed interest in widening its capability to general ecological studies. WES, which had been modeling pollution for years, sought to grow

competencies in more traditional ecological studies. Both WES and CERC recommended in 1969 the formation of consultant boards of environmentalists to help develop and guide Corps programs. In May 1970, Clarke launched the Environmental Advisory Board (EAB), a group of scientists and organization leaders to advise the Corps on policy and projects while improving its relationship with the environmental community. Although its focus was mostly on procedural issues – it reviewed the Corps’ Environmental Guidelines and frequently addressed inadequacies in Corps EISs – it periodically reviewed Corps research and projects, such as a review of the Dredged Material Research Program in October 1972, a survey of the Atchafalaya Basin Project in 1973, and an August 1980 visit to WES. However, Corps research programs faced several problems, one of which was personnel. By 1970, Corps districts employed more than 280 biologists, foresters, and other environmental specialists, but other than sanitation engineers, Corps labs had only limited staffing to support environmental research, and new hires sometimes experienced an adversarial relationship with engineers. As late as 1979, the EAB expressed concern that, Corps-wide, “environmental personnel are not equal partners.” The labs would need to rapidly staff up while forming multidiscipline teams. Another issue was developing appropriate research programs. At the multi-agency 1971 Conference on Coordination on Research Activities, Grant Ash, chief of the Environmental Resources Branch in the OCE Civil Works Directorate, observed that Corps research to date was directed to increasing general knowledge of the environment, not solving specific problems needed for EISs, which led him to question, “Don’t we need a different blend of research activity?” The environmental research programs that developed over the next 20 years would need to include both basic and applied research.²¹²

NEPA and Military Construction

NEPA greatly increased Corps responsibilities in several ways. Requirements for interagency planning meant the Corps had to cooperate with federal and state agencies, not only to add mitigation features at the end of a project, but to help choose from project alternatives at the beginning. NEPA also required greater cooperation with the public through documentation and consideration of objections. Mainly, however, it required an EIS for all construction projects that had an environmental impact. These EISs could be burdensome for some Corps offices because of the level of coordination and environmental science required, and as a result, early Corps EISs suffered in both quantity and quality. Although large public works obviously required an EIS and received a great deal of attention, some Army installation commanders and local Corps offices initially assumed that Army bases were exempt from these requirements. When guidance made clear this was not the case, many lacked the resources to develop EISs for their numerous small construction projects, and both they and civil works districts faced technical problems with drafting EISs. Historian Richard Andrews concluded that, although Corps EISs were of higher quality than those produced by other agencies during the same time period, those published in the two years following NEPA’s passage were “superficial” and “not based upon any new studies or reassessments” except under threat of litigation. Lack of specific guidance from the Council on Environmental Quality until after 1975 made the issue

particularly difficult, with the most pressing problem being incorporation of an appropriate level of science.²¹³

Although CERL included environmental and energy laboratories in preliminary organization charts, with little work in these areas, it dropped them from the September 1969 chart. In 1971, it had four environmental specialists working mostly in the Electromechanical and Environmental Systems Division researching wastewater treatment and pollution, but most early projects, as Louis Torres observed, took a “negative approach to environmental research – research that was aimed more at protecting the military and its housing from the effects of a hostile environment.” However, requirements for installation EIS support quickly made environmental research one of its largest fields. By 1972, CERL was adding biologists to the Environmental Systems Branch of the Special Projects Division to meet the demand. These helped prepare a *Handbook on Environmental Impact Statements* providing general guidelines on EIS preparation and a *Compendium of Administrators of Land Use and Related Programs* that listed 1,600 officials to help locate personnel needed for coordinating on EISs. By 1975, CERL completed an Environmental Impact Computer System that predicted the impact of construction ranging from barracks to firing ranges, and it started work on a Computerized Environmental Legislative Data System database of federal and state regulations. Another system, the Environmental Impact Forecast System, helped predict environmental effects of Army facilities using a process of baselining pre-project environmental status, monitoring and quantifying changes, and modeling and predicting effects. CERL used these resources to help it consult on preparing EISs. For example, it supported Fort Campbell, Kentucky, in construction planning related to return of the 101st Airborne Division from Vietnam, and it helped prepare EISs in 1974 for the removal of 13 million blackbirds at two installations, and for construction of the Mississippi Army Ammunition Plant. In 1974, CERL centralized most environmental research in the Environmental and Energy Systems Division, renamed the Environmental Division in 1978.²¹⁴

Even as EIS support grew, so did research related to pollution abatement. Military installations faced unique issues in bringing activities into conformance with clean water and air legislation. National readiness required continued training, arms manufacture and storage, and military construction. Research helped to minimize the harmful activities the Army could not eliminate. By 1975, as part of the Army Pollution Abatement Program, CERL built an environmental chemistry lab to test water samples and initiated studies with EPA and other agencies at Rock Island Arsenal, Illinois; Holston Army Ammunition Plant, Tennessee; Louisiana Army Ammunition Plant; Red River Army Depot, Texas; Fort Bragg, North Carolina; Watervliet Arsenal, New York; and Letterkenny Army Depot, Pennsylvania. These involved developing wastewater treatment and landfill designs, reducing the spread of nitrogen oxides, and mitigating sludge disposal at ammunition plants. A major program evolved for reducing noise pollution from artillery, aircraft, and vehicles to meet requirements of the Clean Air Act of 1970, the Noise Control Act of 1972, and the Quiet Communities Act of 1978. CERL improved commercial devices to monitor noise, which were often too sensitive for military uses, and developed a computer-based method for creating noise contour maps that placed activities in one of three noise zones based on measurements. The Army Environmental Hygiene Agency

provided the maps to base planners, who could isolate noisy activities from residences, hospitals, and schools. With restrictions on water use and wastewater disposal, one problem faced by many installations was pollution from washing vehicles. In 1975, CERL participated in a pilot project at Fort Drum, New York, where it gathered information and devised an innovative concept – a centralized washrack that contained water runoff, allowing easier treatment of oily water. When implemented at Fort Polk, Louisiana, and Fort Lewis, Washington, the following year, the system reduced water usage by 90 percent by dropping wash times by several hours. In 1984, CERL estimated a washrack installed at Fort Hood, Texas, saved millions of dollars on wastewater treatment.²¹⁵

With the growing energy crisis after 1974, the energy conservation research that once received little attention at CERL grew considerably. Working with the Facilities Engineering Support Agency (FESA) in OCE, CERL focused primarily on two areas – alternative fuels and utility or energy planning and management. Although the nuclear power that FESA and its predecessors developed was no longer an acceptable alternative, high oil costs made gasoline generators increasingly problematic, while coal conversion was expensive. CERL initially became involved in alternative fuel research in a project for the Naval Facilities Engineering Command in which the lab looked at the reuse of solid wastes as fuel, thereby reducing both energy and waste disposal costs. This included experiments in human and animal waste, but mostly focused

on biomass fuels such as wood scraps, algae, and corn, of which there was an excess on most bases. CERL developed pilot project plants, such as a wood-burning plant at Fort Stewart, Georgia, to help test the idea, and concluded that waste-derived fuels saved a barrel of oil per ton of waste used. Eventually, other alternatives gained acceptance. By the mid-1970s, CERL was experimenting with solar energy. Using a Solar Test Facility, in which 220 square feet of solar panels heated a 1,500-gallon storage tank, CERL developed design procedures and acceptance tests for installing solar energy technologies. After 1992,

CERL became involved in researching hydrogen fuel cells. Although the concept has been around since 1839 when Sir William Robert Grove conducted early experiments on a “gas voltaic battery” that created energy through a reaction of hydrogen and oxygen, it was not until after 1990 that the technology became refined and low-cost enough to implement widely. In the 1993 and 1994 Defense Appropriations Acts, Congress authorized \$36 million to implement and operate fuel cell equipment on military installations. Working with contractor ONSI Corporation, CERL helped purchase, site engineer, install, and maintain Phosphoric Acid Fuel Cell Power Plant packages. These packages created energy through a chemical reaction in which



Bank of phosphoric acid fuel cells demonstrated at Watervliet Arsenal, New York.

hydrogen from hydrocarbon fuels combines with oxygen in phosphoric acid to produce 200 kilowatt hours with the only by-product being hot water or steam. Each system displaced 1.5 million kilowatt hours per year of purchased electricity, saving up to \$103,000. By 2000, CERL had implemented the packages at 31 demonstration sites.²¹⁶

The other major area of energy research at CERL was developing methods and systems to aid in reducing energy costs. In 1977, CERL completed development of the Building Loads Analysis and Systems Thermodynamics (BLAST) computer program, which helped architects evaluate the effects of energy conservation technologies. In 1978, it started work on the Energy Monitoring and Control Systems based on tri-services specifications to automatically manage building temperatures, and in 1980 began developing the Computer Evaluation of Utility Plans, which evaluated utility loads. All three programs found wide use on military installations. Huntsville Division assumed management for these products after 1980 with its assignment as the responsible agency for most Corps software maintenance. However, CERL continued research on energy use, energy engineering analysis, and emerging energy technology, and so remained involved in the maintenance of these systems.²¹⁷

CERL also supported natural resources management at military bases. By 1980, with increased numbers of installation natural resource managers, the development of a Department of Defense Natural Resources Group, and the outsourcing of many staff positions at the OCE Building and Grounds Branch, Corps oversight of day-to-day base conservation was considerably less. Yet new land management regulations required increased research and development, and the branch's chief agronomist spent about 25 percent of his time overseeing research conducted mostly by CERL. The earliest of these projects was a maintenance management system that included grounds maintenance. Keeping track and planning uses of Army lands was a major chore. Under the leadership of William Severinghaus, Robert Lacy, and others, CERL developed the Integrated Training Area Management (ITAM) program to help address the issue. The program included six initiatives to analyze land use, coordinate among natural resources managers, increase environmental awareness, apply soil conservation and revegetation techniques, and implement technologies, including a computerized range management system to evaluate the impact of training on base property. The Geographic Resources Analysis Support System (GRASS), developed in 1984, used digital maps to analyze land for various uses and helped in planning and supporting recreation management, wildlife and wetlands management, permitting, water quality management, timber production, and other issues. The Land Condition-Trend Analysis System assessed data on land conditions for multiple uses. CERL helped some bases analyze vegetation loss and develop methods of dust control. Another area requiring considerable attention was wildlife management. In 1973, Congress passed a new Endangered Species Act that required all federal agencies to inventory and protect species on its properties. However, funding was limited to complete the inventories in the face of competing priorities – not until 1977 did the Army fund studies by CERL. By 1982, 33 installations had identified 115 endangered species, but it was uncertain what impact military operations had on some species, if any. In several instances, CERL helped installations with these inventories or conducted research on the impact of military operations on specific species such as the

red-cockaded woodpecker, gopher tortoise, or golden-cheeked warbler and general studies of the ecological effects of noise and smoke.²¹⁸

CRREL also became involved in a variety of environmental issues touching military construction. At the consolidation of CRREL in 1962, its Research Division included an Environmental Research Branch headed by Paul Camp and Robert Gerdel. However, most of its research involved understanding the arctic environment, its impact on military operations, and only later how human activities affected it. For example, CRREL conducted research on dispersing fog in cold regions using propane gas or helicopters to improve visibility. With the increase of Alaskan oil exploration in the late 1960s, CRREL became involved in the congressionally mandated (PL 91-438) International Biological Programme (IBP). At the request of the National Science Foundation (NSF), Jerry Brown organized and served as director of the U.S. IBP Tundra Biome project that involved 50 senior researchers from more than 20 U.S. academic institutions. The Biome's main goal was to develop predictive understanding of how cold-dominated ecosystems functioned. The five-year program included applied research on the impacts of industrial development, oil spills, and off-road traffic on sensitive tundra and taiga ecosystems. A follow-on program funded by CRREL, USGS, the Department of Energy, and Federal Highway Administration examined permafrost and long-term ecological impacts and recovery in the National Petroleum Reserve-Alaska and along the route of the Trans-Alaska Pipeline. Over 10 years, the projects resulted in the most detailed descriptions of the Alaskan environment to date and formed the foundation for documentation of climate change impacts, a major focus of CRREL research in the modern era (see below). Results were subsequently reported in many reports, journals, and the proceedings of the Third and Fourth International Conferences on Permafrost in 1978 and 1983. Other CRREL divisions, such as the Experimental Engineering Division, sought to understand environmental issues that impacted or were impacted by construction in cold regions. CRREL conducted pioneering work in detecting heat loss through building walls and roofs using infrared sensors, which it then corrected using metal heat shields, worked with WES to detect wet roof insulation, and developed a roof blister pressure relief valve. As was the case since its origin, CRREL spent considerable effort in analyzing the effect of permafrost, snow drifts, or other climate issues on military construction and started to examine pollution abatement in frozen climes, such as a pilot project completed in 1987 showing how freezing helped separate water from sludge.²¹⁹

From 1980, Thomas Jenkins led a CRREL team to develop methods for detecting explosive contaminants that helped improve environmental quality of military installations and ranges. Residues from the explosives TNT, RDX, and HMX rapidly migrate and contaminate groundwater, but detection using laboratory tests can take weeks. CRREL developed field analysis methods that EPA adopted after an independent analysis proved the methods less expensive and more accurate than other tests. Using this method, which involved taking water and soil samples that changed colors when exposed to a solvent, the group was the first to document explosive residues at firing ranges and other military training areas. Due to the program's success, the Defense Advanced Research Projects Agency sponsored research to characterize the chemical signatures of buried landmines to aid in detection. CRREL also developed capabilities

The Plight of the Woodpecker

Nearly a quarter of remaining red-cockaded woodpeckers (*Picoides borealis*), an endangered species identified in the Endangered Species Act of 1973, found homes in pine forests on nine Southeastern military reservations, including Fort Bragg, North Carolina; Fort Stewart, Georgia; and Fort Polk, Louisiana. Army guidelines issued in 1984 greatly restricted training near the birds. When the Army revised these guidelines in 1996 to allow more training, the U.S. Fish and Wildlife Service (FWS) objected. The Corps of Engineers requested that the Construction Engineering Research Laboratory (CERL) analyze the impact of the new rules.

In essence, the 1984 guidelines had established a 200-foot buffer zone around all trees in which the woodpecker nested, which Army biologists had to inventory. On many bases, this greatly restricted training, closing broad regions of forested ranges to soldiers. The 1996 rules, scheduled to go into effect in 2000, allowed transient training within 50

feet of woodpecker trees, including gunfire, smoke and flares, vehicle and personnel travel, and digging fighting positions. The FWS, wishing to err on the side of caution, preferred the larger buffer and requested a reassessment of the new guidelines and a joint monitoring program.

The problem was that no one knew with any precision what impact military operations would have. Scientists had conducted very few investigations on the effect of noise or human disturbance on birds, and most of these studies were anecdotal in nature. Based on observations of hawks, falcons, and eagles – there had been very little research on woodpeckers – the fear was that many birds flushed or scared from nests during incubation of eggs would not return, thereby further lowering species counts. CERL needed to quantify impacts on the birds to set an accurate buffer distance.



Red-cockaded woodpecker.

After meeting with FWS to further define the problem, the Corps established several research projects to measure the effects of various military maneuvers, noise, smoke, and weather events on woodpeckers in several test areas and recommend potential mitigation. FWS and base personnel helped collect the data. Prior to the studies, researchers gathered demographic data on occupancy, mating, and nesting for set age groups and collected preliminary data on bird behavior from behind camouflaged blinds. Video cameras and microphones helped capture data for prolonged periods. The studies defined specific reactions, such as at-

tentiveness, flushing, recovery time, prey deliveries to chicks, and trips away from nests. The teams collected data, both during accidental passive disturbances such as helicopters flying overhead and staged active disturbances such as gunfire, vehicle traffic, or smoke at various distances from the nests.

Although woodpecker responses varied by distance and noise type – with steady noises and close distances eliciting the greatest response – in fact populations increased under some circumstances. While studies of the birds continue, CERL was able to verify specific distances that were much lower than originally estimated and helped establish scientifically based guidelines on allowable training activities and distances. As CERL biologist Hal Balbach explained, the studies helped replace “initial guesswork and speculation” with “knowing the real effects” of training activities. “In the end, everyone can agree on reasonable restrictions that restrict the Army as little as possible but still protect the species.”



Baby long-leaf pine, the preferred nest site for red-cockaded woodpeckers, planted to divert habitat away from training ranges.

for understanding plant genetics, species management, and biochemical processes to support remediation of munitions sites, to include revegetation, chemical decontamination, and species restoration, particularly of cold region sites. One of the largest munitions contamination projects that CRREL supported was at Eagle River Flats, Alaska, in Fort Richardson. Eagle River Flats is an important estuarine salt marsh and staging area for migrating waterfowl. It was also a munitions impact area since World War II. After bird populations showed a high mortality rate, in 1982 the Army, FWS, EPA, and Alaska formed a task force to investigate the issue. Samples taken from water, plants, and animal tissue from 1983 to 1988 showed high levels of phosphorus, leading to the involvement of CRREL to test for contamination. Analysis in 1990 demonstrated that white phosphorus used in smoke munitions was not breaking down as rapidly as in other ecologies because of the anoxic sediments. Further studies from 1991 to 1994 helped identify transport mechanisms, document contaminated sites, and evaluate remediation methods. Among these were the use of geosynthetic material to cover and isolate contaminated areas, chemical treatment, and dredging or draining contaminated ponds. In 1994, EPA placed the site on the National Priorities List, making it a Superfund site. Remediation of the site, managed by the Alaska District, started in 1998 and achieved a goal of 50 percent reduction in mortality by 2003. Site remediation has continued, as have reductions in waterfowl mortality.²²⁰

Coastal Ecology and Coastal Zone Management

Several years before NEPA, CERC also started an ecological research program. CERC had investigated the impact of construction on the coastal environment since its origin but other than a few limited areas focused mostly on beach processes, not marine ecosystems. Its formal ecological program began with the 1968 New York Bight project, in which OCE requested it investigate the effect of dumping sewage wastes in a New York bay that had occurred under a Corps-issued permit. The project required the hiring of the first CERC biologist, who completed the study despite lack of oversight from OCE, whose own ecological consultants could devote little time to helping CERC because of work on another project. Since the New York study originally included a proposal for a consultant board, CERC proposed a similar body to guide an enlarged ecological program. It also proposed a single research organization to study coastal waste management, dredging operations, aquatic plant control, and construction impact. In 1970, approval came for an organization with oversight only over coastal ecology. With the passage of NEPA, the formation of the EAB, the highly publicized results of the New York study, and several new projects waiting in the wings, time was ripe for growth of the program. CERC formed the Coastal Ecology Branch in its Research Division. Within months, it grew to include three full-time biologists and several active projects, including new marine disposal studies, Ecological Monitoring of Off-Shore Borrow Areas for Beach Nourishment, and Stabilization and Productive Use of Dredge Spoil, of which the latter two developed from previously existing CERC projects.²²¹

The two largest programs under the Coastal Ecology Branch concerned vegetative plantings and dredged material placement. Vegetative plantings research was a continuation of a Beach Erosion Board program, ongoing periodically since 1956, involving experimentation

with dune grasses such as *Spartina alterniflora* to stabilize beaches. Projects in North Carolina and Texas had demonstrated that by capturing wind-transported sand, grasses could increase beach heights by a foot over a five-year period. By 1971, the branch had restored two parts of an eroded island in Chesapeake Bay and had turned a barren island near Cape Fear into productive marsh. After a 1976 conference, it introduced the method into the Great Lakes to control erosion and published a series of reports in 1977 and 1979. CERC's dredged material disposal program grew initially out of finding acceptable disposal sites, but by 1972 expanded to include investigating the effects of offshore dredging on estuary organisms, material deposition, and using dredged material for beach fill. In support of the WES Dredged Material Research Program, CERC also experimented in the late 1970s with marsh creation using vegetative plantings on dredged material. In addition, CERC experimented with creating marine environments out of rubble mounds from destroyed coastal structures and established an extensive environmental measurement program on completion of its Field Research Facility at Duck, North Carolina, in 1980.²²²

By 1972, environmental legislation had grown to include the coastal zone. Management of coastal resources first became a concern before World War II because of disputes over ownership of coastal resources, mainly oil. In 1945, President Harry S. Truman issued a proclamation claiming U.S. control of sub-ocean soils to the continental shelf, thereby changing international law. The Submerged Land Act of 1953 gave individual states authority to manage submerged lands out to three miles from shore other than for defense, navigation, flood control, or power production. Over the next dozen years, individual states passed a patchwork of laws covering a range of issues. It was not until a series of coastal environmental disasters, such as the Santa Barbara oil spill of 1969, that Congress moved to tighten up regulation of the coastal zone, particularly related to environmental protection. The 1972 Coastal Zone Management Act (PL 92-583) and its 1974, 1976, and 1980 amendments encouraged states to develop coastal zone management (CZM) programs to manage coastal lands and resources while protecting habitats and areas of concern. The act provides grants through the Secretary of Commerce to those coastal states with an approved CZM program that defines a zone and includes planning, permitting, access controls, and interagency standards. Rather than dictating programs, the law leaves it to states to voluntarily develop programs based on existing federal laws, such as the Clean Water Acts and the Submerged Land Act. The state legislation that resulted from the act radically changed coastal land use management and environmental regulation and quality, leading the National Planning Association to conclude that "the CZMA has helped fuel the 'quiet revolution' in land-use control."²²³

CERC became deeply involved in several CZM issues. It continued to consult on coastal construction projects, as it had for decades, with a significant uptick in work resulting from participation in the Shoreline Erosion Advisory Panel after 1974. Ninety percent of offshore construction takes place in water less than 50 feet deep, and this was the emphasis of early Beach Erosion Board and CERC studies. After 1976, CERC turned to helping Corps districts and divisions solve deep-water issues. Its Offshore Engineering Program included four elements. First, it pioneered the field of sub-ocean soil mechanics by gathering data on the ocean floor and

experimenting with construction activities and equipment. Second, it conducted laboratory experiments on construction materials such as concrete blocks and piping, leading, for example, to the publication of a 1978 study on submerged pipelines. Third, it collected data from field studies on breakwater and pipeline performance, including a modular floating tire breakwater. Finally, it conducted feasibility studies of specific projects, the primary example of which was the Rincon Island Study, an artificial island built a half-mile offshore in the Santa Barbara Channel in 1959 to develop an offshore oil lease. Its owner, Atlantic Richfield Company, arranged for CERC to determine the feasibility of a steel-pile causeway, determine whether the island was effective, and assess its impact on the environment. Another issue that soon came to the forefront was barrier island studies. More than half of U.S. coast lines are composed of barrier islands – shore-parallel linear islands that form unique ecosystems. Particularly after 1973, development of the islands and coastal erosion threatened these fragile systems. CERC had been gathering data on the islands since 1969, but launched a comprehensive study in 1980 that included surveys, core samples, sonar tests, carbon dating, and mapping that advanced knowledge on the formation, conditions, and changes to the islands. When CERC moved to Vicksburg in 1983, several barrier island team members remained in Washington, D.C., within OCE to continue non-research consulting on controversial barrier island issues faced by the districts, including subsidence and short-term temperature fluctuations such as the El Niño cycle.²²⁴

Evolution of the Environmental Laboratory

By the late 1960s, WES leaders realized the need for a more robust ecological program. In 1967, while visiting WES, Director of Civil Works Brig. Gen. H.G. Woodbury, Jr., remarked that its research program “did not respond fully to the broadening public concern in multiple purpose use of water resources” and recommended developing a capability for defining ecological effects and limits of Corps projects. In response, WES initiated a study by biologists John Cairns, Jr., of Virginia Polytechnic Institute and Phillip S. Humphrey of the University of Kansas. Their May 1969 report identified various ecological problems affecting Corps projects, noting that current approaches were “restrictive rather than directive.” Instead of “coping with environmental problems one fragment or component at a time,” WES should develop programs

“on the basis of the environment as a dynamic system.” Its recommendations were to form a water resources ecology group using existing staff from various fields, form an advisory board to help build relations with other organizations, and select a pilot project. An ad hoc committee headed by Warren E. Grabau formed in August 1969 to develop a long-range plan and policy, resulting in the 1970 “Program of Research Toward an Environment-Compatible Engineering Policy.” It too recommended a research organization taking a systems approach to the environment that used both physical and biological modeling. Two other proposals submitted in September 1970 and March 1971 recommended various research programs. In January 1971, Dean R.



Warren E. Grabau.

Freitag of the WES Office of Technical Programs and Plans hired biologist John W. Keeley to help formulate and guide the proposed program with a six-man Environmental Quality Control Committee to provide assistance.²²⁵

WES environmental work expanded considerably in 1971. Many districts requested support in preparing EISs, with the EIS for the Illinois Waterway from Chicago to the Mississippi River being the largest. The aquatic plant control program was ramping up, and the Hydraulics Division conducted more than a dozen ecological model investigations, including basic research into diffusion of industrial effluents, oil pollution on water surfaces, heat dispersion, and the mechanics of density stratified flow. It also received several projects related to wastewater management and dredged material analysis and disposal, which became two of the three largest environmental missions at WES. At the recommendation of Keeley and the Environmental Quality Control Committee, WES established the position of Special Assistant to the Director on Environmental Coordination on September 1, 1971, which it filled with John Harrison, a committee member, sanitary engineer, and computer expert in the Mathematical Hydraulics Group. Over the next half-year, Keeley, Maj. W.P. Emge, and eight other civilian and military personnel were assigned to support Harrison, mostly on EIS consulting and dredged material research. In June 1972, Harrison issued his first environmental plan of action, a requirement of the office charter. In it, he recommended changing the name of the office to Special Assistant for Environmental Studies, that it replace the Environmental Quality Control Committee, and that it be given greater space and personnel such as biologists, botanists, and chemists to support its project load, all of which WES Director Col. Ernest D. Peixotto approved. Harrison also developed a pamphlet, "Summary of Environmental Research Capabilities," to promote environmental research among WES customers. By 1973, the 30-member Office for Environmental Studies assumed responsibility for urban planning, wastewater treatment, and started work in simulated ecosystem modeling with a greenhouse laboratory facility in which the office could test impacts to complex ecosystems with controlled lighting, humidity, and temperature. It also started a program to identify appropriate environmental research instrumentation and equipment. Despite this growth, without further guidance from OCE, Peixotto remained uncommitted to a specific plan of action for consolidating environmental research, which, he noted, was only "beginning to mature." Harrison himself delayed making a final recommendation from 1973 to 1974.²²⁶

One of the areas that greatly influenced the growth of environmental research was the Dredged Material Research Program (DMRP). The Corps dredging program was enormous, amounting to \$200 million per year to remove and dispose of 350 million cubic yards of dredged material to keep ports and waterways operational. Although many communities considered dredging essential to prosperity, there were many concerns that dredging and material disposal were environmentally destructive to waterways, particularly when the material was itself contaminated. Since 1966, WES and CERC had researched effects of dredging and dredged material placement, primarily in the Great Lakes, but other than a handful of studies performed for the Lower Mississippi Valley Division and OCE, most concerned the efficiency and economics of placement, not its environmental impact. In the River and Harbor Act of 1970 (PL 91-611),



Dredged Material Research Program – from left to right: Roger Saucier, Thomas Patin, Hanley Smith, Charles Calhoun, and Robert Engler.

Congress authorized a study of the environmental effects of dredged material and alternative disposal methods. OCE assigned WES the program in May 1971, and researchers spent several months developing a research program that included ecological effects of water and land disposal, design and management of disposal facilities, the development and testing of productive uses of dredged material in agriculture or recreation, and the creation of wetlands habitat using dredged material. NOAA, EPA, and other agencies reviewed the plan, with the most extensive comments from the Smithsonian Advisory Committee that guided the CERC New York Bight project stating that WES needed to integrate research topics, focus more on dredged material versus dredging as a whole, and improve sampling. In January 1973, WES formed the Office of Dredged Material Research, also headed by Harrison, which reported directly to the executive office to ensure the program received the highest attention. Research started in March and quickly grew to include more than 200 individual projects. As early as April 1973, Harrison recommended combining the two offices under his purview since the DMRP formed more than 80 percent of environmental research, but the two offices remained separate for another year.²²⁷

Finally, in his 1974 Plan of Action, Harrison recommended establishing an Environmental Effects Laboratory and proposed once again merging the offices of Environmental Studies and Dredged Material Research. The orders approving this change came in August, establishing the

lab effective July 25 and consolidating the largest environmental programs in a single laboratory, although they retained Harrison as a special adviser to the director on dredge research. However, Harrison's recommendation of changing the name of the Mobility and Environmental Systems Laboratory to avoid confusion did not receive approval. Other than the Aquatic Plant Control program, the majority of this lab's environmental work was military in nature. It was not until 1978 that the name issue was resolved with the reorganization of WES laboratories under Col. John L. Cannon. A 1977 study, in which Harrison participated, noted redundancy in some program areas and the confusion the name caused among potential WES customers. Cannon more or less adopted the study's recommendation that non-mobility environmental programs be transferred to the 130-person Environmental Effects Laboratory as an enlarged Environmental Laboratory (EL), although he chose to move mobility research into the Geotechnical Laboratory rather than maintain it as a smaller, separate laboratory. Soon afterwards, when OCE tapped CERL to coordinate Army efforts to develop standard environmental data acquisition procedures, Cannon took the opportunity to promote the use of EL as a "research and development capability in the total area of environmental concerns" for the Army – in essence to consolidate environmental research in a single lab – starting with the acquisition technology baseline, but OCE seemed desirous of maintaining separate civil and military environmental efforts and did not act on the suggestion.²²⁸

EL saw immediate increases in several work areas. It provided support for civil works EISs, for example, a deepwater Mississippi River channel. It also analyzed Water Resources Council standards and Corps policies to develop EIS guidance manuals and methodologies, such as the 1977 Water Resources Assessment Methodology. It continued innovative work on simulated ecosystem modeling (SEM), in which it modeled ecosystems primarily using traditional physical models. As with other models, SEM technicians scaled surfaces and volumes and adjusted water flow or other compartmentalized systems to achieve field conditions. The main difference between SEM and other models was the use of actual field soils and plants in climate-controlled and closely monitored greenhouse facilities. Later, numerical modeling and computer systems aided in analysis. The first model was of DeGray Lake, Arkansas, but this grew within four years to include six others, mostly lakes and reservoirs. By the end of the decade, EL was performing complex simulations and analyses of entire river basins using satellite data. In 1991, Harrison requested and WES Deputy Director Lt. Col. Mack R. Goldman approved the formation of an Ecosystem Modeling Institute to permanently staff a team to model environmental issues for the lab. The Aquatic Plant Control Research Program, which EL inherited from the Mobility and Environmental Systems Laboratory in 1978, expanded to include several species of water milfoil, giant cutgrass, hydrilla, and melaleuca as well as water hyacinth and alligator weed. EL continued to examine mechanical controls as new technology came into use and tested chemicals such as fenac, flouridone, and copper-based herbicides. It also examined biological controls using plant-eating weevils, moths, fish, and fungi and management technologies that integrated multiple controls based on habitats and agency operational limitations. In particular, use of computers helped researchers to map and analyze watersheds, make predictions, and develop long-term plans. Most work occurred in conjunction with other districts, primarily the

Jacksonville District, which OCE assigned as the Center of Expertise for Aquatic Plant Control in 1980.²²⁹

In 1978, EL inherited military environmental research other than mobility research. OCE assigned WES as the responsible laboratory for military hydrology. Although hydrology programs existed in other labs for mobility, mapping, and climate research, these were, as OCE Research and Development Office Chief Col. Maxim Kovel observed, “largely uncoordinated efforts.” EL used data from other labs along with meteorological reports to build computer models to predict hydrological conditions, stream heights and flooding, groundwater locations, and trafficability, and it helped develop field manuals on prediction. In 1979, OCE assigned WES as the principal laboratory for countersurveillance and fixed installation camouflage, which involved both visual and electronic deception technologies. After holding a conference in late 1978 with the other laboratories to determine the status of camouflage research, EL worked with the Army Materiel Development and Readiness Command and NATO allies to develop highly advanced concepts in thermal and microwave camouflage by testing the impacts of various materials on sensor results, culminating in the 1983 Thermal Infrared Experiment. This research eventually extended to the battlefield as EL analyzed the impact of the environment on sensors by testing how grasses or dust affect target signatures. By 1984, it was testing effects on intrusion detection sensors. Although the Geotechnical Laboratory continued mobility studies, EL provided environmental data and conducted similar analyses for helicopter and munitions performance. Another major mission EL received in 1979 was assignment as the principal lab for mine/countermine technology. It developed a five-year program on the environmental constraints on mine placement as well as the detection of mines. Each of these areas – hydrology, camouflage, and mine detection – required expertise in remote sensing, which, as noted previously, WES developed in support of water resources projects over the previous decade. This pushed development of multispectral systems and databases of terrain information. By 1985, WES became deeply involved in the AirLand Battlefield Environment (ALBE) thrust, an effort to monitor battlefield environmental conditions that became a showcase for computer technologies. In 1985, WES became the executive agent for ALBE research and established an ALBE Office, through which it closely coordinated with CERL, CRREL, and ETL. However, EL saw its largest growth in dredging, wetlands, and water quality research programs.²³⁰

Dredging, Wetlands, and Water Quality

DMRP remained the largest EL program well into the 1980s. Not only was it the single largest research program WES ever managed – it included more than 200 individual projects at 120 geographic locations involving 70 agencies or businesses and more than 400 participants with in excess of \$200 million in funding over its life – it was also one of the earliest large research programs in the Corps, setting the standard for later environmental research programs. The overall impact of the DMRP on Corps dredging operations cannot be understated. One of the first DMRP areas to advance was aquatic disposal, which examined dredging and disposal in water systems. Through application of standard testing, researchers confirmed that, aside from contaminated dredged material, turbidity caused by dredging or disposal did not

produce major chemical or biological changes to water, although it sometimes caused geometry changes that impacted some species. From an aesthetic standpoint, devices such as silt curtains, dikes, and management of fill rates helped reduce water clouding. For confined disposal facilities, researchers developed methods of containing, capping, and treating contaminated material and dewatering material using trenches or steamroller-like vehicles. Research demonstrated there was no single preferred disposal method, but each project required region-specific plans. However, EL did research operational issues such as treatment of turbid water, movement of material, containment and treatment of material, and reuse of disposal sites. Perhaps the most important DMRP research came from studying wetlands that developed on islands created from dredged material as early as the nineteenth century. WES engineers realized they could seed dredged material with various plants and quickly create new wetlands. This required an understanding of wetland habitat that would come into great demand the following decade. In 1978, WES published *Beneficial Uses of Dredged Material*, a popular manual on wetland habitat development, which led to radical changes in Corps placement of dredged material. Finally, the program worked to establish uses of dredged material in agriculture as mulch or enriched soils and in recreation areas by creating islands or beach. It even researched productizing material for resale.²³¹

The program involved included hundreds of specific projects to examine the ecological effects of water and land disposal, design and management of disposal facilities, the development and testing of productive uses of dredged material in agriculture or recreation, and the creation of wetlands habitat using dredged material. Many of these were highly successful. For example, one site at the Pointe Mouillee State Game Area on Lake Erie, Michigan, involved restoration of a historic wilderness area on a barrier island near Detroit that had disappeared over 40 years because of rising lake levels, erosion of protective beaches, and dams blocking natural sediment flow on the Huron River. Under a 1974 agreement with the Michigan Department of Natural Resources, the Detroit District worked with WES to develop a 365-hectare contaminated disposal area in the shape of the old barrier island using heavily armored dikes to contain the dredged material and culverts below two causeways to allow sediment from the lake to settle in the wetland area between the island and the shore. Construction of the dikes and roads was complete in 1983, and from 1980 to



Pointe Mouillee confined disposal facility, Lake Erie, Michigan. U.S. Army Corps of Engineers.

1985, the district filled and seeded the compartments as dredging continued. By 1987, more than 400 hectares of marsh developed naturally in the game area and another 1,100 hectares were protected from flooding, while 60 hectares of wetland plants had emerged on the island, mostly around the ponds. Monitors had observed more than 200 species in the new areas, primarily 145 species of birds, but also deer, rabbits, beaver, raccoons, perch, catfish, and other species. Other beneficial use sites included Gaillard Island, Alabama; Southwest Pass, Louisiana; Nott Island, Connecticut; Windmill Point, Virginia; Warroad, Minnesota; Apalachicola Bay, Florida; and Miller Sands Island, Oregon.²³²

As DMRP – then 70 percent complete – started to wind down in 1978, several follow-on programs emerged. In the Field Verification Program, EL and EPA monitored dredging projects to ensure adherence to environmental regulations such as the Clean Water Acts or the International London Dumping Convention of 1972. This required making numerous site visits as well as reviewing disposal plans. The Dredging Operations Technical Support Program, which was the largest technical support program at WES, provided a forum for EL to advise districts and commercial dredgers on operational and technical issues. From 1978 to 2009, EL processed more than 1,000 requests. Through the Long-Term Effects of Dredging Operations Program, EL examined the effects of disposal and monitored both contaminated and uncontaminated sites over many years, including dozens of beneficial use locations. After the Water Resources Development Act of 1986 authorized a series of new dredging projects, WES recommended, and the Corps Directorate of Research and Development approved, a new Dredging Research Program, which President Ronald Reagan funded starting in 1988. This research focused more on dredging operations and management, such as vessel navigation and monitoring, improved equipment and operation, and more precise management of disposal through global positioning systems and computer modeling of sites. Exchange bulletins helped keep industry apprised of developments.²³³

The largest outgrowth of DMRP was evaluation and protection of wetlands. EL conducted wetlands research for beneficial uses of dredged material under DMRP, but wetlands were growing in importance across the Corps. Section 404 of the 1972 Clean Water Act gave the Corps responsibility for permitting discharge and alteration of all waterways, and the 1975 court case *Natural Resources Defense Council vs. Calloway* interpreted this to include wetlands. In 1979, WES proposed expanding DMRP and follow-on programs to include wetland identification and impact analyses. The Wetlands Research Program, authorized in 1982, evolved into six major areas. The first two areas were understanding wetland processes such as hydrology and sedimentation and developing methods to define wetlands. Because of the cost and inconvenience of 404 permits, it was critical to delineate wetlands to avoid permits for altering every pond or stream. EL worked for several years to understand wetland ecosystems, resulting in its 1987 *Wetland Delineation Manual*, a computerized Wetland Evaluation Technique, and training courses. A related issue was valuation of wetlands, which allowed the Corps to estimate benefits and costs of projects in terms of wetlands impacts, for example, using the value of an oyster bed or recreational fees. A third research area was restoration, protection, and establishment of wetlands, including, after the 1983 transfer of CERC to WES, coastal wetlands. In addition to

continued research on creating wetlands from dredged material, a significant amount of work involved researching habitat. WES had investigated water-related wildlife since 1970 to support EIS development. Through methods such as the FWS Habitat Evaluation Procedures, the Benthic Resource Assessment Technique, and the Corps Habitat Suitability Index, the lab could determine suitability of wetland areas for wildlife. After 1980, EL worked to minimize environmental impacts on wetlands to preserve endangered species such as fish, plants, and mollusks. It supported several specific projects, most prominently the Tenn-Tom Waterway and restoration of brown pelicans in Mobile, Alabama. By 1986, the lab developed a comprehensive Wildlife Resources Management Manual. The fifth and sixth research areas, change assessment and management, mainly concerned inventory processes and management information systems. Because of continuous questions from the districts on wetlands-related regulatory questions, OCE also funded a Wetlands Regulation Assistance Program through which EL could consult on wetlands issues.²³⁴

Another growth area in WES environmental research was in water quality, which is not surprising given its close alignment with resident hydrological expertise at the lab. The Office of Environmental Coordination initially became involved in water quality research in developing guidelines in 1972 for the Buffalo District to build a land-based wastewater treatment pilot project in Cleveland, Ohio, that used natural drainage for tertiary treatment of landfill wastewater. The same year, the office started a wastewater management project for CRREL as part of the six-year Land Treatment Research and Development Program. At the time, CRREL was the principal laboratory for wastewater management because it had a resident expert, but with multiple leadership changes and lacking facilities, it had often brought in WES to conduct the work. The research concerned overland flow wastewater systems that used gently sloping permeable soil and an organic mat of grass, roots, and plant residue to filter contaminants such as nitrogen, phosphorus, and heavy metals. In general, EL preferred biological systems such as overland flow, lagoons, or aeration to remove contaminants, and such systems were in use at a Texas Campbell Soup plant and other locations. Over three years, the lab experimented in a greenhouse environment with slopes and organic materials to maximize contaminant absorption before constructing a pilot project at Utica, Mississippi. In 1973, it started development of a spray irrigation wastewater system for the Arkabutla Lake, Mississippi, recreational facility. Based on this study, it developed the Computer Aided Procedure for the Design and Evaluation of Wastewater Treatment Facilities widely used by EPA and others. Starting in 1974, as a response to the Clean Water Act of 1973, the lab also supported EPA in developing solutions for the treatment of solid and industrial municipal wastes, including with chemicals and soil admixtures, as well as isolating wastewater using linings or caps. This led WES increasingly into projects related to waste disposal on military installations, also a research area for CERL. In general, WES supported remediation activities and CERL supported conservation, prevention, and compliance.²³⁵

With the passage of the Resource Conservation and Recovery Act and Superfund, the Defense Department established the Defense Environmental Restoration Program and initiated subprograms for the removal of pollution, including the Installation Restoration Program and

The Perils of Defining Wetlands

In 1972 Congress passed the Federal Water Pollution Control Act or Clean Water Act of 1972. The law amended earlier Clean Water acts to give the newly created Environmental Protection Agency (EPA) responsibility over water quality regulation, but it left the Corps of Engineers responsible for monitoring pollution discharges, dumping, and dredging as it had since 1899. Section 404 spelled out Corps responsibilities and established permit requirements for these activities. In the 1975 *National Resources Defense Council Inc. vs. Calloway*, the courts expanded these responsibilities by ruling that Section 404 permits cover all U.S. waters.

One of the issues that remained unresolved was the definition of a wetland, which, as a body of water, fell under Section 404. Given the vast amount of development, mining, and drilling that took place in wetland areas of Louisiana, Florida, and other states, whether the Corps classified a tract of land as a wetland could mean thousands of dollars in permitting costs or fines. The problem was that there was no consistent definition or standards for delineating wetlands, which can appear dry for long periods of time. By 1985, nearly all federal agencies involved in resource management had their own standards for defining wetlands, with the Fish and Wildlife Service using mostly photographic evaluation and EPA using mostly vegetation indicators.

To help clarify Corps policy on wetlands, the Waterways Experiment Station (WES) developed a *Wetlands Delineation Manual* using standard hydrological and biological definitions, finalized in January 1987. Based on this manual, to classify an area as a wetland, Corps evaluators had to identify and document criteria based on soil, vegetation, and hydrology patterns. With only limited exceptions, the manual instructed evaluators to classify a region as a wetland that showed indicators in each area – inundation for a specific period of time or presence of soils and vegetation associated with wetlands. Although the Corps and other agencies never officially sanctioned the manual, whose goal was only to provide technical guidance, most Corps districts used it unofficially until 1989.

That year, the EPA developed an interagency manual that built on the WES manual. The primary differences between the two were that the EPA manual allowed presumption of hydrology in some circumstances and delineated wetlands with the presence of fewer indicators. Historians Carroll Pursell and William Willingham described the varying approaches by stating that the 1987 manual tried to distinguish between wetland and non-wetland, while the 1989 manual “sought to ensure no wetland was ever missed.” Many business and agricultural interests objected that the new rules would make wetlands out of good, available land, though in practical application, the Corps found the rules made little difference in many disputed areas.

Finally, in the 1992 Energy and Water Appropriations Act, Congress directed the Corps not to use the 1989 manual or other manuals not subject to public comment and notice for 404 permitting. In 1993 the EPA and Corps came to an agreement to use the 1987 manual for all future delineation for 404 permitting, although the federal government and the Corps used the 1989 manual for other purposes.

Despite the fact that some environmental scientists criticized the minimalist approach of the 1987 manual, it nevertheless provided the first attempt based on science to define wetlands for policy purposes. It also informed further discussion on wetland delineation in general, resulting in better science. Thanks to the WES manual, the Corps and EPA developed a standard approach for legally determining a wetland area that reduced evaluation time to less than one hour.



Six major types of wetlands — a) leveed, b) prairie pothole, c) floodplain, d) freshwater, e) riparian, and f) depressional.

Formerly Used Defense Sites. WES supported the Army and Coast Guard in developing solutions for containing and disposal of hazardous wastes, helped EPA revise engineering guidelines for waste management, and consulted on the standup of a Superfund response group in the Missouri River Division. After working with EPA to develop the Hydrological Evaluation and Landfill Performance computer model, it participated in several projects for wastewater, groundwater, and landfill treatment, supported by its Analytical Laboratory Group facilities. This became part of the WES Hazardous Waste Research Center in 1988 – a 10,000 square-foot pilot research facility to support Superfund projects. As the Army continued to bring itself into regulatory compliance and eventually became the tri-services lead on installation restoration, the workload rapidly expanded, resulting in creation of a Corps-staffed Army Environmental Office in 1988. Funding increased vastly after 1989 when the Army transferred the Toxic and Hazardous Materials Agency from the AMC to the Corps, including hazardous materials research, which WES increasingly performed. A significant part of this work was supporting unexploded ordnance removal in conjunction with the Huntsville Division, the Mandatory Center of Expertise for ordnance removal. Although most of this research was direct-funded support by EPA, such as the examination of best demonstrated available technology, the site-specific nature of most solutions meant EL was deeply involved in several specific project sites.²³⁶

In 1977, the Environmental Effects Laboratory became involved in investigating water quality at civil works projects. The Environmental Water Quality Operational Studies was a six-year program for monitoring and developing methods to manage water quality in waterways and reservoirs. Using mathematical models, the lab analyzed water quality to predict when anaerobic or low-oxygen problems would occur, developed methods to manage algae blooms, and experimented with water flow levels for reservoirs. Based on these studies, EL conducted four long-term field studies to develop water testing and management regimens that resulted in a manual and a computer program to model water quality, CE QUAL. It conducted similar site studies on the Mississippi and Tombigbee rivers to measure the impact of dikes and revetment on the environment that also resulted in a 1984 engineer manual. Later projects examined revegetation of eroding shorelines, site preparation of reservoir areas, fisheries management, and floodplain ecosystems, primarily bottomland forest. This led to the development of mitigation techniques such as greentree reservoirs – forests flooded in winter to provide habitat for waterfowl – developed in a 1980 study in the Mississippi Delta National Forest. Operations then shifted to application of these technologies and knowledge in the Water Operation Technical Support Program, through which EL advised districts on water quality issues. By 1985, EL had received more than 75 requests.²³⁷

EL also entered the natural resource management business, but as opposed to CERL, approached it from the water resources management aspect. At first, this focused mainly on recreation. A major emphasis of the environmental movement was enjoying nature, and laws such as the Wilderness Acts of 1964, 1968, and 1974 and the Nature Trail Act of 1968 regulated the use of wilderness and park areas. Since the 1950s, the Corps had built hundreds of recreational facilities as part of its projects – mostly water recreation areas – at federal expense, though it

often did not maintain them. In 1993, there were more than 4,000 such facilities nationwide, accessed by more than 637 million visitors, nearly twice the number that accessed national parks. As noted previously, the first recreational projects at WES involved wastewater treatment facilities, and by 1974, the Environmental Effects Laboratory was working on a series of wastewater projects at roadside rest areas for the Federal Highway Administration. By 1976, it became involved in a five-year project to develop methods for planning recreational facilities. The initial program included modeling visitor use, planning and design, impact analysis, and management of recreational facilities, but quickly grew to include 24 test projects to develop a common database and approach based on accumulated data. After 1984, EL conducted several projects in cooperation with the Forest Service and Park Service concerning the economic impacts of recreation areas to improve designs and determine fees. This evolved into supporting maintenance of recreation areas – including those on military bases – through vegetation and land use management, culminating in a five-year study of plant growth regulators on military installations. In 1987, EL developed a Natural Resources Technical Support Program, in which the lab advised on natural resources issues, including campground permitting.²³⁸

Ice Research and Climatology

Perhaps the most surprising area of environmental research conducted by the Corps related to the emerging science of long-term climate change. Although the connection between ice core research and climate data is not well known, in fact CRREL contributed greatly to modern understanding of climate change by developing the first successful methods of recovering ice cores. Prior to the twentieth century, most scientists believed world climate had been relatively stable for thousands of years. Based on temperate animal remains found in the extreme north and on growing evidence after 1802 of glacial progress in the distant past, in 1837 Louis Agassiz first proposed an ice ages theory, though it was German botanist K.F. Schimper who actually coined the term *Einzeit* (Ice Age). But as late as 1906, leading scientists viewed these periods as aberrations and believed global temperatures had since fluctuated only by a few degrees. The causes of ice ages remained widely disputed. Most accepted geological explanations, such as mountain-building processes, continental drift, or volcanic eruptions, proposed respectively by Charles Lyell and James Dana, Vladimir Köppen and Alfred Wegener, and William J. Humphreys. Some, including Lyell, C.E.P. Brooks, and Escher Linth, envisioned melting ice or oceanic processes as being at least partially responsible. Swedish researchers Svante Arrhenius and Nils Eckholm blamed carbon dioxide trapping heat in the atmosphere – what later became known as the greenhouse effect. Others looked for astronomical explanations based on theories of solar fluctuation made by William Herschel. Frenchman Joseph Adhemar first suggested in 1842 that ice ages were related to the Earth's orbit; 20 years later Scotsman James Croll noted that ice age dates coincided with periods of elongated orbits – roughly every 11,000 years. American astronomer Charles Greeley Abbot tried to associate sun spots with weather. By 1930, many scientists accepted Serbian Milutin Milankovitch's measurements of orbital effects on radiation at different latitudes as proof that astronomical occurrences were a requirement for an ice age if not a cause. Yet other than a few lone voices, such as Humphreys and Brooks, the latter of

whom wrote that “the unvarying climate of history is evidently a myth,” the presiding theory was one of stability.²³⁹

Several advances in measuring climate change radically altered this view. Development by American Andrew Ellicott Douglass of dendrochronology, or dating by tree rings, allowed analysis of water conditions based on the thickness of rings in giant redwoods and bristlecone pines going back 8,000 years. Based on the pioneering work of R. Sernander in 1908 applying prehistoric plant studies to striations or varves in bogs and lakebeds, Dane Knud Jessen discovered in 1949 that layers containing only fossilized pollen of the alpine plant *Dryas octopetala* (compared to those containing pollen of many plants) indicated ice age periods, with the most recent – termed the *Younger Dryas* – occurring 11,000 years ago. The invention of an ocean sediment core sampling device by Swede Börje Kullenberg led to collection after 1960 of extremely clean ocean-bottom core samples containing striations and fossilized skeletons of tiny foraminifera. Aiding these discoveries was the capability developed in 1947 to measure radioactive isotopes – primarily radiocarbon – that aided dating or temperature estimates. Cosmic rays constantly emit, and all living things absorb, the isotope carbon-14, or carbon atoms with two extra neutrons. Scientists can determine the age of anything that once lived by measuring radiocarbon, which gradually decays over time. In 1957, Wallace S. Broecker first applied this process to climate change when dating peat. Harold C. Urey, Willi Dansgaard, and others estimated ocean temperatures by comparing the proportions of oxygen-18 and oxygen-16 (which vary by temperature) absorbed in shells and in ice. These and other documentary and scientific discoveries suggested that historical temperature drops had occurred more often and recently than supposed. What was needed was a way of making continuous temperature measurements for thousands of years. As author John D. Cox wrote, “A great corrective lens would be applied to the study of ancient climates, and it would be made of polar ice.”²⁴⁰

As early as 1930, when plate tectonics-proponent Alfred Wegener led an expedition to Greenland to investigate glacial movement, geologists recognized the potential of ice preserving geological records. Although he died during the expedition, his assistant Ernst Sorge proposed a theory correlating ice densification with time, based on their work examining strata in ice pits. Henri Bader – the scientist who helped form SIPRE in 1949 – was a renowned expert on mining and snow, having co-written *Snow and Its Metamorphosis*, which argued that snow and ice contain geological secrets similar to rock. He conducted experimental ice drilling in 1939 at the Taku Glacier in Alaska, extracting a core sample of 31 meters and proving the concept. Experiments by Norway, France, and others shortly followed. After the formation of SIPRE, Bader began open pit experiments in Greenland measuring ice strata using Sorge’s Law of Densification, which he reduced to a mathematical formula. In meetings leading up to the 1957 International Geophysical Year (IGY), Bader, as a member of the IGY National Academy of Sciences Committee, proposed extracting a deep ice core in Antarctica with a pilot project in Greenland. In 1956, he and SIPRE researchers Chester C. Langway and B. Lyle Hansen continued experiments with ice drilling and ice core analyses in Greenland, achieving 305 then 411-meter samples. The CRREL team developed a thermal drill using a trichloroethylene-based fluid to keep the bore hole open and a vacuum that removed meltwater. Preliminary drilling

during the IGY at Byrd Station, Antarctica, reached 307 meters by 1958, which at the time was the deepest core recovered from Antarctica. The following year drilling at Little America V reached the bottom of the Ross Ice Shelf at a depth of 843 feet, the first time drilling penetrated the entire thickness of a polar ice shelf. Using NSF funding, the team started drilling at Camp Century, Greenland, in 1961, reached bedrock in 1966 at 1,387 meters, and reached



Byrd Station ice core, 1968.

bedrock at Byrd Station in 1968 at 2,164 meters. In 1970, led by CRREL, the U.S., Denmark, and Switzerland developed the NSF-funded Greenland Ice Sheet Program (GISP), and after drilling three test cores, in 1981 the team reached bedrock at 2,037 meters drilling at a Distant Early Warning DYE-3 radar station. In 1984, GISP-2 began drilling at a point 20 miles from the highest point on the Greenland ice sheet – the Summit – where another team representing several European institutions was also drilling.²⁴¹

The result of this ice research was a clear and uninterrupted record of global climate reaching back 115,000 years BP, which numerous scientific collaborators from more than 20 nations analyzed and cross-correlated. In 1962, Langway and Swiss physicist Hans Oeschger first applied radiocarbon dating to ice samples. Preliminary findings of the Antarctic ice that Anthony Gow and others published from 1970 to 1980 included the first complete profile of ice crystal structure changes in an ice sheet related to ice flow dynamics and the first report of widespread deposition of volcanic ash that most likely originated from volcanoes known to exist in West Antarctica. In 1973, a landmark study by Charles D. Keeling of the Scripps Institution of Oceanography reported that atmospheric measurements made in Hawaii since 1953 showed steady rise of carbon dioxide (CO_2) in the atmosphere. In 1980, analysis of air bubbles in the ice core samples showed a steady rise of CO_2 since the nineteenth century, and GISP measurements showed 30 percent less CO_2 during glacial periods, suggesting a correlation between atmospheric content and climate. Dust, ash, and other aerosols in the layers allowed analysis of annual climatic issues. After GISP confirmed the initial climatic data, Langway – then at the University at Buffalo, New York – joined Oeschger and Dansgaard in presenting a paper in 1984 that described a delicately balanced climate mechanism that could abruptly tip from steady-state climates during high- CO_2 warming events now known as Oeschger-Dansgaard events. The following year, Broecker tied ice ages to the circulation of the ocean. Normally, the North Atlantic Ocean sees greater evaporation due to warm ocean currents and less runoff, which releases heat into the atmosphere. Denser and colder saltwater sinks and flows to the Pacific, where it is freshened and flows back to the North Atlantic, where warming begins again.

Ice Cap Research and the Global Warming Debate

By Charles A. Camillo, Mississippi Valley Division

In July 1966, a Cold Regions Research and Engineering Laboratory (CRREL) team successfully drilled through more than 1,387 meters of hardened and compressed glacial ice to reach the bottom of the Greenland ice sheet. That team, led by Lyle Hansen and composed of Herbert Ueda, John Kalafut, and Donald Garfield, had become the first to



Herbert Ueda, Lyle Hansen, and Donald Garfield.

drill a deep ice core through to the bottom of a polar ice sheet.

Hansen and his crew completed their first drilling accomplishment in a covered subsurface trench at Camp Century – a Cold War facility constructed in 1959 and operated by the Army's Polar Research and Development Center. The camp was actually a network of 21 trenches burrowed some 100 feet beneath the surface and covered with corrugated steel arches. Contained within the tunnels were a few

dozen plywood buildings that served as research labs, dormitories, a mess hall, and even a skating rink and barber shop. While the air temperature within the tunnels was kept at a frigid 20 degrees (F) to prevent the ice walls from melting, the ambiance was much more hospitable than the extremely bitter conditions above, where winter temperatures as low as 70 degrees (F) below zero were accompanied by winds as high as 125 miles per hour.

Drilling through the shifting glacial ice sheet proved a difficult task – one that took six years to complete. After two unsuccessful drilling attempts in 1961 and 1962, the CRREL team started a third bore hole in 1963 and recovered 262 meters of ice core. The next year, the depth was extended to more than 518 meters with the use of a thermal coring drill system. The team recognized that the heating element on the thermal drill, however, would not penetrate bedrock and, in 1965, switched to an electromechanical drill, which accomplished the mission in 1966.

It would be nearly 15 years later before another team drilled a second Greenland ice core. In the meantime, Hansen and his crew set their sights on the opposite end of the globe – Antarctica. In January 1968, a CRREL team drilled to a depth of nearly 2,164 meters at Byrd Station to obtain only the second ice core ever to reach the bottom of a polar ice sheet. Reaching the bottom of the Greenland and the Antarctic ice sheets provided significant engineering research breakthroughs – the Secretary of the Army



Ice core augered from the glacial ice sheet at Camp Century.

recognized Hansen with the prestigious Army Research and Development Award for his deep-core drilling accomplishments.

The fruits of those efforts – the continuous ice cores – contained preserved annual accumulation layers of compressed ice that incorporated a wide range of dust particles, chemicals, trace metals, and air pockets; each providing the first vital clues to the changing climatic history of the planet dating back more than an unprecedented, sequential 100,000 years. Those clues ultimately led to the discovery of numerous past rapid climate changes that challenged the accepted theory that climate changes only occurred gradually over many tens of thousands of years, and provided impetus for future international scientific study programs, originally developed and championed by Chester Langway, a glaciologist working for CRREL.



Interior view of ice tunnel at Camp Century.

During ice ages or warming events, melting ice caps, changing ocean temperatures, and shifting salinity resulted in weakening or reversal of this cycle. Measurements taken by GISP-2 in 1992 confirmed the abrupt climate change theory, as did ocean core samples taken in the Santa Barbara Basin and Arabian Sea in 1995 and 1998.²⁴²

Other climate research concerned understanding the Arctic region, which is often seen as a bellwether of global climate. A number of organizations, including CRREL, NOAA, and leading colleges, had for years independently conducted research on critical areas such as temperature trends, melting sea ice and permafrost, retreat of glaciers, vegetation changes in tundra and boreal forests, and decline of arctic species, all of which had started to indicate global warming after 1980. CRREL widely researched Arctic sea ice cover in collaboration with the Office of Naval Research and the NSF. The largest of these programs was the Surface Heat Budget of the Arctic Ocean (SHEBA), a complex experiment designed to understand the feedback processes that govern ice cover and apply this to climate models. During SHEBA, an icebreaker drifted with sea ice as a floating science platform for 13 months. This gave an interagency team of researchers from CRREL, the Department of Energy, and NASA an opportunity to study atmosphere-ice-ocean interactions over the course of an annual cycle. Don Perovich of CRREL was the experiment's chief scientist. The data collected greatly enhanced the treatment of Arctic sea ice in climate models. SHEBA provided the first comprehensive data of interrelated processes in the Arctic and revolutionized the treatment of sun, ice, and cloud feedbacks in predictive models. By the 1990s, several cooperative initiatives formed to conduct Arctic research, including the Arctic Council, the International Arctic Science Committee, the Arctic Monitoring and Assessment Programme, and the Conservation of Arctic Flora and Fauna. In a 1999 meeting, the latter three proposed a joint international nongovernmental project in 2000, the Arctic Climate Impact Assessment (ACIA). Multinational teams reviewed research, held workshops and committee meetings, and presented a report at a 2004 Iceland symposium – published the following year – that represented the most comprehensive review of Arctic research related to climate change. In 2006, Jackie Richter-Menge of CRREL served as lead author of the NOAA *State of the Arctic* report – a follow-up report to ACIA. It argued that data since 2000 demonstrated continued global warming, but noted there were some indications of return to pre-1990 conditions. It also recommended the expansion of efforts to establish a coordinated Arctic monitoring system.²⁴³

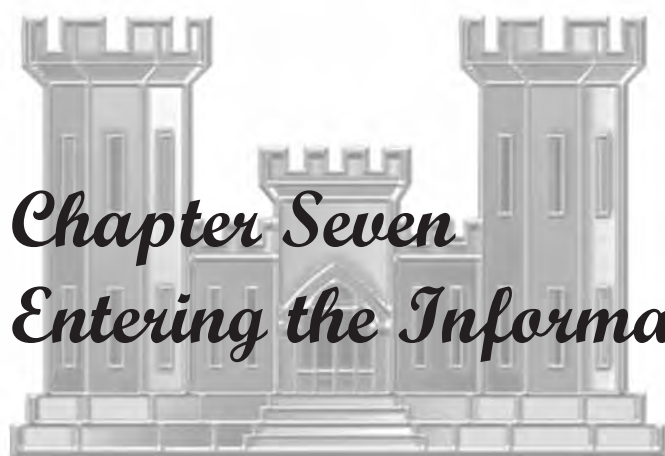
Since 1950, an increasing number of studies have suggested that greenhouse gases resulting from human activities might cause global warming, although it was not until after 1970 that data and projections supported a belief in radical climate change. Rising CO₂ and pollution levels, temperature measurements worldwide, and documentation of glacial, ice cap, and sea ice melting – including the 2000 collapse of Antarctic ice shelves – demonstrated the level of warming. Based on past data, scientists built computer models that suggested not only increase in warming, but a rapid acceleration of these trends as warming released methane and CO₂ frozen in ocean sediment and permafrost and melted more snow and ice, thereby reducing the albedo or reflective nature of the earth's surface. This view, recently popularized by former Vice

President Albert Gore in his Nobel Prize-winning documentary, *An Inconvenient Truth*, has resulted in extensive political debate, often fueled by the large amounts of money involved on both sides of the issue. In 1991, the U.N. first held a panel on climate change, and in 1994, it approved the U.N. Framework Convention on Climate Change, an international treaty to investigate global warming. In 1997, it produced a set of guidelines – known as the Kyoto Protocol because it was signed in Kyoto, Japan – that established caps on carbon-based industrial emissions. The protocol went into effect in 2005 and as of 2009, 184 countries have signed the accords, including the U.S., although the Senate has not ratified the treaty. Others have questioned global warming, its extent, or it being man-made. Even many who support the theory have pointed to issues with some data conflicting with computer models, for example, fewer cirrus clouds and slower warming in recent years than climate models predicted. As climatologist Richard Alley states, “Science wants and needs contrarians to hammer away at the old ideas.” Nevertheless, whether or not manmade global warming becomes universally accepted, Corps ice research has played a major role in revolutionizing scientific understanding of global climate, and the Corps continues to be central in monitoring Arctic conditions.²⁴⁴

At the beginning of the environmental movement, many within that community often viewed the Corps in an adversarial light as a proponent of environmentally destructive construction projects and an ally of big business. In turn, many Corps engineers were suspicious of biologists or environmental scientists and the new projects and methods they supported. Yet, environmental scientists in the movement and in other agencies sympathized with and supported environmental researchers in the Corps, whom they saw as fellow scientists and members of the same communities and societies. While there may have been hostility over some specific projects or issues, over time Corps environmental researchers won over both engineers and fellow scientists by presenting real-world solutions to environmental problems – what Hays called administrative research. In this way, they served as a bridge between the environmental and engineering communities. By increasing a general understanding of the environment through basic research and by clearly defining environmental problems within broad mandates, they vastly improved the Corps’ appreciation of environmental issues and potential resolutions; and by developing and testing acceptable solutions through applied research and agency partnerships, they won the support of the environmental community. Certainly the establishment of a laboratory to research environmental issues demonstrated Corps dedication to meeting new environmental requirements. And although environmental criticism of the Corps continues, environmental researchers in the Corps continue to bridge the gap between lofty environmental goals and engineering reality.²⁴⁵

However, despite the formation of EL, environmental research in the Corps remained decentralized, with CERL, CRREL, and even ETL conducting research into some aspects of civil and military environmental issues. Even with the consolidation of most environmental research at WES in EL, research with environmental implications occurred in multiple laboratories. To a large degree, this was a result of the ever-widening sway of environmental regulation after 1960. Environmental law touched nearly every aspect of Corps missions, so Corps research into ways

to meet these regulations were necessarily broad, making it impractical to house all expertise in a single organization. While EL often served as the lead lab in many environmental research projects, centers of expertise in other labs required continued cooperation on environmental issues. CRREL continued to lead research into civil remote sensing and explosives remediation, while ETL supported analysis of the military environment. CERL gained expertise on ranges and endangered species, while WES continued to research most water resource-related activities of the Corps. Yet even with this decentralization of responsibility, the Corps environmental research program continued to grow. Prior to 1970, the scientific community as a whole lacked an understanding of many ecological issues. As knowledge improved with greater research and data collection, so did the ability of the Corps to quantify problems and devise solutions. The Corps as a whole may have once resisted some proposed environmental restrictions on its operations, but given the level of importance Congress placed on the environment reflecting public concerns, the amount of work – and funding – continued to grow. The Corps fully embraced this once “unexploited opportunity.” With so much of nature still not fully understood, Corps environmental research promises to be a major concern for years to come.



Chapter Seven

Entering the Information Age



An officer at the Engineer Research and Development Center using a battlefield simulation program on a Silicon Graphics computer.

Of the modern changes to the Corps research program, none has proved as broad and far-reaching as the development and application of computers and information systems. Prior to World War II, the difficulties in making multiple complex calculations prevented engineers from achieving exact representation and prediction of many natural processes. Hydrologists needed to calculate volume, velocity, temperature, density, sedimentation, and other factors; marine processes required understanding of salinity, littoral drift, and wave length, height, and period; and soil mechanics required shear, pressure, cohesion, and viscosity; among others. The volume of instrument readings and size of many figures precluded accurate calculations, leading to frequent estimation based on engineering experience, even when there was sound theory. The implementation of computer technology after 1946 started to change this. Although various issues prevented wholesale adoption of computers for many years, gradually engineers began to apply their capabilities to helping solve complex problems – including hydraulics and structural modeling, construction management, photogrammetric and geographic analysis, and many other areas. After 1990, advances in computing allowed assimilation of so many factors at such rapid processing speeds that it suddenly became possible to develop highly realistic computer models capable of closely representing reality. Further, networking personnel working throughout the country enabled near instantaneous collection of data, greater access to information, and closer cooperation on projects, which combined to significantly alter how researchers worked. Because of its vast benefits, information technology became more than a tool to solve complex problems – it became the subject of Corps research.

Development of Computers

“In a sense, computing is as old as mathematics itself,” Stephen G. Nash wrote in 1990. As long as there have been mathematical problems, people have developed tools to solve them. The abacus, which is basically a manual calculator, is thousands of years old, and the Greeks developed an analog device – the Antikythera mechanism – before 100 B.C. for calculating the motions of stars and planets. After Mohammed Ibn Musa Al Khawarismi introduced complex algebraic algorithms in the Middle Ages, mathematicians were often required help to solve scientific or engineering problems. Prior to the advent of electronics, a computer was a person, a clerk who performed mathematical operations. It was in this sense that Andrew Humphreys used a computer to complete calculations for his *Mississippi Delta Report* and early plans for the Waterways Experiment Station (WES) included a computing room. Such clerks handled problems involving hundreds of steps, taking many hours. They used statistical, logarithmic, and trigonometric tables to help make rapid calculations. There were special tables for navigation, astronomy, and artillery published in nautical, farmer’s or other almanacs. In several cases, mathematicians developed machines to speed some tasks. One of the earliest of these was an astronomical calculator developed by Willhelm Schickard sometime after 1592; Blaise Pascal created an adding machine in 1643 for the conversion of money; Gottfried W. Leibnitz invented a machine that could add, subtract, multiply, and divide; and Charles Babbage designed a Difference Engine in 1823 to tabulate complex polynomials for astronomical tables. For the

most part, however, these “hand-crafted curiosities” remained little used, primarily because of their high cost. One of the most popular of the era, built by Charles Xavier Thomas de Colmer, sold a mere 1,500 over 60 years, or fewer than 30 per year.²⁴⁶



Topographic engineers computing control points for a new map using a computing machine. *U.S. Army Engineer School.*

The modern computer developed after 1850 along two different lines. One was creation of machines that could complete large volumes of simple, repetitive mathematical tasks. Industrialization created a need for data processing. The British Bankers Clearing House, created in 1839, was the first to require a large number of clerks expressly for making calculations for the £934 million of business it conducted each year. The Railway Clearing Office in

1842 and the Central Telegraph Office in 1859 also employed thousands of clerks. Soon after, a variety of counting machines evolved to handle the volume of work. In the U.S., E.D. Barbour was the first to receive a patent in 1872 for a recordable adding machine. Frenchman Henry Pottin patented a cash register in 1885. At approximately the same time, John J. Patterson started the National Cash Register (NCR) Company based on the James Ritty cash register. W.S. Burroughs, Leon Bollee, D.E. Felt, Hans Engli, and J.R. Monroe all invented adding machines from 1880 to 1915. The company Burroughs started in 1886 eventually became part of Unisys Corporation, along with Remington Rand, an early typewriter manufacturer. The typewriter, which, as Martin Campbell-Kelly and William Aspray noted, “for many years, historians of information technology neglected” as a “progenitor” of the computer, also evolved from 1850 to 1915. Perhaps the largest counting operation in the nineteenth century was the U.S. census. The 1880 census required 1,495 clerks working full-time for eight years to complete tabulation of the U.S. population. This inspired Herman Hollerith to invent his punch card-based adding machine used in the 1890 census, which, by comparison, required only 80 clerks two- and one-half years. The company he started in 1896 became highly successful after 1911 under the leadership of Thomas Watson and later became part of International Business Machines (IBM) when it formed in 1924. By 1928, IBM, NCR, Burroughs, Remington, and other companies were well-established makers of business machines.²⁴⁷

The second drive for creating the modern computer was the need for calculators for complex scientific problems as opposed to high volumes of simple calculations. Later in life, Charles

Babbage redesigned his Difference Engine to create a programmable Analytical Engine, which he tinkered with until his death in 1871. Although Babbage never completed a prototype, Ada Lovelace actually designed a program to run on this machine, making her, according to some, the first computer programmer. Despite his failure, Babbage inspired other attempts at developing machines capable of computing large numbers, including an electric logarithmic calculator developed by Leonardo Torres Y Querado. After 1912, engineer Vannevar Bush, at General Electric and later at MIT, oversaw the development of several analog computers, including the Differential Analyzer for the Nautical Almanac Office in 1925. In 1930, Wallace Eckert of IBM first connected punch card and accounting machines to create a Difference Tabulator, and from 1935 to 1945 IBM developed 10 different scientific calculators based on Eckert's guidance. In 1936, to help solve differential equations for the Navy, mathematician Howard Aiken, Eckert, and Grace Hopper started development of what would become the Harvard Mark I programmable electro-mechanical computer, which proved the applicability of a fully automated computer. In 1937, George Stibitz of Bell Labs developed an electric binary calculator programmable over telephone lines. The same year, John Astanoff and Clifford Berry at Iowa State University developed the Astanoff-Berry Computer (ABC), the first to use vacuum tubes for switching. With the start of World War II, military demands for greater computing power drove a number of efforts, including several by Bell Labs and IBM primarily for ballistic purposes, as well as efforts to develop a survey computer by the Corps.²⁴⁸

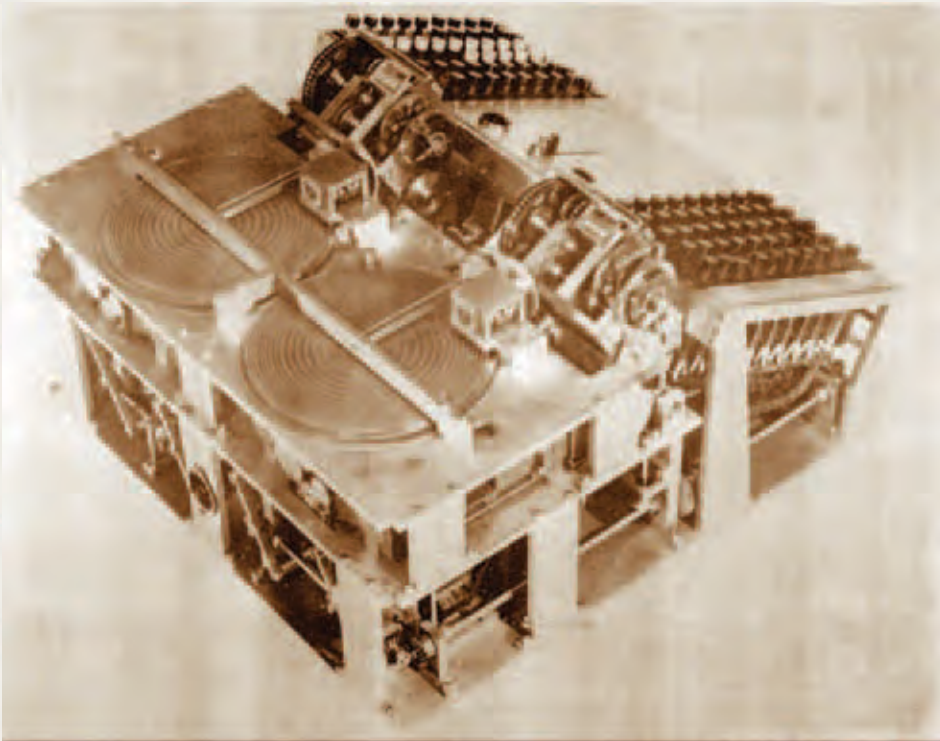
Historians still debate who invented the first computer, with claimants from Babbage to Aiken. Much depends on definitions. Defining computers as digital, fully automated, electronic, and universal (versus analog, partly manual, electro-mechanical, or limited function), most historians agree ENIAC was the first. The Ballistics Research Laboratory, Maryland, contracted John Mauchly of the University of Pennsylvania to build a machine to calculate firing solutions. Inspired by the ABC, Mauchly, J. Presper Eckert, and Capt. Herman H. Goldstine developed an electronic decimal computer that used tubes to store signals, providing speeds hundreds of times faster than mechanical computers but far less expensive. Goldstine later stated, "The entire economy of computing changed overnight." Even before delivery of ENIAC in 1946, Eckert and Mauchly started development of a much more efficient system, EDVAC. Among improvements were fewer tubes and failures, a mercury delay line for greater data storage, punch card programming instead of switches and cables, binary counting, and the von Neumann or stored-program architecture. The latter was particularly important for future computer design. Essentially, it temporarily stores instructions along with data instead of reprogramming the computer each step, which is faster and repeatable while reducing program size and allowing modification while running. Although attributed to mathematician John von Neumann, whom Goldstine brought in as a contractor after meeting him on a train and who distributed a report explaining the idea, the architecture likely evolved from ideas developed by the entire team based on concepts proposed in 1937 by Allen Turing. Because of a patent dispute, in 1946, Eckert and Mauchly launched their own company, EMCC, which won several contracts for its UNIVAC computer before Remington Rand bought it out in 1949. The use of UNIVAC on CBS to accurately predict the 1952 election results helped popularize computers as "electronic brains."²⁴⁹

The Mechanical Survey Computer

In 1946, John Mauchly and Presper Eckert delivered ENIAC – the first fully automated, completely electronic computer in the U.S. – to the Army Ordnance Department for calculating range tables. In late 1943, Howard Aiken conducted the first tests of the Harvard Mark I electromechanical computer for the U.S. Navy. Only a few months earlier, the Corps of Engineers tested its own electro-mechanical computer for calculating survey distances and angles – one of the earliest prototype computers.

The concept originated in 1940 with Capt. Louis J. Rumaggi of the 30th Engineers, who wanted to speed reduction of survey data. In September 1940, the Engineer Board let a contract with W.L. Maxson Corporation of New York to develop the computer with an accuracy of 1:30,000. Overseeing the project was Maj. William C. Cude. In April 1943, Maxson produced a prototype with electrical solenoids, spiral cams, and a series of wheels and levers similar to cosine computers then in use. It could calculate latitudes and departures after users input range and azimuth data on two small keyboards. However, it did not meet the accuracy requirements, it jammed frequently, and it was too noisy for field use. With the contractor unable to correct the deficiencies within a reasonable time, the contract was cancelled in January 1944, but the board believed it a “considerable step forward.”

Development of a survey computer did not resume for several years, after which the board pursued several lines of research. In another contract to develop a mechanical computer, the University of Chattanooga, Tennessee, Industrial Research Institute delivered a model in December 1951 that met requirements for a lightweight, hand-operated



Pilot model of the W.L. Maxon computer. *U.S. Army Engineer School.*

model suitable for field use. This model likewise encountered mechanical problems, and the contract's cancellation ended Corps attempts to develop a mechanical computer. In 1946, the board also initiated a contract with IBM to develop an electronic survey computer. The resulting model, delivered in 1949, was a large desk cabinet with a functional but electronically controllable typewriter as the input/output device. After users input the azimuth and distance, the system calculated 11 other figures within 10 seconds and printed the results on a worksheet. Field tests of the device through 1951 demonstrated its lack of versatility and portability, resulting in revised requirements.

Finally, in February 1952, the Engineer Research and Development Laboratories (ERDL) contracted Monroe Calculating Machine Company to develop a test computer under new requirements, which it delivered in 1955. This model proved successful enough that the Army Map Service requested transfer of the proto-type for its use in 1957. ERDL had initiated another contract, but by this time, the Army assigned electronic data processing and computer development to the Signal Corps. ERDL transferred its contract with AVCO Manufacturing Corporation to the Air Force, which continued development of the survey computer through the end of the contract in 1959. With the development of versatile commercial computers by versatile IBM, UNIVAC, and other commercial computers, there was no longer need to develop separate systems, although the dream of hand-held survey computers did not see fulfillment for many years.



COMPUTER, SURVEY, ELECTRIC
GROUND CONTROL BRANCH, TECHNICAL DEPARTMENT V.
ENGINEER RESEARCH AND DEVELOPMENT LABORATORIES, FT. BELVOIR, VIRGINIA
PROJECT NO. AF 799 MANUFACTURER: IBM
PHOTO NO. 180-2-267 TYPE OF EQUIPMENT: Experimental
DATE: Jul 47 WEIGHT: Estimate: 550-600 lb
MISCELLANEOUS: Electro-mechanical computer, housed in a small desk which is 40 inches long, 20 inches wide, and 30 inches high. The electric typewriter is connected to the computer by cable only. The computer also houses 110-volt AC motor which supplies power for a 40-volt DC generator which operates the computer.

Electric survey computer. U.S. Army Engineer School.

Even in the first decade, computers displayed their most enduring characteristic – rapid obsolescence – typified in Moore’s Law, the 1965 prediction that processor speeds would double every two years. Vacuum tubes gave way to cheaper electrostatic tubes and, after Bell Labs developed integrated circuits in 1947, transistors or semiconductors. These microchips were highly efficient, replacing dozens of tubes each. The first computer to use transistors was the 1950 SEAC, but only after manufacturers started using silicon as the base conductor in 1957 did chips become more reliable. Later, circuit boards such as those Fairchild first mass-produced in 1959, replaced hundreds of tubes. As speeds increased, buffers and input/output interrupts allowed management of data flow. The character size computers could handle per second grew to 30 or 40 by the mid-1950s; not until the IBM 350 did most companies standardize on a 64-bit architecture or processing data in eight bytes of eight binary bits (on/off) each. In 1953, IBM introduced the first modular computer, and UNIVAC first included printers. After the 1957 IBM 7090, computers came in large cases – a mainframe. Data storage evolved to include magnetic drums in 1949, tape in 1950, and disk drives in 1956, although some IBM models continued using punch cards. EDVAC and others used oscilloscopes, but most computers did not include displays – there was no need since results were merely lines of numbers output after processing. The exception was a system developed by MIT in 1951 to provide near real-time computing capabilities for the SAGE missile program by allowing users to see readings from automated ground controls. Such capabilities eventually led to development of minicomputers. CDC developed a small system in 1960 to allow input to a mainframe, and by 1965 DEC released the PDP-8, the most successful minicomputer at the time. In 1973 and 1974, Altair and IBM released the first U.S. microcomputers. By 1965, IBM was growing 15 percent a year; UNIVAC-maker Sperry Corporation owned 12 percent of the market but was barely breaking even; and a third-tier of smaller dealers, including GE, Honeywell, CDC, and RCA, were competing in specific market niches.²⁵⁰

Adopting and Adapting Computers

Even as electronic computing evolved, the Corps was involved with technology development in varying degrees. Before ENIAC, the Corps experimented with numerous electronic devices to automate measurement of everything from water velocity to soil cohesion, including survey equipment such as theodolites, altimeters, and automated rangefinders. It already made wide use of analog computers, primarily in the form of physical models. Analog computers use analogies or physical examples to fill in gaps in theoretical knowledge when precise numbers are unavailable and include everything from slide rules or rulers to astronomical calculators that use wheels to represent planetary motions. Early Corps surveyors invented analog devices such as orreries, and the Corps developed the first national hydraulics laboratory using river models in 1929. By the early twentieth century, most engineers accepted the need for supplementing theoretical calculations with measurements taken in analog devices such as hydraulic models, wind tunnels, and power grid models. In general, computer pioneers saw electronic devices as a way of aiding not replacing these calculations. Von Neumann, for example, argued for using computers to help solve complex problems for long-term meteorological predictions and hydrodynamics. As

Goldstine recalled, “His ‘object all sublime’ was to replace experimentation by computation in so far as possible where the equations for a problem could be unambiguously formulated.” In fact, some believed computers were useful mainly in solving difficult mathematical problems and suggested, as Howard Aiken did, that only a small number would be necessary to meet U.S. computing needs. In 1947, when Harvard held a symposium on mathematical computing, organizers were surprised when double the 300 planned attendees showed up. When it held another in 1949, attendance exceeded 900. The Army participated in both symposia, but focused mostly on ballistics and development of ENIAC.²⁵¹

There were many reasons for doubts about widespread computer use and for delays in their application. At first, technology problems made computers too unreliable and costly for scientists to use other than occasionally. A good example was frequently blowing tubes. ENIAC used some 17,000 tubes, requiring constant vigilance to keep them operational. Later models, such as the EDVAC, UNIVAC, and Mark IV, tried to minimize tubes or allow easier maintenance. Since most blew during start-up, it became standard operating procedure to run computers constantly with a long line of problems to solve. Another issue was programming. Early programs were hand-written and full of errors such as infinite loops, although stored programs helped reduce some difficulties. There were also limitations imposed by character length. Early models allowed only eight to 10 decimal numbers or 32 binary digits, which greatly constrained the ability to compute large numbers, while the complexity of programming made multiple step calculations equally problematic. Character lengths increased rapidly, but remained prohibitive for many years. Computers revealed a further difficulty with algebraic problems – rounding errors. Since computers round up to available characters, most solutions were slightly off, which became particularly noticeable when accumulated after lengthy algorithms or matrices. Although Von Neumann and others identified rounding errors in linear algebraic formulas as early as 1946, mathematician James H. Wilkinson publicized the issue in his 1963 *Rounding Errors in Algebraic Processes* and proposed a solution of iterative refinement. Problems such as random number generation, free boundary calculation, wave resistance, and difference approximations – all issues faced in hydraulics and other rapidly changing mathematical environments – were subjects of computer experiments from 1946 to 1960 and improved in accuracy as system capabilities increased. Yet it was the human element that most often prevented technology adoption. Those who managed research programs at the Waterways Experiment Station (WES) and other institutions, as well as those who managed the computer systems, sometimes doubted the applicability of computers or feared their impact on existing programs or funding.²⁵²

Although most Corps offices were using various adding machines by the early 1950s, the Ohio River Division was perhaps the first to implement an electronic computer. As early as 1952, Chief of Hydraulics Bruce Gilcrest and others examined the possibility of collecting gage readings automatically by radio and using a computer to analyze trends. The division consulted with the University of Cincinnati, New York University (NYU), and IBM on potential processes and systems. Particularly influential was the work of J.J. Stoker of NYU, who developed differential equations of flow in open channels and wave progression to supplement flood routing approximations developed by Gilcrest. Although Stoker noted that calculating flooding

was possible by “hand computation” and was “well within the capacity of modern calculating equipment,” with very long rivers or at junctions, he used UNIVAC computers to make calculations and built a numerical model of the Ohio River. Based on the results of these studies, the division purchased an electronic analog computer, the Goodyear Electronic Differential Analyzer, in 1955. WES first discussed obtaining a computer in 1954 to conduct similar flood routing computations for the Mississippi Basin Model (MBM). Even with automated controls, this model was extremely labor-intensive, making it time-consuming and costly. OCE recommended computers to solve “analytical problems that might otherwise be too laborious on account of the volume of computations” but doubted that “electronic computers as such will ever be an alternate or substitute for hydraulic models except in special cases.” With no experience with computing, WES discussed the issue with hydraulics consultant Arthur T. Ippen of MIT, who opined, “I fail to see how an electronic computer can be set to do the same and how it can reproduce a correctly integrated history of many such interactions.” It would be more than a decade before WES finally developed a computer program for analyzing the river in conjunction with the MBM.²⁵³

Nevertheless, WES proceeded with implementing its first computer in 1957. When WES leaders learned an IBM-650 would become available for rent (IBM preferred to rent early computers rather than sell them), they assigned C.B. Patterson of the Technical Services Division to



Donald Neumann and the IBM-650.

plan and install facilities and recruit personnel, with a goal of 50 percent utilization during the primary shift by the end of the fiscal year. Although it used decimal instead of binary arithmetic, the 1952 IBM-650 was one of the company's most popular models because of its low cost and modularity. After Patterson recruited several operators, programmers, and an operational chief, Donald L. Neumann of the St. Louis District, and quickly assembled the system in the WES administrative building, he launched the first computer center in Mississippi. The system was essentially a 24-hour calculator at the disposal of the entire station, although it was mainly used for bookkeeping. Engineers had very little interaction with the system; in the same way they may have previously left stacks of figures for clerks to tally, they left problems with operators, who input them, reprogrammed the machine as necessary, and output results for later pickup. IBM replaced the 650 after a fire destroyed the Computer Center in 1960, but WES outgrew the system by 1962 and updated it with a GE-225 that was 10 times faster. At that time, the center installed its first plotter. Four years later, the center installed tape drives and floating-point hardware in 1967. In 1968, it upgraded to a GE-440 and in 1973 purchased a Honeywell G-635. By this time, the center staff grew to 24 working seven days a week, 23 hours per day. At the end of 1969, the computer center was processing 1,600 requests per day, including dozens of remote batch programs on late shift per day through time-sharing. About 40 percent of computer

usage was for basic research such as explosive blast data collected from analog sensors and converted to digital tape. During the same period, the Beach Erosion Board, while it contracted use of computers for some reports, had no dedicated staff or computer center. Not until after 1965 did the Coastal Engineering Research Center (CERC) start to widely use computers, primarily to analyze data from wave gage stations and to model sand movement from measurements taken of



Honeywell G-635.

radioactive sand particles in the 1967 Radioisotopic Sand Tracer Program. The CERC facilities in the Kingman Building built at Fort Belvoir, Virginia, after 1968 included a data processing center.²⁵⁴

The other Corps labs also started to implement computers during this time. Although the Engineer Research and Development Laboratories (ERDL) oversaw development of several specialized electronic computers, including the first satisfactory test of a survey computer in

The Waterways Fire of 1960

In the early morning hours of Monday, October 3, 1960, William Bache pounded on the window of the home of Col. Edmund H. Lang, director of the Waterways Experiment Station (WES), to tell him of a fire at the headquarters building. As Lang rushed to the scene, the sky glowed red. Although fireguard Roy B. Jones had already called the Vicksburg, Mississippi, Fire Department, which was fighting the blaze, the fire had destroyed the roof when Lang arrived and consumed the building as he watched with a feeling of helplessness.

The loss was tremendous. Altogether, the fire destroyed some \$1.7 million in equipment and facilities, including printing presses and drafting equipment from the Print Shop and Drafting Room, cameras and darkroom equipment from the Photographic Laboratory, the cafeteria, dozens of offices and unclassified records (classified records being kept in fire-proof containers), and the new IBM-650 computer system in the Computer Center that WES installed in 1957, valued at \$400,000. In addition, the fire destroyed what had previously been one of the finest technical libraries in the Southeast, including many irreplaceable volumes as well as a 275,000-card reference system, the result of 15 years of labor, without which the remaining volumes were practically useless.



WES librarians salvaging materials after the fire.

Before firefighters extinguished the blaze, Lang formed three committees. The first was a five-member Board of Investigation, which determined before the fire was out that, although the exact cause was not determinable and no faulty workmanship was found, it was most likely electrical in nature. A second committee began immediately to locate space for employees and plan for continuation of operations. Within two days, all 140 displaced employees were back at work. Most moved to available office space or empty buildings at WES. The Library, Photo Lab, Print Shop, and Reports and Drafting Section moved temporarily to the Vicksburg National Military Park.

The library later moved to an old residential home on WES property in front of the present administrative building. Librarians Alan G. Skelton and Marie Spivey set to work restoring and re-indexing the collection. Although some 75,000 volumes were gone, another 10,000 had been on loan across 40 states. When it became known that WES lost its entire collection, engineering libraries worldwide sent material to WES, including Delft University Library in the Netherlands. The Office of the Chief of Engineers provided more than \$300,000 to make new purchases and hire extra help, and by 1964, the library had obtained 120,000 volumes. As Irene Cook remembered, "Only those of us who were involved in rebuilding the library collection will ever know how hard Marie and Alan and their original staff worked to rebuild a fine collection."

After arranging with IBM to get replacement parts for the 650 system it was renting, the Computer Center relocated on October 5 to the basement of the Peeples-Newman Building in downtown Vicksburg, occupied at the time by the Soils Division. Through the hard work of Donald L. Neumann and others, the center was operational by October 13, a record 10 days after the fire. IBM also provided 100 replacement typewriters and other equipment from across the country.

The third committee formed by Lang began planning for a new headquarters building under the leadership of Joseph Tiffany. After estimating spaces and planning a location, the team let a design contract on December 15, 1960, and awarded the construction contract on October 25, 1961. The administrative staff occupied the new WES headquarters building in June 1963.



Librarians examining damaged materials.

1955 and a computer to support the Automatic Position Survey Equipment in 1959, there is little record of experiments with universal commercial computers until after 1956. Over several years, it directed development of programs to run on computers used by the lab – an IBM-650 in 1958, an IBM-704 in 1960, and an IBM-7090 after 1962. However, the small capacity of these business machines greatly limited their use for these high-demand computing purposes, and the lab soon turned to more powerful systems. In 1968, the Engineer Topographic Laboratories (ETL) established the Computer Sciences Laboratory, which included an Applications Division to support the center and an Advanced Technology Division that pursued solutions to various analytical topographical problems. It primarily used a UNIVAC 1108 to support the computing needs of the entire center, but several branches adopted other models for specific projects, such as Research Institute implementation of DEC PDP-8 minicomputers or use of a CDC 6400 in the Digital Image Analysis Laboratory. In 1976, ETL acquired a Goodyear STARAN associative array processor, a dual-processor computer designed for NASA, which, used with the CDC as input-output device, provided ETL a supercomputer capability needed for digital imagery management.²⁵⁵

Neither the Snow, Ice, and Permafrost Research Establishment (SIPRE) nor initially the Cold Regions Research and Engineering Laboratory (CRREL) had a specific computer organization. However, when CRREL occupied its new headquarters in Hanover, New Hampshire, in 1960, it installed a Bendix G-15 computer with a paper tape-punch and reader in the Engineering and Measurement Services Branch of the Technical Services Division. Originally developed for the Polaris missile system in the late 1950s, this system was reliable but of fairly limited capacity with no off-line storage, making it good for helping with short analytical problems or bookkeeping, but not much else. Because it understood only machine language, it was difficult to program and use. In 1965, CRREL installed a Computer Control Company (later Honeywell) DDP-24 computer with a FORTRAN compiler and tape-punch. Again, because of its small capacity, CRREL mainly used it to solve analytical problems with very limited attempts at complex modeling. For the most part, more complicated problems required use of high-end computers at Dartmouth College or elsewhere. However, several CRREL divisions started to invest in other computers for specific projects. By 1971, the Chemistry Laboratory had installed a DEC PDP-12 minicomputer interfaced to a mass spectrometer used to identify particles in ice cores; one team purchased a PDP-8A to develop a more efficient mortar base plate. Not until 1978 did CRREL purchase a real-time system with capabilities comparable to a mainframe, the Massachusetts-based PRIME 400 minicomputer, which included two tape drives, a disk drive, four graphical displays, and terminals set up in offices throughout the lab. It upgraded to a Prime 9750 in 1980, which provided 48 remote terminals. Users could, however, use Dartmouth's GE-635 computer for more extensive modeling applications. In 1975, CRREL contracted Dartmouth to provide remote access using a Harris Cope 1200 terminal.²⁵⁶

The Construction Engineering Research Laboratory (CERL), however, found the University of Illinois computer center inconvenient for daily use. The Ohio River Division Laboratories used a Harris terminal to process and store digital test data, but it remained at the division when CERL formed. Instead, CERL installed a CDC 100 terminal for accessing remote computer

systems – primarily at the Naval Ship Research and Development Center in Carderock, Maryland. Because of problems with high telephone charges while using this system, CERL Director Col. Edwin S. Townsley established the Computer Services Office in late 1971 under the management of Wayne Schmidt to operate the system, encourage increased computer use, and aid users in developing programs to run on the system. By the end of 1974, the Computer Services Center became a branch in the Information Services Center, which provided library and other information services. By that point, about 30 percent of employees were computer literate. Essentially, users would compile punch cards, which the office would feed into the terminal. In 1973, it added a teletype machine to improve user input, one of the first in the Corps. In 1979, CERL installed its first minicomputer, a Harris 120 Computer, later upgraded to a Harris 400 and PDP 11/45. These were the first modern computers at CERL capable of interactive input/output using distributed Hazeltine or Sytech terminals that allowed users to type in and see input from their desks and make corrections. With the introduction of IBM XT microcomputers in the early 1980s, the center began to focus more on IT management than software support, and many employees, including Schmidt, moved into larger software research and development roles.²⁵⁷

One step that enabled the labs initially to increase computer use was accessing remote computers through time-sharing. As already noted, most computer owners sought saturation of computing time to reduce the cost of 24-hour operation, and time-sharing allowed remote users to buy time on high-end computers ordinarily not available to them. Since the majority of calculations on such systems were routine and could be run without interference, they were ideal for nighttime use. MIT first introduced the concept of time-sharing in 1961, and by 1963 GE and Bell Labs made large banks of computers available through online transaction processing terminals. Most terminals used often inefficient commercial analog telephone lines, but in well-established routes, companies or agencies often developed more robust networks to handle computer traffic. By 1968, WES started to time-share more powerful systems at the Environmental Sciences Services Administration Research Laboratories, Colorado, and the NASA Stennis Space Center, Mississippi, or else researchers traveled to and used systems at the Redstone Arsenal, Alabama, the Los Alamos National Laboratory, New Mexico, or other locations. In January 1968, it installed a terminal for the UNIVAC 1108 in Mississippi, and added four teletype terminals and leased phone lines for a GE-265 computer in Washington, D.C. By the end of 1969, it had networked its GE-420 with GE-115 and GE-225 systems in the Lower Mississippi Valley Division – as well as GE-635 in Maryland and Arizona – and allowed access to its computer from 30 terminals Corps-wide. In 1972, WES installed a high-speed multiplexed network – later termed WESNET – accessible to more than 130 data centers nationwide. “The time saved alone has enabled the GE-420 time-sharing system to pay for itself,” Neumann observed at the time. CERL, as already stated, used time-sharing on remote systems from its foundation, and soon after had networked the entire office complex. In 1979, it had nine remote terminals accessing computers at the University of Illinois; the Lawrence Berkeley Laboratory, California; Boeing Computer Services in Seattle, Washington; and Tymshare at

Valley Forge, Pennsylvania. CRREL started time-sharing mainly with Dartmouth only in 1975 and did not network its offices until after 1980.²⁵⁸

Numerical Modeling to Visualization

For the most part, prior to 1965 WES and the other labs applied computers primarily to solving specific analytical problems or equations reduced from observation, experiments, or physical models, such as soil shear, impulse loads, flood routing, flow around curves, sedimentation, or ocean fall. However, this approach proved less useful as the problem complexity increased. What largely drove the development of more extensive computer applications were the use of more powerful computers only then becoming available and the adoption of the finite element method (FEM) and other mathematical approaches to conduct large-scale analyses of complex problems that often required the aid of these computers. As noted earlier, FEM breaks heterogeneous materials into homogeneous elements or subsystems for easier analysis. In early 2-D problems, this consisted of nodal points on the surface of a continuous plane, such as water or a structure, broken into a grid. In essence, FEM solves approximate equations with an exact solution, in contrast with the finite difference method, from which FEM evolved, which solves exact equations with an approximate difference. For example, finite difference replaces calculus derivatives of distance in governing equations with a difference in water level divided by the distance over which that difference occurs; FEM substitutes a simple algebraic equation for water level variation over the distance and solves the calculus derivative exactly. FEM originated in 1943 as a mathematical method and only later spread to engineering. Because it allowed numerical representation of a space, engineers could model entire schemas or data structures rather than merely solve individual problems, although large computations were still required. Early computer pioneers saw hydraulics as a leading candidate for FEM analysis. With improvements in computers after 1950, their use to perform numerical studies soon grew to include jets, wakes, cavities, planes, wave resistance, artificial viscosity, and density. At the same time, fields such as aerodynamics and nuclear power were also applying numerical methods. By 1955 there were eight large conferences on various numerical analysis topics, and by 1963, the Society for Industrial and Applied Mathematics started publication of *Journal of Numerical Analysis*.²⁵⁹

Ray W. Clough of the University of California, who coined the term FEM, first applied it to civil engineering with the analysis of the Norfolk Dam for the Little Rock District in 1960. The first WES project to incorporate numerical analysis was the 1964 Narragansett Bay, Massachusetts, Hurricane Protection Study. WES provided tidal data from a physical model to the New England District, which then adjusted these numbers using numerical wind analysis to achieve an accurate model without the cost of WES building a physical wind generator. In 1965, WES hired a consultant to consider ways to apply FEM to its projects and in 1966 it adopted programs developed at the University of California at Berkeley and arranged classes attended by engineers from WES and the Nuclear Cratering Group. In 1967, WES started applying FEM to analysis of crater slopes and through the leadership of G.W. Clough for analysis of the Port Allen and Old River lock projects in 1969 and 1972. Although it examined uses of the method for hydraulics issues such as heat transfer, fluid flow, and seepage, it mostly left computation to

others. In a 1968 study of hurricane protection in Galveston Bay, Texas, WES again developed a physical model, which Galveston District's contractor, numerical modeling pioneer Robert O. Reid, used to develop a computer model of wind and surge. Using FEM techniques, the model calculated water height, shear stress of wind on the water surface, and friction loss to predict water surface elevations, which the district corrected using WES data and actual observations. However, it was a lengthy and costly process, taking up to 13 hours for the district computer to complete the calculations.²⁶⁰

By 1968, several young WES engineers began to push to increase numerical modeling, which Hydraulics Division Chief Henry B. Simmons accepted despite reservations. Marden "Burton" Boyd had been an employee since 1956 and was one of the earliest users of computers to calculate lock fill characteristics. On receiving his master's degree in mathematics in 1967, he prompted Simmons to initiate a program to encourage computer use and educate employees. Boyd reviewed literature for computer methods that WES could adopt, organized or taught classes, and assisted others in using computers to solve problems. Recently assigned Capt. John W. Harrison and Boyd started development of programs to analyze tsunamis and canal wave characteristics under the guidance of Garbis Keulegan. When WES discussed the growing issue of computers with consultants in 1968, Ippen now advised,

The importance of building up a staff competent in computer applications should be emphasized. New staff members should be trained in programming and problem-solving by computers. Contacts between technical staff and the computer branch as well as ease of access to the computer should be encouraged.

WES needed no other encouragement. Later that year, Simmons established the Mathematical Hydraulics Group (MHG), including Boyd, Harrison, Lt. John F. Abel, Larry L. Daggett, and Keulegan to provide supervision. Although Keulegan never used a computer (preferring the large slide rule he always carried with him), he nevertheless recognized the utility, low cost, fast development, and easy adaptability of numerical models. Over the next several years, MHG hired or obtained the transfer of other computer experts and pioneers, including Billy H. Johnson, Carl J. Huval, and William A. "Tony" Thomas of the Hydrologic Engineering Center (HEC), California. Meanwhile, Estuaries Branch Chief Frank A. Herrmann hired William H. McNally and other computer modelers.²⁶¹

The MHG soon developed a number of models. In 1968, the MBM Board approved several models to supplement and eventually replace the MBM. WES developed and verified models for the Mississippi River Commission and Missouri River Division by early 1973. In 1969, Boyd started to adapt the Simulated Open Channel Hydraulics (SOCH) program developed by the Tennessee Valley Authority from the work of Stoker on explicit finite difference. He and Johnson created a new application to calculate unsteady flow that included junctions (SOCHJ) on the Ohio, Cumberland, and Tennessee rivers. In 1969, OCE authorized the MHG to develop a numerical model of unsteady flow in the Chesapeake-Delaware Canal as part of the Chesapeake Bay Model. Estuary or harbor modeling was another area where the MHG and the Estuary Branch became particularly active. Because of previous problems with building physical

Hybrid Models – Simulating 3-D

The Columbia River Basin had been one of the most difficult to model in the history of the Waterways Experiment Station (WES). Since 1961, both the University of California at Berkeley and WES had built large-scale physical models of it, but were unable to accurately model shoaling. In 1976, the Portland District asked WES to develop a numerical model. Instead, WES proposed developing the first integrated hybrid physical and numerical model.



William H. McAnally.

William H. McAnally had only recently returned from graduate school at the University of Florida, where, under the tutelage of Emmanuel Partheniades, he had completed his thesis on hybrid models. After pitching the idea to Hydraulics Division leaders, he, Joe V. Letter, and William A. “Tony” Thomas developed a proposal for building a hybrid model for the Columbia River to help solve sedimentation problems, which Portland District accepted.

The concept of hybrid models was not completely new. Engineers had used numerical models since their origins in the 1950s to supplement physical models, for example, to calculate wind or other problems too difficult or costly to simulate in scale models. However, they typically developed numerical models separately, applying them to data from physical models later. With the Columbia River Hybrid Model, McAnally proposed a model that tightly integrated them, “combining them in a closely coupled fashion that permits feedback between the models.”

The model included the RMA-2V numerical model with more than 1,000 data points, a wave dynamics model previously developed by Donald T. Resio and C. Linwood Vincent at WES, the STUDH sedimentation model based on University of California-developed SEDIMENT II, and the RMA-1 utility code to generate an integrated model with digitized bathymetric data from the 1976 National Ocean Survey. WES designed a specialized data management system for the project and utilities to output final numbers.

Nevertheless, the project report explained, “The keystone of the Columbia hybrid model studies was the Corps’ existing physical hydraulic model,” which resolved 3-D problems the numerical model could not. WES developed it in 1961 and had to update contours to reflect recent surveys. Various electronic sensors on the physical model mapped precisely to data points on the numerical model, and the Automated Data Acquisition and Control System developed for earlier models helped capture model data in digital format. Eighteen utility codes processed the data between the models.

For each problem, operators defined the time period, tidal range, salinity, sedimentation, and wave data based on Navy Fleet Numerical Weather Center hindcasts or surveys, all stored in data files. After setting the initial conditions, they would begin discharge

in the physical model and capture data, which fed into RMA-2V along with wave data. Once processed, the data fed into STUDH for calculation of final data, which operators could then display in graphical or tabular formats. Verification proved that the model produced accurate shoaling predictions other than at the outer bar.

Although WES applied hybrid modeling techniques on later projects such as the Red River Model, which also had severe sedimentation problems, within years, other than a handful of exceptions, engineers no longer used physical models. As McAnally and others always argued, hybrid modeling was a transitional approach, useful because “the inadequacies of 3-D computational models require that physical models be used for such studies.” By 1990, 3-D numerical models could reproduce complicated processes previously possible only by combining physical and numerical models. The era of physical models was coming to an end; the era of computer models was starting to arrive.



Columbia River Estuary model.



Mathematical Hydraulics Group. From left to right: Lt. John Abel, Larry Daggett, Marden Boyd, Garbis Keulegan (seated), John Harrison, and Carl Huval.

models of estuaries, numerical analyses held great potential. In 1969, Huval began examination of more than 17 existing models, while Abel investigated harbor oscillations and open-sea boundary conditions. Soon, applied research followed these experimental programs, such as calculation of wind-driven tides in Kaneohe Bay, Hawaii, and harbor oscillations in San Pedro Bay, California, for which McAnally and Donald C. Raney and James R. Houston of the Wave Dynamics Branch modified programs developed by others. MHG projects included prediction of oil slick behavior, determining the effect of viscosity and surface tension on vortices, an analysis of ship-transit capabilities of sea-level canals, watershed runoff and stream geometry based on models developed at various universities, inland waterway simulation to determine navigational requirements for the Illinois Waterway, and a study of tidal equalization in Gastineau Canal, Alaska. By 1975, many at WES were widely using numerical models, including Robert W. Whalin, Donald T. Resio, and C. Linwood Vincent of the Wave Dynamics Branch and Harrison, who became the first civilian chief of the Mathematical Hydraulics Branch in 1971 and later headed the Environmental Laboratory.²⁶²

Although some consultants advised caution on quickly abandoning physical models, Keulegan and others believed numerical models would soon replace them. However, while it was a long-term goal for WES to develop 3-D models, it would take several years. In the interim, WES digitized data captured in physical models. In 1971, Daggett started development of the

Automated Data Acquisition and Control System (ADACS) for the New York Harbor Model. The heart of the system was an EAI-640/693 computer that accepted analog input signals and sent constant signals to maintain or change water levels. Automated sensors for water levels, velocity, salinity, and temperature fed into the computer for storage on magnetic drums. The first project to use ADACS was the Los Angeles-Long Beach (San Pedro Bay) Model then starting development. This received input from 50 wave sensors, which WES analyzed against digital readings taken from the bay. Also adapted for the model were programs developed by Los Angeles District to analyze ship movement and loss of moorings due to wave action. These were the first attempts to integrate digital results from physical and numerical models. This led after 1976 to integrating the models themselves into an interactive hybrid model, a concept developed by McAnally and others for use in the Columbia River Model to simulate a 3-D environment. At the same time, WES developed high-end graphics to allow visualization of these models. By 1974, WES had installed two ADDS/900 and a Tecktronics 4012 display, and by 1977 it started participating in Corps-wide efforts to develop more robust graphical applications to support modeling. Almost immediately, engineers used these systems to display 2-D and 3-D models. As computer and display performance increased, users could animate applications screen-by-screen, eventually achieving speeds similar to film (30 frames per second), and even program visualizations to respond to commands. The first interactive visualization at WES was the 1983 Ship/Tow Simulator – complete with a mock foredeck and wheelhouse – developed by Huval and Daggett based on earlier work for the Maritime Administration. WES used it over the next decade in more than 50 navigational studies at San Juan Harbor, Miami Harbor, Sacramento Deep Water Ship Channel, and elsewhere. In 1985, the multi-agency Chesapeake Bay Program requested a 3-D model of the bay, which WES and its contractors completed from 1987 to 1991 based on the 1986 work of Y. Peter Sheng at the University of Florida. The same year, WES started development of TABS-3, a general use 3-D modeling program.²⁶³

Even as the Hydraulics Laboratory pushed into the forefront of modeling, other organizations expanded the borders of computing. By 1971, Corps districts and divisions had developed hundreds of applications for various purposes meeting the needs of specific problems. Under the leadership of Roy Beard, HEC had been a leading proponent of computers since its inception in 1964 and developed computer models for watershed, river, and reservoir analysis. While CERC entered somewhat later than WES into the numerical modeling business, having used computers mostly for collection, collation, and analysis of observational data, by the mid-1970s the Oceanography Branch of CERC had turned to various models to determine anomalies from mean sea level due to tides and storms to calculate hurricane surge, issues for which physical models had achieved unsatisfactory results because of the inability to model wind. One of the problems it helped to solve was interaction between coastal and inland waters. Building on a flood insurance model built by Tetra Tech of California, which first allowed coastal flooding by removing the programming barrier between land and sea, CERC developed the first model to predict the effects of flooding in an in-shore region on local rivers. By 1976, it had incorporated data from the National Oceanic and Atmospheric Administration (NOAA) SPLASH II model into this in-shore model. At the request of OCE, CERC and WES conducted analyses

of various hurricane surge models, including SPLASH, Tetra Tech, CERC's SURGE models, and the WES Implicit Flooding Model, but due to weak meteorological modeling, these did not agree with each other or with actual observations taken from hurricanes. Problems with developing accurate hurricane models continued for many years.²⁶⁴

CRREL also gradually become involved in numerical studies. As with CERC and WES, its initial use of computers involved collection and correlation of data such as temperature readings, engineering calculations, or hydrological and geotechnical modeling. One novel area requiring extensive modeling was the behavior of ice, which involved complex geometry, wind, currents, thickness, thermodynamics, and related factors. The first comprehensive ice modeling occurred as a result of the Arctic Ice Dynamics Joint Experiment (AIDJEX), in which team members from the U.S., Canada, and Japan analyzed data from an array of drift stations and other experiments traveling through the Arctic Ocean from 1970 to 1978. Some modeling of the mechanical behavior of sea ice had occurred earlier, but with no direct experiments in the Arctic since the International Geophysical Year in 1957, these models were largely based on hypothesis and laboratory experiments. Conceptualized in 1965 and planned in detail in 1968, AIDJEX received funding from the National Science Board and the Army. During the 1970 to 1972 pilot studies and the 1975 to 1976 main experiment, the team collected buoy location data using systems on the Navy Satellite, while teams collected temperature, wind, and ice thickness data from field experiments and aerial photography. Initial computations in 1972 using this large data bank took 20 days for each computation. By 1977, the team was able to develop a fairly complex simulation of Beaufort Sea. Observations helped researchers to better understand ice geometry and thickness, the important role wind played in movement, and the existence of subsurface eddies of varying size, while new computer models helped to significantly change how researchers modeled ice thickness, plasticity, and movement. More than 4,000 reports and papers resulted from the program. Yet researchers recognized limitations of such models imposed by computer speeds, a major hurdle faced by CRREL well into the 1980s. As late as 1985, a major text edited by CRREL scientists focused primarily on physical modeling of ice. For the most part, only after the use of supercomputers in the 1990s could models display all required factors.²⁶⁵

Other problems modeled by CRREL included Arctic Ocean ice cover, thermal regimes of water bodies, ice break-up, surface temperature of snow cover, and development of polar curvilinear coordinates. After AIDJEX, observation and modeling of Arctic sea ice and its thermodynamic conditions continued in conjunction with the Navy, NOAA, the University of Washington, and other agencies and institutions, and included many other experiments, such as the 1997 Surface Heat Budget of the Arctic Ocean (SHEBA). These models became a critical part of understanding and predicting climate change and were incorporated into the Parallel Climate Models developed after 1999. George Ashton, the first head of the Geophysical Research Branch, conducted significant work on thermal processes that impact the behavior of river and lake ice, as well as methods to prevent ice build-up, for which he won the 1981 Army Research and Development Achievement Award. This work included computer modeling of heated water discharges and thinning ice cover. As part of an In-House Laboratory Independent

Research program to continue high-risk research using internal funding, CRREL also helped to develop a new method for generating curvilinear coordinates, an alternate coordinate system useful for solving spherical symmetry problems, for example, polar coordinates. These calculations were essential for modeling a range of engineering issues, such as melting ice, snow blowing around buildings, and seismic activity.²⁶⁶

By 1968, the WES Mobility and Environmental Division started to incorporate computers to simulate roughness of ground for analysis of forces placed on tires and axles. Using results from the Mobility Environmental Research Study in Thailand, in 1971 the division began development of an analytical mobility computer model in conjunction with CRREL and the Tank-Automotive Command. As historian Benjamin Fatherree noted, "For the next two decades – and beyond – this venture remained the focus of the organization's existence." The initial model – the Army Material Command-71 Mobility Model (AMC-71) – compiled 25 years of data to quantify mobility based on terrain, vehicle, and driver cross-referenced to a geographic location. It addressed 13 terrain measurements, five vehicle types, and driver-controlled factors such as visibility, acceleration, and braking. After conducting three years of field tests, including the 1972 Special Study of Wheeled Vehicles, it developed the Army Mobility Model-75 (AMM-75), a significant increase in sophistication from AMC-71. AMM-75 used 22 terrain factors; could more accurately simulate vehicle combinations, various loads, and individual vehicle subsystems; and better quantified driver behavior. The AMC-71 model assumed the driver to be "both omniscient and somewhat mad," one designer noted. In 1977, WES upgraded AMM for use in the NATO Reference Mobility Model. Another, the AMM Water-Crossing Model (WACROSS), looked at mobility rates for 44 vehicle types at river crossings in Germany. All of these systems ran on large mainframe computers, requiring dedicated analysts to complete calculations. After the Army requested a tactical version for use on microcomputers, WES developed the Condensed Army Mobility Model System. Although the initial version lacked the full data set, later versions increased in capability as hardware speeds increased. Starting in 1988, WES was able to bring this expertise to the Engineer Model Improvement Program, a multiyear effort to develop comprehensive computer models and simulations of combat.²⁶⁷

After introducing WES to FEM and computer modeling, the Soils and Weapons Effects laboratories continued to develop 2-D and 3-D numerical models. The Soils and Pavements Laboratory used models to solve problems such as subsidence, slope stability analysis, impulse loadings, structural stresses, layered foundations, liquid formation under pavement, and groundwater flow through saturated soils, resulting in applications such as WESLIQUID, WESLAYER, and STUBBS. The Weapons Effects Laboratory used models to investigate vibration, ejecta, blast loads, projectile penetration, and structural hardness using software such as ANSWER, Projectile Penetration into Geologic Targets (PENC02D), and Computer-Aided Resistance Assessment (COBRA). In fields such as rock mechanics, weapons effects, and ice mechanics, FEM was less helpful because many problems were related to discontinuities such as fault lines or intersections which FEM approximation tended to overlook. In 1971, Peter Cundall of the University of Minnesota developed the distinct element method (DEM), which

creates something like a “brick wall” model of close fitting blocks that represent rock beds. Because of the need to calculate thousands of polygonal points, it was a very computer-intensive method but ideal for calculating dry aggregated or disaggregated rock where water did not play a dominant role. The Geotechnical and Structures Laboratories developed several DEM models into the 1980s that could accommodate cracking in rocks and that allowed deformation. Such models found use in solving problems related to dam or tunnel responses to explosives, unlined spillway channels, tube shapes, and stresses in geosynthetic fabric containers. In 1985, Gen-Hua Shi and R.E. Goodman developed the discontinuity deformation analysis (DDA) that combined the strengths of the two methods. Like DEM, DDA analyzed rock systems, but its calculation of energy minimization and block displacements as linear functions were more akin to FEM. Shi further refined this process in the numerical manifold method of interpolation in 1995. WES hired Shi as a consultant in 1988 and offered him a full-time position in 1992 when he became a U.S. citizen. Although he stayed only through 1997, Shi greatly influenced rock mechanics modeling at WES.²⁶⁸

Software Engineering

Aiding development of models was the capability to write computer code to solve nearly any engineering problem. At the beginning of the computer age, computer programs were ad hoc and highly complex, often being nothing more than a series of switches or cables, punch cards, or machine languages known only by a select few. Bugs were endemic in early code, and as one history noted, “By June 1949, people had begun to realize that it was not so easy to get a program right.” Yet many tasks were repetitive, leading to development of subroutines and batch programs. In 1955, the SHARE IBM user group formed to help distribute these programs. The result of this effort was the compilation of commands into what would eventually become the FORTRAN language in 1957. The federal government, meanwhile, introduced the COBOL language. The simpler BASIC did not appear until 1964. In 1961, as part of the SAGE contract, SDC developed a simple interface that allowed human interaction directly with a computer without knowing code – an operating system. When IBM released its 360 series in 1964, it included OS/360. UNIX followed in 1967 initially for use on minicomputers, and Microsoft developed MS-DOS in 1980 and Windows in 1985 for microcomputers. By 1968, the year IBM first sold software separate from hardware, programs had evolved into self-contained packages, allowing for easier commercialization of computer code, now running into thousands of lines. Over the next decade, a flood of software and vendors appeared. Yet, few programs needed by the Corps were commercially available, and those developed at other institutions required considerable adaptation. As a result, the Corps had to develop its own software programs for many engineering applications. Just within the field of hydraulics, about a quarter of all research reported in leading technical journals from 1968 to 1972 was computer-oriented, and WES consultants spoke of the need for software engineering for the first time, foreshadowing what would become a major research area in the Corps over the next two decades.²⁶⁹

Already, there were extensive efforts ongoing at all levels of the Corps, with more than 200 programs developed Corps-wide, ranging from utility printing programs to complex models.

The OCE Computer Concepts Group and Engineer Computer Applications Group in the Civil Works Engineering Division wanted to encourage computer use while addressing concerns about duplicative efforts, leading to the first effort toward centralized management of standardized programs and procedures. In 1971, OCE discussed new regulations on control, development, storage, and distribution of Corps-developed software in multiple conferences. In an OCE-initiated project, WES worked to develop time-share programs and interfaces usable by engineers without programming skills. As part of the Engineering Studies Program, OCE directed WES to research computer procedures and programs under ES 804, "The Development of Hydraulic Design Criteria," which it had supported since 1951 through publication of 250 design criteria, 30 miscellaneous papers, and three design manuals. WES gathered and reviewed existing programs, many of which were duplicates, modifications of other programs, or project-specific, single-use programs. OCE then helped classify programs based on their design category and worked with districts to test prototype applications. WES helped evaluate them by measuring physical prototype performance and through testing at universities and elsewhere. By 1978, there were more than 50 programs in the resulting library of applications for navigation, wave dynamics, tidal inlets, sediment transport, and hurricane surge, which in 1980 OCE incorporated into the Conversationally Oriented Real-time Programs System (CORPS) library. HEC and WES were already offering training on several of these programs. Over the next decade, development efforts included numerical models such as TABS-2 and TABS-3, WESSEL, STREAMER, and WESCORR; general analysis programs such as Beach Profile Analysis System; and large hydrological and environmental databases for various watersheds.²⁷⁰

A similar situation evolved in other engineering fields. By the mid-1970s, there were dozens of structural applications, many written by Narayanaswamy Radhakrishnan (generally known as Dr. Radha). Educated at the University of Bombay with a doctorate from the University of Texas and assigned to the WES Automated Data Processing (ADP) Center in 1969 because of his computer experience, Radha worked several years on loan to the Soil Dynamics Branch before becoming an instructor of computer classes and adviser on software development. In 1975, he worked with Donald Dressler, then at the Lower Mississippi Valley Division, to arrange the Computer-Aided Structural Design (CASD) conference to capture data for structural applications. About 200 engineers from the districts and OCE attended and, after breaking into groups to discuss requirements and available applications, developed a white paper establishing computer program needs and requirements. Several new applications resulted, such as a program for designing tainter gates developed by the ADP Center through 1978 that saved more than \$200,000. Over the next 20 years, workgroups under the Computer-Aided Structural Engineering (CASE) initiative involving more than 230 Corps offices developed 2-D and 3-D applications for designing T-walls, culverts, cells, pile foundations, miter gates, culverts, locks, basins, and other structures. The teams reviewed existing applications to eliminate redundant programs and standardize, improve, document, and release them for Corps-wide use. By 1981, CASE had released 27 applications, including 10 new programs and several user manuals. This grew in 1988 to more than 60 applications, which the Corps used in designing more than 1,000 structures. By 1980, the Geotechnical Laboratory launched a similar

initiative, Computer Applications for Geotechnical Engineering (CAGE), which surveyed existing applications or developed new programs for slope stability, seepage, stress computation, settlement, grouting, and pavements, as well as boring and instrumentation databases collected from various locations. In CERC, the Microcomputer Applications for Coastal Engineering (MACE) workshops reviewed coastal engineering applications, while the Automated Coastal Engineering System (ACES), initially released in 1987, provided an integrated coastal engineering program.²⁷¹

By 1980, a number of management and engineering information systems also appeared. The National Academy of Sciences Building Research Advisory Board that helped guide early research at CERL identified in 1967 the need for introducing automation to the construction industry. The industry was notoriously conservative in applying new technology such as computers, which leading experts believed could help improve the efficiency of large construction projects. Taking this guidance to heart, CERL became one of the most prolific programmers in the Corps and a “beta” site for the construction industry, as CERL Technical Director Louis R. Shaffer observed. One issue the construction industry faced was the expense of using mainframes, for which they would have to purchase time. As a result, CERL became an early adopter and proponent of microcomputers as a method of standardizing and automating change orders, progress payments, submittal registers, and other forms. It conducted some of the earliest microcomputer experiments in the Corps using a 1976 CROMEMCO Z-80, a sturdy build-it-yourself computer and later the first micro to include UNIX and a FORTRAN compiler. In 1982, CERL formed a Construction Microcomputer User Group (CMUG) among Corps military construction offices, which quickly grew from its initial 40 participants to more than 100. The group advised offices on operating systems, storage space required, and software, and eventually released a buyer’s guide. Although many in the Corps preferred minicomputers and mainframes, microcomputers eventually overtook them as system capabilities increased and costs decreased. As this happened and users became more familiar with microcomputers, participation in CMUG declined.²⁷²

To support construction software needs, CERL immediately started programming systems, focusing at first on standard forms. Within its first five years, it introduced the Automated Military Progress Reporting System to streamline district and installation engineer reporting, the Automated Engineering and Architectural Design System (AEADS, later renamed SEARCH) to help engineers choose building materials, the Hospital Equipment Maintenance System (HEMS) to schedule repair and upkeep of medical equipment, the Army Functional Components System to aid in construction of bases in military environments, the LIFE1 pavement maintenance program, and the Environmental Impact Computer System (EICS). Several of these were highly influential. HEMS became the basis for the Facilities Engineering Equipment Maintenance System that enabled management of most base equipment. After successful testing at Fort Detrick, Maryland, in 1978, it became part of the Integrated Facilities System used at 24 Army installations. LIFE1 was the foundation for the Pavement Maintenance Management System (PAVER), the first of a popular series of maintenance applications that included ROOFER, PIPER, RAILER, and BUILDER. As described in Chapter Six, EICS was the first

of a series of environmental and energy software applications, most notably Computerized Evaluation of Utility Plans (CEUP), Building Loads Analysis and System Thermodynamics (BLAST), and Environmental Impact Forecast System used widely by bases and the Environmental Protection Agency. Throughout the 1980s, CERL worked to migrate these applications, first from batch processes used on mainframes to graphics-supported programs operating on microcomputers, and transitioning from UNIX to the more popular Microsoft operating systems as these became capable of supporting them.²⁷³

In 1980, most business software support functions passed from Corps labs to the Huntsville Division. The Army revised its automated system management and acquisition process in Army Regulation 18-1, published in July 1980. Although many acquisition guidelines did not apply to Corps-developed systems, for example related to specific equipment sets, the regulation established a lifecycle for future efforts that allowed the Corps to separate research and development of systems from long-term management of the products. In essence, the regulation broke software and system development into three phases: concept development and design, system development, and deployment/operation. OCE assigned Huntsville Division as the responsible agent for the last phase, including maintenance and training. Starting in 1978, OCE assigned several software packages and programs to the division mostly from CERL – BLAST, the DD Form 1391 Processor, EDITSPEC, SEARCH, CEUP, CONTEXT, and EEAP, in addition to technical manual/guidance responsibility and the Army Pollution Abatement Program, although CERL continued providing technical support and expertise on these programs. In May 1980 CERL met with division and OCE representatives to work out process issues. When OCE requested software based on field requirements, Huntsville Division determined the best organization to develop products – whether CERL, the division, a contractor, or another Corps organization – and evaluated the final product. However, CERL worked closely with the division on field testing and publication or training development.²⁷⁴

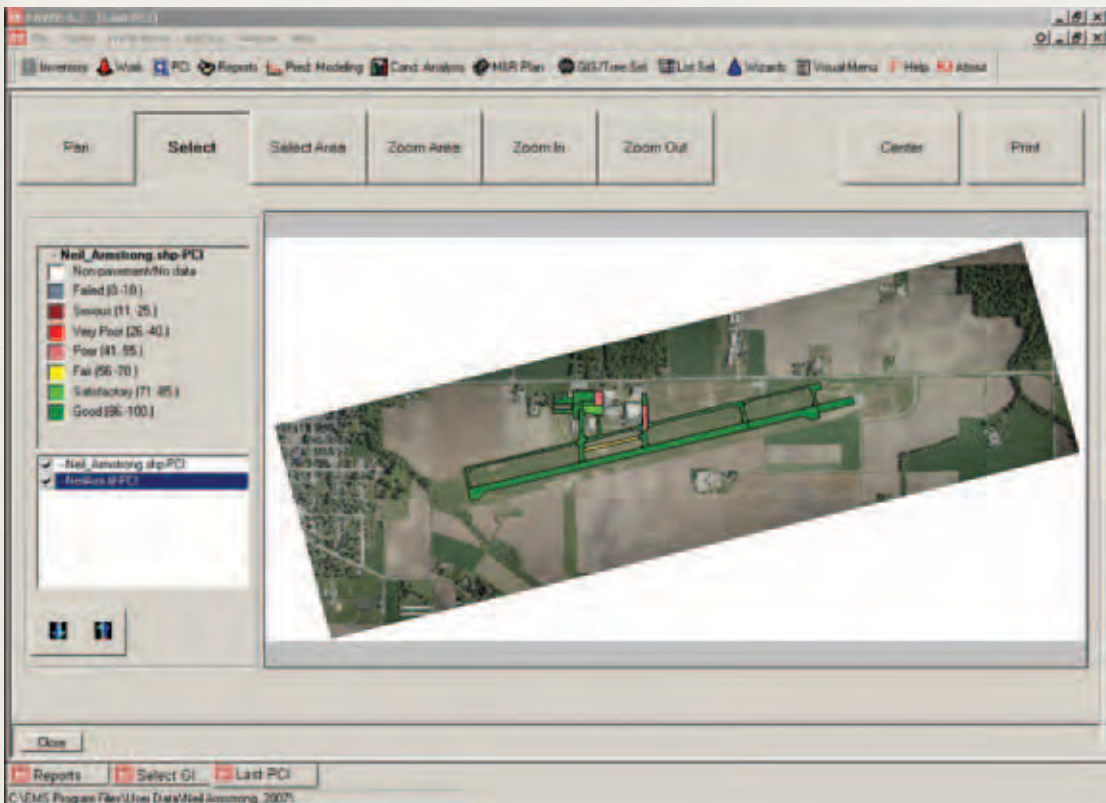
By the mid-1980s, commercialization of software had been ongoing for more than a decade. In specialized areas such as accounting, word processing, and database or data storage, it had long been more convenient to purchase software products than to develop them. Eventually, the same came to pass with engineering software such as computer-aided drafting and design (CADD). When Autodesk, Bentley Systems, Intergraph Corporation, and other companies started offering highly sophisticated software on lower cost operating systems such as UNIX and Windows, and with the evolution of software designed specifically for architecture, utility management, and structural design with ready-made templates, symbols, and commands, most preferred to purchase these products – termed commercial off-the-shelf – to designing their own. Because of the need to develop engineering plans such as blueprints, facility plans, and maps, most early experimentation with CADD occurred at military bases or Corps districts, in particular Huntsville, Savannah, Kansas City, and St. Louis districts. However, the time and cost of these initial forays into technology were high, and with development of multiple incompatible applications, there were problems with sharing technical drawings. Further, many applications lacked drafting capabilities. Huntsville Division experimented with CADD as early as 1978 to draw ammunition plant and mobilization master plans, and in a five-year contract

City Pavement Management and the Corps

A major problem at many military installations was maintenance of road systems. Built over many generations using multiple materials and subjected to differing wear and environments, these roads were falling into various states of disrepair, especially in the face of budget reductions in the 1970s and early 1980s. Lacking expertise on pavement and needing to optimize resources, bases turned to the Corps of Engineers to help develop a method to improve road management.

Some of the earliest work of the Construction Engineering Research Laboratory (CERL) related to pavement and maintenance management. Edward Murphree, Jr., received the Army Research and Development Achievement Award for work on air-field pavements in 1971, and by 1973 CERL had developed its earliest computer-aided system to estimate life-cycle costs for road repairs – LIFE1. Other applications helped installations in managing facility maintenance, including roadways.

To support long-term road maintenance needs, Mohamed Shahin of CERL led efforts to develop a pavement maintenance decision-making method designed to optimize maintenance budgets based on best practices. Among these practices were a systems



PAVER engineered management system, which included tools to schedule maintenance and repair projects at the optimal time, ensuring the best condition of assets with available funds.

approach to pavement that viewed each section as part of a larger roadway system and the concept of pavement management systems – a logical series of steps to establish rational priorities – then coming into acceptance among state highway departments. As part of the method, CERL developed a pavement condition index (PCI) to aid decision-making. This was a score of zero to 100 provided by experienced engineers to objectively grade maintenance needs.

The most popular aspect of the method was a microcomputer application and database, later known as PAVER. Roadway engineers and maintainers built up a database on each roadway using the PCI, which the system then analyzed to determine which roadways needed repair based on available funding. Capabilities for scheduling inspections, inputting PCI ratings, and predicting road conditions allowed bases to better maintain roadways, while economic analysis, budget planning, work planning, and reporting tools supported bases in communicating and justifying budget requirements to higher headquarters.

By 1979, the Air Force had adopted the PCI system for all runways, and a prototype project at Fort Eustis, Virginia, started to test the index and then the software. A 1983 study of return on investment (ROI) for implementation of PAVER at Fort Eustis; the Great Lakes Naval Training Center, Illinois; and Sierra Army Depot, California; demonstrated an initial ROI of 1.6, 1.8, and 1.3 respectively. Although preliminary installation costs were high because of its gradual implementation for larger and larger geographic areas, estimates on annual cost avoidance ROI was 1.7 just at Fort Eustis. The same year, the University of Illinois trained 125 users on the new system.

The success of the program soon drew the attention of the American Public Works Association (APWA), which arranged transfer of the technology from CERL. After testing PAVER in six cities in 1983, APWA implemented the software in 45 cities in the U.S. and Canada for use by city managers, airport managers, and road and highway engineers. Although the Corps continued to maintain and improve PAVER, for example with publication of a user manual in 1985 and upgrades to new operating systems, it was now an application for the nation.



The American Public Works Association became a technology transfer agent for PAVER, recommending and supplying the software to its members.

with what later became Intergraph developed and tested several CADD systems and, with drawings and maps of Sunflower Ammunition Plant, Kansas, demonstrated considerable cost savings. In 1982, the division began working with Headquarters to arrange a long-term CADD procurement, and in 1987, the Corps awarded Intergraph a five-year \$121 million contract through the division to enable 38 Corps offices and 130 other agencies to purchase standard CADD, hardware, training, and other services. To support the districts with technical guidance and user forums, the Corps established a CADD Center at WES the same year. Although the Corps continued to develop smaller programs that provided unavailable functions, they often integrated with or used commercial applications to provide basic visualization, drafting, and plotting features.²⁷⁵

From the 1970s, in addition to accessing computer resources located at other facilities, several Corps applications, such as the Integrated Facilities System, Corps of Engineers Management Information Systems (CEMIS), and the CORPS library, were part of networked systems that allowed users to access data or run programs. By the 1990s, users could access many of these through the Internet. Originally developed as an experiment by the Advanced Research Project Agency (ARPA) in 1969, it became a worldwide phenomenon after 1990. As Ceruzzi observed, “It is difficult to discuss the World Wide Web without confronting a general feeling that this is the culmination of all the development in computing since von Neumann’s EDVAC Report of 1945.” In 1945, Vannevar Bush wrote his famous essay on MEMEX proposing a personal device that networked to other computers and databases. This inspired Douglas Englebart and Ted Nelson of the Xerox Palo Alto Research Center, California, to develop Ethernet network protocols, mouse and window-driven displays, and hypertext. As networks migrated to more reliable protocols and larger bandwidths in the 1980s, ARPANet came to include capabilities such as e-mail, file transfer, and gopher. In 1990, as part of the World Wide Web project, Tim Berners-Lee and others developed the hypertext markup language (HTML) and universal resource locators (URLs), which allowed creation of Web pages and the ability to find them using easy names. In 1993, Marc Anderson of the National Center for Supercomputing Applications developed the MOSAIC Web browser. Even before the Internet was privatized in 1995, the Corps was incorporating many of these capabilities. Although models were too data-heavy at first for effective network access, the Internet was ideal for administrative functions and management information systems where collaborating or sharing information was paramount. For example, the CERL application DrChecks allowed secure online design reviews among client agencies, architect-engineer-construction firms, and Corps managers with access to schedule and cost data. After 1994, CRREL developed a database of ice jams available on the Internet, and many districts began posting survey or other data.²⁷⁶

Geographic Information Systems

One software engineering area in which the Corps became deeply involved was development of geographic information systems (GIS). A GIS is a computer-based system that correlates geographic or spatial data with other types of information, such as land parcels, location of mines or utility facilities, or population. Geographers have attempted to correlate such data for

decades, for example, through the use of map overlays. Although Ian McHarg popularized this technique in ecological planning in 1969, in fact, map overlays had been around for years, having been used by military engineers at the Battle of Yorktown in 1781 and throughout World War II, applied to commercial industries such as railways as early as 1838, and introduced to local government use by 1912 when Warren Manning created thematic maps of Billerica, Massachusetts. Computerizing such data made it easier and faster to process information for use in many industries, but it took many years to bring together the multiple elements needed to create effective GIS. An obvious need was computers with enough power to process the vast spatial data, which did not occur until after 1960. Another was the ability to accurately capture and portray geographic data. As noted in previous chapters, the Corps was a pioneer in topographical engineering and U.S. photogrammetry, and produced early systems for capturing, transferring, and printing maps using analog photograph- and sensor-based systems. Programmers also needed methods of converting data into something usable by computers. In the seventeenth century, Francis Galton, the Secretary of the Royal Geographic Society, first developed methods for recording line shapes using numeric codes (later called Freeman codes). Based on the work of John K. Wright of the American Geographic Society, A.H. Robinson in 1953 simplified geographic measurements to points, lines, and areas. The University of Washington developed land inventory methods for TVA that became the basis for quantitative and statistical geography.²⁷⁷

As with the question of the first computer, identifying the first GIS is a matter of definition, on which, however, there is less agreement. If one defines GIS as the ability to display and interactively modify data, as some textbooks have, no GIS or interactive capabilities existed before 1965 since few computers included displays. Including geographic data processing, one must look to early geocoding in 1957 by the University of Washington or development by the Corps of analytical photogrammetry techniques or map compilation systems before 1960. Although GIS leaders in academia were often ignorant of or downplayed Army influence, as historian John Cloud noted, it was the Defense Department that laid the foundations for GIS through automated mapping, the first digital maps, and investments in technology development. Most GIS pioneers recognize the Canada Geographic Information System (CGIS), developed from 1963 to 1971, as the first to correlate map and tabular data and the first to use the term “GIS.” Yet simultaneous and often independent development of similar systems was underway across several fields. Minnesota, New York, Wisconsin, and Maryland all developed map-based systems for managing land information from 1963 to 1974. Work at Harvard University led to the 1965 and 1968 GIS applications SYMAP and GRID, which influenced other universities as well as GIS pioneers Jack Dangermond at the Environmental Systems Research Institute (ESRI) and David Sinton at Intergraph. Early management information systems developed in Pennsylvania and New York for Bell Telephone and utilities in 1964 led to development of the first automated mapping / facilities management (AM/FM) system in 1968 for Public Service Company of Colorado. Meanwhile, Oak Ridge National Laboratory was developing a GIS for the Department of Energy. In 1967, the Census Bureau started development of the Dual Independent Map Encoding System – the successor of Hollerith’s attempts at georeferencing and automatically tabulating population. With development of photo-analysis and multispectral

image capture by the Corps and NASA contractors, attempts began as early as 1964 to digitize these images, leading to the 1966 Purdue Laboratory for Agricultural Remote Sensing GIS (LARSYS). Another path, less documented but influential, was Corps work in photogrammetry, which laid the groundwork for remote sensing and automated mapping. As GIS pioneer Timothy Foresman noted, while early vector- or coordinate-based systems developed at universities are “ubiquitously cited in the literature,” in fact raster- or pixel-based systems originating with photogrammetry and remote sensing formed one of the earliest roots of GIS.²⁷⁸

Corps use of computers to process geographic information to support analytical photogrammetry began in the mid-1950s, but these programs accepted limited input and mostly output numerical solutions, although they grew increasingly sophisticated after 1960. Since the early Cold War, ERDL developed electronic devices for creating maps, including automatic map compilers, mosaicking systems, contour plotters, point readers or markers, plotters, and cartographic systems, but these were mostly analog. It even developed an analog “GIS” that stored 11,000 microfilm images for use in targeting. The primary impetus for moving to digital systems was development of analytical photogrammetry. The advantages of triangulating location without a ground control in a combat zone were many, but the calculations required were cumbersome and time-consuming. Computers removed this obstacle. Several projects investigating computer processing of analytical methods were underway in the mid-1950s. By 1958, G.W. Herget and Robert Zurlindin of Cornell University both developed analytical methods for use with UNIVAC, IBM, or Royal McBee computers, but they processed only six or so photos at a time and output only numerical solutions. From 1960 to 1962, ERDL completed six new programs, each processing more data. By 1962, it had started development on a program for sequential, image-coordinate measurement.²⁷⁹

Prior to 1960, ERDL investigated digitizing photographs, and although it conducted successful tests with an experimental IBM digital scanner, it was unable to complete a successful prototype until after 1969, when it started to use densitometers to measure and capture gray-scale information from pixels. It nevertheless produced several hybrid analog and automated systems for measuring points and lines, digitally capturing contour lines and other map data, and producing cartographic products. The most comprehensive of these were the 1963 Universal Automatic Map Compiler Equipment (UNAMACE), which output files in a digital format, and the Semi-Automated Cartography System (SACARTS), whose development began in 1968. The latter included the Digital Input/Output Display Equipment, which allowed onscreen viewing and editing of map data. By 1974, ETL could display and print high quality maps and 3-D terrain models. As discussed in Chapter Six, Robert Frost and Jack Rinker had long supported NASA in sensor-based analysis techniques and helped develop multispectral data capture and digitization. After launch of LANDSAT in 1972, ETL helped code the satellite signal to provide an end-to-end digital process. The Digital Image Analysis Laboratory (DIAL), established in the ETL Computer Sciences Laboratory in 1969, was in effect a testing ground of many of these new technologies and demonstrated a complete digital environment when it became fully operational in 1976. Among capabilities tested at DIAL were digital image matching, creation of digital “synthetic photographs,” and digital feature extraction – the

process used to automate the digitization of hard-copy photographs and maps. Although digital mapping processes were not initially much faster than manual ones, they provided clear advantages for modeling and visualization.²⁸⁰

By the 1970s, ETL started development of GIS that correlated terrain data with other information. Since development of the Rapid Combat Mapping Systems (RACOMS) equipment started in 1956, ETL worked to provide systems to support field commanders with map products and, after 1965, digital displays showing intelligence such as targeting, hydrological conditions, and changes in terrain. Although equipment tests from 1968 to 1970 showed RACOMS to be too unwieldy and sensitive to field conditions to be effective, over the next decade, ETL planned and started development on several systems, including the Topographic Support System that was scheduled for fielding in 1978 and Army Terrain Information System, on which it started development the same year. Unfortunately, funding cuts killed both developmental efforts. It was not until ETL displayed GIS capabilities in the Field Exploitation of Elevation Data mobile demonstration that commitment to a field GIS renewed. Plans for a new Digital Topographic Support System (DTSS) evolved with a delivery date of 1990. In the interim, ETL fielded the Terrain Analyst Workstation (TAWS) in 1984 based on an in-house test system it developed from 1979 to 1983. This system included a map production system, a terrain analysis package, and the Battlefield Environmental Effects Software developed from 1979 to 1983 to help estimate battlefield obscuration and calculate the impact of environmental factors on materiel such as weaponry. TAWS became part of a highly successful AirLand Battlefield Environment (ALBE) demonstration project in 1986, which used GIS to analyze atmosphere, terrain, contaminants, background signatures, and illumination. Based on the success of TAWS, development of the DTSS continued and after successful field tests in 1987, ETL prepared for fielding. As an outgrowth of the work of the Center for Artificial Intelligence, established in 1982 in the Research Institute under Robert Leighty to develop navigation systems for robotics, development efforts sought to automate a variety of tasks in GIS systems, such as route planning, delineation of drainage patterns, motion detection, and terrain modeling. In 1984, ETL developed the Terrain Visualization Test Bed to test an immersive 3-D model that could integrate with DTSS or other applications.²⁸¹

There were innumerable problems on the way to a completely digital topographic environment. One was determining the best approach to structuring and storing data. Most data resulting from imagery were raster-based, which systems collected and reconstructed row-by-row and column-by-column in small squares or pixels in a specific order. Those resulting from digitally redrawing maps were usually vector-based, which systems read as a series of points and connecting lines. Each had its advantages and disadvantages: vector data were more compact, easy to store, and could be easily scaled without loss of resolution; raster data were more memory-intensive and could lose resolution, but could initially be processed more quickly in parallel format. In 1976, the Defense Mapping Agency (DMA) tasked ETL with the first of several projects examining translation between raster and vector data on various platforms. In 1978, ETL started a series of comparisons of differing raster and vector formats. Another problem involved standardizing on a digital topographic data format. Several formats had evolved

throughout the Defense Department, the most popular being Digital Terrain Elevation Data (DTED), which DMA built and edited using an ETL-developed system. With the growth of digital systems, DMA requested that ETL conduct an extended study of topographic data requirements and evaluate the two leading formats. ETL completed the four-volume study in 1984, which identified 75 military systems using topographic data, five of which used DMA formats. The study was “the first time the total Army requirements for DTD were stated and approved by the Department of the Army,” one employee explained. As a result of these studies, ETL established the Concepts and Analysis Division to continually review data requirements and work toward standardizing data formats through closer management. A further study in 1987 forecast data needs through 1993.²⁸²

On the civil works side, the Corps developed GIS for navigation, water control, coastal zone management, wetlands permitting, and other areas. For example, the Spatial Analysis Methodology, developed by HEC in the mid-1970s and successfully tested at Pennypack Creek, Pennsylvania, in 1978, integrated GIS and hydrological models. Although computer-intensive and slow, it came into wide use throughout the 1980s by the Fort Worth District, the Omaha District, WES, CRREL, and CERL. Other districts, such as the Rock Island and Detroit districts, also developed interesting GIS applications during this time. WES first became involved in GIS to support mapping river basins for environmental planning projects. As it started to work with CADD after 1987, one issue that arose was using GIS to design facilities extending beyond internal building designs, which allowed layered analysis of features such as utilities, architecture, telecommunications, or socioeconomic factors. Starting in 1989, WES held several workshops to develop standards and integrate GIS with CADD software. By supporting districts in mapping large civil works sites, WES repositioned the CADD Center to include GIS in 1992. CRREL also became heavily involved in GIS in relation to its remote sensing and environmental missions and periodically supported Corps districts in these issues. Particularly after the Exxon Valdez oil spill and Hurricane Hugo in 1989, in which CRREL staff used GIS for environmental restoration, emergency response, and civil works rehabilitation under Public Law 84-99, CRREL gained recognition as an expert in integrating GIS and remote sensing. As a result, Harlan “Ike” McKim formed a Remote Sensing/GIS Center (RSGISC) to aid Corps districts and entities such as NOAA and the Coast Guard. Recognized by OCE the following year, the RSGISC became the go-to center for emergency response GIS. For example, it helped build maps of power outages and debris after 1992 Hurricane Andrew. In the 1993 Gila River, Arizona, flood, it helped build complicated GIS combining HEC hydrological data and state map data to build a digital elevation model. Other efforts included GIS for sea ice, vegetation, or flood plains. Under its second director, Timothy Pangburn, RSGISC activities ranged from emergency management support of Hurricane Katrina and North Dakota regional flooding events to development of CorpsMap, a nationwide enterprise GIS that served as the single authoritative source for Corps national geospatial data assets. The RSGISC also led Corps efforts to develop a GIS-based nationwide levee database to enhance inspection and rehabilitation of this critical national infrastructure.²⁸³

Installations, meanwhile, pursued their own GIS applications. Several applications developed by CERL flirted with automated mapping after 1975, including the Environmental Technical Information System and Environmental Early Warning System, but although tested at military bases, they were developmental and were not used outside of the pilot sites and the lab. Soon after, Fort Riley, Kansas, used the Harvard SYMAP application for an erosion study, and in 1981 Fort Hood, Texas, fielded the CERL-developed Fort Hood Information System for environmental impact assessments. In 1983, Fort McClellan, Alabama, implemented the next generation Installation GIS; Fort Benning, Georgia, implemented the Earth Resources Data Analysis Systems Inc. GIS in its forestry department; and Fort Lewis, Washington, implemented a similar system. With the growing demand for GIS applications, CERL began development in 1984 of what would become the most popular Corps GIS package – the Geographic Resources Analysis Support System (GRASS). After pilot projects at Fort Hood, Fort Lewis, Fort McClellan, Central Washington University, and the University of California at Berkeley, CERL held the first user group meeting in 1985 to collect input. Among attendees were representatives from the Soil Conservation Service, which was deeply interested in the project for soils mapping, watershed mapping, and farm planning. It later funded implementation of GRASS in local government. When CERL released the Integrated Training Area Management protocols later that year, it included GRASS, which installations such as Camp Grayling, Michigan; Camp Shelby, Mississippi; Fort Polk, Louisiana; Fort Benjamin Harrison, Indiana; and others learned to use for applications such as evaluating construction sites, assessing soil stability, protecting endangered species, managing natural resources, planning recreation, tracking water quality, and planning archaeological digs. Development of GRASS continued with, for example, the Xgen toolkit for UNIX and several software add-ons for decision support. Through the adoption of digital software distribution, the user base grew from about 300 in the mid-1980s to more than 6,000 across multiple agencies, universities, and local government. Development of GRASS ended in 1995 when the user community agreed that commercial off-the-shelf software was available that vastly improved on its capabilities. By this point, some 38 agencies across the Department of Defense were using various GIS packages.²⁸⁴

By the mid-1980s, the diverse approaches to GIS were becoming a problem across many industries. Because of the nonlinear development of GIS technology, developers had taken differing approaches to geocoding map data, display and printing, and other technical issues that resulted in interoperability problems – programs could not read data from other applications, which prevented data sharing among agencies and wedded users to one particular product to avoid losing investments in proprietary datasets. Even within the Corps, there were different approaches: remote sensing-based GIS supported by ETL and later the CorpsMap system developed by CRREL, CADD-based AM/FM systems supported by WES, the GRASS application supported by CERL, and various other applications developed or purchased by Corps districts and divisions. At a 1987 meeting of the Environmental Advisory Board, Corps consultants and Chief of Engineers Lt. Gen. E.R. Heiberg received a briefing on GIS use that revealed the many approaches and the lack of coordination on this important technology. At the urging of

the board, Heiberg formed a working group headed by William Klesch of the Civil Works Directorate. After a year of study, the group recommended appointing a GIS coordinator and steering committee, and the new chief, Lt. Gen. Henry Hatch, assigned responsibility to the Civil Works Engineering Division. After spending several years trying to recruit a coordinator, M.K. Miles himself became the first Spatial Data Systems Coordinator in 1990. Among the many accomplishments of his office were participating in the Federal Geographic Data Committee starting in 1990, which helped to guide GIS policy across the entire federal government, including the Corps in 1991 in the Tri-Service CADD/GIS contract managed by the Naval Facilities Command. As part of the latter, WES formed a CADD/GIS Technology Center that helped develop data standards, including a data dictionary, standard schema, and common symbology.²⁸⁵

At approximately the same time, GRASS user groups gradually evolved into a non-profit commercial organization dedicated to solving interoperability issues – the Open Geospatial Consortium (OGC), originally conceived by CERL's William Goran. In 1986, the GRASS user community formed GRASS: The User Forum (GRASS TURF) to guide development of the application. Since the program's inception, several agencies had advised CERL on GRASS development. In 1990, a formal memorandum of understanding created the GRASS Interagency Steering Committee (GIASC). The following year, prominent members of the user community formed a private non-profit business to help coordinate user issues. In 1992, GRASS TURF voted to merge with GIASC, which was renamed the Open GRASS Foundation. More and more of the foundation's meetings focused on technical issues to help solve interoperability problems, eventually resulting in the Open Geodata Interoperability Specification Project in 1993. To better support the project, the foundation reformed as OGC in 1994. This organization grew over several years to include more than 400 members, including major technology vendors such as Intergraph, Oracle Corporation, Sun Microsystems, Microsoft Corporation, and Lockheed-Martin; colleges such as the University of Arkansas and the University of California at Berkeley; and agencies such as the Corps, NASA, the National Imagery and Mapping Agency, and the Agriculture Department. It worked to develop vendor-neutral standards and technologies, including its OpenGIS specifications. Despite such advances, GIS interoperability remained a problem well into the twenty-first century both for the Corps and the Army as a whole.²⁸⁶

Formation of the Information Technology Laboratory

While the ETL Computer Sciences Laboratory and CERL and CRREL computer centers conducted important work in expanding computer use in their respective laboratories and developing applications specific to their missions, over time the WES Automated Data Processing (ADP) Center broadened its mandate to serving the entire Corps community. In 1970, WES established the ADP Center as an administrative function separate from the Technical Information Services Center and library, but by the end of the year moved it among the technical staff because of its research support. It took an immediate lead in offering training to the Corps and had by 1971 trained more than 300 in FEM, numerical modeling, FORTRAN, and other subjects. It continued to offer periodic training in various technologies. From 1978 to 1981, it trained anywhere from 150 to 220 employees each year in 17 different courses. In 1977, the center started

the CASE working group to develop and standardize structural applications and quickly became involved in several Corps-wide computing efforts, such as CORPS and Engineering Computer Programs Library (ECPL) to develop libraries of applications and the Computer Graphics System (CGS) and Corps-Extended Easy Graphics (CEEG) development of graphical programs. When OCE began to evaluate use of microcomputers in 1983, the ADP Center participated in the Microcomputer Evaluation and Application Team and in 1984 began participating in the Corps of Engineers Automation Plan (CEAP) development. It distributed, on average, more than a dozen technical bulletins each year and in 1979 began publication of its long-running newsletter, *Engineering Computer Notes*, on various computer-aided engineering issues. It continued to expand the computing capabilities of the center through implementation of a Texas Instrument Advanced Scientific Computer in 1979, Harris 300 minicomputer in 1981, IBM-4331 mainframe in 1982, and Ethernet network throughout the campus. In 1985, the center also began working toward purchasing a supercomputer to support high-demand modeling requirements.²⁸⁷

With increases in microcomputer procurement and in response to Army Regulation (AR) 18-1 and other regulations, from 1978 to 1980 each Corps lab established an ADP Coordinator position to focus on acquisition and technology planning issues. This was typically a dual-hatted position held by ADP Center chiefs – Donald Neumann at WES, D.E. Howell at ETL, Greg Fellers at CRREL, and Wayne Schmidt at CERL – who served as advisers to the commander in addition to other duties. In essence, the position would coordinate and plan financial and technical issues, assign development and procurement priorities, and provide awareness of issues affecting computer implementation. In 1982 WES Commander Col. Tilford C. Creel requested the establishment of a separate ADP Coordinator Office in the advisory staff, elevating this position to provide leadership on computer acquisition and planning in order to allow the ADP Center to concentrate on technical support of the labs. Robert Powers of the OCE Resources Management Office questioned having two ADP offices at equal levels since he viewed the ADP Center as a “support data processing function,” and believed that “an organization structure of this type would not truly solve the ADP problem at WES.” OCE nevertheless approved the office with minor changes in 1983. Creel named acting ADP Center Chief George Hyde as the ADP Coordinator. Hyde quickly became involved in CEAP meetings and other planning and acquisition issues. Meanwhile, Creel requested reorganization of the ADP Center to include Computer Services, Information Systems, and Scientific and Engineering Application divisions to allow closer support on hardware, software, and computer research areas, and in 1985 renamed it the Automation Technology Center (ATC) to capture its new function. With retirement of Neumann in 1982 and assignment of Hyde as coordinator, Creel named Radha to head the center in 1983.²⁸⁸

As it turned out, Powers was correct that an ADP Coordinator Office did not solve organizational problem at WES, but only because he underestimated the importance computers had gained in Corps research. The Army itself was struggling with how to approach information technology issues. The 1982 Department of the Army Information Resource Management Program required each command to establish an Automation Management Office, which WES met through the ADP Coordinator. General John A. Wickham, appointed as Army Chief of Staff in 1983, made it his goal to streamline information management, including consolidation

Supercomputing at the Information Technology Laboratory

When Robert W. Whalin became Technical Director of the Waterways Experiment Station (WES) in 1985, he requested ideas for ways to improve the lab. Narayanaswamy Radhakrisnan (known as Dr. Radha), director of the Automated Data Processing (ADP) Center and later the Information Technology Laboratory (ITL), suggested purchasing a supercomputer. At the time, WES was spending more than \$2 million per year to buy time on supercomputers at Boeing Corporation or Kirtland Air Force Base, New Mexico, to run highly complex structural and explosive analyses. Unfortunately, the Army had no modern supercomputers available, and the Corps was not a high priority to get one.

WES had, in fact, been discussing establishing a supercomputer center for many years. Although it had purchased a Texas Instrument Advanced Scientific Computer in 1979, even at that time it was not top of the line and by 1985 was nearing obsolescence. Because a modern supercomputer was critical to WES research, it was looking at buying a computer, but could never get enough funding to cover the expense.

When the Army started acquisition of a supercomputer for the Pentagon, WES served on the selection board, many of whose members also wanted supercomputers. After attending several meetings, ADP Coordinator George Hyde requested support from Whalin to face the Senior Executives and General Officers sitting across the table. Whalin agreed and over the next three years spent about 20 percent of his time negotiating for the computer. In an early meeting, Undersecretary of the Army James R. Ambrose agreed to purchase seven supercomputers, but with the Army Research Laboratory, Tank-Automotive Command, and others vying for them, the Corps did not make the first cut. Only after Whalin suggested in a June 1986 meeting with the Deputy Undersecretary for Operations Research that a fair gauge of need was the amount of money being spent on supercomputer use did WES finally move up on the list. The fight continued several years, with WES facing unannounced meetings, short deadlines, and winning the support of Chief of Engineers Lt. Gen. E.R. Heiberg.

Finally, in 1989, WES established a Supercomputer Center – the third in the Army – at the newly occupied ITL headquarters building. The computer installed, a 1988 Cray

Y-MP, was top of the line with multiple 333 megaflop processors for a sustained speed of 2.3 gigaflops – a gigaflop equals one billion floating point operations per second. To support the center, the ITL building had to install four external generators, enough 60-ton air handlers to cool 135 homes, and a high-speed Fiber Distributed Data Interface (FDDI) fiber network.



CRAY Y-MP, the first supercomputer at the Waterways Experiment Station.

In 1992, Radha and Whalin started working with Anita Jones, the director of Defense Research and Engineering, on the High Performance Computing Modernization Program to provide Defense laboratories high-performance computing capabilities. In 1993, the program established four Major Shared Resource Centers (MSRC) – one each in the Navy and Air Force and two in the



CRAY C90, installed in 1993.



CRAY XT3, installed in 2005.

Army at WES and the Army Research Laboratory – which scientists throughout the Defense Department could access for state-of-the-art high-end computing, data storage, archiving, visualization, training, and shared computing expertise. In 1993, the WES MSRC included the Y-MP and a Cray C90 and in 1996 received \$202 million to support the program. It went through several upgrades over the years, including the 2005 installation of a Cray XT3 with 315 terabytes of storage space, 16 terabytes of RAM, and 42.6 teraflops of computing speed. It would take 1,000 scientists 1,300 years to complete the same number of calculations the Cray could to in a single second. In 2008, the MSRC installed an XT4, which added an additional 3,738 terabytes of storage, 17.2 terabytes of RAM, and 75.7 teraflops computing speed. Together, the systems provide three petabytes of storage, equivalent to nearly six million PCs or 15 channels of HD video recorded every day for a year.



CRAY XT4, installed in 2008.

of computer-related regulations in AR 25-5 and reorganization of the Information Mission Area, for example, through establishment of Information Management Offices (IMOs). In meetings throughout the summer of 1985, the Corps agreed in memoranda of understanding to establish a Directorate of Information Management with IMO chiefs in all Corps elements by end of the fiscal year. It would merge all automation, communication, audio-visual, records, and publishing elements by the end of the following year. Hyde, who had been tracking these



Allen F. Grum.

developments, recommended in June the replacement of his office with an IMO and drafted proposed mission and functions statements. However, although incoming WES Director Col. Allen F. Grum temporarily assigned Hyde as IMO chief to meet Army requirements, he and Technical Director Robert Whalin preferred to use the change to advance WES research. With the consolidation of nearly 200 employees, with the possibility of getting a super-computer center, and with the advanced work the ATC was doing with CASE, Grum suggested creating an Information Technology Laboratory (ITL). Whalin immediately seized on the idea. After forming a study group and meeting with the lab directors, the Directorate of Research and Development, Directorate of Resource

Management, and Directorate of Information Management, all of whom opposed the idea, Grum and Whalin won approval from Chief of Engineers Heiberg. Although it had a different name, ITL technically met Army requirements for a consolidated Information Mission Area. Grum announced the decision February 6, 1986, and selected Radha as the first director of ITL in July.²⁸⁹

Although ITL initially served merely to consolidate IT functions, Grum later observed, "It turned out to be a bigger deal than I thought." As required, WES moved the Technical Information Center, the Library, the Visual Production Center, and Mail and Records sections under ITL. The management challenges were large. Until construction of the ITL headquarters, the \$6.2 million Jamie L. Whitten Building, the lab had offices spread throughout the campus. Construction of the facility required considerable planning, as it had to contain a secure area, a raised floor, 3,000 square feet of space (later expanded to 15,000), and additional air handlers and back-up generators to house CDC financial systems centralized at WES under CEAP in 1988 and later for the supercomputer center established at WES in 1989. This also required upgrading the entire WES campus to a 9.5 mile network of high-speed Fiber Distributed Data Interface (FDDI) cable to allow faster access to ITL systems. Construction began in 1987 and was complete in late 1989, with the official dedication ceremony in 1990. At first, the lab received only the direct funds normally received by its various offices and about \$5 million in research funds, totaling less than \$15 million. To fund the lab, Radha started to charge per service and worked to bring in additional research funding. Grum did not initially include the ATC Engineering and Applications Group in ITL, preferring instead to retain it as an executive office staffed by ITL members until personnel could assume these functions inside the other labs. This changed only in November 1987 with the group's merger with the ITL Information Research

Division. In 1995, the Instrumentation Services Development Division also became a part of ITL, greatly expanding its responsibilities. By 1996, ITL funding was roughly \$100 million.²⁹⁰

At first, ITL had no defined mission other than internal automation and information functions, training missions, and work on CASE, CEAP, CGS, ECPL, and CORPS. It soon received tasking to support the Corps of Engineers Management Information Systems (CEMIS), Corps of Engineers Time, Attendance, Labor System (CETAL), Project Cost Management Information System (PCMIS), and other systems. It also soon started to attract consulting projects in assistance to other districts, such as analyzing locks for St. Louis District or modeling a wall at the Bonneville Dam for Seattle District. Four missions greatly expanded ITL responsibilities and facilities by the end of the decade. The first was the creation in ITL of the CADD Center in 1987. As discussed previously, with the growth of commercial design applications by the mid-1980s capable of supporting Corps needs and with a desire to standardize design and drafting, in 1987, the Corps entered into a multiyear contract with Intergraph Corporation, administered through the Huntsville Division with oversight from the Construction and Engineering Directorate of the Headquarters of the Corps of Engineers (HQUSACE). Because of ITL's work on CASE, HQUSACE tasked it with standing up a center to support the contract. The CADD Center worked to integrate and standardize CASE products with those offered on the contract while supporting legacy products, thus providing maximum return on investment from the contract. It conducted training, consulted on CADD use, developed user manuals, and held workgroups and symposia on various topics, such as integration with GIS. Because of the program's success, when the Corps moved to a tri-services contract managed by the Naval Facilities Command for CADD and GIS products in 1991, ITL became the Tri-Service CADD/GIS Technical Center in 1992.²⁹¹

Several programs in 1988 and 1989 added new equipment to ITL. In Phase IV of CEAP, WES participated in acquisition of CDC computers to replace all existing mainframes supporting administrative functions. This, the third procurement under CEAP, was the largest computer contract awarded to date for the Corps and one of the largest in the federal government. ITL supported benchmarking and technical specifications for the systems, which included the CDC 962 with an industry-leading 36 GB of storage and office automation programs such as WordPerfect. In 1985, WES had begun negotiating to acquire one of seven supercomputers planned for the Army. By 1988, the purchase of a Cray Y-MP had begun. In the interim, ITL purchased a VAX 8800 with more than 100 remote terminals, which provided access in 1988 to the Tank-Automotive Command supercomputer and, after 1989, to the WES supercomputer. At its installation, the latter was the fastest supercomputer in the Army. Within months, WES saturated about 90 percent of time on the supercomputer, which dropped eventually to around 50 percent, with the rest used mostly by the Air Force, Navy, or other Corps labs, who could access the system through the Internet, the Army Supercomputer Network, or modem



Narayanaswamy Radhakrishnan,
also known as Dr. Radha.

connection to the VAX. One of the first major uses of the supercomputer was a visualization of Chesapeake Bay water quality model that incorporated analysis of a dozen different chemical elements, which was so successful Radha, James R. Houston, Jeffery P. Holland, Don Robey, and others used it as a demonstration at a convention later that year. Later projects, such as analysis of the 1993 World Trade Center or 1995 Khobar Tower bombings, calculating the movement of millions of pieces of glass, concrete, and metal, were extremely useful in forensic examination of these events, as well as development of solutions to reduce casualties and damage in future terrorist attacks.²⁹²

In 1989, the HQUSACE Civil Works Directorate assigned a new mission to ITL – the Civil Works Guidance Update Program. Because of underfunding, the Corps had not updated engineering manuals for 25 years on average, some for more than 60 years. For example, Corps standards still used working stress design procedures, while the architecture-engineering-construction industry routinely used load factor resistance design, which resulted in more efficient and less costly steel structures. Because of its close involvement in CASE development, which captured engineering best practice in developing software requirements and criteria documentation, ITL was the ideal choice for the program. As noted previously, WES had long been involved in hydraulic design criteria, and was also briefly involved in updating technical guide specifications until HQUSACE transferred the mission to Huntsville Division in 1978. On being assigned the new mission, ITL established a Guidance Update Center to manage updating the more than 350 manuals, circulars, handbooks, regulations, and guide specifications. In the five-year program, HQUSACE determined the need for updates and assigned the work to laboratories or field organizations, which the center then coordinated and managed. This included conducting studies, product evaluations, and technical reviews as well as preparation, publication, and printing of new guidance. The center oversaw workgroups that included prominent engineers such as Thomas Mudd, Robert Kauffman, Donald Driscoll, William Kling, Herman Getty, and many others and worked to build a consensus on the new standards, often a highly political process. By 1992, the center completed updates on a little less than half of the manuscripts; by 1994, it had completed review of 310 and published 232, with the remainder completed and printed in 1995. Because of the success of the program, HQUSACE established a follow-on program in 1995 to maintain the manuals into the future. This project, a direct result of software development efforts in the Corps, was according to Radha one of the greatest accomplishments of ITL. It was also the most unforeseen result of information technology research, which became a driver of standardization and helped capture engineering knowledge. As Timothy Ables, Radha's long-time deputy, later observed, Radha "recognized before most how much knowledge and skill would be lost.... He did a lot of work with people to capture what they knew, their techniques and developed that into automated systems."²⁹³

While ITL expanded, the other Corps laboratories established their own Information Management organizations in 1986 and 1987 as required by the Army. ETL established its IMO headed by B.F. Kerns, CERL an IMO headed by Diane P. Mann, and CRREL an IM Division headed by Armando J. "Joe" Roberto. Each worked to integrate computer, audio-visual, publishing, and library services. Responsibility to maintain technical data expanded considerably with a 1983 Department of Defense directive and 1985 regulations to establish technical

information analysis centers. After 1987, the Corps established centers for airfields, pavements, and mobility; coastal engineering; cold regions; concrete technology; hydraulic engineering; soil mechanics; and the environment. At CRREL in particular, the result was a significant expansion of its library from 1987 to 1994 to a 4,800 square-foot facility containing 300,000 volumes. The WES library supported the other centers. The IMOs also aggressively upgraded computer infrastructure over the next several years. For example, CERL re-cabled its computer center and buildings and implemented microcomputers – primarily IBM XTs connected to UNIX-based servers. CRREL developed a five-year Information System Plan, installed state-of-the-art networks and switches and its first UNIX-based system, and became manager of the Corps electronic bulletin board system. At least initially, however, none of them were as involved in developmental efforts as at ITL and instead focused on general internal support. Although ETL established an Information Systems Engineering Branch in 1987 to aid development efforts and IMOs had programming experts, most software engineering took place in other divisions within the laboratories. After a 1989 visit to ITL, Roberto saw it as a model for CRREL to establish a successful IM program and worked to develop a long-term relationship with ITL. Nevertheless, although ITL built a credible research organization, some in the other labs questioned its mission, initially seeing it as little more than a glorified IMO.²⁹⁴

The Limits of Computers

Despite the growth of computer use, there remained a need and use for physical experiments and equipment development. Most senior engineers recognized the limitations of computers. As Geotechnical Laboratory Chief William Marcuson observed, “With high-speed computers with wrong assumptions, you can make more mistakes than I can with a slide rule in a



Robert W. Whalin.

lifetime.” Soon after becoming technical director of WES in 1985, Whalin tasked the lab directors to develop a wish list of experimental facilities. The mathematical nature of recent engineering studies at WES and its long-time focus on applied research had created a sense that it was more a testing facility than an experimental laboratory. Observed Whalin,

People around here still talk about tests. I tried to abolish that word from the vocabulary. Technicians do tests. Engineers do experiments.... Doing computational stuff is not going to keep this organization here and at the forefront. What we are known for is experiments, and that is our heritage.

Most equipment at WES existed in greater precision at universities and other research centers. In his mind, what would set WES apart from other labs and enable its existence “as far into perpetuity as it can stay” was the capability to solve large engineering problems using expensive experimental equipment that only the government could buy. Whalin pointed as an example to the large wave tank he had built at WES as director of CERC the previous year or the recently completed rip-rap test facility. The managers returned after several months of brainstorming, and at

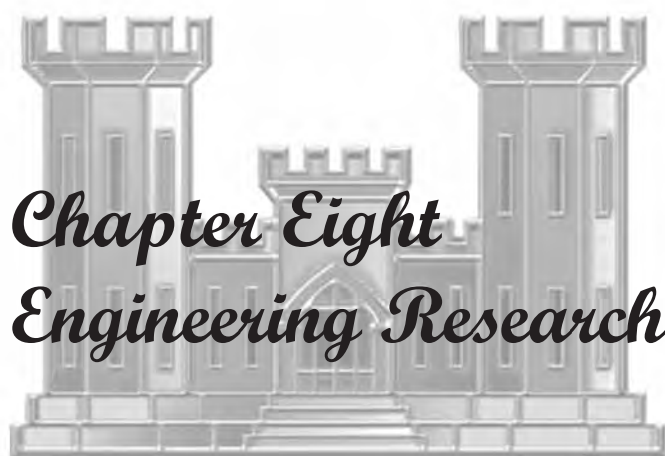
first, no one developed major ideas other than Radha's suggestions for a high-bandwidth network and a supercomputer. Whalin sent them back to the drawing board, and finally several other ideas emerged. Although it took him many years to figure out how to pay for the new facilities through Plant Replacement and Improvement Program money or by re-budgeting unused project funds, by the time he left Vicksburg, Whalin greatly expanded WES experimental equipment.²⁹⁵

The first item suggested was a large centrifuge. Since 1931 when Philip Buckley of Columbia University first performed testing using a centrifuge, engineers had sought to use these facilities to put greater pressure and gravity on soil, rock, and structures, with the Soviet Union having led centrifuge research since 1936. WES leaders had discussed getting a centrifuge ever since former director Fred Brown had seen some in Russia, but had never been able to afford one. Since 1982, Richard H. Ledbetter had conducted research in England using Cambridge University's centrifuge, and in response to Whalin's proposal suggested the idea once more. WES contracted Accutronic of France to build the 6.6-ton maximum payload and 350-g maximum acceleration centrifuge. Several problems followed. Accutronic went bankrupt in 1992 before final assembly, and the French government nearly seized the parts to be shipped in its assets claims. A company in Japan likewise sought to get the parts. Finally, after several months of negotiations, WES arranged shipment to Belgium then to New Orleans and Vicksburg. Installation began on the \$6 million centrifuge in a \$3 million facility in 1995. Other facilities added included a 100,000-pound Big Foot or Heavy Vehicle Load Simulator needed to test the C-17 aircraft, a Mobile Ballistic Research System to test projectile penetration and fractured media on a large scale, and an upgraded Projectile Penetration Facility to include flash x-rays and other instrumentation. Whalin also upgraded the Analytical Chemistry Laboratory and the Hazardous and Toxic Waste Research Facility.²⁹⁶

A last piece of experimental equipment added was the Large Scale Experimental Flume or ESTEX. As discussed earlier, questions had arisen periodically about the accuracy of physical hydraulic models resulting from model distortion as well as problems simulating salinity and sedimentation. Keulegan himself believed that all salinity models were flawed that had a distortion greater than 8:1, which would make many models impractical. By the mid-1980s, many engineers believed 3-D computer models made physical models no longer necessary. When Hydraulics Laboratory Chief Frank Herrmann discussed it with his staff after Whalin's request, McAnally and others proposed a large 10:1 "superflume" to test these and other issues. As T.M. Parture and others later argued, "the upper limit of success of any numerical model is limited to the level of understanding of the physical processes," which can be gained either through field observation or physical modeling. "The traditional role physical models played in coastal engineering in the past has changed, however, the importance and necessity of experimental hydraulics continues to prevail." Unfortunately, most models were too small and device-specific and too far from real conditions in nature. Design of the ESTEX began in 1989. After questions arose as to its adequacy, in 1994 McAnally held a conference of leading hydraulics specialists, who called for a larger facility. Final designs provided for a 520- by 420-foot flume that included a 420- by 69-foot basin, a 480- by 10-foot flume, and a 58- by 50- by 10-foot deepwater basin, although, as events later revealed, even this proved insufficient to attract much academic attention.²⁹⁷

The other labs, meanwhile, continued physical experiments, for which they developed their own facilities. CRREL, for instance, whose program included a much larger percentage of basic research than the other labs, focused less on computers, although it did apply them greatly in remote sensing, sea ice modeling, and other areas. The addition of the Ice Engineering Facility in 1978, which contained a modeling room, flume, and test basin, allowed hydraulic experiments in a refrigerated space. In 1985, it added a 29,000-square-foot Frost Effects Research Facility and a new cold room complex, and in 1988 an Environmental Equipment Test Facility to test equipment performance in cold conditions. In addition, a large percentage of its work remained on-site experiments in Greenland, Antarctica, Alaska, the Arctic Ocean, and other frozen locations. Although CERL developed computer programs to aid in construction design and maintenance issues, it also maintained unique test equipment such as the Shake Table, an HVAC Test Facility, a Low-Frequency Impedance Tube to investigate low-frequency noise, and acoustic field test sites, and it experimented widely with paint and building materials. Such experiments proved that as useful as computers were in modeling and solving many engineering problems, they could never completely replace many experimental research activities, although they often aided, organized, and guided such research. At ETL, despite its increasing focus on software development, digital photogrammetry, and GIS for the warfighter, its main customer – the Army – had the greatest need for hardcopy maps because of the still limited capacity or mobility of most computer systems. Physical mapmaking remained a bottleneck, but the “countless efforts to automate the process” had resulted in “decidedly marginal results,” as historian Robert Hellman observed. It was for this reason that the Terrain Analysis Center and its focus on physical analysis were so successful. Likewise, most developers realized, as John Benton did, that no matter how advanced the program, a computer remained a tool to aid not replace human engineers by “getting it to do what we lack the time to do.”²⁹⁸

Information technology radically changed the research capabilities as well as the research methods of the Corps. By 1990, its laboratories regularly leveraged computers to complete engineering and construction tasks faster and more accurately than previously possible. Designers could create models of greater fidelity than with physical models or mere hand-calculation. Engineers could collect volumes of information automatically from far flung stations, store and instantly retrieve decades of data, and correlate them almost instantly to analyze trends. Topographers and planners could quickly create digital geographic systems that merged a variety of data and plotted accurate maps far faster than a man could draw them. Each Corps lab developed systems to support these functions, which not only automated the activities of the Corps but captured engineering knowledge for easy use by future generations. Computer use had become so important that WES made it the subject of research at ITL. Yet aside from improving the ability of engineers to solve difficult problems, information technology helped to change the culture of the labs, providing more time for research, improving communications, and increasing collaboration. In doing so, it removed what had long existed as the primary impediments for forming a consolidated research and development organization – distance and the political challenges of merging all research activities at a single location. All that remained were the economic and political impediments, which were quickly falling to the wayside.



Chapter Eight *Engineering Research Comes of Age*



ERDC researcher carries out an experiment in the Analytical Chemistry Laboratory.

By the early 1990s, Corps of Engineers laboratory research was more than 65 years old, and all but one of the major laboratories in its research and development system were at least 20 years old. Nine laboratories at four locations – six of them at the Waterways Experiment Station (WES) – had evolved over the years and now provided the nation's leading research and technology development in hydraulics, coastal engineering, geotechnology, structural engineering, construction materials and management, cold regions engineering, environmental engineering, topography and photogrammetry, and computer-aided engineering and modeling. Over many decades, the Corps had been heavily involved in the origin and development of several of these fields and had greatly advanced the technical knowledge of engineers working across government and industry. The vastly diverse research programs had now, for the most part, reached a state of maturity and stability, with the result that they consistently delivered value to the Corps community in both its military and civil works responsibilities, as well as to the U.S. engineering profession as a whole. New laws requiring the transfer of government-developed technology to the private sector increased the contributions of Corps research to even greater levels, making the Corps the ad hoc engineering research agency, not just for the Army, but for the nation.

However, times were changing. The end of the Cold War, shifts in military missions and technology, reorganization of the military and Corps of Engineers, concerns about federal budget deficits and budget cuts, and the increasing need for multidiscipline research combined to raise once more the issue of consolidating Corps research and development into a single organization. It was a drive that had never fully subsided. Several of the individual laboratories went through major organizational changes to address the shifting horizon, including some that impacted all of the labs. One of the most influential changes was the decision by WES Director Col. Ernest D. Peixotto in 1972 to move to a laboratory rather than a divisional organizational structure, a change that WES Director Robert W. Whalin called one of the most brilliant in its history. Within a decade, the Corps established civilian Senior Executive Service directors at the labs, as well as other organizations, and in 1989 directed that they report to a general officer or higher rank civilian according to federal guidance, leading to the promotion of Whalin to civilian director with a military commander serving as deputy. By the early 1990s, the other labs followed suit as they developed laboratory and civilian director structures. Another change was a cost-cutting measure of the Carter Administration that federal research organizations not use private consultants, which ended a 40-year practice of Corps labs relying on the guidance of leading academic advisers. Other changes at the labs created cost efficiencies by consolidating activities and improving cooperation. Despite these changes, with increasing Army demands for efficiency, the Headquarters of the Corps of Engineers (HQUSACE) determined that the best way to ensure the continued existence of its laboratories was to align them closely in a single research and development center. The political challenges of an organizational change were great, potentially impacting the location, leadership, employment level, workload, traditions, and culture of each lab. Yet many argued that only the resolution of these issues would ensure continuation of Corps research, though greatly changed in appearance.²⁹⁹

The Merging of Coastal and Hydraulics Research

The original laboratory that was WES – the Hydraulics Laboratory (HL) – continued its development of both physical and computer models. By 1990, most hydraulics research was computer-aided. Major projects for the Chesapeake Bay, Los Angeles Harbor, San Francisco Bay, the Great Lakes, Redondo Beach, Savannah Harbor, and Truckee River all involved increasingly complex 2-D or 3-D computer models or simulations. In this, both HL and the Coastal Engineering Research Center (CERC), located at WES since 1983, played a leading role. These models were particularly useful in analyzing difficult issues such as salinity, sedimentation, wave movement, hurricane surge, and other complex estuary or tidal processes. As noted in earlier chapters, it had always been difficult to accurately depict these issues in physical models, but it was only in the mid-1980s that computer models were sufficiently sophisticated to calculate the multiple algorithms required. Prior to 1990, most researchers used computer models in tandem with physical ones to achieve true 3-D representations. In addition, using digital models allowed easier publishing of data on the Internet, as CERC did with coastal and wave hindcast data, and it allowed easier re-examination of problems without the expense of rebuilding physical models. For example, the labs were able to apply numerical models to the Columbia River, Atchafalaya Basin, New York Bight, and other troublesome and frequently modeled bodies. In some cases, they used WES- or contractor-developed models, such as the TABS suite of generic modeling programs, the PLUME chemical plume modeling program, or the widely used Advanced Circulation Model (ADCIRC). In others they adapted and improved popular models such as the National Oceanic and Atmospheric Administration (NOAA) SPLASH models or the CH3D model developed by Peter Sheng.³⁰⁰

The latter was central to developing one of several advanced models at WES. The Chesapeake Bay Model Package was a highly complex 3-D numerical model developed by HL, CERC, and the Environmental Laboratory. Funded by the Army and EPA to examine decline in vegetation and shellfish, the model included a time-variable version of CH3D to examine long-term changes



Chesapeake Bay Model.

in vertical density, a post-processor to add intertidal processes, and a water quality model that examined 22 variables including algae, salinity, temperature, and various chemicals to predict oxygen and sediment flux. Another major effort involved the Department of Defense Groundwater Modeling System, which WES developed over a decade with partners that included the Cold Regions Research and Engineering Laboratory, Air Force, Department of Energy, EPA,

U.S. Geological Survey (USGS), industry, and 20 universities. The 3-D model, which found use at numerous remediation sites, included a geostatistical library, animation tools, and links to geographic information systems. Combining the system with the popular Surface Water Modeling System and Watershed Modeling System essentially allowed analysis of all aspects of water movement. More than 4,000 copies of the Groundwater Modeling System were in use in 2009, and it formed the basis for advances in computational testbeds used for missions ranging from environmental management to detection of improvised explosive devices.³⁰¹

There also continued some physical scale modeling of waterways, although such models were “exceptions instead of the dominant tool,” as Lewis E. “Ed” Link, a former deputy CERC director, observed. Some physical modeling of hydraulics issues continued, such as one of Ventura Harbor, California, but most physical models involved testing the operation or placement of structures. From 1990 to 1998, WES modeled Mississippi River Lock and Dam No. 19, No. 22, and No. 25; Truman Spillway, Missouri; a new Bonneville Lock, Washington; and in 1995 became involved in testing dozens of lock designs as part of the Innovative Lock Design Program. In some cases, such models were highly innovative. For the Olmsted Lock, when computer modeling and physical modeling were unable to accurately show the behavior of the gates, Robert Hall of the Structures Laboratory (SL) led development of a working model of the wicket gates, while another model tested two different types of riprap. Some hybrid modeling also occurred, as with the Red River model and integration of Hydrologic Engineering Center (HEC) software with physical models, but for the most part, WES primarily used physical models to verify computer model results or if there was a problem that computer models could not solve. Nevertheless, many engineers continued to push for the need for physical modeling because, as William McAnally noted, “there is no substitute for watching water.” Using such models, HL provided consulting to other agencies through the Hydraulic Engineering Information Analysis Center. HL and other labs not only supported the civil works districts, but also remotely consulted for Army engineers to support operations Desert Storm, Joint Endeavor, and Restore Hope in Kuwait, Bosnia, and Somalia, which evolved into the highly successful TeleEngineering Program.³⁰²

At CERC, in addition to modeling, there remained a greater emphasis on experimental basic research. CERC supported various attempts to gather coastal data, including monitoring of coastal and beach fill projects. Under the Coastal Engineering Data Retrieval Systems, it helped automate collection of coastal data, which it used in building hindcasts for the Wave Information Study. The 1990 Surface Wave Dynamics Experiment conducted for the Navy collected wave data and documented interaction between Gulf Stream currents and waves, while the Coastal Inlets Research Program, launched in 1994, helped gather data on sedimentation processes. CERC conducted several experiments at its Duck, North Carolina, Field Research Facility under the guidance of Curt Mason, particularly the 1992 SAMPSON and DELILAH experiments to investigate underwater acoustic noise and near-shore hydrodynamics. Data collected in SAMPSON in cooperation with the Office of Naval Research fed into DELILAH, in which more than 70 personnel from multiple organizations collected wave, current, beach changes, and surf characteristics using the Coastal Research Amphibious Buggy, a large mobile instrument tower. It produced some of the most detailed near-shore data in years. In the DUCK94, Coastal Ocean Processes, and Sandy

The Bosnia Boys and the Sava River Model

It was 3:00 a.m., December 26, 1995, when Waterways Experiment Station (WES) Commander Col. Bruce K. Howard received a phone call from an Army captain trying to build the largest pontoon bridge since World War II over the flooding Sava River in Bosnia. In early December 1995, President William J. Clinton approved the use of U.S. troops for Operation Joint Endeavor, a United Nations peacekeeping mission in war-torn Bosnia-Herzegovina, where ethnic conflicts between Serbians and Bosnians had raged for years. Moving rapidly into position across the border from Croatia, the troops faced a formidable obstacle in the Sava River in a foreign land where there were few maps and little hydrological or meteorological data.

Within hours, Howard had called in personnel to work the project, including William Martin, Mark Jourdan, and other engineers from WES and the Cold Regions Research and Engineering Laboratory (CRREL). The team worked around the clock to try to predict flood levels. Finally obtaining limited data from the Croatian Flood Ministry through a British operative, less than 72 hours later the team successfully predicted that the river had crested. At approximately the same time, Brig. Gen. Pat O'Neal of the 1st Armored Division requested additional data to support continued decision making. The river had exceeded its highest stages, overtopped levees, and washed away access roads and construction camps needed to move supplies and troops.

Working with Mike McClain and others from CRREL to obtain climatic data and the Topographic Engineering Center (TEC) providing terrain data, WES engineers built



Destroyed bridge at Sava River.

a watershed model of the Sava River. It was, as Jourdan observed, “‘seat-of-the-pants’ engineering” because of the difficulties in getting the data they needed, which, due to the 63,000 square-kilometer area of the watershed, were immense. They pulled together any and every data source they could find, from CNN reports on snow depth to Internet or e-mail

sources to data pulled from bombed out buildings in Sarajevo. The team was able to create a working model by January 3, 1996, but, needing more accurate data to continue sending out updated reports, the team deployed engineers to Bosnia on January 17.

Beginning with an initial two-man team, the so-called “Bosnia Boys” eventually grew to include more than 20 engineers from WES, TEC, and CRREL. Multiple teams met with local officials, reviewed flood control works, collected data on snow depth, took surveys, and



Constructing the Sava River floating bridge.

gathered velocity and stage data of the river at various locations using dozens of gauges and meters dropped in the river. One team inspected bridges and proposed bridge sites. Another tested a snow plow modified by CRREL especially for the Vermont National Guard. A third helped the 130th Engineer Brigade with camp site and road selection. The duty was sometimes hazardous, as the team had to occasionally check for mines.

Back in the U.S., the team sent daily e-mails with current data and predictions up to 10 days out, which, at least through February 20, were accurate within three inches. Eventually, the team established a website to download data, which it maintained for more than two years. The team answered many other calls on a regular basis. WES helped provide mobility evaluations for the U.S. sector muddled by the spring thaw and conducted seismic analyses. CRREL analyzed weather patterns and developed a concrete



Completed Sava River bridge in use.

additive to allow setting under freezing temperatures. TEC fulfilled daily requests for mapping data, including maps of transportation routes, surface water locations, and water supplies in 16 cities.

As a result of the success of the mission, WES created the TeleEngineering Program,

through which it provided remote support via e-mail, Internet, or telephone to deployed units requiring engineering data. As one engineer noted, “We constantly remember that those are our men and women over there, cold and wet and up to their waists in mud. We’ll do anything we can for them.”

Duck experiments, entities including the Navy, NOAA, the USGS, National Science Foundation (NSF), colleges, and foreign governments participated in collecting data on beach erosion, sediment transport, and near-shore oceanic processes. Other experiments took place in the laboratory. CERC participated in the 1991 SUPERTANK sand movement study at Oregon State University and eventually built a Large-Scale Sediment Movement Tank at WES in 1995. Various studies on erosion control, groundwater, and dredging involved computer modeling of various problems, and CERC helped in the development of technologies such as breakwater designs, CORE-LOC concrete breakwater armor units, water injection dredging that fluidizes sediment, and the helicopter-based Scanning Hydrographic Operational Airborne LIDAR Survey system for taking bathymetric surveys. HL likewise aided in developing and evaluating various technologies, such as formed suction intakes for storm water pump stations and pumped-storage operations in dams.³⁰³

In 1996, after more than a decade of CERC maintaining a separate existence in Vicksburg, Whalin quietly merged CERC and HL to form the Coastal and Hydraulics Laboratory (CHL). Despite their important work in basic and applied research, the organizations were the smallest WES laboratories, and their funding had remained flat from 1994. Declining federal budgets, fewer labor-intensive physical models, pressure to outsource many activities, and high overhead costs combined to make it increasingly difficult to justify two separate laboratories with closely aligned projects. After long-time HL Chief Frank A. Herrmann retired in 1995, in October 1996 Whalin called CERC Director James R. Houston into his office and appointed him director of the new organization. CERC continued to exist within CHL, but as a policy-setting and oversight body and an interface to the Coastal Engineering Research Board, which continued to meet and provide guidance to CERC as it had since 1963 according to law. Actual research and technical support came from CHL. The merger came as a shock, especially to HL personnel who lamented loss of identity of the oldest WES lab. By early 1997, as a result of a Corps directive for districts to increase outsourcing of engineering studies in late 1996, the situation deteriorated when lab funding dropped from \$64 to \$50.1 million, which did not cover staff salaries. Since CHL used nearly all reimbursable civil works funding, it was severely affected as the districts requested return of funds and reworked their project loads until the next fiscal year. In February 1997, Houston initiated a major program of staff and overhead reductions in a draconian effort to save the lab. By the end of the year, he had eliminated more than a dozen positions without reductions in force through voluntary buy outs, a hiring freeze, and transfers. He also reduced the seven divisions to four – Estuaries and Hydrosiences under McAnally, River Structures under Phillip G. Combs, Navigation and Harbors under Claude E. “Gene” Chatham, and Coastal Sediments and Engineering under Thomas W. Richardson. With increased synergies between the divisions and with aggressive marketing of the laboratory’s services, Houston returned it to profitability and by 1999 had grown its funding once more to \$60 million per year.³⁰⁴

Militarization of Geotechnical Research

Since formation of the Soils and Pavements Laboratory in 1972, geotechnical research at WES had become increasingly concerned with military missions. Pavement performance often concerned soil conditions, plus adding military construction-oriented pavement research to civil

works-funded soil mechanics and dynamics research ensured a consistent flow of funding. Soon, military research overtook the civil. In 1982, pavement research returned to its World War II roots when the laboratory started a new investigation of airfield pavements at 17 tri-service locations to determine their current condition and capacity, mostly using nondestructive testing – falling weight deflectometers, spectral analysis, radar, and other methods that did not require taking a physical soil sample. WES had been experimenting with nondestructive testing for several decades through the work of Jim Hall and others.. It also conducted studies of the types of pavements needed for super heavy aircraft, such as the C-17 cargo plane, for which it purchased a heavy load simulator that could place loads on pavement in laboratory conditions. One lasting result of pavement research was development of the Pavement-Transportation Computer Assisted Structural Engineering computer program by Walter Barker and Robert Walker. The lab worked with SL, the Federal Aviation Authority, and others to develop design criteria for new paving technologies such as resin modified pavement that mixed asphalt and concrete, roller-compacted concrete, paving blocks, joint sealants, dust control, geogrid-reinforced pavements that used polymer nets to strengthen asphalt, fiber reinforcement of subsurface soils and sand, and micro-surfacing that mixed polymers and asphalt. Harkening back to portable landing mat projects, the lab developed new lightweight interlocking hexagonal aluminum, fiberglass, and plastic mats for building temporary roadways, as well as membranous fiber mats for expedient repair. In a newer mission, the lab also conducted analyses of railroad maintenance and rehabilitation. The Army and Air Force maintained roughly 3,500 miles of railroad at 181 installations, much of which now faced maintenance problems. The lab developed a four-point maintenance program, tested various materials, completed a Handbook of Railroad Track Standards in 1990, and, under the leadership of David Coleman, developed a railroad car-based deflection device to test railroad ballast and tie conditions under heavy vibrations.³⁰⁵

The increase in military funding continued with the addition of mobility research to Soils and Pavements in 1978 to form the Geotechnical Laboratory (GL). As it had since 1970, the primary focus of the Mobility Systems Division was developing software to model mobility in various locations using multiple vehicle types, resulting in the NATO Reference Mobility Model and the PC-based Condensed Army Mobility Model System (CAMMS). In 1994, it completed a new stochastic or nondeterministic model that predicted time of travel based on complex scenarios and factors such as speed, terrain, mobility, and combat risks. In 1991, it completed work on the Engineer Model Improvement Program, a multiyear effort to improve Army-wide models used to plan combat scenarios, and began testing the Obstacle Planner Software simulation and Unit Movement Planning System software programs to aid in planning movement under various mobility constraints. In 1988, the lab began work with the Toxic and Hazardous Material Agency on adapting its cone penetrometer to detect soil contamination using fiber optic cable to view the soil, resulting in the 1990 Site Characterization Analysis Penetrometer System (SCAPS). Although the Environmental Laboratory (EL) assumed responsibility for its continued development, the Mobility Systems Division was responsible for its initial conceptualization and development. Further research with penetrometers achieved the first reliable test results of the devices with gravel in 1997.³⁰⁶

GL also continued testing vehicle mobility, vibration, and loading in various soil conditions, including the High Mobility Multipurpose Wheeled Vehicle (HMMWV or Humvee), Family of Medium Tactical Vehicles (FMTV), Combat Mobility Vehicle, and Light Armored Vehicle. To aid these tests, the lab completed a test track for developing tire inflation standards and over several years built a series of test beds to gauge vehicle concepts before prototype development. Perhaps the most significant research relating to vehicle mobility involved the Abrams M1 Tank



Bradley fighting vehicle swim test.

and M2 Bradley Fighting Vehicle. In 1986, the Tank-Automotive Command tasked WES to test the M1 when its track began slipping and overheating during early trials. Since GL had been involved in testing earlier models, it applied its expertise to fixing the track problem, as well as conducting general studies of tracked versus wheeled locomotion. Initial tests

indicated problems with the pins and pads on the track, and over the next five years WES helped to design new pads and pins. WES became involved in the Bradley vehicle very suddenly after the news program *60 Minutes* began investigating flaws in the vehicle that had led to several accidental deaths during training. At the request of Undersecretary of Defense James Ambrose, mobility researchers flew overnight to the Chattahoochee River in 1986 to ensure the vehicle and drivers could perform riverine egress operations. Additional research in Louisiana and Arkansas over the next two years helped to improve its swimming capability under various armored levels. Other testing occurred to support Operation Desert Storm and Operation Joint Endeavor to establish tire inflation and vehicle operation standards under extreme terrain and climate conditions.³⁰⁷

Of course, GL also continued a wide range of research to support civil works and became heavily involved in development of construction and maintenance technologies as part of the Construction Productivity Advancement Research (CPAR) and the second Repair, Evaluation, Maintenance, and Rehabilitation (REMR-II) programs, the latter of which spanned seven years and \$35 million. In the Mississippi River Stability Study, it studied bank failures and the success of articulated concrete mattress revetment. It conducted studies of soil foundations for various structures, shoreline erosion at reservoirs, cleaning and maintenance of wells, interaction in earth structures made from geotextiles or other elastic materials, detection and mapping of groundwater and leaks, and levee rehabilitation techniques using soil stability analysis and vegetative plantings. By 1992, it started evaluation of trenchless construction techniques such

as directional drilling and microtunneling that allowed placement of pipelines under levees and rivers without disturbing them. In another project, the lab developed systems to aid in profiling river bottom and subbottom soil conditions, greatly advancing the field of submarine soil mechanics. Perhaps its largest area of civil research, which the lab supported since 1972, was earthquake engineering. The lab conducted seismic stability analyses of earth- and rock-fill dams in a dozen states and Panama, and used modeling to assess potential hazards for critical structures such as military bases, large dams, and Department of Energy labs. A major seven-year program initiated in 1991 involved remote measurement, prediction, modeling, and response plan development for water resource structures in 32 states and Puerto Rico. Such research entered a new phase with the purchase and construction of a large centrifuge facility at WES in 1995, which allowed testing of materials under even greater stress. Although GL transferred some earthquake studies and most other soil dynamics work to the Structures Laboratory, it also continued research of liquefaction through the development of new methods for analyzing hydraulic fill dams. Yet, even some of this research was put to military or law enforcement uses. For example, microgravity-based analysis of soil and rock density was widely used in locating tunnels, mainly to detect drug trafficking and hidden bunkers. Based on expertise gained in all of these areas, the lab established information analysis centers to help consult on pavement, mobility, and soil mechanics issues and a fully equipped Materials Testing Center.³⁰⁸

Growth of Civil Structural Research

While GL research gradually became more military-oriented, the mostly weapons-oriented SL became involved in several new civil missions. The formation of SL in 1978 from the Concrete and Weapons Effects laboratories and the Soil Dynamics Division of the Soils and Pavements Laboratory enabled it to achieve greater cooperation in weapons research, although the groups continued to function separately to a large degree. Over the next two years, Bryant Mather and William Flathau merged two of the Weapons Effects divisions – Phenomenology and Explosive Excavation (formerly the Nuclear Cratering Group) – into a single Explosive Effects Division led initially by Jerry Brown. The Structures Division became the Structural Mechanics Division under James Ballard, and the Soil Dynamics Division became the Geomechanics Division led by Guy Jackson. All three were primarily concerned with military applications with only occasional civil projects. The three concrete divisions merged in 1981 as a single, large Concrete Technology Division led by John Scanlon. With the end of the Cold War, however, the military mission declined somewhat even though it remained the largest of the lab. Despite a large number of projects, funding levels and employees working on weapons effects projects declined. As a result, SL merged the smaller Geomechanics and Explosion Effects divisions in 1995.³⁰⁹

Most of the work of the lab remained weapons-oriented, and in 1992 the Defense Nuclear Agency named it the lead laboratory for tri-service weapons effects research. SL continued penetration tests of structures and rock to better predict the effects of conventional and chemical weapons, determine target vulnerability, and develop means of protection. The result was development and evaluation of several hardened structures, such as field fortifications, tunnels, mobile command



Khobar Towers after the terrorist attack.

centers, and antipenetration shields. In some cases, SL tested the effects of new weapons, such as the 1991 evaluation of bunker buster bombs in the Projectile Penetration Research Facility under Bob Rohani, or developed protective technology, such as the work of Bill Huff on geocomposite barricades to protect parked aviation assets from blast and fragmentation, or meth-

ods developed by Kim Davis to safely store explosives in Korea in 1997. Also a concern was the effects of explosions, such as land slides, transient loadings, and free-field shock. Although the lab experienced several years of decline in explosives research following the end of the Cold War, it saw tremendous growth in forensic investigation of terrorist attacks after the 1995 bombing of the Alfred P. Murrah Federal Building in Oklahoma City, Oklahoma, and 1996 bombing of the Khobar Towers in Saudi Arabia. The Army requested WES to support investigations of the bombings using its expert knowledge of explosives, and SL was able to apply the knowledge it gained to improving protection and construction techniques to reduce bomb effects. Over several years, it conducted hundreds of building explosion and fragmentation experiments using dozens of instruments to capture and record the effects. Experiments with explosive excavation also continued with the excavation of Swan Lake, Mississippi. To support these projects, WES upgraded its test site on the Big Black River, Mississippi, and worked to develop new instruments, such as a high-pressure triaxial device; the trailer-mounted Mobile Ballistic Research System for penetration testing; and high-shock, high-stress, high-temperature gages for use in blast environments. As with other structural fields, computers played an increasing role in modeling penetrations and explosions through the development of new discrete deformation models as well as computer-based programs to plan demolition or antiterrorism activities. In particular, the Hybrid-Elastic-Plastic, Microplane, and Nonlinear-Inelastic-Fracture models analyzed wave propagation in underground materials. Based on this expertise, it also was able to support Desert Storm and other operations, primarily through the Munitions Effects Assessment Community, a Defense-wide working group that provided damage assessments to combat units within 36 hours. It used this experience to help develop another program, the Munitions Effects Assessment Expert System.³¹⁰

Yet the civil and military construction content supported by the Structural Mechanics and Geomechanics divisions had also started to grow. The lab had been involved since the early

1980s in testing sheet piles and floodwalls in New Orleans, work that continued into the 1990s. It developed methods and software for the inspection, maintenance, and repair of the more than 3,000 bridges under Army responsibility and experimented with explosively formed penetrators for bridge demolition, which both had broad civil application. It also helped to test SUPERSCANNER, which uses ultrasonic pulse echo to analyze concrete bridge decks. As with GL, SL conducted CPAR and REMR-2 work related to maintenance of steel and concrete structures, which continued under the Civil Works Structural Engineering Research Program. Much of the weapons-related research had application in the closely related fields of wind and earthquake effects analysis, and, although GL had responsibility for most earthquake-related research focusing on soils, by the early-1990s SL had become involved in conducting seismic analysis of the impact of earthquakes on structures. Starting with the Seven Oaks Dam, California, and the Olmsted Locks and Dam, SL went on to analyze intake towers at more than 70 earthen dams and supported investigation of dams in cooperation with the Bureau of Reclamation. One of the more interesting SL projects involved computer analysis of rails for magnetically levitating (Maglev) trains. The Intermodal Surface Transportation Efficiency Act of 1991 authorized experiments led by the Department of Transportation to develop a Maglev, and Stan Woodson of SL supported the effort through dynamic modeling of loading placed on the train's guideways to determine structural issues.³¹¹

Concrete research, which had been a WES mission since 1946, remained a key SL research area despite regulations developed in 1982 that limited its providing testing services to districts and divisions that were offered by commercial vendors. As it had for decades, the Concrete Technology Division developed new methods of strengthening concrete: extremely durable Pyrament cement mixtures, stronger polymer fiber-reinforced concrete, corrosion-resistant sulfur cement, shock-absorbing concrete that abates sound waves and absorbs penetration, and concrete with surfaces treated with sealants. Testing revealed that its high-performance concrete had increased in unconfined compressive strength to between 27,000 and 35,000 pounds per square inch while increasing in direct tensile and flexural strengths to between 2,000 and 5,000 pounds per square inch. Other technologies enabled faster application and setting of concrete. For example, the lab tested ready-made, slow-drying roller-compacted concrete admixtures used widely in civil works projects and precast concrete stay-in-place sheets that allowed quick and low-cost repaving of lock walls. It continued to test a variety of grouts and repair mixtures, and new testing methods such as for rheology or movement within cement.³¹²

By 1999, both the Geotechnical and Structures laboratories were much smaller than they had been in the previous decade through natural attrition. Even with growing military research in mobility and pavements, GL shrunk from roughly 230 to 130 employees, while SL had shrunk from about 180 to 135 employees. Soon after becoming Chief of Engineers in 1996, Lt. Gen. Joe N. Ballard sought to reduce the number of Senior Executives and raised questions about reorganizing the Corps labs, where there was a large concentration of these positions. Some discussions took place about potentially combining GL and SL, and although both long-time chiefs William Marcuson and Bryant Mather favored change, nothing definitive

was decided while both continued to serve. It was widely anticipated that both Marcuson and Mather – informally known as Captain Concrete – would retire soon. Mather had been one of the early members of the Northeast Division Central Concrete Laboratory that moved to WES in 1946, had served as chief of the Concrete and Structures laboratories since 1966, and, having surpassed 80 years of age, had to receive annual exemptions from retirement. Marcuson started at the Corps in 1970, had been chief since 1983, and planned to retire in 2002. In the interim, no major organizational changes in the labs took place.³¹³

Environmental Restoration and Military Installations

As environmental research in the Corps entered its third decade, the founding missions of EL remained relatively stable. The Corps' longest running ecological mission, Aquatic Plant Control, continued through highly innovative research into computer simulations to predict plant propagation and integrating hydroacoustic sensors with global positioning systems to map submersed vegetation using geographic information systems (GIS). In 1989, EL started work on a five-year plant removal project at the highly infested Guntersville Lake, Alabama, and in 1993 opened the Center for Aquatic Plant Research and Technology to distribute information to the public. The follow-on programs to the Dredged Material Research Program – Dredging Operations Technical Support and Long-term Evaluation of Dredging Operations – carried on at smaller but consistent funding levels, and in 1992 EL formed the Center for Contaminated Sediments to help districts evaluate dredged material. By the early-1990s, growth of the Dredging Research Program to develop dredging technologies increased funding yet again. The Wetland Research Program continued to expand under leadership of Robert Engler and Ellis J. "Buddy" Clairain through completion of the *Wetlands Manual*, training of federal agencies on the Wetland Evaluation Technique, consulting provided to the districts under the Wetland Regulatory Assistance Program, and establishment of the Wetlands Research and Technology Center in 1992. EL also proceeded steadfastly with water quality research. It completed the CE-QUAL0W2 computer model and conducted innovative research into gas supersaturation and eutrophication, conditions in which excess air or chemicals in water cause plant and algae growth or kill fish. As already noted, led by Carl F. Cerco and others, EL helped develop one of the most complex environmental models of the era, the Chesapeake Bay Water Quality Model. The 30-year simulation and hindcast documented the relationship of dry and wet years to eutrophication. EL also consulted for dozens of agencies under the Water Operations Technical Support program. In the natural resources front, EL focused not only on habitat research and protection of threatened and endangered species such as the whooping crane and sea turtle, but also control of nuisance species such as the zebra mussel. EL's military missions – mine detection, camouflage, and obstacles identification – also expanded with the support of GL or SL to help test concealment technologies or identify soil patterns above mines. In 1992, SL assumed responsibility for a revamped Joint Test and Evaluation of Camouflage, Concealment, and Deception program.³¹⁴

Despite continuation of traditional environmental missions, a new overarching concern – environmental mitigation and restoration of current and formerly used military installations

– received ever increasing levels of funding. With the passage of the Superfund Act in 1980, establishment of the Defense Environmental Restoration Program (DERP) in 1984, and inclusion of restoration funds in the 1990 Base Closure and Realignment Act, the Department of Defense (DoD) made it a top priority to clean up its bases. More than 1,800 installations required remediation of industrial and explosive wastes, including unexploded ordnance, with estimated cleanup costs of \$24 billion. After 1991, the DoD made the Army the tri-service lead for DERP research. EL was responsible for aiding site investigations and providing technical advice to Corps and EPA districts, which Michael Palermo and others accomplished through review of mitigation plans, computer models such as the Hydrological Evaluation of Land-fill Performance, further refinement of the SCAPS technology developed by GL, its Environmental Chemistry Laboratory facility, and the Hazardous Waste Research Center – a 10,000 square-foot lab to develop waste treatment technologies. EL invested considerable resources in developing bioremediation technologies to reduce the footprint of TNT, for example, through organic compounds, peroxone oxidation, absorption, and use of electrokinetics to treat heavy-metal-contaminated soil. It led a multi-laboratory effort in 1992 for the LEGACY Biological Resources Program and in 1993 received Strategic Environmental Research and Development Program funding to help advance this field. A major issue involved environmental risk assessment. Beginning in 1993, EL worked with the Department of Energy and Battelle to develop a predictive method – Fate and Effects – that evaluated contamination to a given endpoint based on exposure and effect. Considerable basic research was required to determine geophysical and microbial contamination transport mechanisms. Some of this work was groundbreaking, including developing biomarkers – biochemical features to measure progress of diseases – to identify carcinogens in contaminated soils. It also developed biomonitoring technologies using sensitive molecular probes that glowed in the presence of explosive compounds. In 1996, EL held its first workshop on the method, drawing more than 100 people.³¹⁵

Environmental restoration of military facilities was also a major concern of the Construction Engineering Research Laboratory (CERL) and Cold Regions Research and Engineering Laboratory (CRREL). CERL was mainly concerned with research on environmental impacts of the use of military land and facilities, with its primary focus being on the migration, degradation, and treatment of explosives residue rather than detection and prevention. For example, CERL conducted breakthrough research on the mechanisms by which microorganisms such as bacteria break down munitions-related wastes, it examined the impact of ultrasound on degradation of compounds in munitions plant wastewater, and it developed electrochemical treatments to convert nitrate organics in explosives to amino acids for further treatment by aerobic biological treatment. It also supported specific environmental compliance projects, including industrial waste and wastewater treatment for the Army Industrial Operations Command and DoD-wide efforts involving regulatory compliance and ecosystem management modeling. CERL continued to provide support for land use and conservation issues, including large projects such as drop zone rehabilitation at Fort Bragg, North Carolina, and smaller requests through its Conservation Assistance Program, and it continued to conduct research on threatened and endangered species such as the red-cockaded woodpecker. A significant amount of its environmental

Avoiding Being Musseled Out

The zebra mussel (*Dreissena polymorpha*) – a species not indigenous to the U.S. – was infesting river systems and threatening operation of locks and dams, drainage structures, and private and commercial vessels. Brought accidentally to Lake St. Clair, Michigan, in the ballast water of ocean vessels from northern Europe in the 1980s, they had quickly spread throughout U.S. river systems. With no known indigenous predator, estimates were that their spread could cause \$5 billion in damages by 2000. The Corps had to respond rapidly to control the species.

After passage of the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990, the Corps initiated a four-year Zebra Mussel Research Program in 1992 headed by the Environmental Laboratory (EL) to develop environmentally acceptable control methods. Overseeing the research was the multi-agency Zebra Mussel Coordination Committee that included members of the U.S. Geological Survey, U.S. Fish and Wildlife Service, Tennessee Valley Authority, Bureau of Reclamation, National Oceanic and Atmospheric Administration, Environmental Protection Agency (EPA), and U.S. Coast Guard. After 1993, the first year of full funding, the effort exceeded \$9 million.

In its initial investigations to scope the problem, EL organized a workshop attended by members of federal and state agencies, academia, and industry as well as working groups to help identify public facilities at risk for infestation, analyze the mussels to identify potential control methods, and establish test methods. The workshop – Control



Zebra mussels attached to native mussels.

of Zebra Mussels at Public Facilities – became an annual event attended by more than 200 persons each year to distribute findings.

Preliminary efforts focused on physical removal of the mussels when accessible and use of nontoxic antifoulant coatings developed by the Construction Engineering Research Laboratory for locations out of reach. In addition, the labs tested metal-based paints that resisted attachment by the mussels without affecting indigenous species, hot water treatments, magnetic fields to prevent attachment of larvae, and use of air bubbles to force removal from lock walls. By 1994, the team had established demonstrations of chlorination and carbon dioxide systems for use at hydropower facilities, modification of trash racks at navigation structures to collect the mussels, and filtration systems to keep them out of water intakes for irrigation and water supply.

In 1996, EL evaluated hydrothal, a break-through aquatic chemical agent approved by EPA and the Department of Agriculture. It also completed an evaluation of biological controls (microbes and insects) effective in Eastern Europe and Asia in controlling the mussels. To support control efforts, it developed methods of predicting muscle population growth and characterizing seasonal trends.

At the end of 1996, EL completed its evaluation of coatings that could prevent attachment of the mussels and published its initial guidance. In general, it found that the mussels could not attach to low-surface energy silicone elastomeric and fluorinated polyurethane coatings, or to metallic coatings containing zinc and copper. However, nonchemical methods – such as heat, shock, freezing, or desiccation (dehydration) – accounted for a quarter of all control methods and by themselves had saved an estimated \$10 million.



Lock wall infested with Zebra mussels.

research involved development of environmental management computer systems, including the Defense Environmental Network and Information Exchange, the Land Management System suite of tools, and the Ecological Dynamics Simulation model. In furtherance of the trend toward environmental restoration, in 1998, the Army reprogrammed \$12 million of operations and maintenance funds for the first time to develop environmental technologies, some of which CERL supported.³¹⁶

CRREL researchers continued extensive research related to cold weather-related environmental phenomena, such as working with NOAA to automate mapping of clouds and snow, conducting basic research on the physical properties of ice and ice vapor transport mechanisms, and further examination of climate change through drilling in the second Greenland Ice Sheet Program. But it also researched environmental mitigation issues. Through the analytical chemistry work of Thomas Jenkins and others, CRREL tested low-cost rhizosphere-enhanced biotreatments useful for remediation in cold regions, which it applied to several Formerly Used Defense Sites in Alaska, including Annette Island, Galena-Campion, and Barrow. A particularly difficult problem involved treatment of phosphorus-based munitions at Fort Richardson, which CRREL addressed through speeding the natural break-down of the elements by draining exposed ponds. In 1998, it successfully transferred the screening techniques it developed to detect these munitions to the Ravenna Army Ammunition Plant, Ohio, which achieved \$375,000 in savings at a single site. Other testing procedures, such as field-screening volatile compounds using a portable photoionization detector, promised similar results across the DoD. Daniel Lawson and others conducted several experiments with ground-penetrating radar to locate permafrost zones at Fort Wainwright, Alaska, and partnered with Worcester Polytechnic Institute, Massachusetts, to expand this technology to identify and monitor contaminated sites. CRREL also experimented with containing hazards using ice. Because of the expertise gained, CRREL became part of the EPA Remediation Technology Development Forum Working Group, which demonstrated solutions useful to other remediation sites outside the Army. In addition, CRREL conducted research related to installation conservation, for example, identification of genetic diversity of grasses to enable breeding of plants resistant to land disturbances and the work of Lawrence Gatto predicting thaw-induced soil erosion and runoff at Yakima Training Center, Washington. As with CERL and WES, CRREL also worked to develop computer-aided techniques to speed analysis of environmental issues, such as contaminant plume modeling and the use of remote sensing to track erosion or climate change through monitoring of boreal forest growth and coastal wetland loss.³¹⁷

Continued Development of Information Technology

By the early 1990s, modeling throughout the Corps was becoming much more advanced than in previous decades. Researchers incorporated not only more complex 2-D and 3-D finite element models but new numerical methods such as the distinct element method and discontinuity deformation analysis (discussed in Chapter Seven), the boundary element method, and the shear ring method. The boundary element method used boundary conditions on a surface mesh to replace values used throughout a space in a partial differential equation, which was

often more efficient than finite element method (FEM) for 2-D calculations. The boundary element-finite element method further combined the methods to gain fidelity and efficiency. The shear ring method helped to model soil-piles that assumed rotational failure. The Computer-Aided Structural Engineering and Computer Applications for Geotechnical Engineering (CASE and CAGE) development efforts continued, resulting in many new applications. WES expanded its TABS software from a 2-D to a 3-D application and even developed a Fast-TABS version in 1991 that produced lower fidelity models more quickly. Similarly, CERC released a PC version of its Automated Coastal Engineering System software in 1995, GL produced CAMMS, and HL released a portable version of its Ship Simulator. Several programs evolved to model specific problems, such as the HAD-1 sediment model, SMS and SBEACH sand models, GENESIS shoreline protection model, PLUME contaminant model, the PENCVR3D penetration model, LEVEEMSU seepage analysis package, WESSHAKE earthquake analysis program, and literally hundreds of others. At the same time, CRREL greatly advanced modeling of cold regions issues. It developed the SNAP snowmelt analytical package and models of brackish ice, as well as project-specific models such as the Allegheny Ice model. Other models were related to specific hydraulics issues. For example, CRREL developed a model of subsurface water expulsion due to freezing soil. In cooperation with HEC, CRREL developed a 3-D discrete element model of ice jams to be incorporated into the HEC-River Analysis System software and adapted HEC-2 to represent shallow, ice-covered rivers.³¹⁸

CERL continued to develop highly innovative information technology products for construction and base management, many of which relied on the Internet to enable greater collaboration from distributed personnel. DrChecks allowed designers, contracting officers, company executives, engineers, and fabrication or construction teams to securely access project data, each with its own views or user rights. Project CITY, tested at Fort Gordon, Georgia, in 1998, provided public works personnel a collaborative work environment using commercial off-the-shelf applications. CERL upgraded or revised many of its traditional programs. It continued to maintain programs in the Engineered Management System, such as PAVER and ROOFER, which the National Research Council for Canada included in its Building Envelope Life Cycle Assets Management project. EnergyPlus essentially built on the capabilities of the BLAST application. The Army Training and Testing Area Carrying Capacity software provided many capabilities required for the Integrated Training Area Management program to determine training range capacity, including economic considerations for land management. The Small Arms Range Noise Assessment Model automated the noise contour mapping process, and the Computerized Maintenance Management System expanded on CERL's earliest applications in the Integrated Facilities Management suite. CERL also developed newer applications such as VegSpec, a computer tool for planning vegetative plantings to restore ranges or other locations, which CERL developed in cooperation with the National Resources Conservation Service and USGS. As more commercial programs became available to meet various needs, CERL increasingly worked to adapt or incorporate them, often partnering with software developers. For example, it adopted the Logical Technology Inc. HAZMIN product to handle facility emission, leveraged applications developed by FM Systems in its Computer Aided Facilities Management

3-D Modeling Applications

When the Information Technology Laboratory (ITL) implemented a Cray C90 in 1993 and Cray T3E, IBM SP, and Silicon Graphics 2000 supercomputers in 1997 as part of the Department of Defense High Performance Computing (HPC) Center, it did more than simply increase storage. By offering the largest computing power of any Army computer at that time, it enabled advanced research in 3-D modeling, simulation, and visualization not previously possible. Aided by ITL engineers, scientists, and technicians, experts in hydraulic, geotechnical, environmental, and structural engineering were able to conduct complex analyses of estuaries, groundwater, soils, and structures.

The additional computing power was helpful in a number of hydraulic problems requiring vast computations, such as modeling vessel-generated currents over time on the Upper Mississippi River, developing wave height forecasts for El Nino, or calculating salinity and circulation in Florida Bay by modeling winds, tides, freshwater inflows, rainfall, evaporation, density gradients, and other factors. In some cases, researchers were able to solve these problems using modified 2-D models such as TABS-MD or HIVEL2D.

Perhaps the most often modeled problems in the 1990s involved contaminant flow. Using CH3D-based models, researchers developed simulations of contaminant surface movement in New York Bight based on underlying hydrodynamics and sediment transport and a water quality model of San Juan Bay that integrated hydrodynamics with the salinity, chemical, and organic make-up of the water. Using FEMWATER-based models,



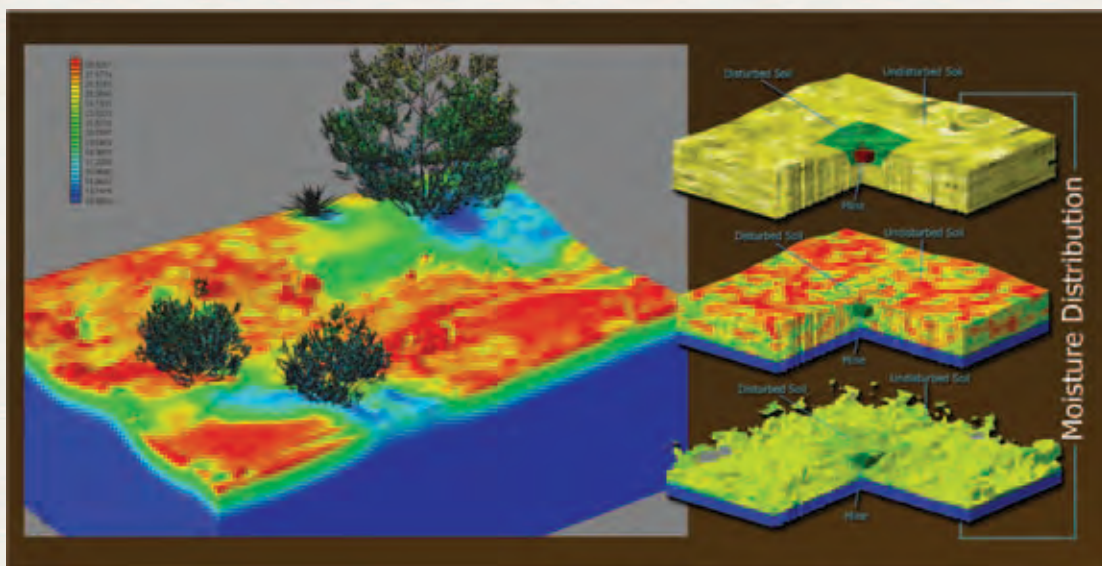
CRAY T3E.

they examined interactions between surface and groundwater in the Everglades National Park and plume containment at Army installations.

Some problems involved the behavior of groundwater or contaminants in certain soils. One team used molecular models to visualize the geometry of trinitrotoluene (TNT) contaminants to determine their location in clay soils. Another used the PARFLOW finite difference model to statistically represent subsurface variances. A major problem was the processing required for random-walk particle transport and dispersion techniques. Most software modeled soil permeability in random locations. Replacing this with statistically determined flow fields required fewer computations, and in fact velocity statistics of flow through porous materials showed interesting historical scale effects.

Increasingly, supercomputers aided structural analysis and forensics. For example, analysts built a discrete element model of a multistory building – complete with walls, doorways, windows, and stairways – composed of 85 million 3-D cells. They processed the data using the CTH and ParaDyn software to simulate a TNT blast and the structural response over time. Another project used DYNA3D and ParaDyn to analyze survivability of hardened structures and soil-structure interaction from explosion-induced shock. For penetration analysis, analysts used the WES-developed code, PENCVR3D, to calculate target material resistance and projectile kinematics, then applied the results to finite element models of a target of approximately 95,000 eight-noded hexahedral elements.

Although results varied based on the problem and hardware and software used, in many of the projects, estimates were that using the supercomputers saved dozens of hours of processing time that it would have taken with traditional high-end PCs. Other projects, one analyst noted, “would not be computationally possible without DoD scalable HPC resources.”



Example of a 3-D model.

Suite, and worked to incorporate interfaces to commercial products in its Modular Design System suite. It also produced the next generation of the Environmental Compliance Assessment System, first developed during the 1980s as The Environmental Assessment Manual Guide to support military sites worldwide in regulatory compliance.³¹⁹

GIS remained an important development area. The Topographic Engineering Center (TEC), the inheritor of the Engineer Topographic Laboratories (ETL), continued development of several combat GIS systems, for which 1992 proved a break-out year. It passed a major milestone in the AirLand Battlefield Environment (ALBE) software suite – over which TEC now served as program manager – when it demonstrated and released version 2.0 to much enthusiasm. Included in ALBE was the highly successful Battlefield Environmental Effects Software. Based on the latter and environmental software used for materiel acquisition, TEC planned follow-on Battlefield Environmental Effects Modules. The Digital Topographic Support System (DTSS), which included the ALBE software, completed final environmental and technical tests the same year. The Army fielded the heavy version (DTSS-H) in 1997 and 1998, and after completing testing of the light version (DTSS-L), fielded it started in 1999. TEC continued demonstrating and evaluating the Laptop Terrain Analysis System and prototypes of the Quick Response Multicolor Printer. TEC also made major strides in terrain modeling. After releasing its DrawLand visualization toolkit in 1991, which it also included in DTSS, TEC continued development to include various data types and formats from the National Imagery and Mapping Agency and others. Using an upgraded Battlefield Visualization Test Bed, TEC supported numerous exercises, including the 73 Easting simulation based on the Operation Desert Storm battle of the same name and the Synthetic Theater of War and Warsteed exercises. TEC's Field Support Office helped package, field, support, and train users of these systems, while TEC continued to support DoD through terrain analysis and GIS support.

In the civil engineering field, GIS found many uses. While WES developed some military applications, most notably groundwater and contamination maps used for DERP, the majority of its GIS applications were civil. For example, it helped to map land loss in Louisiana, developed a database of erosion control projects in 15 watersheds of the Yazoo Basin, and mapped ecosystems or locations of aquatic plants to better manage environmental issues. The GEOSHED GIS application developed initially for military hydrology found application in civil fields, often used in cooperation with or integrated with HEC-1 or other watershed modeling programs. Although the Information Technology Laboratory Computer-Aided Design and Drafting (CADD) / GIS Technology Center supported use and development of GIS applications, its primary focus was on developing software and data standards and determining development and acquisition needs. The GRASS GIS application, developed by William Goran and others at CERL to support military installations but used by a variety of civilian agencies, had by the early 1990s declined in use as commercial GIS had become available (see Chapter Seven). In 1995, CERL made the decision to end its development and support of the program. However, several robust commercial GIS were built on the original GRASS platform since it was available in the public domain. By 1993, the CRREL Remote Sensing/GIS Center became the Corps lead and technical assistance hub for supporting Corps civil GIS requirements. It

supported various emergency management activities, such as response to hurricanes and flooding of the Ohio, Mississippi, and Red Rivers, and it worked with the HQUSACE Readiness Branch to create a GIS interface to the EngLink intranet and databases. Among products it supported was the CorpsView visualization software used by most Corps districts and divisions to calculate reservoir storage, assess snow cover, and map and analyze flooding. Use of this software and LANDSAT satellite data to determine reservoir storage saved the Los Angeles District \$600,000 in just one application. In 1998, CRREL initiated a GIS Research and Development Program to address integration of civil works GIS applications and data, including CADD and numerical models.³²¹

The Information Technology Laboratory (ITL), formed in 1986, continued to rapidly expand and mature. In 1990, it added a Scientific Visualization Center to help develop 3-D viewing and immersive virtual reality applications, in 1992 it expanded the CADD Center to the Tri-Services CADD/GIS Technology Center, in 1993 it rechartered the Army Supercomputer Center as the first Department of Defense High Performance Major Shared Resource Computing Center, and in 1995 it established the Software Technology Center to aid in software development issues and incorporated the WES Instrumentation Services Division into ITL. Several of these efforts proved very successful – the CADD/GIS Center won a Hammer Award for eliminating waste through automated contracting, and Stephen Adamec, Brad Comes, Alexander Carrillo, John West, David Stinson, and Dennis Gilman won awards for developing the High Performance Computing Center. The combination of these activities made ITL one of the largest laboratories at WES. ITL continued to support a number of developmental efforts, such as the CASE effort and its 1992 off-shoot, Computer-Aided Structural Modeling; new applications for modeling groundwater, earthquake loading, steel structures, and risk and reliability; and continued development and testing of administrative and financial applications. It supported the information management requirements of WES through operation of the library, audio-visual center, publishing, acquisition and maintenance of computers, and development of a corporate database and WESLIB library. As the largest information management organization in the Corps, it also continued to support fielding and development of a variety of Corps- or Army-wide applications. These included the Research and Development Management Information System, the Corps of Engineers Financial Management System, the Program and Project Management Information System, the Defense Site Environmental Restoration Tracking System, the Army Compliance Tracking System, and the Formerly Used Defense Sites database.³²²

Topographical Research and Warfighter Support

By 1990, ETL was at a transition. Many leading researchers had retired, including remote sensing pioneer Robert Frost and survey equipment developer John Armitage. At the same time, lab funding had more than doubled over the previous decade, reaching a peak of \$107 million and 429 personnel in 1992. With the growth of the Terrain Analysis Center and Col. David F. Maune's marketing of the lab's capabilities to field units, its work focused more on direct support of the warfighter and management of digital terrain data for the Army and less on research

and development. Because of these changes, the Corps redesignated ETL as TEC in May 1991 and shortly thereafter reassigned the Engineer Studies Center to TEC. This was a small in-house think tank established during World War II in the Office of the Chief of Engineers War Plans Division to study engineer-related problems as components of larger, Defense-wide programs. In 1947, it became part of the Army Map Service and Defense Mapping Agency until reassigned to the Corps in 1977. Consisting of fewer than 60 employees for most of its history, the organization published more than 300 studies on topics such as nuclear weapon effects, force structuring, mobilization, organization, military engineering, management analysis, and operational feasibility. Its inclusion in TEC further cemented the emphasis on engineering issues needed to support the warfighter. As with WES, TEC moved to a civilian-led organization headed by Director Walter E. Boge and in 1993 realigned its structure under three associate directors: a Programs Division headed by Frank G. Capece to plan topographical and force development systems; a Technology Division headed by Richard B. Gomez to research remote sensing, GIS, and simulation; and an Operations Division headed by T.W. Howard to conduct terrain analysis, generate products, and directly support the warfighter. By 1997, when William E. Roper became director, funding had dropped precipitously. He initiated strategic planning sessions with the division chiefs to align capabilities with growth areas, while divisions expanded to include Topographic Research, Topographic Systems, Force Development, Operations, and Geospatial Information Management. Within four years, TEC funding had doubled.³²⁴

The largest research area at TEC was software development of GIS, discussed previously, as well as photogrammetric systems, which remained the primary focus of the laboratory. By 1990, nearly all photogrammetric systems under development were almost completely automated, from digital capture of satellite images to automated extraction of feature data into a vector format with minimal editing to integration with GIS or cartographic computer systems that output maps on large color plotters. Development efforts continued unabated in the areas of automated feature extraction, geospatial databases, data mining, and spatial temporal reasoning that automated route planning or other functions, but as one developer noted, “The pace of development is faster.” Some of this involved significant basic research in mathematical and geostatistical approaches to solving extraction or automation problems, such as improving generalization of features or data conflation. Others involved development of software or hardware components. A major effort, led by Dan Edwards, involved development of the all-digital Terrain Information Extraction System, a high-resolution desktop image digitizing program. In 1997, TEC had started pilot testing of this software at TEC, the USGS, and intelligence agencies as part of the Digital Stereo Photogrammetric Workstation. Other efforts included incorporation of third-party systems such as Internet-based collaboration or visual learning tools.³²⁴

By 1990, TEC also greatly advanced development of global positioning systems (GPS). Similar systems using satellites to automatically triangulate position, such as the Sequential Collation of Range System, had been under development at TEC’s precursors since the 1950s but were slow and less accurate. GPS developed in the 1960s using the Navy TRANSIT satellite took 25 satellite passes to get accuracy within five meters – good enough for some surveys but not for mobile operations. While development of GPS continued, ETL focused on other

survey methods, such as triangulation of horizontal points, circumpolar navigation using stars in the northern hemisphere, electronic ranging, and inertial positioning using gyroscopes or other devices to calculate a position from the earth's rotation and changes in acceleration and time. In 1959, ETL had started studies of inertial surveys, and in 1971 awarded a contract to Litton Guidance and Control Systems to develop a prototype of the Position and Azimuth Determining System, which used an aircraft inertial navigation system mounted on the back of a jeep to calculate locations. Although accurate and fairly quick, it could only function where a jeep could drive. The Modular Azimuth and Positioning System, developed from 1985 to 1992, completed the same function using two small computers instead of mechanical methods. This system was highly popular, eventually being integrated into the Firefighter and Paladin firing systems. Development of GPS, however, continued under the work of Kenneth Robertson and could by 1984 achieve great accuracy in 30 minutes to two hours. The Corps started to frequently use such systems in monitoring civil works projects, such as a dam safety monitoring system developed by Robertson in 1985 that was installed at Dworshak Dam, Idaho, in 1988. After further refinement of GPS to use additional channels and include more stable antennas and enhanced hardware, it improved calculation speed to a few seconds. ETL set about promoting the technology through a series of demonstrations, such as measuring Mount Ranier, Washington, or positioning a moving Coast Guard platform. Soon after, TEC began investigation of using GPS for targeting and awarded a proof-of-concept contract in 1992. By 1997, it had integrated GPS into remote sensing systems to quickly build digital elevation models.³²⁵

Two relatively new missions for ETL were in artificial intelligence and space programs. As early as 1978, Center for Consolidated Optics Director Robert Leighty had urged ETL management to move past mere geographic pattern recognition in automating feature extraction to developing artificial intelligence (AI) that could understand context. Application of AI to remote sensing was initially unsuccessful, but Leighty got his opportunity after 1981 when the Army asked ETL to survey AI/robotics applications. The following year, ETL replaced the Optics Center with the Center for Artificial Intelligence in the Research Institute and developed a test-bed facility used widely by the Defense Advanced Research Project Agency (DARPA). By 1983, it was developing tactical



Autonomous Land Vehicle, a test robotic vehicle developed by the Engineering Topographic Laboratories. Office of History, U.S. Army Corps of Engineers.

robotics systems in conjunction with DARPA and the Tank-Automotive Command, including a prototype Autonomous Land Vehicle. ETL's involvement centered on development of the terrain analysis, optics, and navigation portions of the system. In 1985 and 1986, demonstrations of this vehicle drew national attention, and although intelligent robotics remained a dream of the future, the concepts developed in visualization, planning, and object tracking were extraordinarily useful in systems that TEC improved over the next decade. During the same period, the Special Projects Division of the Topographic Development Laboratory was helping develop smart guidance systems for the Pershing missile using systems that could correlate images from radar and topographic data. The result was a system so accurate that it intimidated Soviets who witnessed demonstrations. "Quite simply, it made them afraid of us – and a lot of missile treaty negotiations resulted," Anthony Stoll said. In the 1990s, TEC further developed these concepts in the Joint Precision Strike Demonstration Program, a high-profile demonstration program in which TEC showed navigational capabilities in visualizations developed with other agencies, and the DARPA Warbreaker demonstration, for which TEC was responsible for managing intelligence data. Much of its work over the next decade involved integrating positioning technologies into weapon systems such as the Patriot, Hawk, and Paladin.³²⁶

The newest TEC mission was space programs. Although ETL had conducted considerable research with NASA over the years on remote sensing and had seen growing funding since 1979 from the Army Space Program Office, it was not until 1986 that ETL formed a Space Programs Laboratory to consolidate space-related work. Some of the lab's missions were supporting development of hyperspectral imaging systems in conjunction with the Center for Remote Sensing, but it also included work on the Strategic Defense Initiative (SDI) and space experiments. SDI originated after President Ronald Reagan proposed development of a space-based missile defense system using guided missiles and lasers, which became known as "Star Wars." ETL helped establish the Army Space Research Committee that managed the Army's role in the program, with Associate Technical Director Richard Gomez serving as its executive secretary. Most of the space experiments ETL supported involved terrain analysis from space. Although the Challenger Shuttle disaster delayed the program for many years, ETL participated in the Military Man in Space initiative, Richard Muniz created experiments to test instruments for terrain analysis, and Capt. Jim Karpiscak developed a manual for astronaut terrain analysis actually used in 1990. Later, the majority of this work involved hyperspectral imaging. Samuel Barr, Robert Rand, Robert Pazak, and others developed and continued to expand the HyperCube software, developed digital multispectral video, and built a direct downlink system to receive satellite intelligence for the Eagle Vision II initiative. As it had for decades, TEC continued to conduct image exploitation, such as for the Joint Agency Multispectral Project, and served as the Army Program Manager for the Commercial Satellite Imagery Program, in which it managed Army image requests.³²⁷

Retooling Cold Regions Research

By 1990, CRREL had begun a purposed shift in activities as it reached a point where it could no longer support current staffing levels through its traditional mission. With the easing

of tensions with the Soviet Union in the mid-1980s and the end of the Cold War in 1989, the *raison d'être* for much of the previous half-century's cold regions research and engineering support came to an end, and funding levels for the lab's cold region research missions gradually declined. Finding new missions related to its traditional mission became the priority for the lab's leadership, including its new technical director, Lewis E. "Ed" Link, who transferred from WES in 1986. As already mentioned, a significant amount of this new research focused on environmental quality issues such as detection and remediation of explosives residue or use of remote sensing and GIS to analyze issues such as oil spills, emergency response, or climate change. CRREL became involved in these missions as a result of restoration of military sites in Alaska or using remote sensing to track snow and ice cover. Another new focus was research related to the dynamics of the military operating environment and its impact on the Army's mission. It researched methods of predicting terrain appearance – including the ocean surface – due to changes in seasons or times. Other projects involved understanding and preventing the impact of rapid weather changes on construction materials, whether frozen or thawed. Donald Albert, Austin Kovacs, and others determined the effect of weather-related occurrences on radar, infrared, millimeter, or seismic sensors used in targeting, mine detection, studying sea ice, and other functions. As early as 1981, CRREL participated in the SNOW programs to test optical and electromagnetic sensors in a winter environment. Through the Smart Weapons Operability Enhancement Program initiated by Link, CRREL helped model terrain for smart weapons testing and development. One unique project involved the chemical detection of mines through assessment of vapor signatures found in TNT. CRREL also supported mobility and soils research involving more than just snow and ice, for example, by helping WES incorporate soil moisture data into the CAMMS model, aiding in the preparation of a maintenance manual for Semi-Prepared Runway Surfaces for C-17 aircraft, contributing to development of roadway subgrade failure criteria, and testing the effects of low tire pressure on bituminous surfaces. After 1991, a significant amount of this research involved desert climes, which became a leading concern of the Army after Operation Desert Storm.³²⁸

Despite this shift in mission, more than half of CRREL's funding remained geared toward cold climate issues, often in support of cold regions military operations. Walter "Terry" Tucker, Jackie Menge, Gunther Frankenstein, and others participated from 1986 to 1992 in arctic submarine and icebreaker vessel research for the Navy to test ice dynamics, provide insight into operating in frozen waters, and map ice thickness. Later, Tucker led efforts to declassify and analyze Navy submarine data on ice thickness in the Arctic Ocean. Declassified in 1998, the data established a 40 percent thinning of ice cover over the previous 25 years. After 1984, CRREL conducted more than 30 site surveys and developed design criteria for the Air Force North Warning Radar System stretching across Alaska, Canada, and Greenland and saved \$65 million by reutilizing Distant Early Warning line sites. In the 1990s, CRREL experimented with Blue Ice runways, developed insulated or ice-resistant runway materials, and researched how to prevent airframes from freezing. It eventually developed new manuals and aided both military and civilian agencies with highway snow control. At Army sites, it developed or evaluated construction and

maintenance technologies such as roof snow load and moisture sensors, cold-resistant concrete, and use of geotextiles to prevent ice upheaval and shore up frozen soils. It conducted important work on cold regions mobility, including development of a snow penetrometer, shallow snow models for wheeled vehicles, and tactical military bridging over icy waters, as well as testing Caterpillar tractors and a mobile launcher for the Air Force Ballistic Missile Office. There was a significant spike in such activities after 1995 due to the Bosnian conflict. Fought mostly in the mountains of Eastern Europe, estimates were that harsh winters cost the Army an additional \$329 million (a 13 percent increase) in equipment repairs and maintenance. To reduce this number, the Army initiated the Bosnia Winter Operability Thrust initiative, which CRREL supported through tracking snow cover in the region, testing equipment for the Army Facilities Component System, and developing technologies such as strengthened antifreeze, HMMWV snow plows, concrete bonds, ice-phobic coatings, and cold-resistant mine detection capabilities. On the civil works side, CRREL supported ice jam engineering and other low-temperature navigation issues. William T. Burch and Jon Zufelt developed equipment and techniques to cut through jammed ice. It also continued to support civilian scientific missions for the National Science Foundation and others, such as climate change research, ice core drilling, development of the South Pole Tunneling System, and construction of new facilities in McMurdo Station, Antarctica. The latter involved testing and cutting a 600-meter corridor, 65-meter spur, power plant, storage, and shop from January 1996 to December 2000.³²⁹

Throughout its history, CRREL had something of a split personality. Formed by combining a cold regions engineering organization and snow and ice research center (the Arctic Construction and Frost Engineering Laboratory and the Snow, Ice, and Permafrost Research Establishment), CRREL had largely merged the two organizations without much melding of their activities. Since its founding, its two primary technical divisions – Experimental Engineering and Research – concentrated on applied engineering and basic research respectively, each tracing its lineage to the earlier organizations. The other technical division, Photographic Interpretation Research, had previously transferred to ETL in 1970. Given the change in mission status and the increasingly multidiscipline nature of Corps research, CRREL could no longer afford to maintain this separation in missions. Thus, the first major organizational change of CRREL's history directed by Link in 1993 was the merging of these two divisions under a single Research and Engineering Director, George D. Ashton. The division's seven branches then became independent divisions: Applied Research, Civil Engineering, Geochemical Sciences, Geological Sciences, Geophysical Sciences, Snow and Ice, and Ice Engineering Research. The Remote Sensing/GIS Center remained a separate element under Ike McKim, who, as chief of Program Development, also oversaw the Plans and Programs and Public Affairs offices. The Technical Resource Center continued as the primary technical support element. It was a flatter organization that allowed greater responsiveness from the divisions to problems without needing to place them in organizational context. As a result of the reorganization, change in focus, and new missions, CRREL had stabilized and started to increase personnel from 315 permanent employees in 1987 to 345 in 1997.³³⁰

Construction Materials and Technology

The Construction Engineering Research Laboratory (CERL), or Laboratories as it styled itself in the early 1990s, continued to pursue military construction issues in its research. Much of this work involved developing computer systems to speed and standardize construction, reporting, and maintenance processes, as already noted. A major emphasis of CERL research involved development of new lower cost, more durable building materials, which included some of the lab's most ground-breaking work. CERL had long been involved in developing technologies that extended building life such as a Welding Quality Monitor to help identify flaws in welded joints or lighter weight ceramic anodes to replace sacrificial anodes in cathodic protection systems. By the 1990s, Richard Lampo led the lab in researching building materials made out of plastic or other recycled materials, and CERL was conducting experiments with stronger fiber-reinforced polymer concrete, magnetostrictive composites that used magnetic fields to better monitor structural loads, electro-osmotic pulse technology that used electricity to repel water, a robotic system to inspect underground piles or storage tanks, wireless systems to monitor building structural integrity, and application of plasma or ultrasonic technology to eliminate waste materials. In several cases, CERL worked to help develop standards and engineering manuals for new building materials, such as recycled plastics, low-cost earthquake-resistant cold-formed steel, and new types of lubricants. The Paint Technology Center, still under leadership of Alfred D. Beitelman, continued to perfect various coatings as well as methods to remove them. For example, it conducted research into new arc-spray methods of metalizing surfaces for corrosion protection, which produced higher quality results than previous flame-spray methods authorized in the 1980s. It conducted field tests of new paints that could be applied to wet surfaces, which promised great savings by not having to dewater locks before coating. Vince Hock and Susan Drozd developed abrasive blasting techniques as well as chemical methods to stabilize lead-based paint wastes. They also experimented with microwave and thermal processes for removing lead-based paint that were faster and cheaper than manual methods.³³¹

CERL continued to conduct research into newly available energy, heating, ventilating and air-conditioning (HVAC) systems for more efficient building operation. As discussed in Chapter Six, it had researched alternative energy technologies such as solar energy, biomass fuel, and by the 1990s was turning to hydrogen fuel cells. Based on this work, CERL won recognition in the 1998 Federal Energy Saver Showcases highlighting energy-saving projects. Using technologies such as low emission boilers, gas cooling systems, and chilled water storage cooling, which circulates air through tanks of cold water to lower temperature, CERL was able to reduce energy costs while lowering environmentally harmful emissions. Chilled water technologies installed at Fort Jackson saved \$430,000 the first year, and CERL projected savings of \$70 million for the 44 sites where it deployed gas cooling. In 1998, it completed a report on water efficiency measures such as water-saving fixtures, water reuse, leak detection, and alternative landscaping to aid water movement, and it supported specific projects at Elmendorf Air Force Base, Alaska, to correct corrosion in water pipes, and at Fort Drum, New York, to extend the life of heat distribution systems. Its work with pushed liquid recirculation systems that use scrubbers to control emissions reduced air recirculation requirements by more than 70 percent in early tests.³³²

Recycled Building Materials

Wooden building materials, although initially cheap, often have high maintenance costs. They require frequent paint or stains to reduce wear, and, especially in wet environments, face constant threats from rot and organisms such as marine borers, a worm that feasts on lumber pilings. The hardest low-cost alternative – lumber made from recycled plastic – had been used for years in picnic tables and other low-stress applications, but few used them in more demanding environments. The Construction Engineering Research Laboratory (CERL) sought to determine if this was possible.

In 1992, CERL and Rutgers University's Center for Plastics Recycling Research (CPRR) began a collaborative effort as part of the Construction Productivity Advancement Research (CPAR) program to examine the behavior and long-term performance of plastic wood and document its environmental and fire risks. The CPRR was established in 1986 with support from New Jersey and the National Science Foundation to research products made of plastic waste. A 1994 study showed that, of the 8.4 billion pounds of plastic waste, only 2.4 billion pounds – high-density polyethylene and polyethylene terephthalate containers – are recyclable. About 20 manufacturers made this waste into building materials. A core group of these manufacturers formed the Plastic Lumber Trade Association in support of the project. "The industry is there. It is struggling," Richard Lampo of CERL said in 1992.

The project included several lines of research. Because there were no standards for plastic building materials, CERL worked with the American Society for Testing and



An all-recycled thermoplastic composite bridge developed by the Construction Engineering Research Laboratory supporting a 71-ton M1 Abrams tank.

Materials (ASTM) to develop test methods to measure density, compression, flexure, creep, shear, and mechanical fasteners. By 1996, the Environmental Protection Agency funded a follow-on project for CERL and ASTM to develop generic building specifications to enable it to establish a national program for stimulating use of recycled building materials.

Another line of research involved developing more efficient designs and concepts. The initial strategy was to work with manufacturers to modify plastic properties to resemble that of wood. Using ASTM-developed methods, manufacturers developed standard quality control measures. Because even these plastics retained a certain amount of elasticity, CPRR experimented with building designs and uses that increased the efficiency of the materials. For example, it designed an innovative arch concept that maximized the stiffness of the materials.

In a third line of research, CERL worked with various partners to apply the materials to structural uses. In a project with two railroad companies, CERL, Rutgers University, and Earth Care Products tested plastic ties to reduce the 15 million wood ties replaced each year. In New York, CERL and Rutgers helped to rebuild a waterfront structure on Tiffany Street. On this project and at Port Newark, New Jersey, CERL worked with the Naval Facilities Engineering Services Center, the Port Authority of New York, and other Corps labs to install plastic pilings. At Fort Leonard Wood, Missouri, CERL helped to install a plastic bridge at Gammon Field.

Such projects proved the viability of building with plastic materials, the lower maintenance costs, and the environmental benefits. “With the projected economies of scale as the industry takes off, recycled plastic lumber could become the material of choice for many applications—not just as a novelty,” Lampo wrote in 1996.



A recycled plastic bridge on Gammon Field supporting the weight of a HMMWV.



Michael J. O'Connor.

By the mid-1990s, like the other laboratories CERL also faced major changes, some of a sad kind. In May 1994, long-time CERL Technical Director Louis R. Shaffer passed away during official travel to Washington, D.C. As a member of the National Academy of Sciences Building Research Advisory Board that oversaw the formation of CERL, he had a direct hand in its formation as well as its location near the University of Illinois, where he was a faculty member. As its first and only technical director prior to his death, he had guided it throughout its existence while maintaining an excellent relationship with the university. Paralleling developments at other Corps labs, he became the first civilian director of CERL in

1993 as CERL started to transition from a division to a laboratory organizational structure with the formation of Infrastructure and Environmental Sustainment laboratories. With Shaffer gone, CERL Commander Lt. Col. David J. Rehbein assumed the role of acting director and selected Michael J. O'Connor, chief of the Infrastructure Laboratory, to serve as acting technical director. Reorganization continued in 1995 with the transition to four laboratories: Facilities Technology, Land Management, Planning and Management, and Utilities and Industrial Operations, each with three divisions. Each lab had a chief responsible for planning/customer relations and an operations chief responsible for day-to-day operations. The four laboratory chiefs were O'Connor, William Goran, David Joncich, and Gary Schanche respectively, with O'Connor and Goran serving as associate directors of CERL. Finally, after a two-year selection process, O'Connor became the second director of CERL in July 1996. With his promotion and that of Goran to technical director, the new management team included Donald Fournier, William Severinghaus, Michael Golish, and John Bandy.³³³

Technology Transfer

Throughout its history, the Corps supported sharing technical data with commercial industry to increase general engineering knowledge. In addition to publishing project reports as part of the public information process, the Corps widely distributed research reports. Congressionally established Corps boards such as the Beach Erosion Board, Board on Water Hyacinth Removal, and Board on Towboat Experiments published their findings in congressional documents. Each year, the Corps labs produced hundreds of reports, papers, and technical bulletins on various research results, such as the *CERL Abstracts* or *ITL Engineering Computer Notes*. Researchers published dozens of articles each year in journals such as the *American Society of Civil Engineering Proceedings*, the *Military Engineer*, and various academic journals. Research contractors benefited greatly from research conducted for and with the Corps, and the Corps labs frequently provided data to support ongoing construction projects on a cost-reimbursable basis or as directed and funded by Congress or HQUSACE. Many state, local, and federal agencies outside of the Corps, as well as businesses under contract, had ongoing memoranda of agreement to obtain Corps laboratory support, particularly the other military services and laboratories, NASA, the Nuclear Regulatory Commission, Bureau of Reclamation, USGS,

NOAA, NSF, EPA, State Department, and various state and local mining, natural resource, or levee organizations. By 1990, most Corps labs had consulting centers to provide technical support in various fields. In 1970, the Soils, Mobility and Environmental, and Concrete divisions at WES each established technical support and analysis centers to field technical questions, ostensibly for the Corps districts, but in reality for any organization. The Structural Engineering Center, established in 1984, provided support to organizations as it had for CASE. EL had established a Dredging Operations Technical Support Program, a Water Operations Technical Support Program, and a Wetlands Regulation Assistance Program. ITL operated the CADD/GIS Center, and CRREL had the Remote Sensing/GIS Center. In its Small Problems Program, CERL answered free of charge any questions related to environmental, maintenance, engineering, facilities, or construction issues requiring one person two or fewer days. CERL also created a Technical Assistance Center headed by Ronald Webster, which operated more or less autonomously. Several of the labs had widely recognized experts who consulted for various agencies on specific problems, such as CRREL snow expert Samuel C. Colbeck – also known as Dr. Snow – who advised not only the Army on snowmelt and avalanches in Bosnia but also consulted on skiing accidents and other issues.³³⁴

From 1980, there were significant changes to the legal requirements for sharing technical information with the private sector that greatly expanded the already liberal Corps policies concerning providing research findings to commercial industry. That year, Congress passed the Stevenson-Wydler Technology Innovation Act (PL 96-480), the pioneer legislation for technology transfer. It required greater dissemination of federal research to private industry and especially required laboratories to take an active role in technology transfer. For example, it required the establishment of an Office of Research and Technology Application (ORTA) in all federal agencies conducting research. After the Army issued its guidance in early 1982, WES established its ORTA in December within the Office of Technical Programs and Plans. CERL, CRREL, and TEC established ORTA personnel as special assistants to the commander. As amended by the Federal Technology Transfer Act of 1986 (PL 99-502), the law also required greater cooperation with private entities, including academic institutions, to conduct research through Cooperative Research and Development Agreements (CRADAs). The Water Resources Development Act of 1988 authorized the Corps to enter into and fund up to 50 percent of CRADAs, and over the next 20 years, the Corps would conduct some of its finest research through such agreements. Other laws, such as the Bayh-Dole Act of 1980 and the Trademark Clarification Act of 1984 loosened patent laws to allow such partners to obtain patents to technology developed under government contract and for government labs to license technology. The Small Business Innovative Research Act of 1982 and Small Business Technology Transfer Act of 1992 established programs to encourage cooperative research specifically with small, disadvantaged businesses. The Water Resources Development Acts of 1988, 1990, and 1992 established technical and research and development assistance programs, international outreach programs to increase foreign cooperative research, and the CPAR program to develop technologies with commercial industry to improve construction techniques.

Other acts and executive orders promoted commercialization of technology, authorized further use of CRADAs, improved the rights of partners, and established various organizations to help distribute technology.³³⁵

As a result of these legal requirements, the DoD, Army, and Corps of Engineers established a series of programs to support technology transfer. Section 823 of the National Defense Authorization Act of 1989 required the DoD to begin submitting an annual plan on its science and technology needs. In response, it released Defense Management Review Decision 922, a plan on how to develop this plan while consolidating Research, Development, Test, and Evaluation (RDT&E) activities. To meet the plan's requirements, the DoD established Project Reliance, which included the Army, Air Force, Navy, DARPA, the Deputy Director of Defense for Research and Engineering, and other agencies. Under Reliance, the DoD developed science and technology plans based on input from the services, established and ensured resourcing of priorities, consolidated work, and eliminated redundancy. Reliance agreements allowed agencies to conduct joint planning or research. Other congressionally established programs, such as the multi-agency Strategic Environmental Research and Development Program created by the Defense Authorization Act of 1991 and the Environmental Security Technology Certification Program, also included technology transfer provisions. In addition, Congress directed the establishment of various joint projects for developing fuel cells or other technology. Based on these programs and requirements, by 1993 the DoD was pushing an initiative to increase dual-use technology, i.e., technology that had application for military and commercial uses. In 1994, Secretary of Defense Richard Perry directed use of commercial specifications in acquisition, changes formalized in the Federal Acquisition and Streamlining Act of 1994. By 1995, approximately 25 percent of DoD research was dual use, most of it electronics- and IT-related. After several years of discussion, in Section 203 of the 1998 Defense Authorization Act (PL 105-85), Congress formally established the Dual Use Science and Technology Program, which required the DoD to establish a dual-use program official, gradually increase dual-use funding to 15 percent of RDT&E spending by 2001, and capped federal cost-sharing at 50 percent. In 1993, the Corps laboratories developed a series of initiatives, including dual-use plans and marketing materials and assigning coordinators to increase technology transfer.³³⁶

The labs had, of course, transferred a number of technologies to commercial industry and been deeply involved in dual-use development. The Corps had itself commercialized or developed prototypes of a number of products and methods that were being licensed and used by private industry. These included ceramic anodes, the digital compass, roof blister valves, break-water armor units, roller-compacted and water-resistant concrete, diurnal ice storage systems, various corrosion-resistant coatings, geotextiles, geogrid-reinforced expedient surfaces, airport design criteria, automated railroad track condition assessment systems, pavement recycling, earthquake engineering, microgravity-based underground analysis, the Logistics-Over-The-Shore system, etc. As with the DoD as a whole, a significant amount of technology transfer was related to software development. Among the programs the Corps published and distributed were the GRASS GIS software, the PAVER family of maintenance management systems, BLAST, the DrawLand 3-D terrain modeler, and the HELP and CADPET landfill and

wastewater analysis software. Using CRADAs or other agreements, the labs forged partnerships to conduct joint research or develop demonstration projects with companies such as CH2M Hill, Optec Inc., and Caterpillar Inc.; academic institutions such as Rutgers University, Georgia Tech, and the University of Nebraska; federal and local agencies such as the USGS and the Alaska Department of Transportation; and foreign governments such as Dubai. Further, they regularly provided engineering assistance to others, for example, modeling the Missouri Bend for Dow Chemical, modeling a hydroelectric plant at Old River for the city of Vidalia, Louisiana, working with North American Shipbuilding on an ice breaker, working with Oregon State University to evaluate pavement, and analyzing ice forces on offshore structures for Amoco Production. There was some concern that Corps research was preempting that of private industry. As late as 1998, Chief of Engineers Lt. Gen. Joe Ballard encouraged continued support of federal agencies, state and local governments, and U.S. businesses, but warned, "Our actions must avoid perceptions that we are marketing our services to displace or compete with private firms." Nevertheless, the Corps routinely shared research with others through technology transfer activities.³³⁷

Doing More with Less

By the early 1990s, the U.S. military and fiscal situation had changed radically from even the mid-1980s. After decades of heightened defensive posture and defense spending during the Cold War, a policy of *glasnost* (openness) in the Soviet Union, Eastern European revolutions after 1988, the fall of the Berlin Wall in November 1989, and finally collapse of the Soviet Union in 1991 resulted in a definite shift in military strategy and spending priorities. A force structure supporting the European theater quickly became antiquated, and many in Congress no longer deemed high troop levels as necessary. With a decline in troops, many bases seemed superfluous, but closing these local sources of income was highly political. Congress included the Base Closure Realignment and Closure Act (BRAC) in the National Defense Authorization Act of 1991 as a vehicle to accomplish military downsizing. Under the BRAC process, the Secretary of Defense submitted a list of bases for closure, which a BRAC Commission reviewed before sending to Congress, who would take an up or down vote on the entire list to minimize altering it for political reasons. Secretary of Defense Richard Cheney submitted the first list of bases in December 1990 and a second list in 1991. Other than engineer units that were tenants on the identified bases, the Corps was not a part of the BRAC process, which, because of its civil works responsibilities, would have greatly complicated the approval process by requiring inclusion of both Senate Public Works and Armed Services committees. The BRAC Commission intended to include the Corps until several members of Congress objected before the commission submitted the first list and had it removed from consideration. The Nunn Amendment of 1991 permanently removed the Corps from the process. BRAC did influence the Corps in other ways. The Army had already reduced construction spending in Europe, and in 1990, Cheney imposed a moratorium on military construction and a hiring freeze that lasted into 1991. With fewer projects and the loss of field offices on closing military installations, construction funding declined drastically in the years ahead, although environmental restoration increased.³³⁸

Corps leaders were, nevertheless, sensitive to the changing fiscal environment and the need to reorganize. In 1988, military construction was 20 percent lower than in the previous two years and projects for 1989 appeared to be even less. A paper delivered at a commander's conference in 1988 recommended they "tighten their belts." Outsourcing most design projects meant even less of this money stayed in Corps offices. With completion of several large projects, the civil works program had shifted to greater operation and maintenance funding, which grew considerably. In 1989, incoming Chief of Engineers Lt. Gen. Henry J. Hatch proposed organizational changes at Headquarters, primarily the division of the Engineering and Construction Directorate between Military Programs and Civil Works, and he started reorganizing European divisions in 1990. With no major changes to Corps districts since World War II, the domestic civil works program was next on his list for reorganization. In 1989, the Energy and Water Subcommittee of the Appropriations Committee provided funding for a reorganization study and repeatedly encouraged Corps realignment in reports sent with the Energy and Water Development Appropriations of 1990 and 1991. Completed on January 4, 1991, the Bayley Phase I Report recommended closing 14 of 38 district offices and three of 11 division offices, with one division downgraded to a district. Estimated savings were \$112 million per year. However, once Congress rejected including this plan in the BRAC process, the report's recommendations more or less died in committee. After Assistant Secretary of the Army for Civil Works Nancy Dorn again testified of the need to reorganize, Congress funded reorganization of Corps Headquarters and divisions (but not districts) in the Energy and Water Development Appropriations Act of 1993. The Corps submitted a new plan, but Congress again put it on hold. Again in 1996, Congress requested a new plan to reduce the number of divisions and districts and finally approved a plan submitted in 1997. Like the Bayley Report, the plan reduced the number of districts and divisions with only a few variations.³³⁹

DoD laboratories, meanwhile, were undergoing their own reorganizations and reductions. As part of a general department downsizing, Congress and the president imposed RDT&E reductions amounting to approximately four percent a year while requiring greater outsourcing. This resulted in several hiring freezes between 1988 and 1999. Although spending in basic research remained steady and technology demonstrations increased, in addition to a general decline in RDT&E funding there was also a decline in applied research as a whole over the next decade. Over 15 years, Congress periodically required reports on how to improve research efficiency and reduce redundancy. The department had routinely studied such issues since the 1960s. Most recently, the 1980 Required In-House Capabilities for DoD RDT&E report, or Perry Report after chairman William Perry, the 1983 Report of the White House Science Council Federal Laboratory Review Panel, or Packard Report after chairman David Packard, and the 1987 Defense Science Board Summer Study on Technology Base Management all commented on researcher salaries, budget inadequacy, in-house versus out-of-house spending, and related federal or defense laboratory issues. Some of these studies resulted in very inventive ways to improve laboratory efficiency. For example, the Civil Service Reform Act of 1978 authorized demonstration programs to test improved personnel management procedures. Because of the success of early prototypes, in 1989 Deputy Secretary of Defense Donald Atwood

directed each service to develop at least one Laboratory Demonstration Program. In essence, the program created a process through which participating labs could request changes to or waivers from regulations that were causing high personnel turnover or that impeded research. Within the Corps, WES elected to participate starting in 1995. Although it required a lot of paperwork and working through multiple layers of bureaucracy, WES used the program to allow greater flexibility in hiring and promoting, provide alternate compensation, and give larger pay increases as recruiting and retention incentives during the first few years of employment.³⁴⁰

In 1989, Congress required the first of several reports on ways to consolidate research and eliminate overlap, resulting in Project Reliance discussed earlier. As part of the Vision 21 strategy to improve defense posture to meet 21st century challenges, the Army developed a LAB 21 proposal in 1990 to consolidate its laboratories. Essentially, the proposal promoted a federated laboratory concept in which smaller, geographically distributed centers of expertise under a centralized organization works with industry and agency partners and, when necessary, develops in-house programs. Fluidity among government, industry, and academia encouraged dual-use development, while centralized management and a coordinated structure reduced overlap and overhead. The Army had discussed similar concepts for several years and steadily worked toward consolidation of its laboratories, for example, through the 1978 Electronics Research and Development Command and the 1985 Laboratory Command. In the latter, first proposed by Lt. Gen. Robert L. Moore, the Army Materiel Command (AMC) merged its laboratories under a single Major Subordinate Command – a precursor to LAB 21. Congress formally adopted LAB 21 during the 1991 BRAC session. As a result, AMC established the Army Research Laboratory (ARL) in 1992 and consolidated seven laboratories at six locations under what was formerly LABCOM, and the Medical Command consolidated three labs as the Medical Research Development, Acquisition, and Logistics Command in 1995. Despite the efforts made toward consolidation, Congress continued to encourage and request plans for improving efficiency in the acquisition process. The 1996 and 1998 National Defense Authorization Acts (PL 104-106 and 105-85) required a five-year plan that would further consolidate research and reduce overall acquisition personnel by 25,000.³⁴¹

These reorganizations initially had little direct impact on Corps labs. CRREL was the main installation BRAC would have potentially impacted – WES had a large civil works mission, CERL rented its property, and TEC was located on the Humphreys Engineer Center near Fort Belvoir, Virginia, adjacent to Corps Headquarters. The Corps reorganization plans mostly concerned its civil works organization through changes to districts and divisions, although they did have subtle influences. Fewer districts meant fewer potential customers, and the restrictions on military construction reduced related applied research projects even though the environmental requirements for closing the bases, such as DERP, engendered increased research and support of districts in this area. Even at WES, by the mid-1990s, more than half of its \$365 million program was military in nature, of which the majority concerned military engineering and construction or environmental restoration, with approximately 25 percent of its funding supporting Army high-performance computing. Reorganization of Army laboratories primarily affected those in the AMC, although it increased the pressure on improving performance, and

concepts behind the formation of ARL – LAB 21, consolidation, and federated laboratories – would eventually have great influence on Corps reorganization. The emphasis on working with private industry under CRADAs or other partnerships, while achieving greater technology transfer, also reduced the funding executed by the laboratories. “The pressure to contract more dollars from a shrinking budget to academia and private industry *will be very intense*,” Whalin reported after a lab leaders conference in 1993.³⁴²

All of these factors gradually placed enormous pressure on Corps labs to improve performance. The many lab studies since 1968 had led to reorganization of HQUSACE research management and a general increase in efficiency, for example, through establishment of research review organizations and by reducing laboratory manpower to achieve 30 percent personnel reduction directed by the Corps in 1978. The labs greatly cut their workforce, with a 14 percent reduction in slots overall and a 33 percent management reduction at two labs, mostly achieved through attrition and voluntary separation incentive pay. The introduction of standard information systems, outsourcing, and program justification remained constant concerns throughout the 1980s and 1990s. As with the rest of the Army, the labs implemented Total Quality Management to improve efficiency, although WES did not create a formal quality organization, preferring to work through the existing management structure to run process action teams on plant replacement, data collection, procurement, and other areas. In other programs, such as the Laboratory Quality Improvement Program, Army Communities of Excellence, and Army Performance Improvement Criteria, Corps labs competed with the rest of the Army for recognition as having most improved quality. There was also a significant increase in cooperation. At semi-annual laboratory director meetings, the Corps of Engineers Research and Development Directorate (CERD) was able to hash out issues ranging from technical monitoring to technology transfer to retention. Other changes, such as implementation of field review groups by then director of Civil Works Research and Development William Roper, improved coordination with major Corps elements. After implementation of Reliance, the Corps assigned lead laboratory functions for DoD-identified research areas, with WES serving as lead on airfields, hydrology, and installation restoration; CERL serving as lead on conventional facilities, noise abatement, conservation, and compliance; CRREL serving as lead on cold regions engineering and remote sensing; and TEC serving as lead on surveying and mapping; among other areas. The labs made concerted efforts to reduce redundancy through site visits and workgroups, such as WES and TEC adding functionality to the AirLand Battlefield Environment software or mobility models and WES and CERL resolving differences over their seismic and environmental research programs.³⁴³

The Fight for ERDC

In 1993, CERD director Robert Oswald started preliminary planning for consolidation of Corps labs in a federated system along the lines of ARL, but he had not gotten far before his 1996 retirement. His replacement, CRREL Director Ed Link, continued to review the issue. Soon after, the incoming Chief of Engineers, Lt. Gen. Joe N. Ballard, provided a new impetus

for consolidation when he expressed an interest in changing the business model for Corps research. Almost immediately after coming into office, he made some preliminary steps toward consolidation, such as moving the environmental laboratory in Omaha District under WES. Ballard wanted a combined laboratory organization under a single military commander like a division, and also to make CERD, the only HQUSACE directorate with line responsibilities, more of a staff element in line with current Army organization. Both he and Link understood that the Army was the largest customer of the Corps labs, and that with the post-Cold War changes in military strategy focusing on rapid deployment and a reconfigured command structure, they needed to align the labs to support the Vision 21 initiative. Multidiscipline teams were critical in this fast-moving environment, while competition among the labs was confusing customers and had sometimes led to a loss of business – a critical issue for reimbursable work. Financial concerns were an equally important reason for reorganization. Given the pressures to reduce RDT&E spending, it was essential to increase laboratory efficiency before the Army required further reductions in force. Combining assets by sharing support functions and research facilities would reduce cost while making the labs more responsive. Link began holding frequent directors conferences with O'Connor, Whalin, acting TEC director Col. Robert F. Kirby, and acting CRREL director Lt. Col. Mark Nelson or their designees anywhere from every other month to every few weeks to begin conceptualizing the organization, developing a process, and planning implementation of a laboratory command.³⁴⁴

Ballard established the goal of consolidating the labs, made a few key decisions, and set constraints, but he largely left the laboratory directors to work out the details. As such, the fight over how to consolidate was a shared effort among lab directors to reach mutual decisions on the future of the organization at least nominally based on business metrics and strategies. As one might assume, the directors brought different attitudes to this process depending on the situation of their laboratories. The strongest proponent for consolidation was O'Connor, who later said, "CERL had quite frankly maybe even a bigger stake in it than some of the other labs. CERL was always thought to be the most vulnerable. If any lab was going to dry up and blow away, there was a great likelihood that it would be CERL." Because of its civil works research, WES did not share the same levels of budgetary fluctuations that CERL saw over the previous decade, and in general WES was older and more stable. Whalin, although sometimes criticized as the largest opponent of consolidation, in fact supported efforts to improve efficiency. Nevertheless, he generally favored a WES-central approach and argued strongly for continuation of the WES brand, for headquartering the new command in Vicksburg, for maintaining Senior Executive status for laboratory directors, and for greater incorporation of ITL into the process, fights he did not always win but always influenced. Kirby and later Roper tended to emphasize TEC's unique position as a mostly military warfighter support center that had greater security requirements. Only in 1998 at the end of the process did CRREL have a permanent director, Barbara Sotirin, too late to influence the early key decisions, including what the organization



Lewis "Ed" Link.

would look like. Link served as mediator of the discussions and final arbiter of the many disputes that erupted, but ultimately, the plan that evolved was developed by the laboratories.³⁴⁵

Although all directors wanted to improve efficiency through increased coordination or partial consolidation, they disagreed about what the end state should be. They argued about the location of the new organization. There was wide agreement it should include multiple sites similar to ARL, but where to put the headquarters? Those at WES assumed that as the largest site in terms of laboratories, personnel, and acreage, it would be the headquarters. Those at TEC argued strongly that its convenience to HQUSACE and the National Capitol Region made it ideal for at least some functions. Others argued the relative benefits of sites in terms of accessibility or local needs. In the end, after the directors considered placing the headquarters in the Humphreys Engineering Center, WES won out as its location to support the majority of personnel stationed there. Then there were the unavoidable political issues of leadership. Would there be a director at every site and at what pay grade? Lab directors could only report to a higher ranked civilian or a general officer, but in time it became apparent the Corps would not get approval for a new general. That left maintaining a colonel as commander and having directors report to Link, an overall director, or someone else in Washington, but Ballard wanted to keep CERD separate from laboratory management. Surprisingly, one of the most contentious issues was the name. Each laboratory had built a certain amount of name recognition and branding because of long histories, none more than WES, whose name was recognized throughout the engineering world as a leader in hydraulics research. Over time, the proposed command went through several names. At first, it was the Research, Development, and Engineering Center or, more generically, the Laboratory Command. By the end of 1997, the title Engineering Institute was in vogue and remained so until mid-1998. Those at WES continued to decry loss of its brand. In the end, the directors reached something of a compromise – they settled on the Engineer Research and Development Center (ERDC) as the name but retained WES as the name of Vicksburg site, which satisfied few at WES, who argued that it was the only lab to lose its name. Merely merging administrative functions without improving technical work defeated the purpose of reorganization, but this required additional thought. Finally, they all wished to avoid the mistakes of ARL – not funding the organizational changes, trying to maintain too many campuses and too large of a support staff at each location, and not re-engineering the management staff at the same time.³⁴⁶

By April 1997, laboratory directors accepted consolidation under a single command to achieve a goal of 20 percent savings. As WES commander Col. Bruce K. Howard observed, “If this is in fact our future, we must focus our energies to achieve this goal yet maintain enough flexibility to perform our mission in the interim and ideally grow to our new end-state.” On May 5, 1997, he distributed a plan based on a WES study. He emphasized the primary need to consolidate under a single financial database, without which “consolidation” would be “unachievable except in name only.” The study determined that Audit, Legal, and Equal Opportunity offices could merge immediately without ill effect; that Public Works, Security, and Safety, Public Affairs, and Contracting could merge by the end of the year under various options for

partial or complete consolidation; and that Resource Management and Logistics could merge the following year. "All that is lacking from doing the above is a *collective political will*," Howard concluded. The response from CERL and TEC came within days. While CERL objected to WES shoe-horning CERL support offices to fit its organization, Deputy Director John Bandy laid out an alternate vision that included a two-phased implementation with separate merging of technical elements, a matrix support structure that included consolidated headquarters and on-site support, virtual teams to develop cross-laboratory plans, and an emphasis on the need to re-engineer processes to achieve savings. Kirby raised concerns about the WES plan assuming consolidation in Vicksburg when TEC's co-location with headquarters made some functions preferable there. He argued that given TEC's high level of classified research, some elements of security, contracting, audit, and resource management needed to continue at its location. Finally, he pointed to lack of consideration of outsourcing some support elements and pointed to TEC's own arrangement with the Humphreys Engineering Center Support Element as a model. Even as director conferences continued, by the end of May, Link's staff kicked off business process team meetings including Bandy, John Harrison of EL, Bobbie Kerns from TEC, and Joe Roberto from CRREL to work out the details of support function integration, define metrics and business practices, develop cost analysis and staffing, and prepare a decision briefing. The team held its final meeting in August 1997 and completed its work by the end of the year. Included in this study were four different management options for the new organization for review by Ballard and Link.³⁴⁷

After discussing the plan with commanders and laboratory directors (including by this point the individual WES laboratories) on January 21 and 22, 1998, and receiving their feedback, Link briefed the plan to Ballard on January 29, 1998. He discussed the current baseline and laid out a plan for an organization with an integrated command and business structure but distributed technical execution that relied heavily on cross-laboratory virtual teaming to develop integrated macro-plans, very similar to the CERL plan. There would be eight technical laboratories at four sites, and also cross-laboratory capability packages managed by program managers. The Engineer Institute would report to the Deputy Commanding General and not to CERD. A board of directors headed by Link would guide the technical program. Estimated savings for just the immediate consolidation and rightsizing of support functions was 10 to 14 percent, more than half of the goal of 20 percent, which planners believed the labs would achieve once it reached end state. Feedback from an independent industry review of the proposed plan suggested support for the new organization but also warned that it would require at least annual updates to keep processes aligned. The presentation also suggested a timeline for site selection, establishing the command, system consolidation, and technical consolidation ranging from three to 15 months. Ballard approved the concept and authorized work on an implementation plan, but recommended looking into a consolidated Civilian Personnel Advisory Center – the regional human resources organization – and selecting a firm implementation date. He requested preparation of a congressional briefing and also asked for an in-progress review for a final decision.³⁴⁸



Col. Robin R. Cababa.

Link immediately established an Implementation Team selected by the laboratory directors, headed by Peter Swart, Assistant Director of CERD for Lab Operations and reporting to the R&D Board of Directors. The team, which included Swart, Bandy, Roberto, Frank Capece of TEC, Dennis Smith of WES, and William Lovelady of the WES Office of Counsel, began meeting March 12, 1998, and quickly established an implementation plan and timeline. They then turned to the communications plan, including marketing plans, a congressional briefing, an implementation Web site, and the first of a series of information papers for public distribution. On April 6, 1998, Link provided Ballard an in-progress review in which he explained the progress and timeline, identified the process going forward, and discussed the problem with Senior Executive Service reporting – the laboratory directors would manage the technical program but not report to the commander, who would be responsible for everything else. Ballard approved the concept, the appointment of newly assigned WES Commander Col. Robin C. Cababa as the commander, and a date of October 1, 1998, for creation of the new organization. He signed the decision document on June 4. Preparations for the institute stepped up immediately after the review. The Implementation Team met again on April 10 and assigned consolidation planning for each support function to different team members. On April 15, Ballard sent a notification letter to congressional leaders of states where the laboratories were located and the heads of the committees that had oversight of the Corps. On request, Link briefed Mississippi senators Trent Lott and Thad Cochran, as well as Virginia Representative Owen Pickett. Later in April, Link held town meetings to discuss the reorganization and established an electronic bulletin board to post questions. Most of the questions concerned leadership changes, reporting processes, and changes to the technical program. Preparation of a press announcement proceeded, with final publication of the news release on July 28.³⁴⁹

As implementation planning proceeded, on April 3, 1998, Link kicked off the technical program improvement with the start of the macro-planning process. Essentially, these were business plans developed by cross-laboratory teams for multidiscipline virtual technology areas composed of individual capability packages the labs could deliver. The initial teams Link identified included Infrastructure Design and Management headed by O'Connor, Basic Research headed by Sotirin, Rapid Mapping/Terrain Visualization/Image Exploitation headed by Roper, Environmental Quality headed by Harrison, Force Protection/ Sustainment/Logistics headed by Marcuson, Water and Sediment Management headed by Houston, and High Performance Materials headed by Mather. Link appointed Whalin to coordinate the plans and avoid duplication of effort. A few days later, Link provided guidance that the plans include an assessment of need, product development, and resourcing and management plans. Although Whalin suggested adding High Performance Computing and Software Engineering under Radha, it was not immediately included. Whalin requested that the teams start meeting by early May, a schedule he acknowledged was "ambitious." It was, he noted, "an outstanding opportunity not only to

critically review our own program but also to develop the underpinning for an enhanced corporate investment strategy,” an effort to which he was “totally committed.” In fact, most of the teams did not start meeting until the end of May, each taking different approaches to developing the plans. Marcuson’s team met first on May 7 and provided a first stab at defining a plan, which several others used as a model. Later, O’Connor circulated highly detailed macro- and capability package plans as examples. Disagreement abounded over the plans and how to develop them, but as Link explained to one team on May 19, the initial round of planning would not be perfect but would force them into a new paradigm of thinking holistically, and the teams could refine the plans the next year. He later explained that the goal was to “manage, not stamp out” competition among the labs, which sometimes had positive effects. As confusion continued, Link explained in an information paper that macro-planning was a non-structural horizontal process to improve quality and would not result in a new reporting scheme. Several of the groups continued meeting on and off over the next several months to complete the plans for their areas.³⁵⁰

Even as plans for reorganization continued, additional problems arose that resulted in considerable debate. One such issue was how to handle the Laboratory Personnel Demonstration project. As discussed previously, WES had participated in the demonstration since 1995 with excellent results. The other laboratories had since developed and submitted their own programs. However, by early 1998, the DoD was reluctant to accept new plans for fear of creating too many systems. Since the WES program was already approved, the implementation team decided to expand it to the other labs. Another issue was the concept of a temporary site manager. During its reorganization, ARL developed site managers reporting to the director to manage reorganization on-site, and former ARL Chief of Staff Kevin Kirby considered the position “key to the successful consolidation of ARL support elements.” However, Cababa, Whalin, and Smith had questions about how it would operate. Preliminary job descriptions had site managers reporting to CERD since they would exist prior to assignment of the commander. After discussion of the issue in July, the Board of Directors decided against a uniform site manager but left it to Cababa or laboratory directors to establish chief of staff or other positions to aid in the transition. In April, Information Management personnel began to raise the difficulties in changing or correctly coding the various computer systems, particularly the Corps of Engineers Financial Management System, and the teams worked to resolve the issues. At the director’s meeting on June 4, concern arose that there was no clear decision-making process, that there was not clear communication with the various planning teams, and that some focus needed to return to current operational issues. As a result, efforts began within days to develop a decision matrix, and the Implementation Team scheduled a meeting to update the directors on July 9. By mid-July, the directors had settled on a new structure with a director to whom the laboratory directors would report and by the end of August on ERDC as the name of the organization.³⁵¹

At the end of September 1998, everything was set to begin the transition to the new laboratory organization. Establishment of an ERDC support organizational structure was complete by the end of June. By the end of August, the Implementation Team had approved a final decision timeline, Cababa had appointed interim personnel to head the new offices, and

the Implementation Team had realigned personnel records and related IT systems, although timecard systems would not change until October 11. A final series of town hall briefings in September explained the current organizational plan and name changes to lab personnel at each site. Final orders were ready for signature. After more than 50 years of gradual evolution, merging, and maturation of Corps laboratory research; after more than 20 years of study, debate, and delay of multiple reorganizational plans; and after more than a decade of incremental streamlining, efficiency improvements, and increased coordination; the Corps was finally poised to consolidate the majority of its laboratory research and development programs into a single organization. The complicated and sometimes contentious planning process to create ERDC had lasted nearly two years, during which the laboratories had worked closely together to define the new structure, rightsize support functions, and plan realignment of the technical program. Only by taking the final step would its planners know whether the meticulous preparations would result in the cost efficiencies and improvements that Ballard and Link originally envisioned.³⁵²



Chapter Nine *Engineer Research and* *Development Center*



ERDC entrance sign in Vicksburg, Mississippi.

On October 1, 1998, Chief of Engineers Lt. Gen. Joe Ballard issued orders establishing the U.S. Army Engineer Research and Development Center (ERDC). With its formation, the Corps of Engineers entered a new era of research and development, an era of consolidated and closely coordinated laboratory research. While there remained eight different laboratories at four geographic locations, they utilized the same support structure and offices under a single commander. Integration of personnel, computer systems, and offices took many months, but there was an almost immediate reduction in the cost of operations. Within a year, the technical laboratories merged to consolidate research activities based on customer-aligned plans, which promised to reduce competition and thus allow more cooperation in bringing new solutions to age-old engineering problems. Yet the challenges that remained were immense. For nearly two years, there was no permanent director of ERDC, and most of the core leaders of the labs left or retired, leaving it to a committee of mostly new or acting laboratory directors to make most decisions. There was wide disagreement about the direction of the technical programs as debates among directors continued for many months, while parochialism in the labs prevented the level of cooperation that Ballard initially sought. Despite the change in management, corporate cultures at the sites were very different, and morale was low. Additional organizational changes and movement of personnel complicated the situation greatly. It was by no means clear at the outset that ERDC would be successful. Only with the stabilization and introduction of new ERDC leadership and evolution of new approaches would ERDC begin to operate as initially envisioned.

Standup of ERDC

According to orders, the Corps officially established ERDC on October 1, 1998, assigned as its commander Col. Robin R. Cababa of the Waterways Experiment Station (WES), and transferred 328 support personnel and 33 military personnel to ERDC under him. An operations order issued by Ballard the same day explained how consolidation would take place. According to plans developed the previous two years, the formation of ERDC would occur in two phases. In the first phase during fiscal year 1999, ERDC would consolidate support functions under the new deputy commander and commander, who, Ballard ordered, “will have CFO responsibility” for all business, site, and financial operations with a goal of creating “a streamlined organizational structure suitable for the integrated command and distributed technical program execution.” Thus, the Audit, Contracting, Counsel, Equal Employment Opportunity, Public Works, Logistics, Public Affairs, Resource Management, Safety, and Security offices from WES, the Topographic Engineering Center (TEC), Cold Regions Research and Engineering Laboratory (CRREL), and Construction Engineering Research Laboratory (CERL) transferred to ERDC. The majority of personnel from each office would remain at the individual geographic locations, but their headquarters would be in Vicksburg, Mississippi. Eventually, the Contracting Office headquarters would relocate to the Vicksburg District but would maintain separate operations from the district. The Civilian Personnel Advisory Center (human resources) selected to support ERDC was that of the Mississippi Valley Division co-located in Vicksburg, Mississippi, near the largest ERDC campus. The second phase of standup – consolidation of the technical laboratories – would occur no

later than October 1, 1999, and would also include two phases. In the first phase during 1999, the labs would complete new macro-plans for future operations, finances, and research investments, essentially a process of improving the preliminary plans developed in 1998. The last phase was integration and organizational realignment starting in fiscal year 2000 with the laboratory directors and Programs and Plans Office reporting to a civilian director of ERDC, yet to be identified. With the consolidation of the technical laboratories, standup of ERDC would be complete, but the process of creating ERDC would have just begun.³⁵³

The orders also reorganized the Headquarters of the U.S. Army Corps of Engineers (HQUSACE). The Director of Corps Research and Development (CERD), Lewis E. "Ed" Link, became the HQUSACE Deputy Chief of Staff for Research and Development reporting to the Deputy Commanding General of the Corps. He would also serve as the head of the Research and Development Board of Directors, which included all of the laboratory directors. Under the Deputy Chief of Staff was a board of program integration officers. The orders assigned the former commanders of CRREL, TEC, and CERL – Lt. Col. John B. McLeod, Col. Gary Thomas, and Col. James A. Walter – as program integration officers for Military Engineering, Topography, and Installation Support, respectively. The program integration officers were to act as the single door through which these customers could define requirements, serve as advocates for their constituencies, and manage technology transfer. Although they continued to reside at their individual sites for several months to maintain a military presence, they neither managed personnel at the laboratories nor reported or had responsibilities through ERDC. In fact, with the transfer or rotation of the original commanders and less need for the position, the board's role faded and more or less ended within three years. Also according to the orders, HQUSACE would provide staff support to ERDC during its formation, while the CERD would support the transition through management of paperwork and resources, transfer of missions, participation in planning, and active communications.³⁵⁴

Within days, Cababa sent a welcome note to the new organization, that acknowledged, "Bringing all of the diverse laboratory operations into a cohesive organization which utilizes the best business practices will be no small task, but I am confident that we will succeed." There were indeed some very large tasks. One was reduction of support personnel. According to plans, there would be an overall reduction of 125 from 1996 baseline numbers, although a significant percentage of these had already left or retired by the time ERDC stood up. It would achieve the rest through voluntary separation incentive pay rather than reductions in force. Another was creating a single budget and budgeting process, which had already begun with planning the 1999 budget. A major issue was reducing General and Administrative (G&A) charges to avoid high overhead, and some shifting occurred from G&A to indirect and departmental charges. Facilities issues were complicated because of the varying arrangements of the laboratories: CERL received support through the University of Illinois from whom it leased property; TEC outsourced support to the Humphreys Engineering Center Support Activity; at WES, facilities personnel were also responsible for transportation and safety. Cababa decided to maintain separate Public Works and Logistics Directorates with managers at each site except TEC. Information management represented something of a quandary because, other than at WES, most considered it an administrative function. Cababa

decided to transfer these organizations to the Information Technology Laboratory (ITL), which would maintain local coordination centers. Nevertheless, resolution of technology issues was complicated. Visibility of business processes required standardizing on a single financial and reporting system, the recently implemented Corps of Engineers Financial Management System (CEFMS). All labs had to migrate to an Oracle database and the CEFMS software. Conducting an inventory of the diverse systems alone took several weeks, and problems periodically arose requiring development of new reports and interfaces. To support him during these changes, in March 1999 Cababa assigned Joe Roberto of CRREL as deputy to the commander of ERDC.³⁵⁵

As with most reorganizations, there were morale issues with everything from the new name to new processes receiving some criticism. There was also a noticeable change in upper management during the first two years, leaving the impression that most left because of the reorganization. WES Director Robert W. Whalin, whom many expected to become the first director of ERDC, received an offer to interview for director of the Army Research Laboratory (ARL) in April 1998 before a final decision on ERDC had been made. He accepted the ARL position in July and left WES in December 1998. In June 1999, N. Radhakrisnan, director of ITL, joined him at ARL with a promotion to Senior Executive Service. After being deeply involved in ERDC planning, Environmental Laboratory (EL) Director John Harrison retired in 1999. Bryant Mather and William F. Marcuson both retired in early 2000. William E. Roper, who had moved from HQUSACE only in mid-1997 to serve as director of TEC, also retired to accept a position at George Washington University. Barbara J. Sotirin transferred from CRREL to HQUSACE in 2003. Many of the deputy directors also retired, transferred, or left the Corps during the same period. For those that remained, suspicions continued of the intentions of leaders from other labs.³⁵⁶

Perhaps the most problematic issue with consolidation was finding a new civilian director for ERDC. The Corps twice advertised for a director position located in Washington, D.C., but none who applied were precisely what Link and Ballard wanted. The most obvious choice, Whalin, had already committed to another job and left at the end of 1998. Harrison and Radha left in 1999. Of the remaining directors far enough from retirement to entertain taking the position, the most experienced were James R. Houston, who had been director of the Coastal Engineering Research Center since 1986 and of the Coastal and Hydraulics Laboratory (CHL) since 1996, and Michael J. O'Connor, who had been director or acting director of CERL since 1994. Ballard mentioned the position to Houston in 1999. However, Houston told Ballard he did not want the position, noting his background was primarily civil works, whereas the majority of ERDC's overall budget was military-oriented. He also had no desire to move to Washington. Meanwhile, arrangements were already underway to transfer O'Connor to the Geotechnical Laboratory. In the interim, Link continued to provide guidance to the independently operating labs as Deputy Chief of Staff for Research and Development. For the first few months, this was not a problem, since only the support functions had consolidated under the day-to-day management of Cababa. As the labs geared up for consolidation of the technical elements, this would no longer be the case. In March 1999, after discussion with the directors, Link formally established the Office of ERDC Directors, assumed the position of acting director of ERDC, assigned Assistant CERD Director for Military Programs Donald J. Leverenz as acting deputy director, and in April assigned

Dennis Smith of WES as acting assistant director to interface with Cababa. The plan was for each laboratory director to report to the ERDC director instead of the director of CERD (although Link temporarily held both positions). The WES director position was formally abolished under the ERDC organization. While Link provided general oversight for the continued evolution of the technical program, he was only marginally involved in the discussions that followed, leaving most of the work to Leverenz or to integrated process teams that reviewed special issues such as military operational support or the Graduate Institute. Nevertheless, on October 1, 1999, Link stood in as ERDC director during the official activation ceremony.³⁵⁷

The organization as it existed at that time included more than 2,100 employees, 1,780 of which were technical personnel in the laboratories. There were eight laboratories, each headed by a director responsible for planning and spending program funds, conducting quality control, and managing and mentoring technical teams. Led by Sotirin, CRREL included Remote Sensing/GIS, Engineering Resources, Applied Research, Geological Sciences, Geophysical Sciences, Civil Engineering Research, Snow and Ice, Ice Engineering, and Geochemical divisions. TEC, under Roper, consisted of Topographical Research, Topographical Systems, Force Development, Operations, and Geospatial Information divisions. Under O'Connor, CERL reduced its divisions to just two: Facilities and Installations. The Structures and Geotechnical laboratories, led by Mather and Marcuson, respectively, included Concrete and Materials, Geomechanics and Explosion Effects, and Structural Mechanics divisions and the Earthquake Engineering and Geosciences, Airfields and Pavement, Mobility Systems, and Soil and Rock Mechanics divisions. Now under Timothy D. Ables, ITL included Information Management, Instrumentation Systems Development, Computer Science, and Computer Aided Engineering divisions plus its computer centers. EL under John W. Keeley included Environmental Processes and Effects, Natural Resources, and Environmental Engineering divisions, and CHL under Houston included Estuaries and Hydrosciences, Rivers and Structures, Coastal Sediments Engineering, and Navigation and Harbors divisions. Unlike the previous situation, nearly all laboratories had strong deputies who could step into the role as director since it was widely anticipated that, as the 1999 Lab of the Year submission stated, "In the next 10 years, ERDC will experience almost 100 percent turnover" in its Senior Executive Service and GS-15 leadership.³⁵⁸

Technical Program Development

When Link assumed the role of acting director in March 1999, his primary task was continued development of the technical program. A program management board composed of Leverenz and the laboratory directors, who had already been meeting regularly since spring 1998, were responsible for developing processes for program growth and execution. The program integration officers, support offices, and an Integrated Planning and Programming Office (IPPO) were to provide support. The board's first tasks were establishing its own charter and processes, developing program priorities and initiatives, determining how to fund them, and developing a technical indirect budget to fund technical overhead no longer falling within the ERDC G&A. Integrated process teams were to develop the composition and functions of the IPPO, determine the most effective means of program management, and plan and install information systems to support the

technical program. Because of concerns about the IPPO, in April Link delayed its implementation in April and instead created a task force headed by Thomas Hart, composed of individual Plans and Programs Office chiefs reporting to Leverenz. Guiding efforts of the various teams were planning sessions conducted with the Dartmouth College Tuck School of Business in November and December 1998 and the Commander's Intent for Phase II, briefed to the laboratory directors in January 1999 and finalized in February. Among concepts discussed were a "learning organization" that maintains expertise and promotes knowledge sharing through mentoring; a "project/team paradigm of program management" with a technical director working across multiple locations focused on a single problem, customer, or solution set; and a streamlined management structure that provides maximum technical support through a formal inverted pyramid organization and maximum reachback through an informal spider web organization. Other issues included providing incentives for rotating principal investigators among laboratories to gain expertise, developing a repository of technical knowledge, and encouraging submission of research ideas by client managers. The monthly board meetings were at times highly contentious as the directors debated program elements and results of integrated process team investigations. With Link absorbed with staff responsibilities, Leverenz and the directors often made the primary decisions about the future direction of research investments or how and when to work together, while individual laboratory directors independently made decisions affecting their programs.³⁵⁹

One of the first issues in the development of the technical program was refinement of macro-plans by the laboratory directors. Noting that "the first draft of the Macro plans is an important step in gaining a more corporate investment strategy," Link directed Leverenz to form an integrated process team to review the existing plans and determine how to update them and synopsize them for presentation to Corps leadership. An immediate concern was the Civil Works and Research, Development, Test, and Evaluation (RDT&E) budgeting priorities for the next two fiscal years. With reorganization of the labs and staff reduction at headquarters, the task of putting together justification sheets for each research area fell to the program integration officers with technical coordination provided by assigned lead laboratories. CERD would review and finalize the sheets by July. The macro-plans would need to align with these requests. The program integration officers would ensure the plans met requirements specified by major proponents. Link requested initial plans by September 1 and final plans by October 1, 1999. The macro-planning teams met again to work through the plans, with some adjustment in their composition and focus. The names and direction of some business lines changed, as did some leaders. The Force Protection/Sustainment/Logistics area became simply Military Engineering. Rapid Mapping/Terrain Visualization/Imagery Exploitation became Topography, Imagery, and Geospatial. Infrastructure Design and Management became Infrastructure Asset Management and Delivery. Environmental Quality came under the management of Keeley. There was also the addition of an Information Technology area, initially under Radha. The inter-laboratory approach not only provided, "an opportunity to build a sound team relationship across the labs in each mission area," as Link stated, it allowed greater marketing of the services and enabled greater reachback to lab resources. "Make no mistake, we will look at all pragmatic options in an endeavor to get more total horsepower out of the R&D engine," Link wrote in March 1999.³⁶⁰

Another concept that the program management board introduced was technical directors – cross-laboratory program managers in the “project/team paradigm” to oversee the technical programs. In this matrix structure, although personnel management continued under existing laboratory management structures, program management occurred under a technical director across multiple organizations. The concept of cross-laboratory program managers, or “flex-lab” as some called it, was not completely new. The Corps had for many years used program managers across organizations within the same districts or labs to bring attention to common activities, as well as centers of expertise to serve as lead organizations on specific issues, such as unexploded ordnance removal. For example, WES applied flex-lab in developing groundwater modeling and Logistics-Over-The-Shore, both multilab efforts. In ERDC, the laboratory directors served as business line managers in their responsibility for macro-planning and management of lead laboratories. Some individual program managers also became technical directors with responsibilities for programs that crossed organizational lines. As O’Connor, who was a major proponent of the approach, explained, “The idea was to develop your programs independent of organizational structure so that you filled the best program and then got it executed by the right portion of the organization.” Some questioned the cost and need to consistently execute research in this way, but Link supported the concept. The board established an integrated process team that included William Goran, Jeffery P. Holland, Thomas Hart, and its own representatives to develop the initial concept by June 1 and final recommendations by August 1, 1999. There continued problems resolving virtual responsibilities with compensation and performance reviews that came through the formal lab organization, many of which the board did not address until late 2000, and some managers felt they lost control of technical assets. Nevertheless, it was, O’Connor believed, “conceptually significant and important.”³⁶¹

Interrupting these discussions were a series of day-to-day and long-term management issues that required resolution as the ERDC labs started to integrate. The program management board closely examined lab manning requirements, particularly high-grade positions. It also continued to review budgeting issues, such as budget formats, departmental budgets, G&A rates and waivers, and handling of contracted personnel. Planning started on a permanent executive office, including its budget and manning. After Ballard noted ERDC’s low level of small business participation in late 1999, the board discussed ways of improving it. Another issue was implementing the Program Management Information System, and in May 2000 the board completed policies on its implementation and training. When some lab directors expressed concerns about other labs “poaching” employees in attempts to spread expertise under the “learning organization” concept, the board discussed and in March 2000 established policies giving directors final approval over transfers. Concerns also arose that support service costs were unequally distributed since some costs at WES fell under G&A versus departmental budgets. Although “this may be more of a perception than a reality,” Leverenz agreed to review the issue when scrubbing final departmental budgets in June. As the year progressed and some of the labs struggled under new accounting procedures, the board considered subsidies for facilities or other areas. Finally, after months of these issues absorbing most board discussions, in announcing the May 2000 meeting Leverenz stressed, “At last, a [program management board] that talks about program.”³⁶²

By May 2000, discussions finally turned to the lab reorganization plans, the technical program for 2001, and the role of technical directors and laboratory directors. In June, the program management board completed review of the CHL, CERL, and CRREL realignment plans, by August reviewed that of TEC, and in October reviewed those of EL and ITL. In most cases, the only changes the board made to the plans were to ensure that the labs had an appropriate number of branches and divisions based on manning guidance provided by Ballard to reduce the number of second line supervisors. In June, the board reviewed unfunded requirements for 2001, started to review work priorities, assigned technical directors to new business lines, and set schedules on deliverables. Soon afterwards, the board became aware that obligation and execution of some 2000 military direct programs were behind schedule, although in only two cases were there outstanding commitments. It could only review the causes and make corrections for the future. The most problematic issue related to processes for program execution. In June, the board identified several new business areas, suggested lead laboratory assignments, and assigned customer interface roles to each director. Col. James A. Walter, who moved from CERL to serve as acting director of TEC, suggested that ERDC needed to coordinate with the Maneuver Support Center, Aviation School, and others to identify technology development funding, which, Leverenz noted, “resonated” with the board. By the following month, disputes arose over the lead laboratory assignments, with Sotirin expressing frustration that CRREL did not initially have program development responsibilities. “What should my Cold Region Technical Director do?” she asked. The other labs agreed to review the matter in the long term while involving CRREL in new missions in the short term, but Leverenz noted this would not involve “a cleaving of mission from other labs.” Overlaps among various organizations dealing with geospatial products such as geographic information systems (GIS) were another topic of discussion. Leverenz, meanwhile, questioned the financial sustainability of the number of labs and requested additional studies. At least for the time being, however, ERDC had stabilized and was moving into the future. By September 2000, the board completed and distributed the technical director roles and responsibilities document as well as a list of specific business line assignments, and it finalized reorganizational plans in November.³⁶³

Continued Organizational Adjustment

As a second year dragged on with no permanent ERDC director, by March 2000 the Corps finally advertised the position in Vicksburg since 60 percent of its functions and personnel resided there and advertised the deputy director position in Washington. Unfortunately, the applicants were still not acceptable. Finally, Link discussed the matter with Houston while he was in Washington and told him that Ballard wanted him to take the job. Houston reluctantly agreed, saying, “I am going to take it because we have been without a director for two years and nine months, and we sorely need a permanent director.” By this point, the laboratory directors just wanted someone in the job. Although Houston did not



James R. Houston.

originally want the position, he later said he was glad that Ballard asked him. Houston became the first director of ERDC in June 2000 and guided the organization through its most difficult period. By mid-2000, the future of ERDC was anything but sure. Six of the eight labs had temporary leadership, and the most senior leader – Sotirin – had only been in the position for a little more than two years. The cultures of the labs were highly fragmented, a situation that would improve only with time as new personnel worked together on projects. The primary mover in creating ERDC – Lt. Gen. Joe Ballard – completed his term as Chief of Engineers in August 2000, carrying with him much of the motivation and vision for initiating the changes. There was, at first, considerable confusion about the roles of the director and commander since Ballard had originally intended and still preferred working through the military officer. For the first month, there were two signature lines on most orders for the commander and director. Cababa retired shortly thereafter, and Houston worked with incoming commander Col. James S. Weller to define responsibilities. Admittedly lacking experience with the military side of the Corps, Houston worked to build contacts in the Pentagon, eventually hiring Walter “Rick” Morrison, formerly the Senior Executive Service Director of Research and Laboratory Management in the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology, as deputy director in Washington, D.C. This became particularly important with the September 11, 2001 terrorist attacks, after which funding increased rapidly for ERDC to provide technology for antiterrorism and the Global War on Terror. By 2009, funding was \$1.5 billion per year, triple the level when Houston became director, only 20 percent of which was for civil works.³⁶⁴

At Houston’s first meeting with the laboratory directors after assuming the directorship, he stressed the need to fill key positions and complete laboratory reorganizations to provide ERDC a measure of stability, to implement the concept of lab directors and technical directors having ERDC-wide responsibilities, and to improve morale. The latter had become so bad that Cababa had requested an Inspector General Command Climate Study to recommend improvements. Houston speculated that morale would improve through filling empty positions that employees saw as a sign of leaders being uncommitted or through improving communication of ERDC benefits that many had yet to see, such as reduction of support costs and no loss in RDT&E funding for 2000. To adjust to new research demands, ERDC continued to evolve under Houston over the next decade. In October 2000, the program management board considered several minor organizational issues raised by Weller – that ERDC establish a congressional liaison and geographic coordinators. It decided to assign Outreach Coordinator Jeffrey Walaszek congressional responsibilities, and an integrated process team studied regional coordination. Several other larger organizational adjustments occurred in the months and years that followed.³⁶⁵

The first major change – initiated prior to Houston becoming director – was the merging of the Geotechnical and Structures laboratories. The gradual decline in the funding and personnel in the two laboratories during the 1990s and the synergies among their military programs provided strong reason to merge their activities. However, lab parochialism prevented action at that time. Both laboratories had strong traditions, having existed in the case of the Structures Laboratory since the formation of the Central Concrete Laboratory at West Point, New York,

in 1938 and in the case of the Geotechnical Laboratory since the formation of WES in 1930. Both had long-serving directors, Mather and Marcuson, who customers strongly associated with the laboratories. Mather was widely recognized as a concrete expert, served as president of the American Concrete Institute and American Society of Testing and Materials, and had been a member of the National Academy of Engineers since 1986. O'Connor later observed of him that "Mr. Concrete was the Structures Lab." Marcuson was also widely recognized, having been named to the National Academy of Engineers in 1996 and having served as regional vice president of the American Society of Civil Engineers (ASCE), received its highest honor – the Norman Medal – in 1997, and delivered its coveted Terzaghi Lecture in 1999. After the formation of ERDC, Link sought to proceed with the merger as Ballard desired while attempting to change the culture of the organizations. He spoke with the 84-year-old Mather about finally retiring and arranged to switch O'Connor and Marcuson, thereby bringing his process-oriented ERDC ally to the Geotechnical Laboratory to lead efforts to merge the labs, while moving Marcuson to CERL. However, Marcuson, who had been director of the lab since 1983, decided to retire in January 2000 just before Mather instead of moving to Champaign, Illinois. In announcing Marcuson's retirement in late 1999, Ballard named O'Connor as the new director. Mather then retired in February. Both Mather and Marcuson stayed on at ERDC in an emeritus role while pursuing professional interests. Mather passed away in 2001, but Marcuson continued at WES while later serving as president of ASCE in 2006.³⁶⁶



William F. Marcuson, III.

Thus, O'Connor became director of the Geotechnical Laboratory in January 2000 and acting director of Structures in February. In many ways, he was the ideal choice. He had for years led efforts at CERL to conduct cooperative research with the Geotechnical Laboratory and knew its work well, he was an early and lasting proponent of using computers that were increasingly critical for structural research, his experiences at CERL led him to seek to reduce competition in favor of customer-oriented services, and his deep involvement in the formation of ERDC made him very process-oriented. Most of his brief tenure was focused on the merger. Similar to the process leading to the formation of ERDC, he organized a series of teams to "try to figure out how to do it" and work through the various planning, organizational, personnel, and financial issues requiring resolution. In this way, he involved the personnel directly affected by the merger. He was, Marcuson said, "good at getting buy-in." He completed plans for the reorganization by June and briefed the program management board. In October 2000, ERDC officially established the Geotechnical and Structures Laboratory (GSL). It had 360 personnel with two major divisions – Engineering Systems and Materials and Geosciences and Structures – and six technical support centers focusing on airfields, concrete, materials, soil mechanics, centrifuge research, and TeleEngineering. This was a significant reduction from the seven major divisions under the two previous laboratories. O'Connor continued as director of GSL until May 2003, when he moved to HQUSACE as the Director of Research and Development, the

The Miracle of the Pentagon on 9/11



The Pentagon after the September 11 attacks.

At 9:37 a.m. on September 11, 2001, American Airlines Flight 77 smashed into the side of the Pentagon, killing 125 persons. The crash destroyed the first and second floors of the two outer rings of Wedge 1 on the western side of the Pentagon, throwing debris into a third ring and into Wedge 2. But for more than 35 minutes, floors three through five stood in suspension, allowing evacuation of hundreds of personnel before these floors collapsed from the heat and flame. What helped keep the floors up for those precious minutes were antiterrorist designs developed by the Engineer Research and Development Center (ERDC) that the Pentagon had added to that wedge in recent renovations.

Since the 1983 bombing of the U.S. Marine Corps barracks in Lebanon, the Corps of Engineers had conducted research into antiterrorist building de-



Reed Mosher.

signs, resulting in the creation of protective designs and building materials that could resist future attacks. In the decades that followed, Corps investigative teams visited the sites of major terrorist attacks to glean lessons learned from the destruction. For example, in the 1995 Oklahoma City bombing, the majority of the 168 deaths occurred because of

the progressive collapse of the Alfred P. Murrah Federal Building. Greater structural support would have saved many. In the 1996 bombing of the Khobar Towers in Saudi Arabia, most deaths and injuries resulted from flying debris, which could have been reduced by blast-resistant materials.

In addition, teams at ERDC led by Reed Mosher conducted a variety of experiments on new building technologies that could prevent further destruction. Using scale models and full-scale building mock-ups, they conducted hundreds of explosive tests while measuring and recording the results. They tested blast resistant glass, windows with anchors, building frames and

braces of varying materials, the use of ballistic cloths or plastic coatings to prevent brick and concrete walls from shattering, and other innovations. Using supercomputers making trillions of calculations per second, ERDC modeled in detail the performance of materials under a variety of circumstances and was able to predict the direction and speed of every glass shard or piece of debris from explosions of different strengths and direction. In short, ERDC has made a science of antiterrorism.

The result of these investigations has been the strengthening of many government buildings, including the Pentagon. Just prior to 9/11, the Pentagon had started a renovation project in which it incorporated many of the design elements developed at ERDC: interlocking steel beams and columns provided a matrix of steel that prevented the collapse of floors and walls; ballistic cloth similar to Kevlar lined the walls to prevent the limestone exterior from sending flying debris; and all windows included anchor straps and blast-resistant glass to prevent windows from exploding into the building. The renovations, applied first to Wedge 1 where the plane hit, were only five days from completion. In fact, had the planes hit a year earlier or had hit a different wedge on another side of the Pentagon, the death count would have been far higher.

After 9/11, the Pentagon immediately set to work on a second renovation of Wedge 1, which was complete on September 11, 2002 – one year to the day after the attacks. It then started renovation of the other four wedges. Other government buildings have likewise incorporated the antiterrorist building measures. Although many died in the attacks, the technology developed by ERDC had proved its mettle.

John Yates, a civilian security manager at the Pentagon who narrowly escaped the blast, later commented, “It’s a testament to the work the people in the renovation did and to the engineers. If it hadn’t been done, if there had been no structural hardening, I can’t imagine what the death and destruction would be. It would have been more catastrophic than it was – 10 times, a 100 times worse.”



Severely damaged unimproved offices located 300 feet from where the plane hit the Pentagon.



Undamaged, improved, walls and windows in offices just 50 feet from where the plane hit the Pentagon.

position recently vacated by Link. Replacing him as director of GSL was his deputy and long-time Pavements Division chief, David W. Pittman.³⁶⁷



Timothy Ables.

computers, but of engineering applications. Contributing to this transition was the decision by the Corps to compete information technology functions under the A-76 process. First issued in 1966 and updated numerous times, Office of Management and Budget (OMB) Circular A-76 provided guidance about determining whether activities in government should be performed in-house, by another agency, or by the private sector. After President George W. Bush made it a priority of his administration to increase competition in government, a 2001 General Accounting Office study he commissioned confirmed that A-76 competition could reduce costs, and by 2002 OMB set a goal of competing at least 15 percent of commercial positions in government.³⁶⁸

In line with these goals, in 2004 ERDC announced the Corps would compete information technology functions for the Corps, one of the largest A-76 studies to that time. “Typically, when these A-76s are formed, they focus on one function at one particular physical location. In our case, this initiative affects 1,300 employees,” nationwide, Corps Chief Information Officer Wilbert Berrios said. To shorten the process, the Corps agreed to compete under the more stringent Most Efficient Organization rules. Holland was the Agency Tender Official and led the creation of the government employee bid. Recognizing that the best way to compete was to partner with the private sector, the new government organization – Army Corps of Engineers Information Technology (ACE-IT), headquartered in Vicksburg – held a competition and selected Lockheed Martin Corporation to be its partner. After resolution of protests, the ACE-IT team signed the contract on April 19, 2007, with anticipated savings of \$1 billion over five years. Despite complaints about the contract during the first year of transition, ACE-IT was much more efficient, reducing IT personnel Corps-wide to approximately 950, reducing the number of IT contracts from 1,500 to one, and reducing the number of help desks from 63 to one. Given that A-76 competitions often resulted in reductions in force, the fact that not a

Another major organizational change during the Houston era involved the continued evolution of ITL. With selection of Timothy Ables as associate director of ERDC in 2001, Houston chose Jeffery P. Holland as the Director of ITL, who had worked mainly in numerical modeling while in CHL. Having been largely in a state of transition since the departure of Radha, ITL was, Holland observed, “hungry for leadership.” His vision was to move away from merely providing services to being more of a consultant, integrator, and partner in solving engineering problems using technology. In his view, ITL was “the glue that connected ERDC.” From 2001 to 2006, he worked to hire additional personnel and leaders that had a strong knowledge, not just of



Jeffery Holland.

single person was laid off was “a major coup,” Holland said. The immediate effect on ITL was that 138 of its 257 employees transferred to ACE-IT, although many worked in the same locations or “just down the hall.” In fact, because a large amount of the work at ITL was research-related, it was affected by the transition the least of Corps IT organizations, with most transfers to ACE-IT being from technical service divisions. Long-term, the A-76 “accelerated reorientation” toward ITL becoming research-focused by getting it out of the information management business, which was not its “core capability.”³⁶⁹

Over the next decade, Houston selected other new directors for each of the labs, which, he later noted, was his greatest legacy. He selected Thomas Richardson as the director of CHL in 2000 and William D. Martin in 2009 on Richardson’s retirement. In EL, he promoted Edwin A. Theriot to director after Keeley retired in 2001, and Beth Fleming to replace Theriot in 2005. In 2001, he promoted Alan Moore as director of CERL and in 2006 promoted deputy director Ilker R. Adiguzel to director. After the transfer of Sotirin in 2003, he finally selected as her permanent replacement Robert E. Davis in 2006. In addition to promoting from within, he worked to broaden ERDC capabilities by hiring directors or deputies with careers outside the Corps: Robert W. Burkhardt as the director of TEC in 2001, Lance D. Hansen as deputy director of CRREL, and Kirankumar V. Topudurti as deputy director of CERL in 2006. Other than leaders, the laboratory sites changed very little, although in 2004, ERDC dedicated a new CHL building and in 2009 broke ground on a new EL building. Because Houston had made a family commitment to retire after 10 years, he also worked to choose a successor. After the retirement of Morrison as deputy director, Houston decided that Holland had the greatest potential to follow him as ERDC director. In 2006, Houston met with Chief of Engineers Lt. Gen. Carl T. Strock and obtained his and later Army approval to move Holland to be the deputy director to understudy him. Reed Mosher of GSL became the new ITL director, continuing its strong engineering heritage. For the next three years, Holland shadowed Houston and gradually took more responsibilities, while Houston arranged with Chief of Engineers Lt. Gen. Robert L. Van Antwerp and the Army for Holland to become his replacement. In April 2009, Van Antwerp announced Houston’s retirement in January 2010 and Holland’s selection, the first time such a transition took place during the tenure of an active director. By 2006, the director’s role expanded considerably. With the retirement of O’Connor from CERD in 2006 and at the suggestion of ERDC Commander Col. James R. Rowan, Strock asked Houston about becoming the new director of Research and Development at HQUSACE in addition to being the ERDC director. Houston agreed and had an office and staff both in Washington, D.C., and Vicksburg. In addition to flattening the organization by having one civilian responsible for Corps research, this allowed the person most knowledgeable of research programs to support the Chief of Engineers.³⁷⁰



William Martin.

By 2009, there was also a major change at TEC related to the development of geospatial products for the Army. As the Army moved to being a consumer of dynamic geospatial data,

such as troop and enemy locations, instead of merely requiring static topographic data such as terrain and building locations, the Corps had moved from physical topographical systems to digital image processing to complete geospatial systems. Typifying this change was the evolution from the Defense Mapping Agency to the National Imagery Management Agency in 1996 to the National Geospatial-Intelligence Agency in 2003. As reliance on purely digital products widened, concerns grew about lack of interoperability in GIS. As discussed in Chapter Seven, the distributed nature of GIS development had led to a number of proprietary systems that could not interoperate. The same was true in the Army. The 1984 and 1987 Digital Topographic Data Requirements Studies conducted by TEC personnel identified more than 75 tactical systems using digital data. This situation only degenerated over time as the Army increased use of digital data and systems. When the Army mostly used printed maps, it was possible to manage map production to standardize cartographic processes, legends and marginalia, projection, formats, symbology, sizes, and datum. Because of the number of digital systems, often with their own proprietary data types, it became increasingly difficult over the next decade to share geographic data among services or even units and agencies just within the Army. The result was potentially disastrous as pilots, artillery, and infantry used incompatible and sometimes conflicting data. Further, reliance on digital data for combat decisions required the most current information possible to ensure intelligence was actionable. Bottlenecks in creation, production, analysis, and distribution of geospatial data – whether due to data or system incompatibility, slow network speeds, or collection and analysis processes – were no longer tolerable.³⁷¹

On November 15, 2004, the Army Requirements Oversight Council approved preliminary work on a Joint Geospatial Enterprise Service to enable integrated geospatial capabilities. The Training and Doctrine Command (TRADOC) tasked its Program Integration Office-Terrain Data to complete a Functional Needs Analysis of the needed capabilities. Completed in late 2005, the analysis identified more than 200 deficiencies in capability offered by current products. Also completed and approved was the Army Geospatial Data Integrated Master Plan, a collaborative effort co-led by the TRADOC Program Integration Office-Terrain Data and the Army G3 Modeling and Simulation Office that also enjoyed strong TEC participation. After the October 2006 meeting of the Geospatial General Officer Steering Committee, which included most of the general staff – the G2 (Intelligence), the G3 (Training and Operations), the G6 (Information Management), and the G8 (Planning and Programs) – as well as the military deputy to the Assistant Secretary of the Army for Acquisition, Logistics, and Technology and the TRADOC Army Capabilities Integration Center, in November 2006 the G3 tasked TRADOC to establish an integrated capabilities development team (ICDT) to address geospatial solutions to battle command interoperability problems. In February 2007, the TRADOC Program Integration Office-Terrain Data chartered a Geospatial ICDT, including TEC, to confirm the need, validate gaps, and develop a Functional Solutions Analysis. Approved on August 2, 2007, the ICDT analysis identified several technical and logical solutions to the identified deficiencies. For example, it proposed developing standard sensor systems to collect data, standard algorithms used across the Army, definition of data flow and compression, and updates to the force structure to improve data production. However, its primary recommendations were the

establishment of a Geospatial Information and Services regulatory body to enforce Army standards and policy and improve interoperability and a Geospatial Knowledge Center to manage and distribute geospatial data. In August and September 2007, the ICDT briefed the Geospatial General Officer Steering Committee recommending the formation of a governing board and appointment and resourcing of TEC as the geospatial technical lead to develop the Army's Geospatial Enterprise. Since the Chief of Engineers is the Topographer of the Army as well as commander of the Corps, it fell to the Corps to start developing the necessary policies, standards, and procedures.³⁷²

Over the next several months, Van Antwerp and TEC forged a reorganizational plan, which, after approval from the Army, he announced on February 25, 2008. First, he nominated and the Army appointed TEC Director Robert Burkhardt as the Army's first Geospatial Information Officer reporting to a Geospatial Governance Board, which replaced the Geospatial General Officer Steering Committee. Van Antwerp would serve as co-chair of the board, along with the Army Deputy Chief of Staff for Intelligence. The board would provide an Army-wide staff to support Burkhardt. It was an enormous task that involved information flow and data fidelity. At the same time, Burkhardt remained the director of TEC. To strengthen oversight of geospatial information, product, and services development and empower TEC to focus on supporting the Army's geospatial enterprise mission, Van Antwerp moved two of the three TEC divisions out of ERDC and made them a direct report to HQUSACE. The basic and applied research-oriented Research Division of TEC and its management – amounting to fewer than 100 personnel – would continue to report through ERDC. The technical director for the geospatial ERDC business area, Michael Powers, would continue in that role. It was, in many ways, a logical progression. TEC had always differed from the other Corps labs in that about two-thirds of its missions concerned topographical information system prototype development, demonstration, and acquisition for use by the rest of the Army. Those elements that conducted research would remain part of ERDC so it could be “a single voice of the Corps with respect to research and development activities,” TEC deputy director Joseph Fontanella said. The rest would focus on standards enforcement, warfighter support, and geospatial product development. In February 2009, the Army further cemented this change by creating the Army Geospatial Center. It would include a warfighter geospatial support and production directorate, a systems acquisition/program management directorate, and a geospatial acquisition support directorate. The TEC Research Division would remain in ERDC with Burkhardt providing day-to-day leadership of the division at the request of Houston as well as being the Geospatial Information Officer.³⁷³

Geospatial Research and Engineering

As established by the macro-plans, ERDC conducted business along major business lines crossing laboratory organizations. These included services and products managed under the oversight of technical directors from the various labs. The initial business lines identified in the 1999 macro-plans – Basic Research, Infrastructure Asset Operation and Delivery, Military Engineering, High-Performance Materials, Water and Sediment Management, Environmental

Quality, Topography/Imagery/Geospatial, and Information Technology – evolved from year to year as programs changed and resources dictated. From 2000 to 2002, ERDC discussed its business lines in alignment with 14 mission areas in the five-year RDT&E and Civil Works research plans developed for the Army. By 2003, it had four consolidated business areas – Battlespace Environment (renamed Geospatial Research and Engineering in 2007), Environmental Quality/Installations, Military Engineering, and Civil Works – although public discussion of ERDC capabilities sometimes used different names or groupings. These business areas included multiple programs or technology thrust areas that periodically changed, each directed by a lead lab director and supported by a lead technical director and business area management team. Support for each business area came from across the ERDC laboratories. All Army direct funded work conducted by ERDC aligned with these business areas whatever the name of the organization managing them.³⁷⁴

Geospatial Research and Engineering was the business area addressing military topographical and geospatial capabilities for military decision making. TEC Director Robert Burkhardt



Robert Burkhardt.

was the original lead lab director and Kevin Backe of TEC was the lead technical director. Michael Powers became the lead technical director in 2007, and with the formation of the Army Geospatial Center in 2009, CRREL Director Robert Davis became the lead lab director. The vast majority of geospatial research and engineering involved GIS or photogrammetric system development, but also included sensor-based spatial applications such as seismic, acoustic, or structural monitoring or analysis. TEC continued to field and support the Digital Terrain Support System, Digital Stereo Photogrammetric Workstation, the Urban Tactical Planner, and Terrain Image Evaluation System, including related software packages such as the Joint Terrain Analysis Tool, the Joint

Countermining Application, and Rapid Terrain Visualization. Future development would include use of a system-of-systems approach to integrate the many applications as well as terrain reasoning to enable easier airspace deconfliction and to support faster military decision making, particularly in urban environments. One of the groundbreaking systems developed through these efforts was the Buckeye Geospatial Collection System. Development began in 2004 using commercial helicopter-mounted digital cameras that produced high-resolution imagery for intelligence, surveillance, and reconnaissance missions. Because of the powerful change detection capabilities of the software, TEC was able to analyze routes in Afghanistan and Iraq to help detect placement of improvised explosive devices. In 2005, TEC delivered a fixed-wing version of Buckeye that included light detection and ranging (LIDAR) elevation data to produce 3-D elevation views of routes. The Buckeye system found immediate use in the Global War on Terror by detecting improvised explosive devices and giving soldiers on the ground unclassified imagery “in the field.” Other labs, including ITL, EL, CERL, and CRREL, continued to develop GIS tools for monitoring climate change or environmental effects, worked with industry through the OpenGIS Consortium to develop GIS applications and aided districts through

the Remote Sensing/GIS Center in developing maps of snow, vegetation, and urban features or modeling complex terrain in adverse conditions.³⁷⁵

In addition, ERDC conducted research involving battlefield or remote sensing that often had a spatial element. ERDC conducted research using acoustic and other sensors to detect landmines or military signatures, with significant advances at CRREL of understanding acoustic sensing in cold regions. TEC conducted research on the use of fluorescence to detect organic, inorganic, and decaying materials for targeting, environmental mitigation, and harmful agents. Although ERDC produced specific GIS and sensor products, it also provided considerable operational support to Army units through modeling of river stages, military hydrology or water detection, groundwater modeling, and other combat-related GIS applications. Through its Water Detection Response Team and interdisciplinary imagery analysis and 3-D modeling services, TEC supported specific warfighter requirements for support in analysis of 2-D and 3-D terrain data, including building complex military simulations. The ability to develop and interoperate between Army command and control systems and simulations allowed a more realistic “train as you fight” simulated environment. As noted previously, TEC also continued to support standards and distribution of geospatial data to topographical units in direct support of the warfighter.³⁷⁶

Military Engineering

Military Engineering was the business area focused on force projection and sustainment, force protection, and antiterrorism. In 2009, GSL Director David Pittman was the lead lab director, Robert Davis of CRREL was the co-lead, and David Horner was the lead technical director. Force projection and sustainment included any engineering capabilities to increase survivability and maneuverability in support of military operations, with research ranging from mobility to cold regions infrastructure development. ERDC continued pavements research to develop safer runways for heavier planes such as C-17s, thereby increasing the airfield reliability and reducing concrete construction. Nondestructive testing allowed easier analysis of pavement reliability, for example, with laser radar that can make more than 1,000 scans per second. Under the Joint Rapid Airfield Construction program, ERDC developed methods and products to improve construction time. After a 2004 pilot project, in 2007 ERDC demonstrated in Joint Exercise Talisman Saber, Australia, that it could triple the throughput of C-17s in 48 hours through rapid construction of taxiways and aprons. Similarly, the Lightweight Modular Causeway System won the Department of Defense 2008 Logistics Technology Implementation of the Year Award by demonstrating it could provide a rapidly deployed causeway to enable the new Joint High Speed Vessel, a fast catamaran, to connect to the shore in austere ports. In 2003, ERDC updated the NATO Reference Mobility Model to support modern joint operations, resulting in the Tri-Service Standard Mobility Model, which included applications to model and simulate modern vehicle performance in any environment. CRREL conducted experiments related to



David Pittman.

mobility in snow, ice, and other deformable soils, including testing snow impacts on the Stryker wheeled vehicle in 2003 or the Opportune Landing Site study, completed in 2007, which examined landing sites based on soil conditions for the Air Force. Other experiments examined methods of field construction, such as developing design criteria and solutions for building in extreme conditions. CRREL developed techniques to reduce snow and icing around buildings as well as monitoring or prediction technologies, such as the Sliding Snow Calculator that predicts impact zones of snow falling off slippery roofs.³⁷⁷

In the force protection area, ERDC provided breakthrough technologies to protect Soldiers in Iraq and Afghanistan from rockets, mortars, and rocket propelled grenades (RPGs). Units in Iraq and Afghanistan implemented ERDC protective designs for rockets and mortars through appropriations eventually reaching \$1 billion. Deaths in Iraq from rockets and mortars plunged from 63 to seven in 2007 with none of the deaths in facilities protected with ERDC technologies. ERDC received many awards for this technology, including an Army Greatest Inventions Award and a Platinum Award from the American Council of Engineering Companies. When the U.S. “surge” in Iraq began in 2007, armor-piercing RPGs became a major problem, with deaths tripling in 2007. The Army seemingly had an impossible requirement for ERDC to develop protection that was lightweight, portable, quickly assembled without specialized equipment, inexpensive, and would stop RPG rounds. ERDC responded by developing the Modular Protective System (MPS). MPS used ERDC-developed concrete panels with the ballistic performance of ceramic armor. Paired with commercial E-glass panels, these panels were part of a man-portable system that could be assembled by four Soldiers with no specialized equipment. In extensive live-fire tests, MPS successfully defeated RPGs and was deployed to Iraq in 2008. Other products developed by GSL, such as cellular geocomposites, provided mobile building blocks of earth or flexible frameworks that engineers could use to build shelters, fighting positions, or other structures. These products and services enabled easier and safer military operations by improving military construction methods.³⁷⁸

Antiterrorism involved analysis of terrorist attacks to develop protective technology. As discussed previously, ERDC laboratories had been involved in antiterrorism research since the bombing of the Marine barracks in Lebanon in 1983. In the Oklahoma City bombing in 1995, ERDC led the forensic team of the American Society of Civil Engineers, and its computer modeling blast code helped the FBI locate the van axle that was key in identifying the vehicle used. It also led the Department of Defense forensic team following the Khobar Towers attack in Saudi Arabia in 1996. As a result of this work, when the plane hit the Pentagon on September 11, 2001, antiblast technologies developed by ERDC protected that wedge of the Pentagon, saving hundreds of lives. To aid analysis of military structures, ERDC developed sophisticated 3-D models of dual-delivery missile systems, penetration of projectiles through rock, and mine plowing. Use of acoustic and seismic sensors allowed forensic analysis of explosions and improvements to or persistent monitoring of structures. The Earth Embankment Planning Software used decades of explosion data collected by WES to aid engineers in planning explosion-resistant embankments, a key concern in the post-September 11, 2001, world. In 2005, ERDC began experiments with feeding sensor data into a soil model that detects

minute variances in electromagnetic, heat, and water conditions to provide analysis of improvised explosive device locations. Continued tests promised to greatly improve sensor capabilities for detection of improvised explosive devices. A major program in the Military Engineering business area was TeleEngineering, in which combat units could request technical support in solving specific field engineering problems. ERDC developed the TeleEngineering Communications Equipment and TeleEngineering Toolkit software – a deployable data, voice, and video teleconferencing system using commercial off-the-shelf products – just before Operation Iraqi Freedom. The equipment connected with an operations center in Vicksburg that operated 24 hours a day; seven days a week. A study by the Army War College concluded that “TeleEngineering was critical in maintaining V Corps’ rapid advance to Baghdad.” By 2009, ERDC received more than 4,000 requests a year for help through TeleEngineering. In 2009, ERDC’s TeleEngineering Operations Center became the Corps of Engineers Reachback Operations Center.³⁷⁹

Environmental Quality/Installations

The Environmental Quality/Installations business area included facility acquisition and operation technologies and services needed to support readiness, as well as environmental issues relating to safety and occupational health of military personnel and adjacent communities, cleanup of installation and range contamination, and endangered species on training lands. CERL Director Alan Moore was the first lead lab director, EL Director Edwin Theriot was co-lead, and John Cullinane was lead technical director. Ilker Adiguzel and Beth Fleming became the lead lab directors, with Adiguzel as the sole lead lab director after 2009. Installations research focused on facility acquisition and revitalization and installation operations. Facility acquisition included tools and services to support construction or renovation of military facilities through planning tools, modeling, and testing. Planning tools included collaboration software such as DrChecks, ProjectWise, or ProjNet that allowed program managers, contractors, and installation managers to work together on planning and review or update progress of efforts, as well as forecasting tools such as BLAST and Furniture Cost Estimating Tool or databases of construction methods or environmental information. Technologies such as computer-aided design (CAD) and building information modeling (BIM) allowed detailed 3-D views of engineering plans and building subsystems, such as utilities. Other developmental efforts involved building materials or technologies, such as paint and anticorrosion systems that extended the life of facilities, electromagnetic shielding that prevented damaging electrical surges, plastic building materials, electro-osmotic pulse technologies that used low-level electricity to



Ilker Adiguzel.

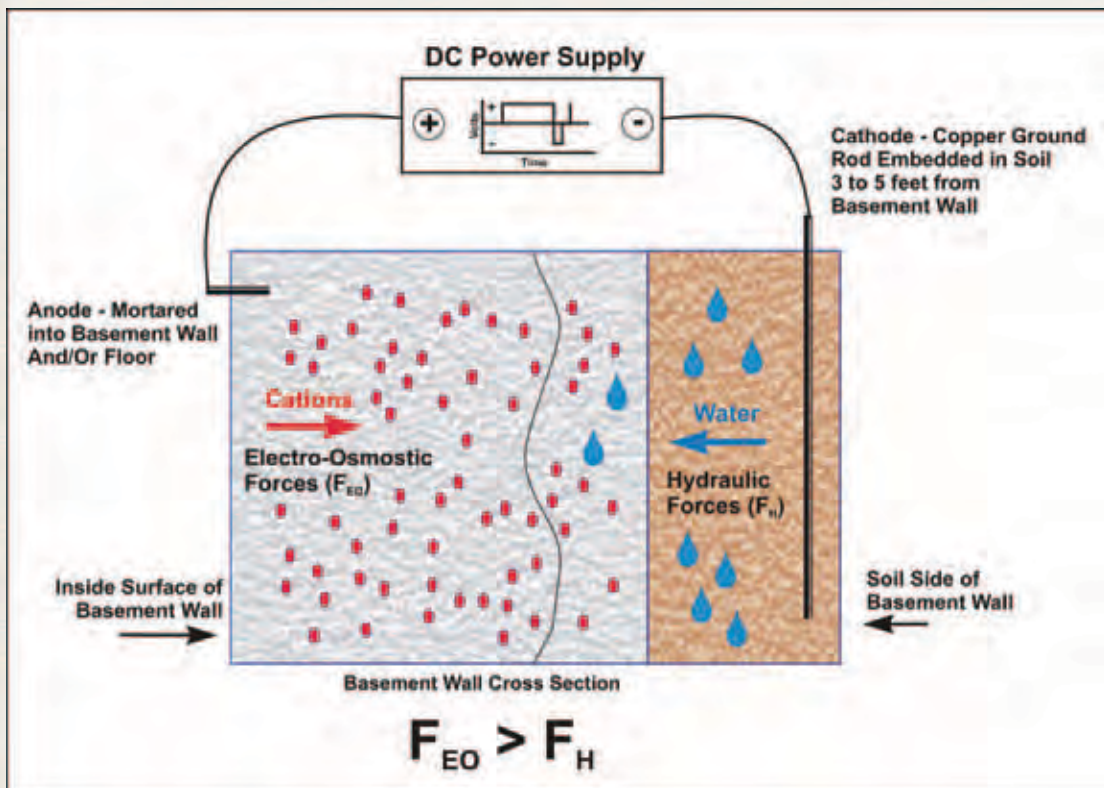


Beth Fleming.

Wired Up and Watertight

A historic barracks building at Fort Jackson, South Carolina, had a history of water seepage into the basement mechanical room. With constant leaks from cracks, there were five centimeters of standing water, at times reaching as high as 36 centimeters, requiring weekly pumping. The water and high humidity were corroding the building plant equipment, which the base was replacing every two years at high cost. Asked to help solve the problem, the Construction Engineering Research Laboratory (CERL) installed an innovative system that used electricity to keep water out of the basement.

Developed in Norway in the 1980s based on century-old concepts, electro-osmotic pulse (EOP) systems create an electric field that repels water by reversing polarity at regular intervals. The system includes wired anodes on the interior walls of a structure and copper cathodes in the outside soil. A control unit sends low-voltage DC pulses in varying intervals on each side, drawing positively charged water molecules toward the cathode. In this way, it overcomes the force of the hydraulic gradient. Using pulses instead of constant power is key because it prevents completely drying out the structure. A monitoring system adjusts the pulses as needed to maintain optimum water content.



Conceptual drawing of electro-osmotic pulse technology developed by the Construction Engineering Research Laboratory and its industry partner Drytronic.

After testing the solution in the laboratory, CERL worked with partner Drytronic, Inc., of Wisconsin to refine the patented technology and install 42 meters of the system around the perimeter of the interior basement wall at the Fort Jackson pilot site in August 1994. Over two years, it adjusted the voltages and pulses and measured results, achieving from a 20 to 40 percent drop in the relative humidity of the interior wall surface. The concrete “was dried out within two weeks and remained dry,” Fort Jackson Chief of Engineering Franklin D. Cooper said. Even under flood conditions, the basement stayed dry. The total installation cost was \$24,000 – less than half the cost of a conventional trench and drain system and other water-proofing techniques – with an electricity consumption of less than \$4 per year. The team immediately began planning another installation at Fort Jackson.

At another pilot project at McAlester Army Ammunition Plant, Oklahoma, in 1996, the team installed the EOP system around 54 percent of a flooded basement from where leaks originated. Once the system was installed, they monitored, not only humidity, but also water table levels and power output. The tests proved that power consumption dropped as water levels dropped, increasing the system’s effectiveness.

Over the course of the next 10 years, CERL installed the EOP system at more than 50 other sites, including various buildings at Fort Monmouth, New Jersey; Tobyhanna Army Depot, Pennsylvania; Fort Hamilton, New York; and at the U.S. Army Tank-Automotive and Armaments Command. Ten of these were historic structures. For example, EOP technology was critical for protection of an underground vault at the U.S. Treasury Building in Washington, D.C. This innovative system installed copper pipes as the cathodes so as to drain water away from the roof of the vault.

With a permanent project life requiring only occasional maintenance, EOP not only had up-front costs 40 to 50 percent less than traditional solutions, it also demonstrated its ability to prevent structural damage, extend the life of crack repairs, prevent corrosion, prevent moisture damage, and improve air quality. The technology won the Construction Innovation Forum’s NOVA Award in 2002.



Before and after photos of a basement at Fort Jackson after application of the electro-osmotic pulse system.

Unjamming the Rivers

Record icing in the winter of 2001 was leading to growing fears of ice jams. Such jams cause an estimated \$125 million in damages in approximately 35 states each year due to flooding and damages to ships or river structures. Each spring, the Soo Locks near Sault Ste. Marie, Michigan, from Lake Superior to the St. Lawrence River system faced delays and increased costs because of ice pushed ahead of vessels entering the locks. Communities in Maine, Vermont, and New Hampshire face nearly annual flooding as ice jams block parts of rivers, forcing water into the countryside. Nebraska expected the Platte River to experience record flooding due to jams. Many other states faced similar problems. To help reduce ice jams, several states and their local Corps of Engineers districts turned to the Cold Regions Research and Engineering Center (CRREL).

Over the previous 15 years, CRREL built up considerable expertise in dealing with ice jams. In 1990, it developed a database of 11,000 ice jams dating back to 1780 to help document and analyze ice jam trends. Although incomplete, the database helps engineers determine factors leading to jams in an effort to predict flooding. An automated River Ice Motion Detector and satellite-based Data Collection Platform developed in conjunction with the U.S. Geological Survey and National Weather Service helps to provide early warning of flooding and finds frequent use in months leading up to spring. After a damaging series of ice jams in 1986, Jon Zufelt at CRREL suggested drilling strategic holes in ice before normal breakup to reduce jamming, a practice that has become standard. Other measures, such as ice control structures – granite blocks spaced across a riverbed – developed by CRREL in 1994, helped to prevent surges of ice on slow-moving rivers. At the same time, engineers have tried everything from dusting areas with dark ash to

increase absorption of sunlight to releasing hot water from nuclear power plants.

In 2001, at the request of Abbot and other Maine towns, the New England District and CRREL conducted aerial surveys of several New England rivers to get a better idea of the problem, including



Connecticut River Ice Jam, 1968.

the Piscataquis, Pemigewasset, Saco, Androscoggin, White, Little Ossipee, and Kennebec. CRREL installed the River Ice Motion Detector to monitor the situation and the Corps and state released several reports with recommendations. However, because of the small populations of many towns and the high cost of ice jam mitigation, little could be done without federal or state aid other than wait for spring.

For the Soo Locks, CRREL had previously recommended using high-flow water jets, air curtain arrays, and point source bubblers to break up ice jams and deflect ice accumulations away from the locks. To test the idea, CRREL built a 1,200- by 110-foot physical hydraulic model at a 1:36 scale showing both Poe and MacArthur locks in its Refrigerated Research Facility, where it could lower temperatures to create icy conditions in the model. Using a model barge to push the ice, it determined that lock operators needed to maintain an ice-free receiving area, which it could do through flushing ice through MacArthur Lock or skimming ice off the surface. It installed prototype point source bubblers along channel sides during dewatering in 2000 and monitored the results in the spring of 2001.

Although the ice jams in 2001 proved to have less impact than expected – certainly much less than the last major ice-related flooding in 1987 – Corps efforts to develop solutions helped to reduce the risk and mitigate the impact of ice jams.



Ice accumulating at Soo Locks, 1980.



Ice jam studies, Lancaster, New Hampshire, 1968.

repel water in damp basements, pothole patch kits that allowed faster repair and maintenance of installation roadways, cold weather concrete admixtures, and carbon nanotube technology that could potentially create stronger and lighter materials at the molecular level. ERDC provided several testing services to support construction. These included standard concrete development and testing, bridge inspection services, structure earthquake loading, and centrifuge facilities for testing. In several cases, ERDC developed tools to support testing, such as the Intelligent Bridge Assessment Repair and Retrofit code used to analyze bridge safety. As in previous decades, the CERL Paint Technology Center continued to provide significant benefits beyond its small staff through testing services, training, and research into specialized paints such as heat resistant coatings. These advances continued to be extremely important to the evolution of the construction industry, which remained very conservative and fragmented in research and development activities.³⁸⁰

The installation operations thrust had a number of breakthroughs, including various energy, fuel, waste management, and maintenance technologies employed at military facilities to improve operations – fuel cell technology that provided low-emission energy, anaerobic carbon-based systems to treat wastewater containing propellant fuels, and energy-efficient thermal storage cooling systems that store and chill coolant during off-peak hours for use during peak hours. In 2001, Congress appropriated funds to implement proton exchange membrane (PEM) fuel cells specifically for residential use. PEM cells use pure hydrogen as a fuel, which reacts with a cathode to create energy with a byproduct of water. CERL worked with the University of Illinois in Champaign and contractors to develop the smaller cells that produced one to 20 kilowatt hours. It implemented 45 cells at 17 installations as the program grew to \$22 million in 2003. Much of this research involved working with Cooperative Research and Development Agreement (CRADA) partners to develop or test commercial products, such as carbon fiber cloth used to enhance air filtration systems, electrostatic dehumidification systems, or phase change material using micro-encapsulated n-tetradecane, which increased by 200 percent the heat transfer of conventional heating systems. Some of these were very futuristic, such as intelligent buildings with sensors that monitor not only internal safety and working environments but also the structural status of the buildings themselves. Other major research efforts involved the development and maintenance of computer systems to analyze energy use or to manage facilities. While continuing development of the PAVER, RAILER, and ROOFER maintenance management products, CERL led new development efforts such as the BUILDER Sustainability Management System and Water PIPER Engineered Management System. The installation operations thrust also included services such as underground tank inspection, tracer gas testing, conducting energy assessments, or development of solid waste management systems.

Environmental Quality was a broad research area that included site remediation and environmental management led mostly by EL, range and land planning led by CERL, and threatened and endangered species management split between EL and CERL. As it had since the late 1980s, the largest portion of environmental research involved remediation and restoration of military installations. Major efforts across multiple laboratories investigated toxicity and transfer of contaminants, ranging from development of techniques for detection and discrimination

of ordnance residue developed by CRREL to standard sample analysis conducted by the EL Hazardous and Toxic Waste Center. A particularly sensitive issue was the detection and removal of unexploded ordnance. The Defense Science Board identified 10 million acres that potentially included unexploded ordnance and estimated cost of remediation at up to \$50 billion. Unfortunately, detection methods such as exploratory digging or magnetometers were not very efficient. ERDC developed numerous potential methods for unexploded ordnance detection, including using polarimetric algorithms to analyze magnetic or seismic models built from sensor readings, using biomarkers such as human hepatoma cells engineered to emit light when near munitions chemicals, and combining the use of electromagnetic induction and magnetometers in 2004 in a single system to reduce false positives during ground analysis. A major breakthrough occurred in using low-level spectral gamma radiation to track movement of chemicals or objects using global positioning systems. When developed to bond with heavy metals resulting from ordnance, the gamma technology would allow engineers to track chemical transportation. ERDC also developed capabilities for remediation of metals through biotreatment or other methods, for example, by applying certain bacteria that can degrade metallic contaminants. Further, use of computer models to analyze mitigation sites promised to reduce risk and cut costs of remediation by up to 20 percent, and ERDC spent considerable resources developing computer models of major remediation sites. Due to its expertise, ERDC sometimes supported Superfund sites, as it did in consulting for ALCOA at an aluminum plant on the Grasse River, in which CRREL modeled ice jams causing erosion near capped contaminated soils. In 2009, the Land Remediation thrust was renamed Military Munitions in the Environment to recognize significant research on environmental, safety, and occupational health affects related to Army training and operations.²⁸²

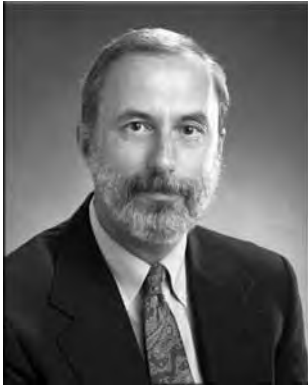
The sustainable ranges and lands thrust area mostly focused on remediation and management of military ranges. One of the major changes to ERDC's approach to land management was to integrate it more closely with facilities research, in essence to view installations as a holistic entity, through the integration of environmental issues in the Facilities business line. Land management primarily involved improving awareness of issues impacting land use. As the inheritor of range management programs, the Land Management Systems software developed by CERL provided tools to aid in the development and management of training areas. A new developmental effort, Sustainable Encroachment and Room to Maneuver, involved Web-based planning tools for managing lands outside of installations. Encroachment on Army installations was a major problem as it often restricted some activities. A good example was Fort Belvoir, Virginia, which, once far outside of Washington, D.C., became surrounded by suburban neighborhoods, greatly impacting equipment testing, range use, training, and other activities. The tools CERL developed proved particularly important for Base Realignment and Closure requirements. Other major research involved meeting the National Environmental Policy Act and newer environmental or cultural resources laws. Since 1970, CERL and WES provided consulting services to help Corps districts in meeting these requirements, and CERL made several efforts to update processes and tools for handling these issues. Land management also included a number of conservation or natural resource programs. Among these were waste

management, contamination assessment, nuisance plant removal, analysis and protection of threatened and endangered species, and experimentation with plants to improve soil stability or remove toxins from the soil. For instance, CRREL helped to breed plants resistant to heavy traffic, such as tanks, which prevented soil erosion on military ranges.²⁸³

To support environmental sustainability and management, ERDC provided services such as ecosystem modeling, plant growth simulation, and information systems to assist in control of invasive plant or animal species, operation of water resources, wetland restoration, and compliance with environmental law. ERDC continued to conduct considerable research related to threatened and endangered species. While studies of the red-cockaded woodpecker continued, ERDC developed digital imaging tools to aid in conducting a census of another endangered species – the gray bat. In a continuation of andronomous fish research that originated at the Bonneville Dams, ERDC created numerical models of fish surrogates to forecast how juvenile salmon would respond to structures. Because of the number of aging dams on small streams, ERDC investigated dam decommissioning and removal as a means of rejuvenating water basins, a strategy employed successfully on streams such as the Cahaba River, Alabama, one of the most diverse places in the country. Other research focused on developing strategies for managing threatened, endangered, or sensitive species through improved land use and habitat restoration. As discussed previously, a significant amount of research involved land planning and stewardship. Research continued on wetlands and wetlands creation, including the use of plants to rehabilitate land. A major developmental effort focused on processing dredged material as soil for reuse in Superfund restoration sites. Here also, computer modeling and tools aided research. Tire-Terrain Modeling services and the Distributed Snow Model leveraged current modeling techniques to aid land use planners, while the ArcGIS-based Gate Analyst and Storm Transform applications provided GIS-based tools for hydrological modeling. Databases such as the Aquatic Plant Information System, Ocean Disposal Database, Regional Internet Bank Information Tracking System, Sustainable Installations Regional Resource Assessment Tool, and PONDS Internet-based land use conflict resolution tool provided information to aid users in land use, dredging, or other environmental issues.³⁸⁴

Civil Works

The Civil Works business area concerned hydrological and structural solutions for water resources facilities – dams, locks, levees, and waterways. CHL Director Thomas Richardson was lead lab director and Robert Engler of EL was the lead technical director. With their retirement, David Richards of ITL became lead technical director in 2005, and EL Director Beth Fleming became lead laboratory director in 2009. This business area was most involved in Corps water resources responsibilities. The foremost of these was flood control and storm risk reduction or related emergency management, and ERDC provided specific solutions such as its traditional mission of hydraulic engineering and modeling, bridge scour analysis, development of the CORE-LOC Concrete Armoring and Samoa Stone products for coastal protection, ice jam modeling and data to prevent flooding in cold regions, and groundwater and flood analysis provided to Army units. In one example of military project work for the Logistics-Over-The-Shore



Thomas W. Richardson.

program, ERDC made great progress through testing of the Rapidly Installed Breakwater XM-2000 System, a tow-installed hydraulically pressurized beam that reduced wave heights by 50 percent to allow loading of vessels in choppy water. Guided by the Coastal Engineering Research Board, CHL continued to lead the Corps' coastal research program, including major efforts in field data collection, coastal inlets research, and shoreline erosion investigations. The National Shoreline Erosion Control Development and Demonstration Program, established by Section 227 of the Water Resources and Development Act of 1996, remained one of the largest programs and included development of methods and

products to retard or reverse coastal land loss. The Navigation technology thrust was central to water resources and included such areas as engineering support, dredging operational research, sediment transport, lock and breakwater design and protection, and navigational simulation. CHL also supported the Monitoring Completed Navigation Projects program to evaluate the effectiveness of more than 800 navigational projects spread over 25,000 miles of waterways. Supporting all of these thrusts were various digital modeling products, such as CH3D, the Ship-Towboat Simulator, and ADCIRC, as well as physical models.³⁸⁵

The Water Resources business line included water resources environmental issues and environmental sustainability and management technology thrust areas, which addressed environmental issues such as dredging effects, watershed modeling, and environmental modeling for snow processes, nuisance plants, and storm flooding. Many of the capabilities for environmental sustainment and management were largely identical to those developed under the Environment Quality business area. Research of toxicity, contaminant transfer, compliance, land rehabilitation, wetlands, and threatened and endangered species management were equally applicable for lands managed by the Corps in the civil works program as for military bases. For example, use of microfluidics and nanofluidics that provide a molecular beacon in the presence of lead or other heavy metals discussed previously promised to dramatically reduce the cost and time to test water quality. The water resources environmental issues thrust examined problems specific to water resources management, such as dredging effects on sea grass, snow process modeling, tracking sediment transport to determine bioaccumulation of chemicals within the food chain using stable isotopes, and control of invasive and nuisance plants. Equally important were capabilities for ecosystem and watershed modeling, which promised to be particularly high-growth areas as the Corps considered broader environmental issues.³⁸⁶

Also important to the Civil Works business area was the infrastructure technology thrust supported by GSL, including analysis and selection of cements or other materials, soil mechanics analyses, dam and levee inspections, and 3-D models and visualization software. These provided tools necessary to analyze concrete and earthen water management structures. For example, GSL supported development and evaluation of armoring technologies used in coastal projects in the Great Lakes and elsewhere. In 1999, GSL became involved once more in investigation of the liquefaction problem after major earthquakes in Turkey and Taiwan. Use

Investigating Hurricane Damage

Within days of Hurricane Katrina's landfall on August 29, 2005, concerns arose that Corps of Engineers floodwalls in New Orleans, Louisiana, did not perform as designed. Over the next month, investigations began by the Louisiana State University-led Team Louisiana, University of California at Berkeley-led Independent Levee Investigation Team, and the American Society of Civil Engineers (ASCE). On October 10, Chief of Engineers Lt. Gen. Carl T. Strock announced formation of the Interagency Performance Evaluation Task Force (IPET), initiating one of most innovative partnerships in Corps research and development.

Led by retired Corps Research and Development Director and now University of Maryland Professor Lewis E. "Ed" Link, the IPET included 150 scientists and engineers throughout the nation and received \$26 million in funding. To reinforce its objectivity, IPET findings underwent review by the ASCE External Review Panel and a National Academies-National Research Council panel reporting to the Assistant Secretary of the Army for Civil Works. Because the Corps – and Engineer Research and Development Center (ERDC) – were members, IPET provided an opportunity to cross-pollinate ideas with leading minds in academia, industry, non-governmental organizations, and other government agencies, resulting in considerable innovation.



New Orleans floodwall breach during Hurricane Katrina, 2005.

The investigation occurred in three phases. During the first few months, the teams interviewed witnesses, collected evidence of flood heights, and went through hundreds of boxes of project reports, surveys, and other data. The second phase consisted of analysis and further investigation. Not until the Corps completed a cofferdam around the breach sites on November 30 could the teams begin to analyze the floodwalls involved by examining sheet

piles and taking soil samples. The reporting phase began with the preliminary reports by the Independent Levee Investigation Team in November 2005 and Team Louisiana in December 2006. IPET published its comprehensive 7,000 page report from January 10, 2006 to June 25, 2009.

The IPET investigation included detailed forensic analyses of the hurricane and levees using advanced computer and physical models. It built on the Corps' ADCIRC model

to analyze Katrina and other hurricane scenarios. A physical model developed by ERDC of the 17th Street Canal provided data in areas where few data points existed about levee and floodwall performance. IPET also ran analyses on the performance of I-walls, T-walls, sheet piles, and levees. A major effort surrounded risk assessments, which involved modeling 350 storms and their potential impact on hundreds of structures while considering dozens of factors, such as geology, weather, and human activities.

From the beginning, the intent was for IPET to provide data to Task Force Guardian, the Corps organization rebuilding the levees. The team provided data related to conditions at the Lake Pontchartrain canals, conditions of levee soils, and analysis of I-wall performance. Risk maps and processes developed by IPET later informed the work of the New Orleans District, as well as the Federal Emergency Management Agency.

The collaboration produced several changes to Corps processes. The models greatly expanded ERDC capabilities. Because of the generic nature of the Saffir/Simpson Scale, which is mostly wind-based and does not take into the physical size of hurricanes or other factors, IPET and the Corps began to use a probability-based risk assessment using frequency of occurrence (50-, 100- and 500-year). Director of Civil Works Maj. Gen. Don Riley stated that the IPET risk model gave the Corps the ability to “lay it out for the (local) folks and then for the Congress and then for the public” to make an informed decision, radically changing the way the Corps communicated with the public.



Members of the Interagency Performance Evaluation Task Force measuring sheet pile removed from the 17th Street Canal to determine if the proper lengths were used during construction.



17th Street Canal model used by the Interagency Performance Evaluation Task Force.

of the GSL centrifuge, installed in 1995, was a significant aid to the research, with 1999 experiments suggesting that water pressures decline as depth increases, which promised to significantly reduce field investigations necessary to determine the safety of a structure. Following the September 11, 2001, attacks, some civil engineering research involved structural safety. In a program for the Federal Highway Administration, ERDC provided training to more than 80 bridge engineers on designing structures to reduce vulnerability to explosions. When rainfall following California wildfires in 2003 triggered a landslide, GSL conducted several landslide investigations in the U.S. and El Salvador. Other research originated with major floods, such as those following 2005's Hurricane Katrina or seasonal flooding along mostly state-operated levees in 2008 and 2009. In 2006, Congress revised the dam inspection program and required a complete inventory of the Corps levee system. GSL provided dam inspection services as well as rapid levee assessments using helicopter-born electromagnetic sensors and LIDAR. It also provided a number of services related to investigation of ground failure. In 2005, ERDC became heavily involved in the investigation of the failure of Corps-built infrastructure in New Orleans, Louisiana, following Katrina as part of the Interagency Performance Evaluation Task Force. For more than three years, ERDC supported forensic investigations of soils and floodwalls, physical and digital modeling of the hurricane and its effects, and risk analysis and modeling of storm scenarios to aid in rebuilding the storm damage reduction system.³⁸⁷

The Civil Works business area also included a Polar Science and Engineering technology thrust area led by CRREL. As it had since its origin, CRREL was one of the leading institutions conducting research related to documenting climate change, including monitoring sea ice, boreal vegetation, and snow melt. In the Sea Ice Mass Balance Buoy Project, CRREL gathered data on ice drift, thickness, and balance from buoys in the Arctic Ocean to help monitor climate change. It continued to conduct investigations related to heat transfer in snow, ice albedo feedback, and understanding the interaction of snow and vegetation. Remote sensing remained important for many of these activities by providing capabilities for monitoring forestation or snow cover, as well as supporting environmental projects such as detecting oil spills in or under ice. However, the largest part of the thrust was research related to mobility and engineering. With anticipation that continued melting of Arctic Sea ice could dramatically change U.S. defensive posture, CRREL entered into several new projects to research maneuver support and sustainment services to aid the Army in planning movement in remote, cold regions. Specific projects included experiments with hauling fuel to Thule Air Force Base, Greenland, with wheeled vehicle performance in the snow, and with cargo sleds to support mobility from McMurdo Station, Antarctica, to the South Pole. It continued to support cold regions facilities design, siting, construction, and operation, for example, by conducting extended experiments with snow drifts, snow excavation, heat transfer, permafrost, and ice fall. It developed and tested many technologies to aid in detecting, predicting, and measuring icing, snow drift, and ice falling from towers. In addition, ERDC continued to conduct considerable basic research on the effects of snow on acoustics, chemical reactions such as oxidation or absorption of munitions contaminants, hydrology and biological processes, and transfer of heat, all critical for helping solve regional mitigation or climate monitoring problems.³⁸⁸

Information Technology Support

Information Technology, although not a formal business line, provided essential support for the four ERDC business areas. In addition to being the information management organization for ERDC until 2008 to support its computing and research needs, ITL was a major provider of computational services for the Army and other agencies through the High Performance Computing Major Shared Resource Center, renamed the ERDC DoD Supercomputing Resource Center in 2009. ITL continued to maintain one of the top 50 fastest supercomputers in the world with implementation of the Cray XT3 in 2005 and Cray XT4 in 2008. The latter was the 14th fastest computer in the world at the time of its implementation. Through the use of these powerful systems, ERDC researchers were able to develop models of structural materials down to the molecular level, allowing development and analysis of new concretes and metallic materials; make detailed analyses of explosion effects on various structures; and provide analysis and data management for forensic examination and hurricane flood control projects following Hurricane Katrina. ERDC also provided a Data Analysis Center to aid users in developing data analysis tools and the Visualization Center to support development of visualizations as well as tools such as EzVIZ. As its precursors had since the early 1970s, ITL served as the test ground for new applications, such as enhancing the P2 project management software used Corps-wide to make it easier to use. After developing the original TeleEngineering Communications Equipment in 1998, it continued to make modifications and upgrades to the system for use by deployed units to remotely access expertise in the states and disaster operations. With increased connection to the Internet, security of Corps systems became a major concern, particularly after attempts in 2000 to penetrate ERDC networks. ITL led efforts to improve security for Corps systems and offered new training courses. As noted previously, although ACE-IT assumed management of user information management requirements, ITL continued to provide leadership for experimental, developmental, and engineering systems and software.³⁸⁹

The other support missions – informatics and geospatial technologies – were services often based on software provided by others, such as Oracle database software, Autodesk CAD software, or ESRI GIS. Informatics typically involved data mining, data analysis, data warehousing, datanets, and other project-specific data services to support programs managed by other business lines across all the laboratories. A major effort initiated in 2001 was the development of the Common Delivery Framework, a Web-based middleware approach to provide interoperability among legacy and new systems to deliver business information to customers, business partners, and employees. The framework promised to improve access to and cost of securely sharing data sources, including high-performance computing resources. The geospatial technologies thrust included such projects as mapping levee conditions and helping to convert coordinates between datum systems. With the expiration of the Navy's Tri-Services CADD/GIS contracts after 1999, the Tri-Services CADD/GIS Technology Center became the CADD/GIS Technology Center for Facilities, Infrastructure, and Environment, and evolved into the CAD/BIM Technology Center by 2007. BIM was an extension of CAD that allowed visualization and management of building information from a spatial interface. Although TEC and CRREL provided leadership in GIS through the development of military geospatial software such as the Combat Terrain

Information Systems and Map Server and the CRREL RS/GISC to support civil works GIS requirements, the CAD/BIM Technology Center continued to support geospatial applications by gaining acceptance of its geospatial data standards by the American National Standards Institute in 2000, by continuing to provide training on computer-aided engineering, or through the development of enterprise GIS (EGIS) systems based on Google Earth.³⁹⁰

Tradition of Excellence

Despite a tumultuous origin, ERDC quickly proved that the pains of integrating Corps research and development were worth the effort. In September 2009, the Assistant Secretary of the Army for Acquisition, Logistics, and Technology named ERDC the Army Research Laboratory of the Year. Based on an evaluation of 60 metrics, a written report, an oral presentation, and an evaluation visit, ERDC had won the award an unprecedented three years running and the fifth time in eight years – nearly every year since the beginning of the Global War on Terror. Even before the formation of ERDC, the Army had recognized Corps labs for more than a decade. Of the 19 years that the Army had held Laboratory of the Year competitions, ERDC or its predecessor laboratories had won 11 times. For many of these years, they had also won other awards, such as the Army Communities of Excellence or the Federal Laboratory Consortium Award for Excellence in Technology Transfer. It was by any measure an extremely impressive record of performance as determined by a panel of experts from research organizations in national academic, government, and industry organizations, and demonstrated that integrating Corps labs in creating ERDC had greatly enhanced its value to the nation.³⁹¹

Perhaps the greatest factor in the tradition of excellence at ERDC was its people. As Houston noted when ERDC won the Laboratory of the Year Award in 2008,

I say it every time we are recognized for our accomplishments, but I mean it as much today as the first time I said it – our people are the strength of this organization. They are the heartbeat of ERDC. You can have the right facilities and the right equipment, but without the right people, you may as well close your doors and go home. It's their knowledge and expertise that solve the challenges we're faced with today. This award belongs to them.

Looking at the accomplishments of the people, it is easy to see why the laboratory won. The list of Corps employees, contractors, and consultants (see Appendix A) is a roll of some of the nation's greatest engineers, physicists, and scientists over two centuries, spanning fields such as geodesy, topography, hydraulics, soil mechanics, construction and structural engineering, ice and snow mechanics, paleoclimatology, environmental engineering, and computing. Its employees routinely won Army, federal, and civilian awards, such as CERL Deputy Director Topudurti being named 2009 Federal Engineer of the Year, Todd Bridges and Jongbum Kim of EL winning the *International Journal of Human and Ecological Risk Assessment's* Paper of the Year, Andrew M. Tuthill and Carrie M. Vuyovich of CRREL winning the 2009 Committee on River Ice Processes and the Environment Gerard Medal, and more than 19 ERDC employees receiving the Army Research and Development Achievement Award in 2009 alone. The researchers

published hundreds of technical reports and articles in trade journals or presented them at conferences on a variety of topics, and just in 2001, ERDC estimated more than 12,000 technical articles or papers cited its researchers. On average, ERDC employees received more than 12 patents each year after 1998 for a variety of useful devices as well as instruments used in gathering further data. One could look at any given year in the last 50 and find similar results.³⁹²

What made these researchers leaders in their fields was the groundbreaking work that the Corps performed and continues to perform. When the Corps began conducting scientific research after 1802 to support its various projects, very few U.S. engineers held to scientific standards. In this, the Corps blazed the trail with its widely imitated technical education system and scientific approach. Over the course of the next two centuries, methods and technology introduced by Corps officers, civilians, and contractors changed the nation's approach to river and coastal engineering, structural engineering, civil works, topography and photogrammetry, construction and maintenance management, environmental mitigation, computer modeling, geographic information systems, and other fields. As Corps critics are fond of observing, in many cases, the Corps borrowed from European or private practice. At times conservative and confrontational, it was also often willing to adopt – wholesale or greatly improved – academic and industry best practices, and it invited advice and funded research from leading experts worldwide. Yet in several areas, the Corps conducted highly original research, pioneering fields previously unknown. One might mention only a representative sample:

- Publication in 1935 by Spencer Buchanan of the first manual on soil mechanics laboratory instruments and practice, standardizing for the first time soil testing methods;
- The classic study by Capt. J.F. Friedkin from 1941 to 1945 of meandering streams that demonstrated the causes of bends in alluvial rivers;
- Development and testing of the first vinyl paint (V766) for hydraulic structures from 1946 to 1960 by Fletcher Shanks, Willard N. Lappin, and others, which helped save \$1.2 million per year by 1968 in extending intervals between painting structures;
- The work of Henri Bader, Lyle Hansen, and Chet Langway in Greenland and the Antarctic from 1956 to 1966 that helped establish ice core science and link it with paleoclimatology;
- Development by 1965 of the Universal Automatic Map Compilation Equipment (UNAMACE), the first automated mapping system to output data in a digital format;
- Innovative research by dozens of Corps researchers from 1972 to 1980 on the Dredged Material Research Program, which established beneficial use of dredged material to create wetlands; and
- Application of the first High Performance Computing Major Shared Resource Center in the Department of Defense at ITL to forensic examinations of the 1996 Khobar Towers bombing and September 11, 2001, terrorist attacks.

There are, of course, many other innovations that one could list. These certainly improved the military's ability to perform its mission through more stable runways, enhanced cold regions



Kirankumar Topudurti.

operations, accurate geospatial data, and hardened structures to protect American warfighters. They also increased general engineering knowledge that aided national development through more efficient and longer lasting infrastructure, environmentally safer operations, and a better understanding of fields ranging from hydraulic engineering and soil mechanics to climatology and construction. In this way, ERDC improved “the common stock of knowledge,” as Benjamin Franklin envisioned more than two centuries before ERDC’s formation. This is the true legacy of ERDC and of Corps research.

For more than 200 years, the U.S. Army Corps of Engineers has been a leading proponent of engineering science and engineering research. It introduced scientific education and experimentation to American engineers who often still relied mostly on cumulative experience. It was the first federal agency charged with investigating and managing natural resources. It was the first to establish research facilities to investigate large civil engineering problems. It was the first to consider important engineering issues such as coastal construction, construction on permafrost, and soil and ice mechanics. Yet debates continue as to what the content of that work was and should be, whether it was more engineering or science, and which is the proper domain of the Corps of Engineers. Over the years, critics of the Corps argued that it was too project-oriented and thus not scientific. Others have argued that its approach was too theoretical. Even within the Corps, organizations focusing more on basic research such as the Coastal Engineering Research Center and CRREL differentiated themselves in times past from the applied research conducted by the rest of the Corps. Those who were not engineers, such as physicists and biologists, often stressed the differences of their approaches, while engineers sometimes expressed suspicion of the impracticability of more theoretical science. The modern reliance on computers to solve many engineering problems complicated this picture, as more of the work of Corps labs involved numerical solutions and models. Some sought to increase the experimental work of Corps labs or return to physical modeling. Others believed that all models were merely tools to aid the engineer in completing work that ultimately still relied on experience. Tony Thomas, an early member of the WES Mathematical Hydraulics Group, once said, “The purpose of models is insight, not answers,” and must be considered alongside other factors. Even early proponents of modeling argued, as Capt. Paul Thompson did in 1938, that “the solution of hydraulic problems must, in the main, be by the method of trial (and error)” based on calculation, judgment, and safety factors. Still others argued that in mostly managing contracts for partner research similar to other Department of Defense government-owned, contractor-operated laboratories, ERDC was more concerned with development than research itself.³⁹³

The most often used indicator of the kind of work Corps laboratories do is RDT&E funding categories used by the Department of Defense.³⁹⁴ Overall, the majority of Corps research funding falls within the 6.2 or 6.3 range – applied research or technology development – yet this ranges widely by laboratory and periods of time. In the early days of WES, nearly all activities would have fallen into 6.2 with some 6.3 and 6.1, or basic research, although the categories did not then exist. The Coastal Engineering Research Center and Snow, Ice, and Permafrost

Research Establishment conducted significantly more but not exclusively 6.1 research. The work of the Engineer Board and later the Engineering Research and Development Laboratory was nearly all 6.3, 6.4, and some 6.5 since its mission was to develop engineer equipment. During World War II, the majority of the research in all the labs was 6.2 or higher since nearly all research focused on war-related problem solving. The Engineer Topographic Laboratories has varied the most widely. It conducted groundbreaking basic research on geodesy in the 1950s when such issues were relatively not well understood, but its focus since the advent of computers has been more on developing systems to accomplish specific tasks based on known theory. Likewise, ITL has focused mostly on 6.2 or higher. However, such funding categories are not an exact measure. For example, a project receiving 6.2 funding may involve investigating and correcting levee failures. To understand the problem, a lab may use part of this funding for general investigations, modeling of river phenomena, experimenting with soils under various conditions, or other basic research. Research may result in development of new equipment, levee designs, or methods of armoring that exceed applied research. Such variations were routine, and good managers planned on similar uses of funding. Yet even taking this variability into account, there seems little doubt that most of the work of Corps research over time has been reimbursable applied research.

From the perspective of ERDC leaders, however, it is merely academic whether specific activities are or should be considered science or engineering. In the real world, the two are inseparable parts of a continuous cycle of discovery and application. “They are two sides of one coin,” Holland explained. Both computer modeling and experimentation have their place to solve complex problems or validate data. In some cases, “some problems are not modelable;” in others, such as hydraulics, modeling has a high level of accuracy not possible in physical models. Whether one uses one tool or another depends on the problem, and ultimately, the goal of all research is or should be to solve problems. From this point of view, nearly all research is applied since even most basic research has some end or problem in sight and very few institutions have the luxury of researching merely for its own sake. The fact that 85 percent of ERDC’s funding was reimbursable indicates less the nature of its research than the desire to make itself cost-effective in solving problems for the Army. As ERDC enters its second decade of existence, Holland argued, researchers must keep their focus on “solving tough problems to make the world a safer and better place” for the Corps to continue being successful in its research mission.³⁹⁵



Introduction

- 1 “A Proposal for Promoting Useful Knowledge Among the British Plantations in America,” in Albert Henry Smyth, ed., *The Writings of Benjamin Franklin*, Vol. 2 (NY: Macmillan, 1905): 228. Emphasis mine.
- 2 *Ibid.* See also Brooke Hindle, *The Pursuit of Science in Revolutionary America, 1735-1789* (Chapel Hill: University of North Carolina Press, 1956): 1-5.
- 3 Letter to George Washington, Sept. 10, 1777, at <http://franklinpapers.org>, Vol. 24, Nov. 5, 2009.

Chapter 1

- 4 The various uses of terminology contribute to this problem. For example, historian of science David Lindberg has identified at least eight definitions of science: control of environment, theoretical or technical applications, statements or theories, the experimental method, epistemology based on evidence not authority, content of research, any objective or precise method of inquiry, and a general term of approval; see *The Beginnings of Western Science: The Empirical Scientific Tradition in Philosophical, Religious, and Institutional Context, 600 B.C. to A.D. 1450* (Chicago: Univ. of Chicago Press, 1992): 1-4.
- 5 Layton, “American Ideologies of Science and Engineering,” *Technology and Culture* 17:4 (Winter 1976): 688-701, quote on 688. On the 1988 debate, see Michael Fores, “Transformation and the Myth of ‘Engineering Science’: Magic in a White Coat”; Edwin Layton, “Science as a Form of Action: The Role of the Engineering Sciences”; and David Channell, “Engineering Science as Theory and Practice,” *Technology and Culture* 29:1 (Spring 1988): 64-103.
- 6 John Rae and Rudi Volti, *The Engineer in History* (New York: Peter Lang, 2001): 186-91; Terry S. Reynolds, “The Engineer in 19th Century America,” in Terry S. Reynolds, Ed., *The Engineer in America: A Historical Anthology from Technology and Culture* (Chicago: Chicago University Press, 1991): 10.
- 7 Rae and Volti, pp. 8-25, 32-52; Ervan G. Garrison, *A History of Engineering and Technology: Artful Methods* (Boca Raton: CRC Press, 1991): 24-66; Richard Kirby et al., *Engineering in History* (New York: McGraw-Hill, 1956): 42-84, 95-113; Aristotle quote from *Politics*, 1278a; Hunter Rouse and Simon Ince, *History of Hydraulics* (Ann Arbor, Mich.: State University of Iowa, 1957): 1-42. An example of a traditional study of the Scientific Revolution is H. Butterfield, *The Origins of Modern Science, 1300-1800* (New York: Macmillan Co., 1953). On Aristotle’s inclusion of mechanics in mathematics, compare *Posterior Analytics*, 76a; *Metaphysics*, 1078a; and *Physics*, 194a.
- 8 Aristotle quoted in *Posterior Analytics*, 72b, 73a. An excellent survey of the development of the scientific method is John Losee, *A Historical Introduction to the Philosophy of Science* (NY: Oxford Univ. Press, 2001): on ancient philosophy, see 1-25.
- 9 Bacon quotes from *Novum Organum*, I., 98, 99, Preface; Losee, pp. 26-63.
- 10 *Discourse*, II, IV; *Rules*, IV, VII.; Losee, pp. 63-70.

- 11 Others doubt the degree to which Galileo embraced experimentalism; see Losee, pp. 46-54.
- 12 Losee, pp. 86-142, 153-170, 228. The method as described here is typical of mid- to late-twentieth century philosophy. See, e.g., E.L. Dillow, *Methods of Science: An Introduction to Measurement and Testing for Laymen and Students* (NY: Universe Books, 1970): 16-22.
- 13 Rae and Volti, pp. 52-70, quote on p. 56; Rouse and Ince, pp. 43-72; Garrison, pp. 92-130.
- 14 Garrison, pp. 130-178; Rae and Volti, pp. 76-78; Todd Shallat, *Structures in the Stream: Water, Science, and the Rise of the U.S. Army Corps of Engineers* (Austin: University of Texas Press, 1994): 14-23, quote on 21; Rouse and Ince, pp. 113-140.
- 15 Rae and Volti, pp. 80-96, quote on p. 96; Kirby, pp. 132-144, 187-297; Shallat, pp. 24-29; Rouse and Ince, pp. 120-123. On the Industrial Revolution, see the seminal work, David Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present* (Cambridge University Press, 1969).
- 16 Rae and Volti, pp. 177-181. On early hydraulic experiments, see Shallat, pp. 20-29; Rouse and Ince, pp. 115-138; and Martin Reuss, "The Art of Scientific Precision: River Research in the Army Corps of Engineers to 1945," *Technology and Culture* 40:2 (April 1999): 292-299. For a summary of the origins of geotechnical engineering, see Benjamin H. Fatherree, *The History of Geotechnical Engineering at the Waterways Experiment Station, 1932- 2000* (Vicksburg, Miss.: ERDC, 2006): 1-11.
- 17 Silvio Bedini, *Thinkers and Tinkers: Early American Men of Science* (New York: Charles Scribner's Sons, 1975): 25-78, 118, 164-632, 350, 390; Hindle, pp. 74-79, 80-95, 190-207, 342-346.
- 18 Hindle, pp. 208-215; Tocqueville, *Democracy in America*, Vol. II, Sec. I, Ch. 10.
- 19 Hindle, pp. 31-81, 105-121; Bedini, pp. 173-182, 375-395.
- 20 Bedini, pp. 240-290, quote on p. 298.
- 21 Ibid., pp. 244-249; Shallat, "Building Waterways, 1802-1861: Science and the United States Army in Early Public Works," *Technology and Culture* 31:1 (Jan. 1990): 18-50; *The U.S. Army Corps of Engineers: A History* (Alexandria, Va.: Office of History, USACE, 2007): 1-5. An excellent source on the Corps during the Revolution is Paul K. Walker, *Engineers of Independence: A Documentary History of the Army Engineers in the American Revolution, 1775-1783* (Fort Belvoir: CEHO, 1981). Before Duportail arrived, Deane promised Phillipe Tronson du Coudray a generalship with charge over engineers. Despite objections, Congress felt obliged to promote him, but to Washington's relief, he drowned soon after. "Such thoughts have probably been entertained by subsequent Commanders-in-Chief," Chief of Engineers Maj. Gen. Emerson Itschner once noted, *The Army Engineers' Contribution to American Defense and Advancement* (NY: Newcomen Society, 1959): 9.
- 22 Bedini, pp. 364-5; *Corps of Engineers*, pp. 7-8, 15-16; Shallat, *Structures*, pp. 35-41; Sidney Forman, "Why the United States Military Academy Was Established in 1802," *Military Affairs* 29:1 (Spr. 1965): 16-28. For anecdotes on West Point, see E.D.J. Waugh, *West Point: The Story of the United States Military Academy Which Rising from the Revolutionary Forces Has Taught American Soldiers the Art of Victory* (NY: Macmillian, 1944): 43-45. On L'Enfant's role in designing D.C., see Pamela Scott, *Capital Engineers: The U.S. Army Corps of Engineers in the Development of Washington, D.C., 1790-2004* (Alexandria: CEHO, 2008): 1-19. On Nicola, see Robert Haggard, "The Nicola Affair: Lewis Nicola, George Washington, and American Military Discontent during the Revolutionary War," *Proceedings of the American Philosophical Society* 146:2 (June 2002): 139-169.
- 23 Hill, *Roads, Rails and Waterways: The Army Engineers and Early Transportation* (Norman, Okla.: Oklahoma University Press, 1957): 5-14, quote on p. 5; Craig Collins, "200 Years at West Point," *Duty, Honor, Country: The Bicentennial of the United States Military Academy* (West Point: USMA, 2002): 27-28, quote on 27; *Corps of Engineers*, pp. 16-18; Reynolds, pp. 11-16; Waugh, pp. 47-69; Shallat, "Building Waterways," pp. 22-23.
- 24 Shallat, *Structures*, pp. 79-98; Collins, pp. 29-33; Forest, pp. 12-17; *Corps of Engineers*, pp. 16-18; Reynolds, pp. 11-16; Waugh, pp. 47-69.

- 25 Shallat, pp. 81-96; Waugh, pp. 70-82; Morrison, *'The Best School in the World': West Point in the Pre-Civil War Years, 1833-1866* (Kent State University Press, 1986): 49-52, 91-110.
- 26 Morrison, pp. 49-52; Waugh, pp. 95-109; Brevet Brig. Gen. Henry Abbot, "Early Days of the Engineer School of Application," Occasional Papers, No. 14 (Washington, D.C.: Engineer School of Application, 1904): 1-34.
- 27 Morrison, pp. 111-113, quote on 111; Waugh, pp. 95-109; Shallat, *Structures*, pp. 97-98, 114-116; "Building Waterways," pp. 22-28, 39; Rae and Volti, pp. 123-127; Layton, "Mirror Image Twins: The Communities of Science and Technology in 19th-Century America," in Reynolds, ed., *Engineer in America*, pp. 237-241, quote on p. 238. In fact, as Shallat notes, occupation of Corps officers in private projects engendered a fair amount of criticism.
- 28 Hill, p. 36, 175, 193-4; Shallat, "Building Waterways," pp. 38-43. Perhaps the best overview of the development of the Topographical Engineers is Frank Schubert, ed., *The Nation Builders: A Sesquicentennial History of the Corps of Topographical Engineers, 1838-1863* (Fort Belvoir, Va.: CEHO, 1988).
- 29 J.E. Kaufmann and Tomasz Idzikowski, *Fortress America: The Forts that Defended America, 1600 to the Present* (Cambridge, Mass.: De Capo Press, 2004): 205-211, 228-231; Hill, pp. 5-10; Shallat, "Building Waterways," pp. 43-44; *Structures*, pp. 102-103; R.J.M. Sutherland, Dawn Humm, and Mike Chrimes, *Historic Concrete: Background to Appraisal* (Reston, Va.: Thomas Telford, 2001): 372; U.S. Congress, *Report of the Chief of Engineers, 1967*, H.D. 1, Pt. 2 (40th Cong., 2nd Sess.): 2; Layton, "Mirror Image Twins," pp. 238-9. See also the Reports of the Chief of Engineers for 1868-1870.
- 30 Hill, pp. 25-59, 102-121, 153-182; Shallat, "Building Waterways," pp. 38-46; Schubert, *Nation Builders*, pp. 5-30; Roy Gordon, "Engineering for People: 200 Years of Army Public Works," *TME* (May-Jun. 1976): 180-185; Frank Snyder and Brian Guss, *The District: A History of the Philadelphia District, U.S. Army Corps of Engineers, 1866-1971* (Philadelphia: USACE, 1974): 64-5. The first mechanical dredge (and mechanically driven vehicle), developed by Oliver Evans for the Philadelphia Board of Health, appeared in 1804, but its use was limited.
- 31 William Goetzmann, *Army Exploration in the American West, 1803-1863* (New Haven, Conn.: Yale University Press, 1959): 3-11, 22-108; Frank Schubert, *Vanguard of Expansion: Army Engineers in the Trans-Mississippi West, 1819-1879* (Washington, D.C.: CEHO): 1-36; Schubert, *Nation Builders*, pp. 43-6, 53-7.
- 32 Goetzmann, pp. 153-337, quote on p. 305; Schubert, *Vanguard*, pp. 55-134; Shubert, *Nation Builders*, pp. 59-69.
- 33 Goetzmann, pp. 310-337; Schubert, *Nation Builders*, pp. 69-71; Schubert, *Vanguard*, pp. 115-149; *Corps of Engineers*, pp. 57-64; *American Journal of Science* quoted in Shallat, "Building Waterways," p. 41.
- 34 Schubert, *Vanguard*, pp. 6-13; Porter quote from Hill, pp. 200-201.
- 35 As Shallat observes, one sees this competition most often in hydrology, although West Pointers were often receptive to suggestions of civil engineers; "Building Waterways," pp. 48-49. In this, West Point itself was the focus of the loudest criticism, see Collins, pp. 31-34. The story of the Humphreys-Eads debate has been retold many times; see for example, John Barry, *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America* (NY: Simon and Schuster, 1997): 55-60; Charles Camillo and Matthew Pearcy, *Upon Their Shoulders: A history of the Mississippi River Commission from its inception through the advent of the modern Mississippi River and Tributaries Project* (Vicksburg, Ms.: MRC, 2006): 1-15; Martin Reuss, "Andrew A. Humphreys and the Development of Hydraulic Engineering: Politics and Technology in the Army Corps of Engineers, 1850-1950," *Technology and Culture* 26 (January 1985): 17-23.
- 36 Bedini, p. 395; Kurby, p. 328; Reynolds, "19th Century," pp. 19-21; Rae, pp. 182-189.
- 37 Bedini, pp. 396-7; Garrison, pp. 193-4; Rae, pp. 192-215; Reynolds, "19th Century," pp. 24, "The Engineer in 20th Century America," in Reynolds, ed., *Engineer in America*, pp. 169-190. On the work of the Franklin Institute, see for example, Bruce Sinclair, "At the Turn of a Screw: William Sellers, the Franklin Institute, and a Standard American Thread," in Reynolds, ed., *Engineer in America*, pp. 151-165. On the role of engineering

- societies on engineering practice, see the seminal work of Layton, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession* (Baltimore, Md.: Johns- Hopkins University Press, 1986): 28-84.
- 38 Reynolds, "20th Century," pp. 173-8; Rae, pp. 137-140, 164; Layton, *Revolt*, pp. 110-140. See also Peter Meiksins, "The 'Revolt of the Engineers' Reconsidered," in Reynolds, ed., *Engineer in America*, pp. 399-426.
- 39 Layton, *Revolt*, pp. 227-252; "Mirror-Image," pp. 243-246; Rae, p. 141. For unintended consequences of technology, see also, Daniel Boorstin, *The Republic of Technology: Reflections on our Future Community* (NY: Harper and Row, 1978).
- 40 On criticism of the Corps, see for example, Arthur E. Morgan, *Dams and Other Disasters: A Century of the Army Corps of Engineers in Civil Works* (Boston: Porter Sergeant. 1971); or Shallat, pp. 1-9. One sees this same criticism surface repeatedly ad nauseum in public comments and news stories about the Corps.

Chapter 2

- 41 There have been at least three official histories of WES (one unpublished), two thorough histories of WES laboratories, and many other books and articles that chronicle its founding, in full or in part. See Joseph Tiffany, ed., *History of the Waterways Experiment Station* (Vicksburg, Miss.: WES, 1968); Gordon Cotton, *A History of the Waterways Experiment Station, 1929-1979* (Vicksburg: WES, 1979); Lee and Bonnie Pendergrass, "Mimicking Waterways, Harbors, and Estuaries: A Scholarly History of the Corps of Engineers Hydraulics Laboratory at WES, 1929 to the Present," Unpublished Manuscript (WES Archives, 1979); Benjamin H. Fatherree, *The First 75 Years: History of Hydraulics Engineering at the Waterways Experiment Station* (Vicksburg: ERDC, 2004) and *The History of Geotechnical Engineering at the Waterways Experiment Station, 1932-2000* (Vicksburg: ERDC, 2006); and Chapter 9 of Camillo and Percy. Perhaps the best description of developments in hydraulics and their impact on WES is Reuss, "The Art of Scientific Precision."
- 42 Leland Johnson, *The Ohio River Division, U.S. Army Corps of Engineers: The History of a Central Command* (Cincinnati: ORD, 1992): 25-30 and Martin Reuss and Charles Hendricks, "National Service: 1775-2000," *Engineer Update* (June 2000); Charles Prelini, *Dredges and Dredging* (NY: D. Van Nostrand Co.: 1911): 94-115; Arthur Frazier, *Water Current Meters in the Smithsonian Collections of the National Museum of History and Technology* (Washington, D.C.: Smithsonian Institution Press, 1974): 78-80; Letter, Comstock to Brig. Gen. Lincoln Casey, Jul. 17, 1894 (NARA RG 77, Ent. 103, Bx. 26, Fldr 7036); Col. F.V. Abbot to Goethals, Nov. 12, 1901; Grosche to Brig. Gen. G.L. Gillespie, May 18, 1903 (Bx. 674, Fldr. 30708); Bowker to Chief Engineer, Jan. 17, 1906 (Bx. 1408, Fldr. 58067).
- 43 U.S. Congress, *Report on the Board of Engineers on Deep Waters Between the Great Lakes and the Atlantic Tide Waters*, H.D. 142 (58th Cong., 2nd Sess.): 40-50, 606-691; on special board survey reports, see for example, U.S. Congress, *Bridges Across the Great Kenahwa River*, S.D.114 (48th Cong., 1st Sess.) or *Report of the Board of Engineers regarding obstructions in the Columbia River*, S.D. 7 (53rd Cong., 1st Sess.).
- 44 Taft, *Coast Defenses of the United States and Insular Possessions*, S.D. 248 (59th Cong., 1st Sess.): 1-48; "Report of Board of Review" (CEHO Archives, MIL GEN Coast Defense, Box 1-4, Folder 9-1); Kaufmann and Idzikowski, pp. 297-336. See also Emanuel Lewis, *Seacoast Fortifications of the United States: An Introductory History* (Washington, D.C.: Smithsonian Institution Press, 1970).
- 45 Letter, Taylor to Brig. Gen. W.P. Craighill, Oct. 19, 1896; Suter to Craighill, Jun. 4, 1896, Mar. 24, 1896 (NARA RG 77, Ent. 103, Bx. 265, Fldr. 12417); Roessler to Craighill, Dec. 5, 1901 (Bx. 930, Fldr. 39705); Capt. Craighill to Brig. Gen. Craighill, Mar. 31, 1902 (Bx. 993, Fldr. 42566); Brig. Gen. John Wilson to Eugene Griffin, Nov. 8, 1900; Roessler to Brig. Gen. A. Mackenzie, Aug. 2, 1904 (Bx. 855, Fldr. 37210, 12958); Capt. A.E. Waldron to Chief of Engineers, Dec. 16, 1911 (Bx. 2038, Fldr. 83720); Chief of Engineers to Board of Engineers, Mar. 23, 1917; Col. F.V. Abbot to Chief of Eng., Apr. 9, 1917; Edison to Abbot, Apr. 11, 1917 (Bx. 2435, Fldr. 99735). On status of improvements, see "The Corps of Engineers, U.S. Army" (Bx. 86, Fldr. 50734).
- 46 *History of the Board of Engineers for Rivers and Harbors* (Fort Belvoir, Va.: BERH, 1980): 42-46.

- 47 U.S. Congress, *Water Hyacinth Obstructions*, H.D. 91 (55th Cong, 3rd Sess.): 1-11; Benyaurd to Wilson, Apr. 13, 1899; Col. Gilbert Youngberg to Chief of Engineers, Dec. 19, 1922 (NARA RG 77, Ent. 103, Bx. 672, Fldr. 30674).
- 48 Charles Ward Engineering to Gen. William Bixby, Jun. 14, 1910; Chief of Eng. To Col. W.L. Fisk, Aug. 8, 1910; Alexander McDougall to Chief of Engineers, Nov. 15, 1910; Sec. of War to Beach, Jan. 17, 1911; Beach to Chief of Eng. Feb. 24, 1911; Beach to Sadler, Feb. 24, 1912; Newcomer to Chief, May 19, 1911; Beach to Chief, Nov. 29, 1915 (NARA RG 77, Ent. 103, Bx. 1826, Fldr. 76542); Newcomer to Chief, Mar. 7, 1911; Beach to Chief, Mar. 9, 1911; Beach to Chief, Apr. 26, 1911; Beach to Chief, Jan. 8, 1912 (Bx. 1944, Fldr. 80137); U.S. Congress, *Experimental Towboats*, H.D. 857 (63rd Cong., 2nd Sess.): 1-34.
- 49 U.S. Congress, *Experimental Towboats*, H.D. 108 (67th Cong., 1st Sess.): 1-15; Brig. Gen. Bixby to Senior Member, Towboat Board, Aug. 20, 1918 (Ent. 1826, Fldr. 76542); Newcomer to Senior Member, New York Harbor Line Board, Nov. 16, 1918 (Ent. 103, Bx. 2093, Fldr. 85607); Col. Edward Burr to Commandant, Navy Yard, Nov. 10, 1921; Beach to Commandant, Apr. 3, 1922 (Bx. 2989, Fldr. 132967); *Second Supplementary Report on Investigations of the Board on Experimental Towboats*, June 17, 1929 (CEHO CW GEN, Bx. 43A, Rivers, Mississippi, Fldr. 3, Investigation of Board on Experimental Towboats).
- 50 Brig. Gen. John W.N. Schulz, "Research in the Corps of Engineers" (CEHO MIL-R&D-Engineer Board Studies VI-11-6); Black to Gillespie, Nov. 28, 1902, and endorsements, Dec. 3, 1902-Jan. 10, 1903; Black to Leach, Jan. 14, 1903 (NARA RG 77, Ent. 103, Bx. 1084, Fldr. 45253); Benedict Crowell to Thomas Edison, Feb. 9, 1918 (Bx. 2731, Fldr. 118329); Barry Fowle, ed., *Builders and Fighters: U.S. Army Engineers in World War II* (Fort Belvoir, Va.: CEHO, 1992): 157-8; John Pennington, *History of the U.S. Army Engineer Topographic Laboratories* (Fort Belvoir: ETL, 1973): 1-2.
- 51 U.S. Congress, *Report of the Chief of Engineers, U.S. Army, 1922*, H.D. 422 (67th Cong., 3rd Sess.): 17-21; 1st Lt. F.H. Kohloss to Chief of Engineers, Governmental Testing Laboratories, Dec. 8, 1928 (NARA RG 77, Ent. 109, Bx. 50, Fldr. 1870).
- 52 Mary-Louise Quinn, *The History of the Beach Erosion Board, U.S. Army Corps of Engineers, 1930-63* (Fort Belvoir, Va.: Coastal Engineering Research Center, 1977): 9-18. On the early history of coastal research, see Robert L Wiegall and Thorndike Saville, Jr., "History of Coastal Engineering in the USA," in Nicholas C. Kraus, ed. *History and Heritage of Coastal Engineering* (Long Beach, CA: ASCE, 1996): 513-600.
- 53 Quinn, 18-23.
- 54 Letter, Tawney to Taft, Mar. 20, 1908; Langfitt to MacKenzie, Mar. 27, 1908; MacKenzie to Taft, Apr. 11, 1908 (NARA RG 77, Ent. 103, Bx. 1612, Fldr. 66893); Chief of Engineers to Chief of Staff, Nov. 20, 1915 (Bx. 2429, Fldr. 99541); Kholoss to Chief; Brig. Gen. Herbert Deakyne to Secretary of War, Laboratories, Nov. 3, 1926 (Bx. 50, Fldr. 1870). John Freeman would note contemptuously in Freeman, ed., *Hydraulic Laboratory Practice* (NY: ASME, 1929): 697 the lack of hydraulic facilities at West Point.
- 55 Freeman, pp. 12-15, Rouse and Ince, pp. 117-134; Reuss, "Art of Scientific Precision," pp. 292-299.
- 56 Newton, *Mathematical Principles of Natural Philosophy*, ii, 32.
- 57 Rouse and Ince, pp. 161-164, 169-177, 181-187, 206-211, 220-223; Freeman, pp. 14-17, 35-37; the number of laboratories is based on the facilities listed in the table of contents; on the Greyhound experiments, see David Watson Taylor, *The Speed and Power of Ships: A Manual of Marine Propulsion* (NY: J Wiley and Sons, 1911): 26-29, 85-86, 95.
- 58 Rouse and Ince, pp. 187-192, 224-227; Freeman, pp. 17-32; see also Engineering Foundation, *Hydraulic Laboratories in the United States of America* (NY: Engineering Societies Building, 1922).
- 59 On laboratory practice, see Freeman, passim. On the river flooding, see Camillo and Percy, pp. 121-149; Barry, pp. 173-212; and Reuss, *Designing the Bayous*, pp. 93-101.
- 60 Quote from U.S. Congress, *National Hydraulic Laboratory: Hearings before the Committee on Rivers and Harbors, House of Representatives*, S.1710 (70th Congress, 1st Sess.) 1928.

- 61 *Nat. Hydraulic Lab*, 1928, pp. 21-31; Camillo and Percy, pp. 132-5; Ransdell to Weeks, Jul. 29, 1922; Weeks to Rep. Wesley Jones, Aug. 9, 1922 (NARA RG 77, Ent. 103, Bx. 3014, Fldr. 134377); see also Morgan, *Dams and Other Disasters*, pp. 194. Morgan's often polemical interpretation of events is highly questionable at times, but he provides detailed transcripts of primary sources, many of which could not be located in the National Archives.
- 62 Camillo and Percy, pp. 42, 123-135; *To Establish a National Hydraulic Laboratory: Hearing before a Subcommittee of the Committee on Commerce*, United States Senate, 67th Congress, 2nd Session, Pursuant to S.J. Res. 209, Sept. 8, 1922 (Washington, D.C.: GPO, 1922): Freeman quote on p. 4, Ockerson quotes on pp. 47, 53.
- 63 Freeman, pp. vii-xii; *Nat. Hydraulic Lab*, 1928, pp. 21-22; Draft letter, Sec. of War Dwight Davis to Sen. W.L. Jones, Apr. 23, 1926; Freeman to Jadwin, Mar. 24, 1927; Jadwin to Freeman, Apr. 2, 1927 (NARA RG 77 Ent. 109 Bx. 50, Fldr. 1850).
- 64 Freeman, pp. xii-xvi; *Nat. Hydraulic Lab*, 1928, pp. 23; Rouse and Ince, p. 227; Jadwin to Freeman, Apr. 2, 1927; Van Leer to Jadwin, June 5, 1928 (NARA RG 77 Ent. 109 Bx. 50, Fldr. 1850).
- 65 U.S. Congress, *Flood Control in the Mississippi Valley*, H.D. 90 (70th Cong., 1st Sess.): 33; Hoover to Jadwin, Jun. 17, 1927; Davis to Bureau of Budget Director H.M. Lord, Mar. 3, 1928 (NARA RG 77 Ent. 109, Bx. 50, Fldr. 1870); Freeman, p. 18; Morgan, pp. 212-213; *Nat. Hydraulic Lab*, 1928, pp. 63-89, Jadwin quote on p. 64.
- 66 Lyon to Beach, Aug. 7, 1922; Jervey to Beach, Oct. 11 and Oct. 22, 1922; Hoffman to Taylor, Sept. 12, 1922; Townsend to Beach, Sept. 29, 1922 (NARA RG 77, Ent. 103, Bx. 3014, Fldr. 134377); Newcomer to Chief of Engineers, Lectures of Dr. de Thierry at Cambridge, Mass., Apr. 16, 1927 (NARA RG 77, Ent. 109, Bx. 50, Fldr. 1870); Morgan, pp. 188-213.
- 67 Abbot, "Engineer School of Application," p. 7; Robert E. McMath, "Relation Between Stage and Mean Velocity," Mar. 14, 1881 (Miscellaneous Papers of the MRC, Vol. II): 15-16; Lyon to Beach; Weeks to Jones; Morgan, pp. 196-8; *Nat. Hydraulic Lab*, 1928, p. 71; see also Reuss, "Art of Scientific Precision," pp. 298-304 and note 16. On construction of the Gatun Dam, see Ira Bennett, *The History of the Panama Canal* (Washington, D.C.: Historical Publishing Co, 1915): chapter 25.
- 68 Townsend quote from letter, Townsend to Beach, Sept. 12, 1922; Hoffman quote from letter, Hoffman to Taylor; Townsend to Beach, Sept. 30, 1922; Beach to Weeks, Aug. 9, 1922 (NARA RG 77, Ent. 103, Bx. 3014, Fldr. 134377); Vogel, "Conception, Birth and Development of the U.S. Waterways Experiment Station (CEHO GEN 123-6): 2; Interview with Vogel by Charles Crawford, Jan. 9, 1970, Memphis State University (CEHO Oral History, Career Interview, Vogel, Herbert). In one ludicrous example, Townsend raised the issue of a Weather Bureau experiment measuring stream flow being upset by a thirsty cow.
- 69 Beach to Jervey, Nov. 13, 1922; Hoffman to Beach; Weeks to Jones; Freeman to Jadwin, Mar. 21, 1927 (NARA MD RG 77, Ent. 109, Bx. 50, Fldr. 1870); *Nat. Hydraulic Lab*, 1928, pp. 63-84.
- 70 *Nat. Hydraulic Lab*, 1922, pp. 47-57, quotes on pp. 48, 50; Jadwin quoted in *Nat. Hydraulic Lab*, 1928, p. 73.
- 71 Abbot, pp. 4-5; Townsend to Beach, Sept. 29, 1922; Beach to Jervey, Nov. 13, 1922; Weeks to Jones; *Nat. Hydraulic Lab*, 1928, pp. 64-67, quote on 66; Hawes quote from U.S. Congress, *Hearings before the Committee on Commerce, U.S. Senate, Flood Control of the Mississippi River, Feb. 9, 10, 11, and 24, 1928*, Pt. 3 (70th Cong., 1st Sess.): 578.
- 72 Cotton, *A History of WES*, pp. 5-8; Memo, Jadwin to Pres. MRC, Establishment of Hydraulic Laboratory in the Alluvial Valley of the Mississippi, June 18, 1929 (CEHO GEN 123-1-1); "Financial History – Waterways Experiment Station" (MRC Historical Files, Drawer 3-2, General A16 Section, File 28); Blake Vanleer to Jadwin, Jun. 23, 1928; Vanleer to Jackson, Jan. 19, 1929 (NARA MD RG 77, Ent. 109, Bx. 50, Fldr. 1870); letter, Maj. P. S. Reinecke to Col. F. B. Wilby, Aug. 2, 1929 (MRC Historical Files); telegram quoted in Brig. Gen. (ret.) Herbert D. Vogel, "Origin of the Waterways Experiment Station," *TME* (Mar.-Apr. 1961): 133; Memo to Memphis DE, Hydraulic Laboratory, Nov. 25, 1929 (CEHO GEN 123-1-1).

- 73 “Origin of WES,” pp. 133-4; Vogel, “The U.S. Waterways Experiment Station,” *TME* (Mar. - Apr. 1931): 152-3; Vogel, “Application of Model Research to Mississippi Flood Problems,” *Engineering News-Record (ENR)* (Jul. 16, 1931): 84-6; Cotton, p. 8-10. Of the original buildings, only the director’s house is still in original condition. The laboratory building, which has been renovated several times, is now the headquarters of the Environmental Laboratory, while Brown Lake, no longer needed as a water supply, has largely returned to nature.
- 74 Interview with Vogel, by the Public Works Historical Society (PWHS) for the Historical Division, U.S. Army Corps of Engineers (Nov. 10-Dec. 1, 1976): 43-44, 50; “Origin of WES,” p. 134-5; quote from Memphis Interview.
- 75 Morgan, pp. 223-227, quote on 225; Jadwin quoted in *National Hydraulic Laboratory*, p. 76; Rouse and Ince, p. 227.
- 76 *Nat. Hydraulic Lab*, 1928, p. 73; Rouse and Ince, p. 227.

Chapter 3

- 77 Fatherree, *First 75 Years*, pp. 17; Vogel, “Research at Waterways Experiment Station,” *TME* (Jul.-Aug. 1932): 335.
- 78 Fatherree, *First 75 Years*, pp. 19-20; Vogel, “Origin of WES,” quote on p. 134.
- 79 Fatherree, *First 75 Years*, pp. 18, 27-28; Vogel, “Research at WES,” pp. 332-5; Vogel, “Application of Model Research,” pp. 87-88; “First Floodflow Experiments of Vicksburg Laboratory,” *ENR* (Jun. 11, 1931): 370.
- 80 Fatherree, *First 75 Years*, p. 29, 52-54; Vogel, “Research at WES,” p. 335.
- 81 PWHS Interview, pp. 37-38, quote p. 56; Memphis Interview; Tiffany, *History*, pp. IV-1-14.
- 82 Fatherree, *First 75 Years*, pp. 20-29; Vogel, “Research at WES,” p. 333; Vogel, “Application of Model Research,” pp. 86-87.
- 83 Fatherree, *First 75 Years*, pp. 27-8, 47-49, 73-5; “Mississippi River Flood-Control Model,” *Experiment Station Hydraulics Bulletin* 5:1 (Vicksburg: WES, 1942): 1-15. On the MR&T Project, see in particular, Camillo and Percy, pp. 150-178; Martin Reuss, *Designing the Bayous: The Control of Water in the Atchafalaya Basin, 1800-1995* (Alexandria, Va.: USACE, 1998): 103-134; Emory L. Kemp, *Stemming the Tide: Design and Operation of the Bonnet Carre Spillway* (Chicago: Public Works Historical Society, 1990): 12-13.
- 84 “Financial History – WES”; G.O. No. 9, Jul. 29, 1949, Change in Jurisdiction of Waterways Experiment Station, Vicksburg, Mississippi (ERDC Archives); Cotton, p. 10.
- 85 Tiffany, *History*, p. IV-3; Vogel quote from PWHS Interview, p. 66; Paul Thompson, “Flowing Water and the Small-Scale Model,” Dec. 1938, in *Miscellaneous Articles on Experiment Station Work* (Vicksburg: WES, N.D.): quote on p. 3. The river statistics provided reflect modern measurements and do not take into account recent changes such as deepening or widening of channels.
- 86 Fatherree, *First 75 Years*, pp. 38-45. Tiffany’s recollection was that “all the Lab work for about four years was completely inaccurate and useless,” obviously an exaggeration. See Tiffany, “WES Had Tentative Start, But Came Through Strong,” *Vicksburg Sunday Post* (Sun., Jun. 30, 1991), clipping in ERDC Archives.
- 87 Vogel quote from PWHS Interview, p. 66; Thompson quotes from “Flowing Water,” pp. 4, 7. 88 PWHS Interview, p. 40-48; Tiffany, *History*, pp. IV-1-2; Fatherree, *First 75 Years*, pp. 30-33.
- 89 Fatherree, *First 75 Years*, pp. 75-77; Friedkin, *Results of Laboratory Study of the Meandering of Alluvial Rivers* (Vicksburg: MRC, 1946).
- 90 Terzaghi quote from “Soil Mechanics – A New Chapter in Engineering Science,” 1939, reprinted in L.F. Cooling et al, ed., *A Century of Soil Mechanics: Classic papers on soil mechanics published by the Institution of Civil Engineers, 1844-1946* (London: Inst. Civ. Eng., 1969): 155; Baker quote from “The Actual Lateral Pressure of Earthwork,” 1881 in Cooling, p. 16; see also C.H. Gregory, “On railway cuttings and embankments

- with an account of some slips in London Clay, on the line of the London and Croydon Railway,” 1884, in Cooling, pp. 3-13.
- 91 Darwin, “On the horizontal thrust of a mass of sand,” 1883, in Cooling, pp. 63-92, quote on 92; Bell, “The lateral pressure and resistance of clay, and the supporting power of clay foundations,” 1915, in Cooling, pp. 95-149; Terzaghi, “Principles of Soil Mechanics: VIII – Future Development and Problems,” *ENR* (Dec. 31, 1925): 1064-8, quote on 1064; Fatherree, *Geotechnical Engineering at WES*, pp. 4-7.
 - 92 Fatherree, *Geotechnical Engineering*, pp. 5-11.
 - 93 Terzaghi, “Soil Mechanics – Future Developments,” quote on p. 1064; “Soil Mechanics: New Chapter,” quote on p. 13; see also his comments in *Theoretical Soil Mechanics* (NY: John Wiley and Sons, 1943): 3 and the 1st edition introduction to Terzaghi, Ralph Deck, and Gholamneza Mesri, *Soil Mechanics in Engineering Practice*, 3rd ed. (NY: Wiley and Sons, 1996): xxi.
 - 94 Fatherree, *Geotechnical Engineering*, pp. 11-14, 19-28.
 - 95 Tiffany, *History*, p. V-3; Fatherree, *Geotechnical Engineering*, pp. 17-20; PWHS Vogel Interview, p. 50.
 - 96 Fatherree, *Geotechnical Engineering*, pp. 19-30.
 - 97 *Ibid.*, pp. 29-31, Falkner quoted p. 26; Cotton, pp. 24-26.
 - 98 Although he focuses mostly on Danish history, perhaps the best recent summary of the early history of concrete is in Gunnar M. Idorn, *Concrete Progress from Antiquity to the Third Millennium* (London: Thomas Telford, 1997): 18-30, Aspdin quote on 22, Reid quote on 23. For more on Roman concrete engineering, see David Moore, *The Roman Pantheon: The Triumph of Concrete* (1995). See the discussion of Totten’s experiments in Ch. 1.
 - 99 Robert E. Wilde, *ACI: A Century of Progress* (NP: ACI, 2003): 2-13; Galvin Davis Sims, “Hoover Dam was Test of Engineer’s Theories,” *NYT* (Tues., Oct. 15, 1985): online version; David Moore, “The Hoover Dam: A World Renowned Concrete Monument,” at www.romanconcrete.com. For a general discussion of dam development, see Patrick James, “Historical Development of Arch Dams,” *Australian Civil Engineering Transactions* (2002): 39-56.
 - 100 Tiffany, *History*, p. VII-1-2; Cotton, pp. 55-6; Peggy Price, Interview with Bryant Mather, Mar. 22, 2001 (ERDC Archives).
 - 101 *Ibid.*
 - 102 Brig. Gen. Max Tyler, “The U.S. Waterways Experiment Station: Its Service for Harbor Improvement Problems,” *TME* (Oct. 1941): 26-29, 49; Paul Thompson, “Current Waterways Studies,” *ENR* (Dec. 29, 1938) in *Miscellaneous Articles*, pp. 1-3; Cotton, pp. 35-39; Fatherree, *First 75 Years*, pp. 45-46; on previous tidal studies, see J.M. Caldwell, “Tides and Seiches,” in *Miscellaneous Articles*, pp. 7-13.
 - 103 Quinn, pp. 20-23; quote from U.S. Congress, An Act Authorizing the construction, repair, and preservation of certain public works on rivers and harbors and for other purposes (71st Cong. 2nd Sess.): Sec. 2; Jamie and Dorothy Moore, “The Corps of Engineers and Beach Erosion Control 1930-1982,” *Beach and Shore* (Jan. 1983): 13-17.
 - 104 Quinn, pp. 22-40; compare with “Financial History of WES.”
 - 105 Quinn, pp. 31-36, 169-173.
 - 106 Robert Livingston, *Impact of the USAETL Field Office and Its Predecessors on Military Mapping Research and Development* (Fort Belvoir: TEC, 1992): 6-13; Pennington, pp. 2-3. The Army Air Service became the Army Air Corps in 1926 and the Army Air Force in 1941. In 1927, the Photographic Laboratory moved to Wright Field.
 - 107 Livingston, pp. 7-8, Pennington, pp. 29-31.
 - 108 Pennington, pp. 32-48.
 - 109 *Ibid.*, pp. 349-63; Livingston, p. 11.

- 110 F.Y. Parker, "Less-Used and Experimental Bank Revetment Structures," *ENR* (Aug. 20, 1931): 301-3; "Report on Experimental Groins for Bank Protection at New Madrid Bend, Happy Valley Bend, by Memphis Engineer District, Mar. 31, 1931"; "Experiment with low elevation dikes, Vicksburg District," May 16, 1945; "Experimental work (dredging), Profit Island (Arbroth Bend)," Apr. 2, 1947; "Experimental Discharge Measurements at St. Louis, Missouri, During June and July 1935," Aug. 29, 1935 (MRC Archives Dr. 1-1, Bank Protection, File 24, 38, 45; Dr. 2-1, Discharges, File 85, 87; Dr. 1-5, Discharges, File 46).
- 111 See Reuss, "Scientific Precision," note 66.
- 112 Fatherree, *First 75 Years*, p. 38; Todd Jennings et al., *Currents of Change: A History of the Portland District*, U.S. Army Corps of Engineers, 1980-2000 (Portland, Ore.: Portland District, 2003): 1-17, 128; Louis Torres, *A History of USA-CERL, 1968-1986* (Champaign, Ill.: CERL, 1987): 1-28.
- 113 Tiffany, *History*, pp. 8-9; WES Org Charts; "Financial History of WES".
- 114 On industry trends at the time, see for example, Rouse and Ince, pp. 243-246.

Chapter 4

- 115 Bush, *Modern Arms and Free Men: A Discussion of the Role of Science in Preserving Democracy* (NY: Simon and Schuster, 1949): 2-6; Schulz quoted in "Research in the Corps of Engineers," p. 26. For example, in his article, "Engineering a New Order: Military Institutions, Technical Education, and the Rise of the Industrial State," *Technology and Culture* 34:1 (Spring 1993): 1-27, Barton C. Hacker summarizes the influence of the military on American education, management techniques, industrialism, and social institutions and argues that weapons research was "both the product and the cause of social change." Political scientist Francis Fukuyama, *The End of History and the Last Man* (NY: Free Press, 1992): 73, argued that "science confers a decisive military advantage" that "forces states to accept modern technological civilization" in driving a modern dialectical political process.
- 116 Pennington, pp. 24-29, 63-72.
- 117 "Research and Development"; Frank Schubert, "The Portable SCR-625 Mine Detector"; Martin Gordon, "The Tank Dozer"; and Larry Roberts, "The Bailey: The Amazing, All-Purpose Bridge," in *Builders and Fighters*, pp. 157-159, 161-169, 171-179, 181-193; Schulz, pp. 10-11, 23-26.
- 118 Reuss, "Organization and Responsibilities," in *Builders and Fighters*, pp. 1-12; Fatherree, *First 75 Years*, pp. 63-69; Cotton, pp. 34-35, 49.
- 119 Fatherree, *First 75 Years*, pp. 63-69; Cotton, pp. 34-35, 49; Fatherree, *Geotechnical Engineering*, p. 34; on war-time harbor research, see also Brig. Gen. Max C. Tyler, "The U.S. Waterways Experiment Station: Its Service for Harbor Improvement Problems," *World Ports* (Oct. 1941): 26-29. On military construction, see Charles Hendricks, "The Air Corps Construction Mission," and Frank Schubert, "The Military Construction Mission," in *Builders and Fighters*, pp. 17-25 and 97-105.
- 120 Quinn, pp. 40-43; "Financial History of WES."
- 121 Quinn, p. 43; Tiffany, *History*, pp. 10-11; Tiffany, "WES Had Tentative Start"; Fatherree, *First 75 Years*, pp. 62-63, 71-72; Cotton, pp. 34-35; Pennington, pp. 3, 311-314; Col. John Harden to ORD Engineer, American Council of Commercial Laboratories, Sept. 6, 1942 (NARA MD RG 77 Ent. 109, Bx. 50, Fldr. 1870). Matthes was the first to have the title technical director, even though Tiffany served in a similar position under various titles, such as Assistant Director or Executive Officer, until becoming technical director in 1956.
- 122 Schulz, pp. 8-14; Memo, Maj. William C. Baker to CO, Fort Belvoir, New Facilities for the Engineer Board, Feb. 22, 1941; Brig. Gen. John J. Kingman to Undersecretary of War, Additional Funds for Extension of Facilities for the Engineer Board, Aug. 13, 1941 (CEHO MIL R&D Eng. Board Reports, VI-1).
- 123 Quinn, p. 44; Fatherree, *First 75 Years*, pp. 62-63; Tiffany, *History*, pp. 10-11; Pennington, p. 3. On the role of women during World War II, see for example, Doris Weatherford, *American Women and World War II* (NY:

- Facts on File, 1990) and Penny Colman, *Rosie the Riveter: Women Working on the Home Front in World War II* (NY: Crown, 1995).
- 124 Tiffany, *History*, pp. 10-13, IV-13-15; Quinn, p. 68; the number of WES personnel having served in Korea and Vietnam as of 1968 was 238.
 - 125 Michael C. Robinson, "Mobilizing the Waterways: The Mississippi River Navigation System," in *Builders and Fighters*, pp. 259-275; Fatherree, *First 75 Years*, pp. 63-67, 120; Cotton, pp. 35-38, 70-71; Caldwell to Mr. Norsworthy, Memo, Hydraulics research and development, Nov. 13, 1945 (CEHO MIL R&D Eng. Board Studies VI-11-2 Articles and Memoranda).
 - 126 Fatherree, *First 75 Years*, pp. 75-80, 99-107; Fatherree, *Geotechnical Engineering*, pp. 98-118, Cotton, pp. 52-54; Tiffany V-16-19.
 - 127 Quinn, pp. 42-45; Fatherree, *First 75 Years*, p. 66, 69-73; Cotton, pp. 35, 45-47; Joseph Caldwell, Memo for Record, Military Intelligence Activities of the Beach Erosion Board, Jun. 16, 1964; Caldwell, Memo for Record, Military Equipment Development Testing at the Beach Erosion Board, Jun. 16, 1964 (CEHO GEN 119A-16). On the Normandy breakwaters, compare Cotton, pp. 44-46 and note 37; William H. Smith, "Artificial Harbors for Normandy Beaches," *Civil Engineering* 15:6 (Jun. 1945): 255-259; Robert Y. Hudson, "Model Tests of Portable Breakwaters for D-Day Invasion Harbors," *Civil Engineering* 15:9 (Sept. 1945): 405-408; with Fatherree, *First 75 Years*, pp. 69-71. Without comparing the actual design documents and British deliberations, there is no way of determining the final impact of WES tests; however, those involved seem to suggest some changes, though minor, were made. According to Tiffany, in a chance meeting with General Eisenhower after the war, Eisenhower told him the research by WES "helped make the invasion a success"; see Tiffany, "WES Had Tentative Start."
 - 128 Fatherree, *Geotechnical Engineering*, pp. 34-35; Cotton, p. 39.
 - 129 Dan McNichol, *Paving the Way* (Lanham, Md.: National Asphalt Pavement Association, 2005): 23-133.
 - 130 Fatherree, *Geotechnical Engineering*, pp. 35-37; Lenore Fine and Jesse A. Remington, *The Corps of Engineers, Construction in the United States* (D.C.: Office of Chief of Military History, U.S. Army, 1972): 614-649; Anthony F. Turhollow, "Airfields for Heavy Bombers," in *Builders and Fighters*, pp. 207-208.
 - 131 Turhollow, pp. 209-213; McNichol, pp. 180-181; Fatherree, *Geotechnical Engineering*, pp. 34-44; Cotton, pp. 39-42; Lenore and Remington, pp. 618-626.
 - 132 Fatherree, *Geotechnical Engineering*, pp. 45-48, 59-72; McNichol, pp. 182-199, 204-241; Cotton, pp. 58-9; "Airfield Pavement Investigation" (CEHO MIL R&D Eng. Board Studies VI-11-2).
 - 133 Cotton, pp. 80-86; Turhollow, pp. 208-209; Fatherree, *Geotechnical Engineering*, pp. 74-76; McNichols, pp. 197-200; Fine and Remington, pp. 618-20, quote on 20.
 - 134 Fatherree, *Geotechnical Engineering*, pp. 48-49; Cotton, pp. 46-48; on the origins of the penetrometer, see Dan Rooney et al., "Mapping Soils with a Multiple-Sensor Penetrometer," Fertilizer, Aglime, and Pest Management Conference (University of Wisconsin, 2001).
 - 135 Fatherree, *Geotechnical Engineering*, pp. 80-89; Cotton, pp. 77-79.
 - 136 Fatherree, *Geotechnical Engineering*, pp. 89-94, Cotton, pp. 114-120.
 - 137 Fatherree, *Geotechnical Engineering*, pp. 94-97; Cotton, p. 77.
 - 138 Middlebrooks, Memo to Norsworthy, Soil Mechanics and Related Research Work in the Corps of Engineers, Nov. 13, 1945; "Research in the Corps of Engineers," Nov. 16, 1945 (CEHO MIL R&D Eng. Board Studies VI-11-2).
 - 139 Edmund A. Wright, *CRREL's First 25 Years, 1961-1986* (Hannover, N.H.: CRREL, 1986): ii-5; McNichol, pp. 182-190; W.A. Jacobs and Lyman Woodman, *The Alaska District, United States Army Corps of Engineers, 1946-1974* (Elmendorf Air Force Base, Aka.: Alaska District, 1976): 1-10; Lisa Mighetto and Carla Homstad, *Engineering in the Far North: A History of the U.S. Army Engineer District in Alaska, 1867-1992* (N.P.: Historical Research Associates Inc., 1993): 11-54. See also "Conference on Construction of Airfields Upon Permanently Frozen Ground (Permafrost)," HQ Army Air Forces, Dec. 6, 1944; Draft Letter, Casagrande

- to Col. Urquhart, Feb. 24, 1945 (CRREL Archives, Dwr. 4, Fldr. Dr. Gerdal's Historical Files); Brig. Gen. L.P. Whitten to Chief of Engineers, Construction of Plank Runways, Feb. 19, 1944; Chief of Engineers to Northwest Division Engineer, Arctic Runway Construction, Feb. 26, 1944 (CEHO MIL R&D Eng. Board Historical Studies, VI-11).
- 140 Wright, pp. 4-7; Aubrey Parkman, *Army Engineers in New England: The Military and Civil Work of the Corps of Engineers in New England, 1775-1975* (Waltham, Mass.: New England Division, 1978): 154-5; Raymond Merritt, *Creativity, Conflict, and Controversy: A History of the St. Paul District, U.S. Army Corps of Engineers* (St. Paul, Minn.: St. Paul District, 1979): 404; Engineer Board to Chief of Engineers, Work Order DAC 3033, May 5 and May 11, 1944 (CEHO MIL R&D Eng. Board Hist. Studies VI-11); "Conference on Permafrost"; Casagrande to Urquhart, Feb. 24, 1945.
- 141 Wright, pp. 5-8; Memo, R.W. Gerdel to Norman Ashton, Jul. 23, 1979 (CRREL Dwr. 4, Fldr. Gerdel); Col. H.J. Woodbury to St. Paul District Engineer, Apr. 1, 1949, Snow, Ice, and Permafrost Research Establishment (CRREL Dwr. 4, Fldr. Dr. Gerdel's Historical Files); Memo, Maj. Gen. C.G. Heimick to General Staff, Jun. 10, 1949, Assignment of Research and Development Cognizance in the Fields of Cryological Phenomena, Meteorology, and Environmental Research (CRREL Dwr. 4, Fldr. SIPRE Personnel – Bender). According to Gerdel, OCE gave St. Paul District specific instructions to locate a facility "AWAY from St. Paul or any other Engineer dominated organization," so it could focus on basic research independent of the district.
- 142 Gerdel to Ashton Memo; Wright, pp. 12-18; Memo, Lt. Col. Richard Flint to Chief Engineer Research and Development Division, Review of status of Snow, Ice, and Permafrost Research Establishment (OCE) with recommended changes, Dec. 29, 1950; Memo, Gerdel to Lahlum, Items for Discussion, Office, Chief of Engineers, Jan. 3, 1951 (Dwr. 4, Fldr. Dr. Gerdel's Historical Files). On the establishment of Camp Fistclench and Camp Century, see Elmer F. Clark, "Camp Century Evolution of Concept and History of Design, Construction, and Performance" (Hanover: CRREL, 1965): 1-38.
- 143 Janet A. McDonnell, "Formation of the Manhattan Engineer District," in *Builders and Fighters*, pp. 147-156; Groves, "Development of the Atomic Bomb," (NARA MD RG 77 ENT 390 Row 1, Comp 11, Shelf 05, Bx. 2); Maj. Gen. Leslie R. Groves Bio (CEHO BIO-IND, box GRE-GUY); Historical Vignette 113, (Fort Belvoir: Corps of Engineers History Office, 2008).
- 144 Cotton, pp. 66-69; Tiffany, *History*, pp. VIII-1-2; Interview with Mather; Caldwell, Military Equipment.
- 145 Tiffany, *History*, pp. VIII-2, 7-9; Interview with Mather; Damon Manders, Interview with Bill Flathau, Jul. 21, 2009.
- 146 Tiffany, *History*, pp. VIII-2-7; Cotton, pp. 68-71, 105-7; Fatherree, *Geotechnical Engineering*, pp. 158-170; *History of the U.S. Army Nuclear Cratering Group* (Livermore, Ca.: Lawrence Radiation Laboratory, 1969): 17-87; Caldwell, Military Equipment.
- 147 Tiffany, *History*, pp. VIII-4-7; Cotton, pp. 100-105; Fatherree, *Geotechnical Engineering*, pp. 158-161.
- 148 Bush, *Modern Arms*, pp. 182, 232.

Chapter 5

- 149 Office of Technology Assessment, U.S. Congress, *A History of the Department of Defense Federally Funded Research and Development Centers* (Washington, D.C.: GPO, 1995): 17-28; U.S. Congress, "Report to the President on Government Contracting for Research and Development," (87th Cong., 2nd Sess., S.D. 94): 21-24, quote on 24.
- 150 ERDL, *Historical Summary, World War II to 30 June 1950*, 2nd ed. (Fort Belvoir: ERDL, 1950): 1-16; Pennington, pp. 1-5.
- 151 Pennington, pp. 1-11.
- 152 Lawrence Suid, *The Army's Nuclear Power Program: The Evolution of a Support Agency* (NY: Greenwood Press, 1990): 20-39; *History of the U.S. Army Corps of Engineers* (Fort Belvoir: CEHO, 1998): 119-120; GO No. 46,

- “Transfers of Installations and Activities to the U.S. Army Materiel Command” (Washington, D.C.: HQDA, 25 Jul. 1962); GO No. 34, IV. (Washington, D.C.: HQDA, 28 Aug. 1967). According to James E. Hewes, Jr., *From Root to McNamara: Army Organization and Administration* (Washington, D.C.: Center of Military History, 1975): 316-343, the Hoelscher Report moved research under AMC despite objections from its R&D task force that this would weaken research.
- 153 Quote from Disposition Form, “The Role of Corps of Engineers in Research and Development,” Mar. 16, 1964 (CERL Archives); Pennington, pp. 72-163, 192-302; see also Frederick Doyle, ed., “Analytical Photogrammetry” in Morris Thompson, ed., *Manual of Photogrammetry*, 3rd Ed., Vol. 1 (Falls Church, Va.: Am. Soc. of Photogrammetry, 1966); Damon Manders, Interview with Sam Barr, Nov. 18, 2008.
 - 154 Pennington, pp. 171-188, 321; Baldini, “Absolute Orientation of Satellite Triangulation”; Schmid, “Status of Data Reduction and Analysis Methods for the Worldwide Geometric Satellite Triangulation Program”; Rutschmidt, “Preliminary Results of the Secor Equatorial Network”; Henriksen et al., “Summary,” in Henriksen et al., ed., *The Use of Artificial Satellites for Geodesy* (Washington, D.C.: American Geophysical Union, 1972): 19-25, 27-41, 49-58, 289-298. On automation of analytical photogrammetry, see Chapter Seven.
 - 155 Wright, pp. 12-21; Memo, K.B. Woods to Lt. Col. A.H. Lahlum, Corps of Engineer Research and Development Program in Greenland, July 14, 1954 (CRREL Dwr. 3, File Memo to CO); Memo, Engineer Outlook: Greenland Icecap, Dec. 29, 1955; Draft Briefing, The Corps of Engineers R&D Program in Greenland; “History of Army Research and Development in Greenland”; “Snow Icecap Operations”; “Organization for Supervision and Support of Arctic and Polar R&D,” Oct. 22, 1957; Memo, William Foster to Coordinating Committee on Science, Dec. 6, 1957; Memo, Support of Corps of Engineers Greenland Icecap Operations, Aug. 24, 1956; Memo, General McCrimmon to General Viney, Mar. 26, 1958; “Corps of Engineers Capabilities Applicable to the Antarctic” (Dwr. 5, Greenland-Arctic R&D Reference Papers); Memo, Report of Conference on 25 Feb. 1953 on the Central Sierra Snow Laboratory, Mar. 3, 1953 (Dwr. 4, CSI-SIPRE Conference, 1950-1954). See also Charles Collins, “CRREL’s Projects Office Celebrates 60 Years,” *ERDC Information Bulletin* (Sept. 18, 2006).
 - 156 Trudeau quoted in Basic Research Branch, 24 May 1960; Basic Research Branch, USA SIPRE (Dwr. 4, SIPRE Personnel – Bender).
 - 157 Memo, R.W. Gerdel to Lahlum, Adequacy of Plans for the Wilmette Establishment, Jun. 7, 1951; Memo, Bucher to Lahlum, Recommendation for a new internal organization for SIPRE and its facilities, Feb. 6, 1951; Flint to Engineer R&D Division, Review of status of SIPRE (OCE) with recommended changes, Dec. 29, 1950; Bucher, Proposal for the Foundation of an American Institute for Snow and Ice Research, Jan. 7, 1951; (CRREL Dwr. 4, Dr. Gerdel’s Historical Files); “Establishment of CRREL,” Assembled May 13, 1959 (Dwr. 4); Sanger, “SIPRE Research Program,” Dec. 10, 1959; Sanger, Disposition Form (DF), Jun. 9, 1960; Report of Board of Consultants to the Director of SIPRE, Dec. 1-3, 1960 (Dwr. 4, SIPRE Personnel – Bender).
 - 158 Wright, pp.21-27; “Establishment of CRREL”; DF, Reorganization of USA CRREL (Technical Staff), Mar. 24, 1961; Memo, Transfer of CRREL to Hanover, New Hampshire, Jul 5, 1961; “ACFEL Personnel as of 23 Feb. 1961” (Dwr. 4, Lobnez – Move to Hanover); DF, Letter from General McCrimmon, Jul. 17, 1958 (Dwr. 3, Bender); Memo, Gerdel to Boyd, Distribution of Responsibility for Cold Regions Research, Dec. 10, 1958 (Dwr. 4, Experts, Professional and Technical, SIPRE); “Fire Rakes Lab,” Manchester, N.H., *Union Leader* (Fri., Jan. 5, 1962): 1, 8; “Only ‘Skeleton’ Crew Working at SIPRE Site,” Houghton, Michigan, *Daily Mining Gazette* (Nov. 1, 1962).
 - 159 Wright pp. 20-53; Boyd, Long Range Program for Snow and Ice Research in CRREL, Sept. 27, 1961; Memo for Mr. Boyd, Responsibilities for Work in Antarctica; Gerdel to Bender, Research Projects, Environmental Research Branch, Apr. 11, 1962 (Dwr. 4, SIPRE Personnel – Bender); Collins, “CRREL’s Alaska Project Office”; “A Study of USACRREL Capabilities and Limitations (Dwr. 3, Philippe – Earth Sciences Lab); Interview with Barr.

- 160 Wright pp. 30-53; GO No. 34; Melvin Martin, "Comments of Chief, Civil Works R&D Team, Research and Development Office," Oct. 2, 1978 (CEHO MIL R&D VI-1); E-mail, Peter Smallidge to Charles Camillo, RE: History of Research & Development – Review of Manuscript, Apr. 1, 2009.
- 161 Quinn, pp. 48-94; Jamie W. and Dorothy P. Moore, *History of the Coastal Engineering Research Center, 1963-1983* (Vicksburg: WES, 1991): 1-11; BEB, "History of the Research and Development Program of the Beach Erosion Board," Jul. 11, 1955; CERC, Memo for Record, Failure Record of Coastal Engineering Projects, Oct. 10, 1968 (CEHO, GEN 119A- 1-1).
- 162 Quinn, pp. 93-94; Moore and Moore, pp. viii-ix, 13-14.
- 163 Moore and Moore, pp. 13-24, staffer quoted on 16.
- 164 Moore and Moore, pp. 19-32; Thorndike Saville, Jr., et al., "The Coastal Engineering Research Center," *TME* (Nov.-Dec. 1974): 368-371; Martin, "Comments of Chief." For a history of the Duck facility, see William A. Birkemeier and K. Todd Holland, "The U.S. Army Corps of Engineers Field Research Facility: More than Two Decades of Coastal Research," at www.frf.usace.army.mil/faqs/FRF_history_1977-2000.pdf.
- 165 *Ibid.*
- 166 Cotton, pp. 71-76; Fatherree, *First 75 Years*, pp. 107-112, 119-129; "Monetary Savings Resulting From Model Studies," WES, 1950 (ERDC Archives); Tom Pokrefke, "The WES Niagara Falls Model," and "The Distortion Flume," draft articles for *As Time Goes By* newsletters.
- 167 Cotton, pp. 71-76; Fatherree, *First 75 Years*, pp. 107-112, 119-129; WES org charts; "Monetary Savings."
- 168 Moore and Moore, pp. 30-31, 54-61, 63-72; Fatherree, *First 75 Years*, pp. 155-159; Damon Manders, Interview with Robert Whalin, Mar. 31, 2009; Damon Manders and Charles Camillo, Interview with James Houston, Aug. 27, 2009; *Feasibility Study: Dredging/Nearshore Disposal Plan, Oregon Inlet, N.C.* (Wilmington, N.C.: Wilmington District, 1983): 1, 2-2-2-17; DA-USACE, Permanent Orders 5-1, Mar. 21, 1983, USACE Coastal Engineering Research Center (ERDC Archives). Moore and Moore note that of the 24, two were hired from WES in 1982 and one was hired for transfer to WES. Whalin recalls 15 transferring, with three remaining at Duck. Of these, 10 were scientists or engineers, seven with PhDs – half of those at CERC.
- 169 Cotton, pp. 115-120, 133-146; Fatherree, *Geotechnical Engineering*, pp. 171-173; WES org charts, 1958-1963 (ERDC Archives); Charles Jaeger, *Rock Mechanics and Engineering* (Cambridge University Press, 1972): 1-4. On Terzaghi's comments on geology, see "Past and Future of Applied Soil Mechanics," in W. Allen Marr, Ed., *A History of Progress: Selected U.S. Papers in Geotechnical Engineering*, Vol. 2 (Reston, Va.: ASCE, 2003): 888- 891.
- 170 Terzaghi, "Past and Future," pp. 870-892; Fatherree, *Geotechnical Engineering*, pp. 174- 178; Cotton, pp. 181-2. On FEM, see Chandrakant S. Desai and John F. Abel, *Introduction to the Finite Element Method: A Numerical Method for Engineering Analysis* (NY: Von Nostrand, 1972): 1-7, 245-261; and Clough and Edward Wilson, "Early Finite Element Research at Berkeley," Fifth U.S. National Conference on Computational Mechanics, Aug. 4-6, 1999 (www.edwilson.org/history/fe-history.pdf, Dec. 8, 2008).
- 171 Fatherree, *Geotechnical Engineering*, pp. 185-189, quote on p. 187. A good discussion of liquefaction is H. Bolton Seed and Kenneth L. Lee, "Liquefaction of Saturated Sands During Cyclic Loading," *Journal of the Soil Mechanics and Foundations Division, Proceedings of ASCE* (Nov. 1966): 105-134. One off-shoot of the research was the discovery by Roger Saucier that the geological dating of liquefaction at archaeological sites could help develop a history of seismic activity in a region.
- 172 Fatherree, *Geotechnical Engineering*, pp. 151-162, 179-185; WES org charts, 1963-1978. For an introductory treatment of soil dynamics, see, for example, Shamsher Psakash, *Soil Dynamics* (NY: McGraw Hill, 1981).
- 173 Cotton, pp. 82-86, 110-111, 140-143; Fatherree, pp. 122-136; Mather Interview.
- 174 Cotton, pp. 120-125; Fatherree, pp. 122-136; Guy Aburthnot, Jr., "WES Support of DNA Programs," *Army Research and Development News* (Sept. - Oct. 1973): 20-22; WES organizational charts, 1977-1978; Mather Interview. Interview with Flathau. When WES informed Air Force Maj. Gen. William W. Wisman of the test

- results on Project 85, he quipped that it was like “watching your brand new Cadillac going over a cliff with your mother-in-law inside.”
- 175 Interview with Mather; Damon Manders, Interview with Pat Bonner, July 8, 2008.
 - 176 *Long-Range Master Plan for the Waterways Experiment Station* (Vicksburg: WES, 1965): 1-2, A1-C2; *Activities Summary FY 1980* (Vicksburg: WES, 1980): 7, 95; *Activities Summary*, FY '69 (Vicksburg: WES, 1969): 26-28; “Study of Retirement Patterns of Waterways Experiment Station Organizations” (Vicksburg: WES Personnel Office, 1967): 2-3; Mary K. Vincent, “Loss of Doctorates from WES, 1980-1987” (Vicksburg: WES, 1987): 1-2; Damon Manders, Interview with Al Bush, July 7, 2008; Damon Manders, Interview with Jim Pennington, July 8, 2008; Interview with Whalin.
 - 177 “Accomplishments, Ohio River Division Laboratories, Construction Research” (CERL Archives, Fldr Staff Study Development of CE Constr. R&D Program); Johnson, pp. 258, 286-290; Torres, pp. 3-11. In 1973, AASHO was renamed the American Association of State Highway and Transportation Officials (AASHTO).
 - 178 DE, Meeting of Corps of Engineers Technical Committee (CETC) Subcommittee on Military Construction Materials and Techniques (pending), Oct. 1, 1964, and attachments; Memo, Col. Clifton Chamberlain to Commanding Gen., AMC, Technical Committee Processing Request, Dec. 21, 1964; DE, Planning for Corps of Engineers Laboratory and Construction Research Program, Feb. 17, 1965; Corps of Engineers Laboratory for Construction Research: Criteria for Site Selection, Apr. 6, 1965; (CERL, Fldr., Construction Engineer Research Lab Concept and Staff Study); “Construction Engineering Research Laboratory History,” a documentary collection (CERL); Torres, pp. 5-15.
 - 179 “Construction Engineering Research Laboratory History”; Memo, Quarles, “Discussion of CERL with Mr. Hooper of OST,” May 9, 1966; Itinerary for C131, July 25, 1969 (CERL, Fldr. ECR Laboratory); DE, “Establishment of the U.S. Army Engineer Construction Research Laboratory,” Dec. 19, 1966 (Proposed Activities and Forecasts, Engr. Const. Research Laboratory); quotes from Memo, Quarles, Congressional Staff Briefing on CERL, Aug. 16, 1967; Clarke to Rivers, Aug. 17, 1967; Ignatius to Rivers, Aug. 18, 1967; Statement by Maj. Gen. F.J. Clarke, Deputy Chief of Engineers on Proposed Leasing of Facilities for Construction Engineering Research Laboratory, Aug. 24, 1967 (1st Sess., 90th Cong.); Clarke statement, Oct. 4, 1967; Col. Edward Waddell to Cox, Aug. 21, 1967 (Construction Research Lab – Planning); GO No. 17, Organization of the U.S. Army Construction Engineering Research Laboratory, Sept. 9, 1968; Torres, pp. 6, 14-29; Gary A. Stellar, *CERL: A History of the U.S. Army Construction Engineering Research Laboratory, 1968-1974* (CERL, [1975]): 7-11. As was sometimes the case, development of the GO at OCE lagged behind actual formation of the facility by some months.
 - 180 Presentation, Construction Research Program, Jan. 1, 1966 (CERL Fldr., Construction Research Program); BRAB, Final Report on Evaluation of Corps of Engineers Construction Research Program (Washington, D.C.: NAS-NRC, 1967): 1-16, quotes on 1-2; Torres, pp. 54-64.
 - 181 “Corps Builds New Lab for Systems Research,” *ENR* (Feb. 6, 1969): 130-131, Cox quoted on 130; Torres, pp. 57-61, 75-97; Stellar, pp. 20-27; “Anniversary of CERL,” *Army Research and Development News* (May-June 1973): 16-18. The topic of systems theory is extensive; for a good introduction, see Joel de Rosnay, *The Macroscopic* (NY: Harper and Rowe, 1979), out of print but available at Principia Cybernetica Web (<http://pespmc1.vub.ac.be/MARCBOK.html>, acc. Feb. 3, 2009); on its application to construction, see Anthony Walker, *Project Management in Construction*, 4th ed. (NY: Wiley and Sons, 2002): 37-41.
 - 182 Interview with Beitelman, by Damon Manders, Nov. 12, 2008; “It all started in 1837,” *Chemical Progress* (Mar. 1977): 6; Beitelman, “Why Paint Fails,” draft article (CERL, Fldr., Beitelman Paint Newsletter Article); *Research for Civil Works: A Progress Report* (Washington, D.C.: OCE-CW, 1968): 1-2, 41-42.
 - 183 *Research for Civil Works*, pp. 215-216; *Corps of Engineers Laboratory, Investigational, Research and Testing Facilities* (Washington, D.C.: OCE, 1979): 31-33; Fatherree, *Geotechnical Engineering*, p. 171-173.
 - 184 Suid, *The Army's Nuclear Power Program*, pp. 1-27, 102-125; Todd Tucker, *Atomic America: How a Deadly Explosion and a Feared Admiral Changed the Course of Nuclear History* (NY: Free Press, 2009): 1-8, 21-28, 51-122, 145-198.

- 185 Joseph Hagwood, Jr., *Commitment to Excellence: A History of the Sacramento District, U.S. Army Corps of Engineers, 1929-1973* (Sacramento: USACE, 1976): 271-2; Corps Lab Facilities, p. 28; Research for Civil Works, pp. 58-59; Gregory Graves, *Pursuing Excellence in Water Planning and Policy Analysis: A History of the Institute for Water Resources, U.S. Army Corps of Engineers* (Fort Belvoir: IWR, 1995): 98-102, 166-7; "HEC History" (www.hec.usace.army.mil/whoware/history.html, Dec. 10, 2008). Melvin Martin, "Comments of Chief, Civil Works R&D Team, Research and Development Office," Oct. 2, 1978 (CEHO MIL R&D VI-1). In 2000, HEC became once again part of IWR.
- 186 Graves, pp. 8-41, 57-102.
- 187 James Bender, "Notes on General Gribble's Speech," Mar. 8, 1965; John Bryant, Interview with Chalmers W. Sherwin, June 12, 1991 (Boston: Rutgers University and IEEE History Center, 1991): 34-36; *Research for Civil Works*, pp. 1-8, 215-216; Hewes, pp. 316-343; "AR Redefines Policies for Managing Labs," *Army Research and Development* (Mar. 1968): 1- 2, 30.
- 188 DF, "CE Research and Investigation (R&I) Program," Aug. 30, 1972; DF, "Research and Development Policy," Dec. 20, 1972; Memo, Col. Wesley E. Peel, "Boards, Commissions and Committees: OCE Research and Development Review Board (RDRB)," Jan. 8, 1973; William B. Taylor, "Study of Engineer Research and Development Management (Washington, D.C.: OCE, 1973): 18-24, 35-40; DCW Memo, Assignment of Laboratory Responsibilities, Nov. 13, 1970 (ERDC); Draft, Approach to Research in the Corps of Engineers; Draft, Report of Panel on Development of Civil Works Research Program; HQUSACE Org Charts, 1968-1972 (CEHO, MIL R&D VI-1, GEN 105-2).
- 189 Taylor, pp. 22-34, 41-53, quote p. 1; Memo, Hilt, "Study of Engineer Research and Development Management, Dec. 1973," Jan. 3, 1974; Disp. Form, "Establishment of an Office of R&D Management," Jan. 15, 1974; OCE GO No. 4, "Reorganization of CE Research and Development Management," Jan. 30, 1974 (ERDC Archives); Peixotto, *Exit Report* (Vicksburg: WES, 1973): 25-26. On Gribble's background, see "Lieutenant General William C. Gribble, Jr.," (CEHO BIO-IND, box GRE-GUY). For a lab perspective on these events, see Moore and Moore, pp. 53-54.
- 190 John Allen, Rodney Grantham, and Donald Nichols, *The DoD Laboratory Utilization Study* (Washington, D.C.: ODDR&E, 1975): 13-21, 29-35, 39-57, quote p. xi.; *Corps Laboratory Study* (Washington, D.C.: OCE-RDO, 1978): 1-2, 23-37, 88-93; see also draft in ERDC Archives; George Camota, "Research," Apr. 1, 1979, pp. 21-22; Jerry Priscoli et al., *Research and Development Prioritization Study* (NP: IWR, [1980]): 11-25.
- 191 Cannon to Morris, Feb. 9, 1979; DF, Cannon to Chairman, WES '82 Study Group, Functions and Organization, WES '82, Apr. 12, 1977; WES '82 Study Group, *Functions and Organization, 1977-1982* (Vicksburg: WES 1977): 23-39, 84-94; Cannon, "'Think Piece' on Corps R&D Management and Operations," Feb. 5, 1979; Don Banks et al., *A U.S. Army Engineer Research and Development Command – A Feasibility Study* (WES, 1979): 1-5, 20-24; Kovel quote from DF, "WES R&D Command Study," Sept. 7, 1979.

Chapter 6

- 192 Brooks, *Climate Through the Ages: A Study of the Climatic Factors and Their Variations*, 2nd Ed. (London: Ernest Benn Ltd. 1950): 7; the original poem read: "There are nine and sixty ways of constructing tribal lays/ And-every-single-one-of-them-is-right!"
- 193 Samuel P. Hays, *Conservation and the Gospel of Efficiency: The Progressive Conservation Movement, 1890-1920* (Cambridge, Mass.: Harvard UP, 1959): 1-146; *A History of Environmental Politics Since 1945* (Pittsburg: Pittsburg UP, 2000): 1-21; Richard N.L. Andrews, **Managing the Environment, Managing Ourselves** (New Haven: Yale UP, 1999): 27-165.
- 194 Hays, *Conservation*, pp. 91-121, 147-240; Andrews, pp. 172-207; Carroll Pursell and William Willingham, "Protecting the Nation's Waterways: A History of the U.S. Army Corps of Engineers' Regulatory Responsibilities, 1899-1999," (CEHO unpub. manuscript, 1998): 11-34.

- 195 DE Harrison, WES Environmental Research Program, Oct. 26, 1972 (ERDC Harrison Files); U.S. Congress, *Water-Hyacinth Obstructions in the Waters of the Gulf and South Atlantic States*, H.D. 37, Nov. 8, 1956 (85th Cong., 1st Sess.): v-8; *Expanded Project for Aquatic Plant Control*, H.D. 251, Jul. 28, 1965 (89th Cong., 1st Sess.): 1-21, quote on 20; Cotton, pp. 113-114, 173-175.
- 196 Lisa Mighetto and Wesley J. Ebel, *Saving the Salmon: A History of the U.S. Army Corps of Engineers' Efforts to Protect Anadromous Fish on the Columbia and Snake Rivers* (Seattle: Historical Research Associates, 1994): 49-72; U.S. Congress, *Columbia River and Tributaries, Northwestern United States*, H.D. 531, Mar. 20, 1950, Vol. 1 (81st Cong., 2nd Sess.): 95-99; Black Warrior, Warrior, and Tombigbee Rivers, Alabama, at Jackson Lock and Dam, H.D. 50, Aug. 25, 1959 (86th Cong., 1st Sess.); Platte River and Tributaries, Missouri and Iowa, H.D. 262, Aug. 16, 1965 (89th Cong., 1st Sess.); WES Environmental Research Program.
- 197 Fatherree, *First 75 Years*, pp. 120-123; Cotton, p. 76; WES Environmental Research Program; H.B. Simmons, "Uses of Hydraulic Models for Ecology Studies in Estuaries," WES Press Release; William H. McAnally and Donald W. Pritchard, "Salinity Control in Mississippi River under Drought Flows," *Journal of Waterway, Port, Coastal, and Ocean Engineering* (Jan.-Feb. 1997): 34-40; Dave Schad, "A Salt-Free Solution: The Corps of Engineers battled a salt-water invasion of the Mississippi," *Soldiers* (Jan. 1989): 34-36; "97-Year-Old Still on the Job," *Vicksburg Evening Post* (Wed. July. 15, 1987): A2 (ERDC Harrison Files).
- 198 U.S. Congress, *Ohio River Pollution Control*, Pt. 1, Vol. 1, H.D. 266, Aug. 27, 1943 (78th Cong., 1st Sess.): 1-12; IWR, *The Role of the U.S. Army Corps of Engineers in Water Quality Management* (Springfield, Va.: IWR, 1970): 14; Fatherree, *First 75 Years*, p. 127; WES Environmental Research Program; "Uses of Hydraulic Models." For an example of similar research, see also, for example, G.R. Drummond and D.L. Robey, "Preliminary Analysis of Impoundments for Dissipation of Waste Heat from Power Plants," (Cincinnati: ORD, 1971).
- 199 James R. Arnold and Roberta Wiener, *The U.S. Army Corps of Engineers and Natural Resources Management on Army Installations, 1941-1987* (Fort Belvoir: CEHO, 1989): vii- 34.
- 200 Cotton, pp. 115-120, 145-147; Fatherree, *Geotechnical Engineering*, pp. 139-148; Wright, pp. 40-41; CRREL, p. 7, 14-15.
- 201 Fatherree, *Geotechnical*, pp. 138-147; "Capabilities for Evaluating Environmental Effects on Military Operations" (Vicksburg: WES, 1963); "Report of Seventh Meeting of the Corps of Engineers Working Group on Terrain Analysis (Vicksburg: WES, 1962): 3-5. See also, "A Program for the Analysis, Implementation and Test of a Waterways Experiment Station Terrain Analysis Radar (Project WESTAR)," (Vicksburg: Texas Instruments, 1961).
- 202 Edward C. Ezell, *ETL History Update*, 1968-1978 (Fort Belvoir: ETL, 1979): 87-88.
- 203 Ezell, p. 88; Andrew Hamilton and Robert Hellman, *A History Update of the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, 1979-1983* (Fort Belvoir: ETL): 29-32; Robert Hellman, *A History Update of the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, 1984-1988* (Fort Belvoir: ETL, 1994): 43-47, 52-63, Maune quote on 53.
- 204 Damon Manders, Interview with Jack Rinker, Mar. 22, 2009; Letter, Rinker to Manders, Mar. 30, 2009; Wright, pp. 28-33, 44; James B. Campbell, *Introduction to Remote Sensing*, 4th ed. (NY: Guilford Press, 2007): 7-14. Evelyn Pruitt of the Office of Naval Research first used the term "remote sensing" in 1958.
- 205 "Report of Seventh Meeting of the Corps of Engineers Working Group on Terrain Analysis (Vicksburg: WES, 1962): 1-3; Pennington, pp. 96, 212-219, 289-296; Ezell, pp. 84-85; Hellman, pp. 83-85; Frost quote in Hamilton and Hellman, p. 107; Interview with Rinker; Interview with Barr; Memo, Maxim I. Kovel to Cdr. ETL, Principal Laboratory Responsibility for the Corps of Engineers Remote Sensing Program, Mar. 5, 1979 (ERDC Archives).
- 206 Hamilton and Hellman, pp. 52-58, 108-111, Rinker quote on 109; Hellman, pp. 67-70, Rinker quote on 70; Rinker, *Tutorial I: Introduction to Spectral Remote Sensing* (San Diego: International Symposium on Spectral Sensing Research, 1994); Interview with Barr; Interview with Rinker. As Rinker observed, the issue with

- automating remote sensing is not lack of capability but rather the removal of the human element and its unique perspective from interpreting images.
- 207 Wright, pp. 43-54; CRREL, *Cold Regions Research and Engineering Laboratory, Retrospective, 1986-1991* (Hanover: CRREL, 1991): 11-12; CRREL, "FY87 Annual Report" (Hanover: CRREL, 1987): 13-14; "Cold Regions Research and Engineering Laboratory" (Hanover: CRREL, 1988): 18-19; Fatherree, *Geotechnical Engineering*, pp. 144-148; Cotton, pp. 135-136; Letter, Creel to James Choromokos, Feb. 15, 1983 (ERDC Archives); William Goran, "GIS Technology Takes Root in the Department of Defense," in Timothy W. Foresman, ed., *The History of Geographic Information Systems: Perspectives from the Pioneers* (Upper Saddle River, N.J.: Prentice Hall, 1998): 199-229; "Remote Sensing/GIS Center, Hanover, New Hampshire" (CRREL, N.D.).
 - 208 Hays, *Conservation*, pp. 261-276; Hays, *Beauty, Health, and Permanence: Environmental Policy in the United States, 1955-1985* (NY: Cambridge UP, 1987): 3-57; Andrews, pp. 29-54. 136-223, quote on p. 179; see also James S. Bowman, "The Environmental Movement: An Assessment of Ecological Politics" *Environmental Affairs* 5 (1976): 649-666.
 - 209 Hays, *Beauty, Health, and Permanence*, pp. 52-53, 183; U.S. Congress, *An Act to establish a national policy for the environment, to provide for the establishment of a Council on Environmental Quality, and for other purposes* (NEPA), Jan. 1, 1970, PL 91-190 (91st Cong., 2nd Sess.): Sec. 1 and Title 1, Sec. 102; Pursell and Willingham, pp. 41-44; Patrick E. Barney, "The Programmatic Environmental Impact Statement and the National Environmental Policy Act Regulations," *Land and Water Law Review* 16:1 (Win. 1981): 1- 31. EIA is the process of conducting an analysis of environmental impact often preceding preparation of an EIS document and is often used as a generic term in international law. See John Glasson, *Introduction to Environmental Impact Assessment*, 3rd Ed. (London: UCL Press, 1998): 1-35. In the practice that developed over the next 20 years, the EIA was all that was necessary if no impact were found. The Corps labs helped with EIAs and EIS preparation; however, future references discuss only EIS since it was the more commonly used term.
 - 210 Hays, *Environmental Politics*, pp. 137-153, 170-184, quote on 139.
 - 211 U.S. Congress, "Policies, Standards, and Procedures in the Formation, Evaluation, and Review of Plans for Use and Development of Water and Related Land Resources," May 29, 1962, S.D. 97 (87th Cong., 2nd Sess.): 1-11; Memo: Environmental Policy, 2 June 1970; Memo: Environmental Guidelines for the Civil Works Program, 8 Oct. 1976. (CEHO CW IV-18-8 Environmental Policy); IWR, *Role of Corps in Water Quality*, pp. 1-10, 43-81.
 - 212 Martin Reuss, *Shaping Environmental Awareness: The United States Army Corps of Engineers Environmental Advisory Board, 1970-1980* (Fort Belvoir: CEHO, 1982): 1-7, quote on p. 52; Ash comments quoted in full in Harrison, "Plan of Action for a More Centralized Management of WES Environmental Projects" (Vicksburg: Special Advisor for Environmental Coordination, 1972): 20-23.
 - 213 Reuss, "Coping with Uncertainty: Social Scientists, Engineers, and Federal Water Resources Planning," *Natural Resources Journal* 32:1 (Win. 1992): 101-135. Mazmanian and Nienaber, *Can Organizations Change?*, pp. 78-101; Damon Manders, Interview with Hal Balbach, Oct. 22, 2008.
 - 214 Torres, pp. 39-43, 57-58, 70-74, quote on 57; Stellar, pp. 15-18, 25-26, 33-36; "Construction engineering research laboratory" (Champaign, Ill.: CERL, 1974): 17-20; "Ten Years of Accomplishment" (CERL, N.D.): 10-12; Balbach Interview. On the preliminary organization, compare the charts on Stellar, p. 33 and Torres, p. 40.
 - 215 Torres, pp. 57-59, 88-91; "Ten Years," pp. 14-15, 22; Catherine M. Stewart and George A Luz, "Environmental Noise Contouring in the 21st Century," *Federal Facilities Environmental Journal* (Spring 1998): 77-85.
 - 216 Torres, pp. 90-94; "Ten Years," pp. 5-6, 9, 14, 17; "Fuel Cells," *Electrical Engineering Newsletter* (Feb. 1997): 5-6; "Pollution-Free Fuel Cell Installed at SSCOM," *The Warrior* (Aug. 1995):19; Jim Radford, "Fuel Cells Enter Commercial Market," *Engineer's Guidebook* (1995): 6-7.

- 217 Torres, pp. 90-94; "Ten Years," pp. 2-5, 10, 12, 14; "HND/CERL Meeting," [May 9, 1980], (CERL Archives, HND (Masters) fldr.): Sec. 1 and 5.
- 218 Torres, pp. 87-89; Arnold and Weiner, pp. 73-86; Bill Goran and Dana Finney, "GRASS GIS Critical to Army's Land Management Program," *GIS World* (Dec. 1991): 48-53; Balbach Interview.
- 219 Wright, pp. 28-46; Brown, "Tundra Biome Program," *Science* 167:3922 (Feb. 27, 1970): 1278; CRREL, pp. 2-10; see also L.E. Link, Jr., "Thermal IR Techniques: A Possible Reconnaissance Tool for Roof Maintenance," Apr. 1975 (ERDC Archives); Brown comments to author, Jul. 15, 2009.
- 220 "Envir. Site Charac. Contam. Detect. Summary"; "Eagle River Flats History," (www.crrel.usace.army.mil/erf/history/, acc. May 19, 2009).
- 221 Moore and Moore, pp. 45-46; "Proposal for Development of a Corps of Engineers Ecological Research Program," Sept. 8, 1969; Memo, Lt. Col. Edward Willis to Chief of Engineers, "Corps of Engineers Coastal Zone Ecological Research Program," Nov. 25, 1969; Memo, Marine Biologist to Director, CERC, "Recommendations for Improving CERC Coastal Ecology Program," May 12, 1970 (CEHO GEN 119-11 and 119-20).
- 222 Moore and Moore, pp. 44-46; Thorndike Saville, Richard Weggel, and Lt. Cdr. Kenneth Rush, "The Coastal Engineering Research Center," *TME* (Nov.-Dec. 1974): 368-371.
- 223 U.S. Congress, *An Act to establish a national policy and develop a national program for the management, beneficial use, protection, and development of the land and water resources of the Nation's coastal zones, and for other purposes* (92nd Congress, Sess. 2): Sec. 303- 307; John M. Armstrong and Peter C. Ryner, *Coastal Waters: A Management Analysis* (Ann Arbor, Mich.: Ann Arbor Science Publishers, 1978): 19-63; quote from David J Brower and Daniel S. Carol, *Coastal Zone Management as Land Planning* (Washington, D.C.: NPA, 1984): 41.
- 224 Moore and Moore, pp. 39-49. See also Interview with Whalin.
- 225 Cairns and Humphrey, "A Water Resources Ecology Capability for the Waterways Experiment Station and Corps of Engineers," (Vicksburg: WES, 1969): quotes from pp. 1, 25; Harrison, "Plan of Action," 1972, pp. 6-12, 28-29.
- 226 *Activities Summary FY 1972* (Vicksburg: WES, 1972): 44-45; *Activities Summary FY 1973*, pp. 48-51; Peixotto, *Exit Report*, pp. 29-30, quote on p. 30; WES Environmental Research Program; Harrison, "Plan of Action," 1972, pp. 28-31, 62, 83-87; "Plan of Action for a More Centralized Management for WES Environmental Projects" (Vicksburg: Special Assistant for Environmental Studies, 1973): 81-86; "Summary of Environmental Research Capabilities" (Vicksburg: WES, N.D.). The *Activities Summaries* were all published at WES annually with activities listed by lab. Future notes will reference only the year to avoid lengthy notations; see chapters related specifically to EL for each year.
- 227 Mary K. Vincent, "The Dredged Material Research Program," *TME* (Sept.-Oct. 1976); Michael R. Palermo and Robert M. Engler, "Thirty Years of Dredging Research at the USACE Waterways Experiment Station," *Proceedings Western Dredging Association 22nd Technical Conference and 34th Annual Texas A&M Seminar* (Denver Co.: WEDA, 2002); U.S. Congress, *An Act Authorizing the construction, repair, and preservation of certain public works on rivers and harbors for navigation, flood control, and other purposes*, PL 91-611 (91st Cong., 2nd Sess.): Tit. I, Sec. 123 (i); "Disposal of Dredged Materials: Program Review and Coordination Correspondence" (Vicksburg: WES, 1972); Damon Manders, Interview with Mary Landin, Feb. 26, 2009; Harrison, *1973 Plan of Action*, pp. 20, 83. On positive views of dredging, see, for example, news clip, Eric Goranson, "Dredge key to prosperity," *Oregon Journal* (ERDC Archives).
- 228 Harrison, "Plan of Action for a More Centralized Management for WES Environmental Projects" (Vicksburg: Office for Environmental Studies, 1974): 34-36; WES GO No. 7, Aug. 8, 1974 (ERDC Harrison files); WES '82 Study Group, *Functions and Organization, 1977- 1982*, pp. 17-18, 21-22, 23-35; WES Org. Charts, 1972-1978; Letter, Cannon to Col. James G. Ton, May 2, 1978 (ERDC Archives).
- 229 *Activities Summaries, FY 1972-1980*; H.E. Westerdahl et al., "Development of Scaled Ecosystem Modeling Techniques for Watershed-Reservoir Research," *American Society of Agricultural Engineers* (St. Joseph, Mich.: ASAE, 1975); Memo, Harrison to Don Robey, Formation of the Ecosystem Modeling Institute (EMI),

- Jun. 24, 1991 (ERDC Archives); "Aquatic Plant Control Research Program," *Information Exchange Bulletin* (Vicksburg: WES, [1977]); OCE to Division Engineer, Civil Works Boundary Realignment Study – Proposal for Implementation of an Aquatic Plant Control Center of Competency, Feb. 21, 1980 (ERDC Archives).
- 230 *Activities Summary, FY 1978-1990*; Kovel to WES Commander/Director, Military Hydrology Research Requirements, Oct. 18, 1978; Kovel, Camouflage Conference, Oct. 13, 1978; Kovel to WES Commander/Director, Principal Laboratory for the Corps of Engineers Countersurveillance Program, Mar. 23, 1979; Kovel to WES Commander/Director, Principal Laboratory for the Corps of Engineers Mine/Counter- Mine Program, Aug. 30, 1979 (ERDC Archives).
- 231 Roger T. Saucier, "Ecology and Dredging – An Overview of Events and Progress of the Last Decade," draft (ERDC Archives); *Activities Summary, FY 1974-1985*; Robert M. Engler, "The London Dumping Convention (LDC): Its Role in Regulating Dredged Material"; and Mary C. Landin et al., "Catch the Magic! Dredged Material Beneficial Uses in North America," in J.R. Wilson and V.L. Van Dam, ed., *Dredging: Technology, Environmental, Mining* (Orlando, Fla.: 12th World Dredging Congress, 1989): 43-50, 67-86, 821-832; Landin Interview.
- 232 Mary C. Landin et al., *Long-Term Monitoring of Eleven Corps of Engineers Habitat Development Field Sites Built of Dredged Material, 1974-1987* (Vicksburg: WES, 1989): 1- 7, 43-57; Interview with Landin.
- 233 *Activities Summary, FY 1974-1990*; Clark McNair, "Dredging Research Program of the U.S. Army Corps of Engineers"; Engler, "London Dumping Convention"; and Landin et al., "Catch the Magic!," in Wilson and Van Dam, ed., pp. 43-50, 67-86, 821-832; Landin Interview.
- 234 *Activities Summaries, FY 1975-1990*; Damon Manders, Interview with Russ Tillman, Jul. 8, 2008; Damon Manders, Interview with Buddy Clairain, Apr. 22, 2009. On the Corps response to 404 permitting, see Jeffery Stine, "Regulating Wetlands in the 1970s: U.S. Army Corps of Engineers and the Environmental Organizations," *Journal of Forest History* 27:2 (Apr. 1983): 60-75.
- 235 Harrison, "1973 Plan of Action," p. 28; Charles R. Lee et al., *Highlights of Research on Overland Flow for Advanced Treatment of Wastewater* (Vicksburg: WES, 1976); *Activities Summary, FY 1972-1985*; Damon Manders, Interview with John Cullinane, Jul. 9, 2008; Wright, pp. 43-44.
- 236 *Activities Summary, FY 1972-1992*; Interview with Cullinane; on the transfer of USATHAMA, see Vincent H. Demma, *Department of the Army Historical Summary, Fiscal Year 1989* (Washington: Center of Military History, 1998): 33.
- 237 *Activities Summaries, FY 1975-1990*.
- 238 Hayes, pp. 54, 117-119; Julie Aitken, "Recreation: Then and Now," New Orleans District *Riverside* (June 1993): 3; *Activities Summaries, FY 1973-1990*.
- 239 Cox, *Climate Crash: Abrupt Climate Change and What It Means for Our Future* (Washington: Joseph Henry Press, 2005): 22-23, 65-73; Martin Schwarzbach, *Climates of the Past: An Introduction to Paleoclimatology* (NY: D. Van Nostrand and Co., 1963): 3-8; H.H. Lamb, *Climatic History and the Future*, Vol. 2 (Princeton: Princeton UP, 1977): 280- 362; Brooks, p. 281; Richard B. Alley, *The Two-Mile Time Machine: Ice cores, abrupt climate change, and our future* (Princeton: Princeton UP, 2000): 91-98.
- 240 Cox, pp. 17-31, 73-79, quote on 31; Lamb, pp. 22-279; Alley, pp. 109-128; Campbell, p. 7.
- 241 Langway, "The History of Early Polar Ice Cores" (Hanover: CRREL, 2008): 1-33; Cox, pp. 5-15, 33-46; Wright, pp. 18-21, 33; *CRREL*, pp. 14; Alley, pp. 17-50.
- 242 Langway, pp. 32-37; Cox, pp. 97-144; Alley, pp. 50-79; Alley, pp. 83-89, 131-165; A.J. Gow, "Preliminary results of studies of ice cores from the 2164M deep drill hole, Byrd Station Antarctica," in Gow et al., ed., *International Symposium on Antarctic Glaciological Exploration (ISAGE), Sept 1968, Hanover, NH 86* (Hanover: International Association of Scientific Hydrology, 1970): 78-90. BP or "Before Present" is a measure of age based on radiocarbon dating calibrated to 1950.
- 243 Donald K. Perovich, "SHEBA: The Surface Heat Budget of the Arctic," *Arctic Research of the U.S.* 17:1 (CRREL, 2001): 18-23; ACIA, *Arctic Climate Impact Assessment* (NY: Cambridge UP, 2005): iii, 6-7; Richter-Menge et

- al., *State of the Arctic, October 2006* (NOAA, 2006): 1-3, 27-28; for an overview of current research, see “Hot Times in Alaska,” *Scientific American Frontier* (PBS, 2004).
- 244 Lamb, pp. 655-711; Cox, pp. 143-162; Alley, pp. 169-192, quote on 174; “Global Warning...?” (History Channel, Nov. 27, 2007); the Kyoto Accords are available from U.N. website (unfccc.int/Kyoto_protocol/items/2830.php, acc. Mar. 2, 2009). On opposing views of global climate change, John Christy and Roy Spencer of the University of Alabama in Huntsville have written widely about the inaccuracy of climate models based on NOAA satellite temperature readings and a lack of knowledge of some meteorological processes. See, for example, “Cirrus disappearance: Warming might thin heat-trapping clouds,” UAH press release, Aug. 9, 2007 (www.uah.edu/news/newsread.php?newsID=875, acc. Mar. 2, 2009).
- 245 On adversarial views of the Corps, see e.g., Martin Heuvelmans, *The River Killers* (Harrisburg, Pa.: Stackpole Books, 1974) or Barnard Shanks, “Dams and Disasters: The Social Problems of Water Development Policies,” in John Biden and Richard L. Stroup, ed., *Bureaucracy vs. Environment: The Environmental Costs of Bureaucratic Governance* (Ann Arbor: Michigan UP, 1981). On the relationship among Corps researchers, engineers, and environmental scientists, see Damon Manders, Interview with John Harrison et al., May 13, 2008; Interview with Balbach; Interview with Cullinane; Interview with Tillman.

Chapter 7

- 246 Quote from Nash, ed. *A History of Scientific Computing* (NY: ACM Press, 1990): xi; Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York: Basic Books, 1996): 2-15, quote on 28; Renee Moreau, *The Computer Comes of Age: The People, the Hardware, and the Software* (Cambridge, Mass.: MIT Press, 1984): 6-12; “Ancient Computer?” *Ancient Discoveries* (History Channel, Thurs., Apr. 30, 2009).
- 247 Campbell-Kelly and Aspray, pp. 16-48, quote on 34; Moreau, pp. 18-25; J.A.V. Truck, *Origin of Modern Calculating Machines* (Chicago: Western Society of Engineers, 1921): 50-189.
- 248 Campbell-Kelly and Aspray, pp. 29-79; Moreau, pp. 26-33; Paul E. Ceruzzi, *A History of Modern Computing* (Cambridge, Ma.: MIT Press, 2003): 1-20. See also Bernard Cohen, “Howard H. Aiken and the Computer,” in Nash, pp. 41-57. For a detailed description of the Mark computers, see I. Bernard Cohen and Gregory W. Welch, ed., *Makin’ Numbers: Howard Aiken and the Computer* (Cambridge: MIT, 1999).
- 249 Campbell-Kelly and Aspray, pp. 80-121; Moreau, pp. 30-49; Goldstine, “Remembrance of Things Past,” in Nash, pp. 5-16, quote p. 9; Ceruzzi, pp. 1-27; Thomas J. Bergin, ed., *50 Years of Army Computing from ENIAC to MSRC* (Aberdeen Proving Ground: Army Research Laboratory, 1996). Most product names in this era were acronyms: Electronic Numerical Integrator and Calculator (ENIAC), Electronic Discrete Variable Automatic Computer (EDSAC), Universal Automatic Computer (UNIVAC), Eckert and Mauchley Computer Company (EMCC).
- 250 Ceruzzi, pp. 30-183; Campbell-Kelly and Aspray, pp. 106-167.
- 251 Goldstine quoted in Nash, p. 12; Garret Birkhoff, “Fluid Dynamics, Reactor Computations, and Surface Representations,” in Nash, pp. 63-87; Ceruzzi, “An Unforeseen Revolution: Computers and Expectations, 1935-1985,” in Joseph J. Corn, ed., *Imagining Tomorrow: History, Technology, and the American Future* (Cambridge: MIT, 1986): 188-201.
- 252 B.N. Parlett, “The Contribution of J.H. Wilkinson to Numerical Analysis,” in Nash, pp. 17-31; Birkhoff, pp. 65-74; John C. Nash, Interview with James H. Wilkinson, July 13, 1984, Waterloo, Ontario, Canada (Philadelphia: Society for Industrial and Applied Mathematics, 2004) on SIAM History of Numerical Analysis and Scientific Computing Project (<http://history.siam.org>, Mar. 23, 2009); Ceruzzi, “Computers and Expectations,” pp. 190-195; Damon Manders, Interview with William McAnally, Aug. 11, 2008.
- 253 Johnson, pp. 168-169, 191, 230-231, 245; Stoker, *Water Waves: The Mathematical Theory with Applications* (NY: John Wiley and Sons, 1992): 451-504, quote on 484; Stoker et al., “Numerical Solution of Flood Prediction and River Regulation Problems,” (NY: NYU, 1954); OCE, Ippen quoted in Fatherree, *First 75 Years*,

- p.139; Interview with McAnally; J.E. Foster, *History and Description of the Mississippi Basin Model* (Vicksburg: WES, 1971): 33-4.
- 254 Tiffany, *History*, pp. X-5-7; Cotton, pp. 155-156; Moreau, pp. 61-63; Campbell-Kelly and Aspray, pp. 124-136; "Army Corps of Engineers Tames Nature with GE-420 Time Sharing System," Application Profile (N.P.: GE, 1969); Quinn, pp. 167-183; Moore and Moore, pp. 19-30; Interview with McAnally.
- 255 Pennington, pp. 188-191; Ezell, p. 85; Hamilton and Hellman, p. 58; Damon Manders, Interview with Wayne Schmidt, Apr. 7, 2009; Interview with Barr.
- 256 Gregory Fellers, "Notes on Technology at CRREL," Apr. 21, 2009; "The Bendix G-15 CPM/PERT Program," brochure (Los Angeles: Bendix, N.D.); Wright, pp. 28, 58-59; USA SIPRE Research Program, 1 July 1959-30 June 1960 (Willamette: SIPRE, 1960): 6-7; Gregg Hoge, "History of Central Computing at CRREL."
- 257 "Summary of Capabilities: Ohio River Division Laboratory (Cincinnati: ORD, N.D.): 19-20; Interview with Schmidt; Stellar, pp. 15-16, 33-36.
- 258 Moreau, pp. 122-124; Ceruzzi, pp. 250-252; Campbell-Kelly and Aspray, pp. 213-216; *Activities Summary, FY 1970-1972*; Neumann quoted in "Corps Tames Nature," p. 1; Interview with Schmidt; "Ten Years of Accomplishments," pp. 6-7.
- 259 Interview with McAnally; Chandrakant S. Desai and John F. Abel, *Introduction to the Finite Element Method: A Numerical Method for Engineering Analysis* (NY: Von Nostrand, 1972): 1-7, 245-261; Birkoff, pp. 63-79; I. Edward Block, "Shaping the Evolution of Numerical Analysis in the Computer Age: The SIAM Thrust," in Nash, pp. 189-216; See also Tinskey Oden, "Historical Comments on Finite Elements," in Nash, pp. 152-188.
- 260 Fatherree, *Geotechnical Engineering*, pp. 174-178; *First 75 Years*, pp. 141-2; H.B. Simmons, "Protection of Narragansett Bay from Hurricane Surges" (Vicksburg: WES, 1964): 5; J.F. Smith and W.F. Ingram "Development of In-House Capability for Use of the Finite Element Method of Analysis of Boundary Condition Problems" (Vicksburg: WES, 1967); D.C. Banks and J.B. Palmerton, "Application of Finite Element Method in Determining the Stability of Crater Slopes: Preliminary Report" (WES, 1968); Clough and Edward Wilson, "Early Finite Element Research at Berkeley," Fifth U.S. National Conference on Computational Mechanics, Aug. 4-6, 1999 (www.edwilson.org/history/fe-history.pdf, Dec. 8, 2008); "Report of Third Conference of Hydraulics Consultants Board" (WES, 1967): 5-9, III-2, V-1-2, VI-2-3. N.J. Brogdon, "Galveston Bay Hurricane Surge Study" (Vicksburg: WES, 1969, 1973): 5-6, A-2-3; see also Reid and Bernie R. Bodine, "Numerical Model for Storm Surges in Galveston Bay," *Journal of the Waterways and Harbors Division, Proceedings of ASCE* (Feb. 1968): 33-57. Eight conferences of the Hydraulics Consultant Board (HCB) were held from 1964 to 1972. Future references will note the year only.
- 261 Fatherree, *First 75 Years*, pp. 142-150; Interview with McAnally; "1968 HCB Conference," Ippen quote on 24; "1969 HCB Conference."
- 262 Fatherree, *First 75 Years*, pp. 143-153; "Capabilities for Performing Mathematical Modeling of Estuarine Environmental Processes" (Vicksburg: WES, 1970); "1968-1972 HCB Conference"; Robert E. Louque, Jr., and Eugene A. Graves, *Flood Routing Procedure for the Lower Mississippi River* (Vicksburg: MRC, 1972); *Computer Simulation of Missouri River Floods, Pt. 1, Verification with Mississippi Basin Model* (MRD, 1973).
- 263 Fatherree, *First 75 Years*, pp. 143-153, 166-183, 194-199; "1968-1972 HCB Conference"; Ellis B. Pickett et al., *Los Angeles and Long Beach Harbors Model Study*, 4 Vols. (Vicksburg: WES, 1975-1977): Vol. 1: 13-42, Vol. 2: 14-20, Vol. 4: 62-74; see also J.R. Houston, "Los Angeles Harbor and Long Beach Harbor: Finite Element Numerical Model of Harbor Resonance," in *Ports '77*, pp. 119-137; *Activities Summary, FY 1985*. Keulegan saw the future use of physical models as calibrating numerical models.
- 264 Moore and Moore, p. 48. See the discussion of discrepancies in hurricane models in Manders, David Tajkowsky, and Mike Dace, "Rebuilding Hope: Task Force Hope and the U.S. Army Corps of Engineers, Mississippi Valley's Response to Hurricanes Katrina and Rita," unpublished manuscript (Vicksburg: MVD, 2008).

- 265 Wright, pp. 39-40; N. Untersteiner et al., "AIDJEX Revisited: A Look Back at the U.S.- Canadian Arctic Ice Dynamics Joint Experiment, 1970-78," *Arctic* 60:3 (Sept. 2007): 327- 336; Untersteiner, "AIDJEX Review," in Robert S. Prichard, ed., *Sea Ice Processes and Models: Proceedings of the Arctic Ice Dynamics Joint Experiment International Commission on Snow and Ice Symposium* (Seattle: Washington UP, 1977): 1-7; "A Preliminary AIDJEX Model Simulation with 1972 Data," *AIDJEX Bulletin* 37 (Sept. 1977): 1-24. On physical modeling, see Ch. 6 in George D. Ashton, ed., *River Lake Ice Engineering* (Highlands Ranch, Col.: Water Resources Pub., 1978); Damon Manders, Interview with Gregg Hoge, June 2, 2009.
- 266 Wright, pp. 53-54; *CRREL*, pp. 2-8; Donald Perovich et al., "Seasonal changes in Arctic sea-ice morphology," *Annals of Glaciology* 33 (2001): 171-176; John W. Weatherly and Cecilia Bitz, "Natural and Anthropogenic Climate Variations in the Arctic," in *12th Symposium on Global Change and Climate Variations* (Boston: American Meteorological Society, 2001); George D. Ashton, "Ice Deterioration," in *Proceedings of the Great Lakes Ice Research Workshop* (Ann Arbor, Mich.: Great Lakes Environmental Research Laboratory, 1984); Stephen A. Ketcham et al., "FDTD Seismic Simulation of Moving Tracked Vehicle" (Hanover: CRREL, 2000).
- 267 Fatherree, *Geotechnical Engineering*, pp. 144-146, 197-202; "Army Vehicle Mobility Evaluation" (ERDC Archives); *Activity Summary, FY 1978-1989*.
- 268 *Ibid.*, pp. 202-203; Cotton, pp. 155-156, II-13; *Activities Summary, FY 1975-1985*; W.G. Pariseau, "Computational approaches to jointed rock mass mechanics," in Chandrea S. Desai et al., ed. *Computer Methods and Advances in Geomechanics* (NY: Taylor and Francis, 2000): 93-100.
- 269 Campbell-Kelly and Aspray, pp. 181-220, 242-280, quote on 185; Ceruzzi, pp. 79-158, 233- 281; Moreau, pp. 108-121, 164-194; see Bugliarello comments in "1973 HCB Conference," pp. 45-46.
- 270 "1970-1972 HCB Conference"; "Report of Hydraulic Design Conferences, 1971-1973 (Vicksburg: WES, 1973): 34-36; *Activities Summary, 1975-1980*; "HEC History."
- 271 Damon Manders, Interview with Narayanaswamy Radhakrisnan (Radha), Apr. 27-28, 2009; *Activities Summary, FY 1977-1990*.
- 272 BRAB, Final Report; Presentation, Construction Research Program; Damon Manders, Interview with Mike O'Connor, Oct. 22, 2008; Shaffer quoted in Torres, p. 104; on CROMENCO, see "CROMEMCO Computing" (infolab.stanford.edu/pub/voy/museum/pictures/display/3-5-CROMEMCO.html, Jun. 4, 2009).
- 273 Stellar, pp. 22-27; Torres, pp. 85-96; "Ten Years of Accomplishments," pp. 1-14; Interview with Schmidt.
- 274 Capt. Mark W. Reardon, "Automatic Data Processing Equipment Acquisition," *Army Lawyer* (Aug. 1984): 19-23; Louise S. Heidish, *A History of the Huntsville Division, U.S. Army Corps of Engineers, 1977-1981 Update* (Huntsville, Ala.: HND, 1983): 30-34; "HND/CERL Meeting: CERL Briefing" (CERL Archives, HND (Masters) File).
- 275 Goran, "GIS Technology Takes Root," pp. 207-208; Interview with Radha; Heidish, pp. 19-20; Louis Torres, *A History of Huntsville Division, U.S. Army Corps of Engineers: 1982-1987 Update* (Huntsville: HND, 1990): 5-5 – 5-7.
- 276 Ceruzzi, pp. 260-322, quote on 300-1; Campbell-Kelley and Aspray, pp. 237-240, 284- 299; "The Corps' Doctor Will Make House Calls to Check Design," *ENR* (Jun. 3, 2002): 55- 6; Kathleen D. White and Capt. Gene E. Griffin, "Ice Jam Database," *TME* (Aug.-Sept. 1997): 39-40.
- 277 Foresman, "GIS Early Years and the Threads of Revolution," in *History of GIS*, pp. 3-15, quote on p. 5; Roger Tomlinson, "The Canada Geographic Information System," pp. 21-26; Nicholas R. Chrisman, "Academic Origins of GIS," pp. 33-36.
- 278 Foresman, "GIS Early Years"; Tomlinson; Chrisman; Donald F. Cooke, "Topology and TIGER: The Census Bureau's Contribution"; Nickolaus Faust, "Raster Based GIS"; D. David Moyer and Bernard J. Niemann, Jr., "Land Information Systems: Development of Multipurpose Parcel-based Systems"; Keith McDaniel et al., "AM/FM Entry: 25-Year History"; Robert M. Hoffer, "Remote Sensing and GIS in Agriculture and Forestry – The Early Years"; John E. Estes and John R. Jensen, "Development of Remote Sensing Digital Image Processing and Raster GIS"; Jerome E. Dobson and Richard C. Durfee, "A Quarter Century of GIS at Oak Ridge

- National Laboratory”; and Lisa Warnecke, “State and Local Government GIS Initiatives,” in Foresman, pp. 3-180, 231-265, Foresman quoted p. xii; Daniel Charles, “Do Maps Have Morals?” *MIT Technology Review* (June 2005) (www.technologyreview.com/communications/14534/, Mar. 26, 2009). For an example of a narrow definition of GIS, see Duane F. Marble, “Geographic information systems: an overview,” in Donna J. Peuquet and Marble, *Introductory readings in Geographic Information Systems* (NY: Taylor and Francis, 1990): 10.
- 279 Pennington, pp. 97-99, 188-198, 204-233, 235-250; Ezell, pp. 12-55; Hamilton and Hellman, pp. 52-57, 108-109; Hellman, p. 42.
- 280 *Ibid.*
- 281 Ezell, pp. 43-58; Hamilton and Hellman, pp. 3-7, 13-26, 52-58, 98-106; Hellman, pp. 30-51, 70-75.
- 282 Hamilton and Hellman, pp. 7-9, 59, 66-70; Hellman, pp. 8-15.
- 283 Goran, pp. 199-203; Andrew J. Bruzewicz, “New Technology for Disasters,” *TME* (Aug.-Sept. 1997): 25-6; Interview with Radha; Interview with Hoge; *Activities Summary, FY 1989-1992*; E-mail, Peter Smallidge to Charles Camillo, Aug. 3, 2009.
- 284 Interview with O’Connor; Goran, pp. 204-206, 211-222; Goran and Finney, “GRASS GIS Critical to Army’s Land Management Program”; “OGC History (detailed)” (www.opengeospatial.org/ogc/historylong, Apr. 16, 2009).
- 285 Goran, pp. 209-219.
- 286 Goran, pp. 219-225; Interview with O’Connor; “OGC History.”
- 287 *Activities Summary, FY 1970-1984.*
- 288 Ezell, p. 11; Torres, p. 72; “USACRREL SOP for Acquisition of Automated Data Processing Equipment and Support Services, May 1, 1984”; WES supplement 1 to AR-18; Creel, *Exit Report*, p. 80-81; Powers quotes from Memo, Establishment of a WES ADP Coordinator Office, Oct. 6, 1982; Memo, Creel to CDR USACE, Request for Approval to Revise the Waterways Experiment Station (WES) Organization Structure, Jul 8, 1982, and endorsements; PO 4-1, Automatic Data Processing Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, May 2, 1984; WES org charts (ERDC Archives); *Activity Summary, FY 1984-1985*; Interview with Radha.
- 289 DF, Hyde, WES Information Manager, Jun. 17, 1985, and enclosures; XD Communications, Maj. Gen. Delbridge to Cdr. USACE Divisions and Cdr./Dir. USACE Separate FOAs, Information Mission Area (IMA) Implementation in USACE, Jul. 5, 1985; Memo, Lt. Col. Jack R. Stephens to Cdr. USACE, Information Mission Area in USACE, Sept. 23, 1985; Memo, Grum to Cdr. USACE, Proposed Organization of Information Mission Area (IMA) Functions, Nov. 18, 1985; DF, Grum to Chiefs of Laboratories and Separate Staff Elements, Formation of Information Mission Area Organization, Feb. 6, 1986 (ERDC Archives); Interview with Whalin; Interview with Radha; Damon Manders, Interview with Allen Grum, May 19, 2009.
- 290 Quote from Interview with Grum; Interview with Radha; DF, Grum to Lab Chiefs; “ITL Headquarters Building”; WES Orders 11-3, Engineering Applications group, Automation Technology Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, Nov. 24, 1987; “Information Technology Laboratory Timeline, 1957-2006” (ERDC Archives).
- 291 Interview with Radha; *Activities Summary, FY 1986-1992.*
- 292 Interview with Radha; Interview with Moser; *Activities Summary, FY 1986-1989.*
- 293 Interview with Radha; *Activities Summary, FY 1988-1995*; Heidish, p. 34; Ables quoted in Matt Evans, “Profile: Dr. N. Radhakrisnan,” *Business Journal* (Jan. 16-22, 2009): 23.
- 294 Hellman, pp. 90-97; *CRREL*, pp. 4-5; USACERL Org. Chart, 1992; Department of Defense Regulation 3200.12-R-2, “Centers for Analysis of Scientific And Technical Information Regulation,” January 1985; E-mail, Smallidge to Camillo, Aug. 3, 2009; Memo, Roberto to Director, Trip to WES Information Technology Laboratory, Oct. 17, 1989; Interview with Schmidt; Interview with Radha. For more on the CRREL IAC, see www.crrel.usace.army.mil/facilitieslabstestsites/center-crstiac.html, Oct. 14, 2009.

- 295 Damon Manders, Interview with Marcuson, Jun. 10 and 15, 2009; Interview with Whalin; Interview with Radha.
- 296 Interview with Whalin; Fatherree, *Geotechnical Engineering*, pp. 218-223.
- 297 Fatherree, *First 75 Years*, pp. 218-219; T.M Parchure et al., "Objectives of Proposed Large Scale Experimental Facility," *Coastal Dynamics '94* (NY: ASCE, 1994): 808-814, quotes on 811.
- 298 Wright, pp. 47-61; *CRREL*, pp. 3-8; Torres, pp. 87-100; *CERL LOY Report, FY98*; Hellman, 65-75, quotes pp. 71, 73.

Chapter 8

- 299 Interview with Whalin; Interview with Marcuson; Price, Mather Interview; Peixotto, *Exit Report*, pp. 23-24.
- 300 *Activities Summary, FY 1989-1997*; Fatherree, *First 75 Years*, pp. 189-211; R.A. Luettich et al., "Application of ADCIRC 2DDI to Masonboro Inlet, North Carolina: A brief numerical modeling study" (N.P.: WES, 1991).
- 301 *Activities Summary, FY 1989-1997*; Carl F. Cerco, "Chesapeake Bay Three-Dimensional Model Study," in Orville T. Magoon et al., ed, *Coastal Zone '89 4* (NY: ASCE, 1989): 3601- 6; Cerco and Thomas M. Cole, "Calibrating the Chesapeake Bay Water Quality Model," in Malcolm L. Spaulding, ed., *Estuarine and Coastal Modeling* (NY: ASCE, 1989): 192-199.
- 302 *Activities Summary, FY 1990-1997*; *WES LOY Report, FY 1990-1998*; McAnally quoted in Fatherree, *First 75 Years*, p. 218; Interview with Whalin; Richard Stockstill, "Olmsted Lock Outlet, Ohio River: Hydraulic Model Investigation" (Vicksburg: WES, 1992).
- 303 *WES LOY Report, FY 1990-1998*; *Activities Summary, FY 1990-1997*; Birkemeier and Holland, pp. 18-24.
- 304 Fatherree, *First 75 Years*, pp. 216-217; *WES LOY Report, FY 1990-1998*; *Activities Summary, FY 1997*; E-mail, James R. Houston to Deborah Quimby, Aug. 7, 2009; E-mail, Houston to author, Oct. 20, 2009.
- 305 Fatherree, *Geotechnical Engineering*, pp. 211-217; *WES LOY Report, FY 1990-1998*; *Activities Summary, FY 1985-1997*; Interview with Marcuson; Interview with Whalin. On NDT, see Hall, "Comparative study of nondestructive pavement testing, WES NDT methodologies," (Vicksburg: WES, 1985). On railroad evaluation, see Coleman, *Synthesis of railroad design methods, track response models, and evaluation methods for military railroads* (Vicksburg: WES, 1985).
- 306 Fatherree, *Geotechnical Engineering*, pp. 197-202; *WES LOY Report, FY 1990-1998*; *Activities Summary, FY 1986-1997*; Interview with Marcuson.
- 307 Fatherree, *Geotechnical Engineering*, pp. 197-202; *WES LOY Report, FY 1990-1998*; *Activities Summary, FY 1986-1997*; Interview with Whalin; Interview with Marcuson; Peggy Price, Interview with Marcuson, [March 2001]. See also, Newell R. Murphey and Allan S. Lessem, "Stresses in M1 tank tracks," Reports 1-4 (Vicksburg: WES, 1987-1991) and Randolph A. Jones, "Limited evaluation of the operational envelope of the M2 BFVS in ingressing/egressing water obstacles," (Vicksburg: WES, 1992).
- 308 Fatherree, *Geotechnical Engineering*, pp. 202-211; *Activities Summary, FY 1990-1997*; Interview with Marcuson; Price, Marcuson Interview.
- 309 *Activities Summary, FY 1989-1997*; Price, Mather Interview; WES Org Charts.
- 310 *Activities Summary, FY 1989-1997*; *WES LOY Reports, 1991-1998*; Price, Mather Interview; Interview with Flathau; Damon Manders, Interview with Guy Jackson, Jul. 14, 2009.
- 311 *Activities Summary, FY 1989-1997*; *WES LOY Reports, 1991-1998*.
- 312 *Activities Summary, FY 1989-1997*; *WES LOY Reports, 1991-1998*; Price, Mathers Interview.
- 313 Interview with Marcuson; WES org charts, 1966-1998; Fatherree, *Geotechnical Engineering*, p. 228; Price, Mather Interview.
- 314 *WES LOY Report, FY 1990-1998*; *Activities Summary, FY 1989-1997*; Robert D. Doyle, "Potential use of native aquatic plants for long-term control of problem aquatic plants in Guntersville Reservoir, Alabama," Rep.

- 1-2 (Vicksburg: WES, 1993-1995); Cerco and Cole, "Thirty-year simulation of Chesapeake Bay dissolved oxygen," in JHW Lee and YK Cheung, eds., *Environmental Hydraulics* (NY: Brookfield, 1991): 771-776; "Thirty Year Simulation of Chesapeake Bay Eutrophication," in Spaulding et al., eds., *Estuarine and Coastal Modeling* (NY: ASCE, 1992): 116-126 .
- 315 *WES LOY Report, FY 1990-1998; Activities Summary, FY 1990-1997*; Paul Schroeder, "The HELP Program," *TME* (Aug./Sept. 1996): 28-29.
- 316 *CERL LOY Report, FY 1998*.
- 317 *CRREL LOY Report, FY 1997-1998*; see also, Daniel Lawson et al., "Geological and Geophysical Investigations of the Hydrogeology of Fort Wainwright, Alaska," Parts 1-2 (Hanover: CRREL, 1996-1998); Lawrence W. Gatto, "Ground Freezing Effects on Soil Erosion of Army Training Lands," Parts 1-2 (Hanover: CRREL, 1997-1998).
- 318 *WES LOY Report, FY 1990-1998; Activities Summary, FY 1990-1997; CRREL LOY Report, FY 1997-1998*; Darryl Calkins, "Calibrating HEC-2 in a shallow, ice-covered river," (Hannover: CRREL, 1986).
- 319 *CERL LOY Report, FY 1997-1998*; Drury Crawley, "EnergyPlus: Creating a new-generation building energy simulation program," (Champaign: CERL, 2001); Larry L. Pater, "Getting started guide for the small arms range noise assessment model (SARNAM)," (Champaign: CERL, 1999); E-mail, Dana Finney to Charles Camillo, Sept. 11, 2009.
- 320 *TEC LOY Report, 1992-1997*.
- 321 *Activities Summary, FY 1990-1997; WES LOY Report, FY 1990-1998; CERL LOY Report, FY 1998; CRREL LOY Report FY 1997-1998*.
- 322 *WES LOY Report, FY 1990-1998; Activities Summary, FY 1990-1997*.
- 323 Hellman, p. 1; ER 10-1-45, Jun. 1, 1993, Org. and Functions, U.S. Army Topographic Engineering Center; TEC Org Charts, 1988-1994 (ERDC Archives); Damon Manders, Interview with Jim Shine, Jun. 19, 2008; William C. Baldwin, *A History of the U.S. Army Engineer Studies Center, 1943-1982* (Ft. Belvoir: CEHO, [1983]): 1-22, 267-274; Org. and Functions, U.S. Topographic Engineering Center, Oct. 26, 1997; Damon Manders, Interview with William E. Roper, Oct. 21, 2009.
- 324 *TEC LOY Report, FY 1997*; Interview with Shine; Damon Manders, Interview with Doug Caldwell, Jun. 19, 2008; Damon Manders, Interview with John Benton, Nov. 20, 2008.
- 325 Hamilton and Hellman, pp. 33-43; Hellman, pp. 15-24; *TEC Lab of the Year Report, 1992- 1997*.
- 326 Hamilton and Hellman, pp. 98-106; Hellman, pp. 24-27, 70-76, quote on 27; *TEC Lab of the Year Report, 1992-1997*.
- 327 Hellman, pp. 77-85; *TEC Lab of the Year Report, 1992-1997*.
- 328 Damon Manders, Interview with Link, Jun. 16 and 23, 2009; *CRREL LOY Report, FY 1997-1998*; "CRREL."
- 329 Interview with Link; "Newly Declassified Submarine Data Will Help Study of Arctic Ice," NSF News Release, Jan. 28, 1998; "Submarine data helping climate scientists," *USA Today* (Feb. 4, 1998); *CRREL LOY Report, FY 1997-1998*. See also, Walter B. Tucker et al., "Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s," *Geophysical Research Letters* 28:14 (Jul. 15, 2001): 2851-2854; Sherry Simpson, "Permafrost," *Alaska* (Dec. 97/Jan. 98): 28-33; Michael R. Walsh, "Contraption makes ice fly at South Pole: New CRREL digger great success, makes tunneling fast, safe," *Engineer Update* (Feb. 1997); "Rebuilding the SPRP Project," *Civil Engineering* (Dec. 2000): 1-16.
- 330 Interview with Link; Wright, p. 28; FY 87 Annual Report (Hanover: CRREL, 1987): 24; Presentation, "HQUSACE Command Inspection," Jul. 10, 1997 (ERDC Archives).
- 331 Torres, pp. 95-96; *CERL LOY Report, FY 1998*.
- 332 *CERL LOY Report, 1998*.
- 333 Interview with O'Connor; CERL Org Charts, 1988, 1992, 1997; Fax, David Moody to Mary Vincent, Femi Ayorinde, and Betty Mandel, USACERL Reorg – Informal FYI Thing, Mar. 8, 1995 (ERDC Archives).

- 334 *Activities Summary, FY 1980-1996*; Madeline Bodin, "Dr. Snow Makes House Calls," *Ski* (Dec. 1996): 22-23; "Small Problems Program," brochure (Champaign: CERL, 1980); DF, DAEN-ECE to DAEN-RDZ-A, Formation of Structural Engineering Center (SEC) at the Waterways Experiment Station, May 21, 1984 (ERDC Archives).
- 335 U.S. Congress, *An Act to promote United States technology innovation for the achievement of national economic, environmental, and social goals, and for other purposes* (96th Cong., 2nd Sess.); *An Act to amend the Stevenson-Wydler Technology Innovation Act of 1980* (99th Cong., 2nd Sess.); DF, Broadway to Tech Dir, "Establishment of Office of Research and Technology Application (ORTA)," and enclosures (ERDC Archives); Torres, p. 74; Hellman and Hamilton, p. 133; Presentation, "Dual R&D"; for a comprehensive list of technology transfer legislation, see Mark Wang et al., *Technology Transfer of Federally Funded R&D: Perspectives from a Forum* (Santa Monica, Ca.: Rand Corp., 2003): 37-42.
- 336 John D. Moteff, "Defense Research: A Primer on the Department of Defense's Research, Development, Test and Evaluation (RDT&E) Program," Congressional Research Service (Wash.: Library of Congress, Jul. 14, 1999): 6-8; Naval Research Advisory Committee, *Science and Technology: Community in Crisis, May 2002* (Washington, ASN-RDA, 2002): 10-16; "Dual Use Technology: A Defense Strategy for Affordable, Leading-Edge Technology," (Wash.: OASD-ES, 1995): 3-9; "Dual R&D." On SERDP, go to <http://www.serdp.org/general/about/overview/index.cfm>, Jun. 26, 2009).
- 337 "Dual R&D" with "Bullets and Narratives for WES Input"; Thomas M. Cox and Richard B. Marth, Sr., "Personal Navigation"; Paul R. Schroeder, "The HELP Program"; Richard Tynes, "Terrain Visualization"; Ellis L. Krinitzkey and Mary E. Hynes, "The Army Prepares for Earthquakes"; Larry N. Lynch et al., "Expedient Surfaces"; Vincent F. Hock, "Coating Prevents Scale and Corrosion"; Dwain K. Butler, "Microgravity"; Donald T. Resio, "LOTS: More Needed to Do More," in *TME* (Aug.-Sept. 1996): 27-56; *CERL LOY Report, FY 1998*; *CRREL LOY Report, FY 1998*; *WES LOY Report, FY 1998*; *TEC LOY Report, 1997*. Ballard quoted in Commander's Policy Memorandum #7, Reimbursable Support and Our Relationships with the Private Sector, Feb. 10, 1998 (ERDC Archives).
- 338 Moorhus and Graves, pp. 106-112; 131-133; on initial inclusion of the Bayley Report in BRAC, see LTC Carl T. Strock, "Bringing Home the Bacon: Congress and the Reorganization of the U.S. Army Corps of Engineers," (Washington: War College, 1992).
- 339 Moorhus and Graves, pp. 106-116, 175; U.S. Congress, *U.S. Army Corps of Engineers Proposed Reorganization Plan: Hearings before the Subcommittee on Investigations and Oversight of the Committee on Public Works and Transportation, May 6 and 11, 1993* (House, 103rd Cong., 1st Sess.): 2-7.
- 340 Moteff, pp. 3-10; NRAC, pp. 9-23; Interview with Whalin; Interview with Pennington.
- 341 Moteff, pp. 11-12; NRAC, pp. 13-15; *Army Science and Technology Master Plan, 1997* (Washington, D.C.: ASA-RDA, 1997): I-VII-E; "The Genealogy of ARL," (ARL, 1993): 3-11. See in particular Sec. 212 of PL 104-106 and Sec. 912 of PL 105-85.
- 342 Interview with Link; Whalin quoted in Memo for Record, Trip Report: Lab Leaders Conference, WES' Field Research Facility, Duck, NC; 27-29 Jul 93, Aug. 2, 1993 (emphasis in original); Presentation, "MG John F. Sobke and Staff," Feb. 4, 1994 (ERDC Archives).
- 343 Memo for Heads of Field Operating Agencies, Corps of Engineers (Laboratories), COE Reduction Planning; OCE, ER 15-1-17, Research and Development Review Committee (RCDC), Jan. 28, 1983; Memo, Dir. R&D to Lab Commanders, Lab Commanders/Directorate of R&D Meeting, 6-7 Aug. 81, Sept. 16, 1981; Interview with Roper; Sobke Presentation; Presentation, "Corps of Engineers Inter-Laboratory Reliance" (ERDC Archives).
- 344 Interview with Link; Interview with Whalin; Interview with O'Connor.
- 345 Quote from Interview with O'Connor.

- 346 Interview with Link; Interview with O'Connor; Interview with Roper; E-mail, Houston to CHL, Corps' Laboratory Reorganization, Jan. 29, 1998; Presentation, Decision Briefing to LTG Joe N. Ballard: Reengineering R&D in the Corps, 10 Dec. 1997 (ERDC Archives).
- 347 Howard quoted in Memo, Howard to Link, Evaluation for Potential Savings of Lab Support Services (emphasis in original); Memo, Bandy to Howard, CERL Comments on WES Support Staff Analysis, May 9, 1997; Memo, Kirby to Howard, Staff Support Analysis; Presentation, Business Process Team: Best Business Processes Concept, Oct. 3, 1997; E-mail, Link to Whalin et al., Lab Leaders Mtg, Dec. 31, 1997 (ERDC Archives).
- 348 Houston to HCL; Decision Briefing; COL Robert M. Fernandez, Memo for Record, R&D Re-Engineering Briefing, 29 Jan 98, Feb. 4, 1998.
- 349 Swart, Memo for Record, R&D Re-Engineering In-Progress Review, Mar. 24, 1998 and enclosures; Link, Memo for Chief of Engineers, R&D Re-Engineering Implementation Decisions, May 18, 1998 and enclosures; Notes, Implementation Planning Team Task Assignments; Letter, Ballard to Thomas W. Ewing, Apr. 15, 1998; "R&D Re-Engineering News: Information Paper #2," Jun. 1, 1998; Presentation, Preparing Ourselves for the 21st Century: Re-Engineering R&D in the Corps, April 1998; "USACE Laboratory Re-Engineering Town Hall Meeting Questions and Answers: Consolidated Laboratory Operations"; News Release, "Re-Engineering the U.S. Army Corps of Engineers Research and Development Activities," Jul 28, 1998.
- 350 Link quote from Interview with Link; Memo, Link to Lab Leaders, Engineer Institute Integrated R&D Planning Process, Apr. 3, 1998; Fax, Smith to Lab Directors, Outline and Description of Macro Plans, Apr. 9, 1998; E-mail, Whalin to Link, Macro Plan for High Performance Computing and Software Engineering, Apr. 16, 1998; Whalin quote from E-mail, Whalin to Lab Directors, Macro-Plan Schedule, Apr. 15, 1998; E-mail, Marcuson to Jerry Lundien et al., Minutes of 7 May 98 Meeting; E-mail, O'Connor to Alan Moore et al., Infrastructure Macro Plan Group Initial Meeting, May 11, 1998, and replies; Houston to Whalin et al., Discussion with O'Connor on macro-plans, May 7, 1998; E-mail, O'Connor to lab directors, Example Capability Packages, May 27, 1998; "Discussion Notes" Initial Infrastructure Design and Management Macroplan Team Meeting [May 19, 1998]; Link, "Let's Clarify the Purpose of Macro-Plans" Re-Engineering News: Information Paper #4 (Sept. 1, 1998).
- 351 E-mail, Bobbie Kerns to John Deponai et al., LQIP 2 meeting, Feb. 27, 1998; Quote from Swart, Memo for Record, Meeting with Kevin Kirby, Former ARL Chief of Staff – Lessons Learned, May 12, 1998; E-mail, Swart to Cababa, Draft Site Manager Decision Paper, May 12, 1998 and replies; Link, Memo for See Distribution, Resolution of Decision Issue Regarding Site Management; E-mail, Jerome Mahloch to Swart, REOORG STATUS, Apr. 16, 1998 and replies; Whalin, Memo for Record, Minutes of the 4 June USACE R&D Laboratory Director's Meeting, Jun. 5, 1998; "Discussions with Dr. Link," Jun. 8, 1998; E-mail, Swart to Smith, Implementation Team Meeting – 9 July 1998, Jul. 6, 1998; "Re- Engineering News: Information Paper #4," Sept. 4, 1998; E-mail Jeffrey Walaszek to Smith and Cababa, Revised vugraphs from last week's meeting, Jul 14, 1998.
- 352 1998; "Key Decision Issues Requiring Formal Staffing," USAERDC Implementation Planning Team, Aug. 27, 1998; Presentation, U.S. Army Engineer Research and Development Center (USAERDC): Re-engineering USACE Laboratories... Preparing Ourselves for the 21st Century, Sept. 1998.

Chapter 9

- 353 Permanent Orders No. 43-3, 1 Oct. 1998; quotes from OPORD 1 USAERDC, 1 Oct. 1998 (ERDC Archives); Damon Manders and Charles Camillo, Interview with James R. Houston, Aug. 27, 2009. E-mail, Houston to Camillo, Sept. 29, 2009; although orders cite the official date for formation of ERDC as Oct. 1, 1998, the activation ceremony did not take place until Oct. 1, 1999, the day consolidation of laboratories under ERDC was complete.
- 354 OPORD 1 USAERDC.

- 355 Quote from Cababa, Memo for USACE Laboratory Personnel, U.S. Army Engineer Research and Development Center, Oct. 7, 1998; “Re-engineering News: Information Paper No. 4” (Fort Belvoir, CERD, 1998); Permanent Order 10-1, 1 October 1999; Whalin, Memo for Commander, Standard G&A Budget Elements, Oct. 30, 1998; Swart, Memo for Commander, USAERDC, Request for Decision on IMO Organization, Oct. 1, 1998; WES PO 3-1, Restructure within the Information Technology Laboratory, Mar. 8, 1999; Cababa, Memo for ERDC Laboratory Directors and ERDC Chief/Separate Staff Elements, Standardization of ERDC Business Process Information Management Systems, Oct. 30, 1998; E-mail, LTC William Loven to Cababa et al., CRREL Financial Reports VTC – 15Apr, Apr. 16, 1999; (ERDC Archives).
- 356 ERDC Org. Chart, 2000 (ERDC Archives); Interview with Whalin; Interview with Radha; Price, Interview with Mather. Mather recalls seeing a sign with a frog saying, “ERDC.”
- 357 Link, Memo for See Distribution, Establishment of the Office of the ERDC Directors, Mar. 31, 1999; E-mail, Donald Leverenz to Smith et al., Apr. 26, 1999; Link, Memo for CECG, Engineer R&D Center (ERDC) Acting Director and Director’s Office – FOR DECISION, Mar. 2, 1999; Interview with Link; Interview with Whalin; Damon Manders, Interview with James R. Houston, May 14, 2008; Manders and Camillo, Interview with Houston; “Activation Ceremony: U.S. Army Engineer Research and Development Center, 1 October 1999” (NP: ERDC, ND).
- 358 Permanent Order 10-1, 1 October 1999; ERDC Org. Chart, 2000; *ERDC LOY Report, 1999*, quote p. 17.
- 359 Link Memo, Office of ERDC Directors; Memo, Leverenz to Smith et al., Apr. 26, 1999; Presentation, Managing Knowledge Effectively: The U.S. Army Corps of Engineers, Dec. 5, 1998; Ballard quoted in Present., Commander’s Intent #2: Re-Engineering the R&D Component of the USAERDC, [Jan. 29, 1999] (ERDC Archives).
- 360 Link Memo, Office of ERDC Directors. Link quoted in Billy Bridges, “Laboratory restructuring continues,” *Engineer Update* (Mar. 1999): 9.
- 361 E-mail, Houston to Link et al., Commander’s Intent Comments, Feb. 2, 1999; E-mail, Houston to Link et al., Commander’s Intent Comments, Feb. 2, 1999; Damon Manders and Charles Camillo, Interview with Ilker R. Adiguzel and Kumar V. Topudurti, Dec. 1, 2008; O’Connor quotes from Interview with O’Connor.
- 362 Leverenz, “PMB Minutes,” Dec. 1999-May 2000 (ERDC Archives), quotes from Apr. 2000, pp. 2-3.
- 363 *Ibid.*, May 2000-Nov. 2000, quotes from Jul. 2000, Encl. 1.
- 364 Manders, Interview with Houston; Manders and Camillo, Interview with Houston; Interview with Link; Interview with Adiguzel and Topudurti.
- 365 “PMB Minutes,” June 2000, Encl. 1, Oct.-Nov. 2000.
- 366 Interview with O’Connor; Interview with Marcuson; Interview with Link; “PMB Minutes,” May-Sept. 2000; Fatherree, *Geotechnical Engineering*, pp. 228-230.
- 367 Interview with Marcuson; Interview with O’Connor; Fatherree, *Geotechnical Engineering*, pp. 228-229; “ERDC-GSL Who We Are”; “Geotechnical and Structures Laboratory” (www.gsl.erdc.usace.army.mil/WhoWeAre.html, Jun. 25, 2009).
- 368 Damon Manders and Charles Camillo, Interview with Jeffery P. Holland, Aug. 27, 2009; GAO, “DOD Competitive Sourcing: Effects of A-76 Studies on Federal Employees’ Employment, Pay, and Benefits Vary” (D.C.: GAO, 2001); GAO, “Briefing for Congressional Staff: Implementation of OMB Circular A-76 at Science Agencies” (D.C.: GAO, 2007); Alan Joch, “An Intelligent Path,” *FedTech* ([fedtechmagazine.com](http://fedtechmagazine.com/article.asp?item_id=346) article.asp?item_id=346, Sept. 2, 2009).
- 369 ERDC News Release, “U.S. Army Corps of Engineers Announce National A-76 Competition for Information Management/Information Technology Services,” Jun. 2, 2004; Berrios quote from Joch, “An Intelligent Path”; Elise Castelli, “Army Corps IT employees win A-76 competition,” *FederalTimes* (www.federaltimes.com/index.php?S=2694150, Sept. 2, 2009) Interview with Holland; Damon Manders, Interview with Reed Mosher, Jul. 9, 2008.

- 370 Manders and Camillo Interview with Houston; Interview with Holland; E-mail, Chief Sends to Corps, Announcement of ERDC Change in Leadership,” Apr. 1, 2009.
- 371 Damon Manders, Interview with Richard Herrmann, Nov. 20, 2008; Hellman, pp. 10-15; Presentation, Geospatial – Integrated Capabilities Development Team to Geospatial General Officer Steering Committee, Aug. 21, 2007.
- 372 Geospatial ICDT, “The Army Geospatial Enterprise Functional Solutions Analysis,” (Geospatial ICDT, June 2007); ICDT presentation to GGOSC; Damon Manders and Charles Camillo, Interview with Joseph Fontanella, Nov. 18, 2008; Interview with Herrmann.
- 373 Quote from Interview with Fontanella; Interview with Herrmann; Email, Antwerp to All of Corps, Army Geospatial Enterprise Update, Feb. 25, 2008; TEC News Release, “Army Appoints Service’s First Geospatial Information Officer,” Mar. 6, 2008 ; AGC News Release, “Army Establishes New Army Geospatial Center,” Feb. 23, 2009.
- 374 *ERDC LOY Reports, 2000-2005*; The ERDC Road Ahead (Vicksburg: ERDC, 2007): 1-5.
- 375 *ERDC LOY Reports, FY 1999-2005*; ERDC Web Page (www.erd.usace.army.mil, Sept. 10, 2009); “Buck-Eye Fact Sheet: An Airborne High-Resolution Geospatial Collection System” (ERDC, 2008); Presentation, Geospatial Research and Engineering Business Area Strategic Direction (ERDC, 2007); Interview with Fontanella.
- 376 *ERDC LOY Reports, FY 1999-2005*; *GRE Presentation*; *ERDC Web Page*; ERDC Fact Sheet, “Fluorescence Spectroscopy Lab,” (ERDC, 2007).
- 377 *ERDC LOY Reports, 1999-2005*; ERDC Web Page; ERDC Fact Sheet, “Joint Rapid Airfield Construction” (ERDC, 2005); “Stryker Terrain Impact Tests” (ERDC, 2009); ERDC News Release, “ERDC-CRREL Delivers on Opportune Landing Site Program,” May 20, 2008; “LMCS announced winner of 2008 Defense Logistics Award,” Mar. 13, 2009; “ERDC again names Army’s best,” Oct. 10, 2008; Presentation, Military Engineering Strategic Directions (ERDC, 2007); Damon Manders and Marie Darling, Interview with Robert Davis and Lance Hansen, Sept. 17, 2009; E-mail, Houston to Camillo, Sept. 29, 2009.
- 378 GSL Website (gsl.erd.usace.army.mil/Isopotlit.html, Sept. 29, 2009); Houston e-mail to Camillo.
- 379 *ERDC LOY Reports, 1999-2005*; ERDC Web Page; ERDC Fact Sheet, “Remote Damage Assessment and Tactical/Persistent Monitoring” (ERDC, 2007); “SACON Shock Absorbing Concrete” (ERDC, 2005); “GEL-COR” (ERDC, 2006); “TeleEngineering Operations Center (TEOC)” (ERDC, 2007); quote provided in e-mail, Houston to Camillo.
- 380 *ERDC LOY Reports, 1999-2005*; ERDC Web Page; Charles J. Korhonen, “Off-the-Shelf Antifreeze Admixtures,” (Hanover: ERDC/CRREL TR-02-7, 2002); EQ/I Business Area Strategic Directions (ERDC, 2007); Interview with Davis and Hansen; Interview with Adiguzel and Topudurti; CERL Web Page (www.ccerl.army.mil/td/tips/browse/products.cfm?AREA=3&TECHNAME=FACILITIES, Sept. 15, 2009).
- 381 ERDC website; *ERDC LOY Reports, FY 1999-2005*; ERDC Fact Sheet, “Anaerobic, Granular-Activated Fluidized Bed reactors for Treatment of Propellant Wastewaters” (CERL, 2000); “Biofilter Technology to Treat DOD Volatile Organic Compounds in Air Emissions” (CERL, 1999); “The DoD residential PEM fuel cell demonstration program,” *Fuel Cells Bulletin* (Oct. 2003): 11; “DOD Tries Out Residential Fuel Cells,” *DG Insight* 13:3 (Mar. 2003): 8.
- 382 ERDC website; *ERDC LOY Reports, FY 1999-2005*; CRREL TN05-1, “Method to Evaluate Potential Ice Impacts on Sediment Stability,” *Ice Engineering* (Jan. 2005); ERDC Fact Sheet, “Buried Unexploded Ordnance (UXO) Detection Research and Development” (ERDC, 2008).
- 383 *ERDC LOY Reports, 1999-2005*; ERDC Web Page; Interview with Davis and Hansen. See also <https://eko/usace.army.mil/fa/serm>.
- 384 ERDC website; *ERDC LOY Reports, FY 1999-2005*; ERDC Fact Sheet, “Fish Surrogate Model” (ERDC, 2006); Michelle Nijhuis, “The Cahaba: A River of Riches,” *Smithsonian* (Aug. 2009): online.

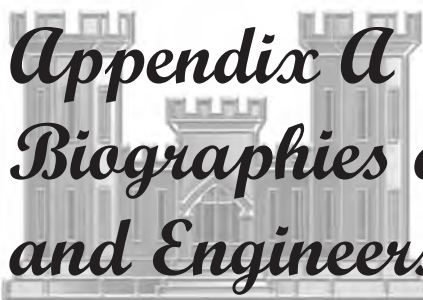
- 385 ERDC website; *ERDC LOY Reports, FY 1999-2005*; Fatherree, *First 75 Years*, pp. 218-219; ERDC Fact Sheet, "Monitoring Completed Navigation Projects Program" (DERC 2009); "National Shoreline Erosion Control Development and Demonstration (Section 227) Program" (ERDC, 2008).
- 386 ERDC website; ERDC Fact Sheet, "Applying Stable Isotopic Analysis to Ecological Problems" (ERDC, 2008); "Noxious and Nuisance Plant Management Information System (PMIS)" (ERDC, 2008); EQ/I Presentation.
- 387 *ERDC LOY Reports, 1999-2005*; ERDC Web Pages; ERDC Fact Sheet, "Landslide Evaluation and Mitigation" (ERDC 2005); "Army Dam Inspection" (ERDC 2007); "Geophysical Surveys for Rapid Assessment of Levees and Levee Foundation Conditions" (ERDC 2007); "Levee Condition Assessment Technology (Lev-CAT)" (ERDC 2007); "Rapid Geotechnical-Based Assessment of Ground Failures" (ERDC 2002).
- 388 ERDC website; *ERDC LOY Reports, FY 1999-2005*; Interview with Davis and Hansen. On the Ice Mass Balance project, see imb.crrel.usace.army.mil.
- 389 *ERDC LOY Reports, 1999-2005*; Interview with Mosher; ERDC Web Page; ITL Web Page; Leverenz, "PMB Minutes" Nov. 2000; ITL Timeline; David Dumas et al., "Jade Becoming Preferred Gem – Users Praise Cray XT4," *ERDC MSRC Resource* (Fall 2008): 26-27.
- 390 *ERDC LOY Reports, 1999-2005*; Interview with Mosher; ERDC Web Page; ITL Web Page; ITL Timeline; ERDC Fact Sheet, "Common Delivery Framework (Research)" (ERDC 2008).
- 391 ERDC News Release, "ERDC – 'Making the World Safer and Better,'" Mar. 12, 2008; News Release, "Vicksburg Corps lab honored," *AP* (Sept. 15, 2009); Manders and Camillo Interview with Houston; ERDC News Release, "ERDC group wins Award for Excellence in Technology Transfer," Feb. 27, 2009 (Vicksburg; ERDC, 2008 at www.erd.usace.army.mil/pls/erdcpub/, Sept. 8, 2009).
- 392 Quote from News Release, "ERDC – 'Making the World Safer and Better'"; News Release, "Topudurti wins 2009 Federal Engineer of the Year Award," Feb. 27, 2009; "Bridges and Kim win Hera award," Aug. 14, 2009; "Corps engineers awarded Gerard Medal," Jun. 16, 2009; "ERDC researchers win 2009 Army R&D Achievement Awards," Aug. 14, 2009 (Vicksburg; ERDC, 2008 at www.erd.usace.army.mil/pls/erdcpub/, Sept. 8, 2009); *ERDC LOY Reports, FY 1998-2005*.
- 393 Interview with Whalin; Interview with Marcuson; Interview with Davis and Hansen; Interview with Adiguzel and Topudurti; Thomas quote from e-mail to Stephen Gambrell, Hi and Quote, Dec. 17, 2009; Thompson quoted in "Flowing Water," p. 2.
- 394 RDT&E funding categories are 6.1 basic research, 6.2 applied research, 6.3 technology development, 6.4 demonstration and validation, 6.5 engineering and manufacturing development, 6.6 management support, and 6.7 operational system development. Typically, only 6.1-6.3 are considered research and development.
- 395 Quotes from Interview with Holland; Interview with Houston.

Notes for Vignettes

- Franklin and Modeling – Franklin letter to Sir John Pringle, May 10, 1768, No. 471, and Letter to Anthony Todd, Oct. 29, 1769, No. 513, in Smyth, Vol. V, 1767-1772, pp. 129-30, 232-3.
- Engineer School – Abbot, "Early Days of the Engineer School of Application," pp. 1-34; Kenneth Moore, "The Engineer School," *The Military Engineer (TME)* (Jan.-Feb. 1935): 9-13.
- Topogs – Michael Brodhead, Corps of Engineers History Office.
- Muddy Waters – Humphreys and Abbot, *Report on the Physics and Hydraulics of the Mississippi* (Washington, D.C.: USACE, 1861): 1-15; Barry, pp. 32-54, quote on pp. 50-51; Camillo and Percy, pp. 17-24; Reuss, "Humphreys," pp. 1-33; Rouse and Ince, p. 177.
- Richardson Highway – U.S. Congress, *A Report of the Board of Road Commissioners for Alaska of Operations for the Season of 1906*, Jan. 17, 1907 (59th Cong., 2nd Sess., HD 523): 11-17, 21; see also Terry McFadden and F.

- Lawrence Bennett, *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers* (NY: John Wiley and Sons, 1991): 493-99.
- Engineer Pilots – Livingston, pp. 1-13; quote from James Bagley, *Aerophography and Aerosurveying* (NY: McGraw-Hill, 1941: vii. For more on the Signal Corps' involvement in development of the Air Corps, see Rebecca Raines, *Getting the Message Through: A Branch History of the U.S. Army Signal Corps* (Washington, D.C.: Center of Military History, 1996): 119-168, 191-200.
- Herbert Vogel – Vogel, "Impressions of Life in Germany under the Weimar Republic, 1928- 1929," Nov. 3, 1960 (ERDC Archives).
- Greenville Bends – Fatherree, *First 75 Years*, pp. 21-27; Gerard Matthes, "Mississippi River Cutoffs," *ASCE Transactions* (Jan. 1946): 1-39; Vogel quote from "Experiment to Determine the Effect of a Cutoff at Tarpley Neck, April 10, 1931," (MRC Archives); "Experiment to Determine the Effects of Various Cut-Offs in the Greenville Bends, Aug. 26, 1931" (MRC Archives); Vogel, "Research at WES"; "Application of Model Research."
- Largest Model – "Mississippi Basin Model," (Vicksburg: WES, N.D.); Foster, *Mississippi Basin Model*, pp. 40-46; Michael Robinson, "Rivers in Miniature: The Mississippi Basin Model," in *Builders and Fighters: U.S. Army Engineers in World War II* (Fort Belvoir, Va.: CEHO, 1992): 277-293; International Red Cross Report, Camp Clinton, Aug. 27, 1943, Apr. 16, 1944, Mar. 7, 1945; Visit to Prisoner of War Camp, Clinton, Miss., Feb. 23, Aug. 5, Sept. 7, 1944; Edward Peer, Memo on Feb. 10-12, 1944, Visit to Camp Clinton, Mississippi; Swiss Legation Memo; Prisoner of War Labor Report, Jun. 15, Jul. 31, Oct. 15, 1944; Feb. 15, Jul. 31, Nov. 30, 1945; Mar. 13, 1946 (ERDC Archives); On German POW experience, see Arnold Kramer, *Nazi Prisoners of War in America* (Lanham, Md.: Scarborough House, 1996).
- Instrumentation – Billy Joe Peyton, "A History of Hydraulic Instrumentation Used at Waterways Experiment Station, Vicksburg, Mississippi" (Washington, D.C.: Historic American Engineering Record, 1987): 4-56.
- Photogrammetry – *Manual of Photogrammetry*, 2nd ed. (Washington, D.C.: American Society of Photogrammetry, 1952): 1-15; see also, "History of Photogrammetry" (NP: Center for Photogrammetric Training, Ferris State University, ND): 1-13.
- Construction Research – Johnson, 141-144, 161-165, 173, 258, 265, 287-291; Torres, pp. 1-29.
- Fake Weapons – *History of the Development of Camouflage Equipment, IV. Decoys and Dummies* (Fort Belvoir: Historical Staff, The Engineer Board, 1946): op cit.
- Start an Invasion – Quinn, pp. 40-48; Caldwell, Military Intelligence.
- Portable Runways – Joy Pettigrew, "A History of Landing Mat Development, 1940-1975," Oct. 1986 (WES Archives): 1-34, quote p. 2; Michael Robinson, "Landing Mat Development at WES," in *Builders and Fighters*, pp. 195-205.
- Nuclear Technology – *Nuclear Cratering Group*, pp. 1-100; *Activities Summary, FY 1972* (Vicksburg: WES): 39-43; *Activities Summary, FY 1975* (Vicksburg: WES): 48-52.
- Manhattan – William R. Hunt, "Northwest Passage Revisited," *Alaska Sportsman* (Jun. 1969): 24-25; Wright to Resor, Mar. 19, 1969; Poor to Wright, Apr. 17, 1969; Wagner to Haas, Apr. 29 and May 9, 1969; DP, Meeting in Washington at Civil Works Directorate with Humble Oil, Dec. 8, 1969; DP, Telephone Call from Humble Oil, Feb. 27, 1970 (CRREL, Dwr. 3, Fldr. 103-2 Manhattan North Slope of Alaska); Donald Nevel and W.F. Weeks, "The Voyage of the S.S. 'Manhattan,'" *TME* (Mar.-Apr. 1970): 80-82; William D. Smith, "Arctic Divers Faced Death in Icy Waters," *NYT* (Sun., Oct. 19, 1969): 1; Smith, "Study Suspended on Use of North Slope Tankers," *NYT* (Thurs., Oct. 22, 1970): 71, 79; Haas quote from Smith, "Trailbazer in the Arctic: Informal Ships, Historic Mission," *NYT* (Mon., Sept. 22, 1969): M29.
- Designing Wheels – Charles A. Camillo; Cotton, pp.133-135; Fatherree, *Geotechnical Engineering*, pp. 141-144.
- Shaking Things Up – Col. E.S. Townsley to Maj. Gen. D.A. Raymond, May 3, 1971, and attachments; "Biaxial Shock Test Facility: A DOD-Wide Resource" (CERL); "Shaketable Simulates Earthquakes and Shock," *Technology Development and Transfer Report* (Mar./Apr. 1997): 13, 24; Scott quoted in Dana Finney, "CERL device shakes, rattles, rolls," *Engineer Update* (Apr. 1996): 3.

- FESA – Suid, pp. 24-102. Unlike what Suid and others state, Tucker argues conclusively that, “To say that the deaths at SL-1 were caused by anything other than a nuclear accident is patently wrong” (p. 176).
- Salmon – Mighetto and Ebel, pp. 49-128, *Scientific American* quoted on p. 57.
- Woodpecker – Balbach Interview; David K. Delaney et al., *Assessment of Training Noise Impacts on the Red-cockaded Woodpecker: 1999 Results* (Champaign: CERL, 2000): 9- 42; Balbach and Patricia M. Kirby, ed., “Red-cockaded Woodpecker Research at ERDC/CERL” (Champaign: CERL, 2001).
- Wetlands – John Grimson Lyon, *Practical Handbook for Wetland Identification and Delineation* (Boca Raton: Lewis Publishing, 1993): 2-15; Pursell and Willingham, pp. 107- 113, quote on p. 109; COE, “Recognizing Wetlands” (COE: 1998); Interview with Clairain.
- Ice Cap – Wright, pp. 18-21, 33.
- Computer – Clarence W. Kitchens, “Interim Report: Computer, Survey, Electric, IBM, Project 8-35-04-001” (Fort Belvoir: ERDL, 1949): v-10, 20-26, quote on 2; Pennington, pp. 66, 142-144.
- Waterways Fire – Tiffany, *History*, pp. XXII-1-4; Cotton, pp. 93-97; e-mail, Irene Cook to Charles A. Camillo, Feb. 26, 2009.
- Hybrid Models – McAnally et al., *Columbia River Estuary Hybrid Model Studies*, Report 1 (Vicksburg: WES, 1983): quotes on pp. 28-29; Interview with McAnally. See also, McAnally et al., “Columbia River Hybrid Modeling” *ASCE Journal of Hydraulic Engineering* 110:3 (Mar. 1984): 300-311 and “Application of Columbia Hybrid Modeling System,” 110:5 (May 1984): 627-643.
- Pavement – K.P. George, “Return-On-Investment On Paver” (Champaign, Ill.: CERL, 1982); Fact Sheet, “Pavement Maintenance Management Package, Nov. 1979 (CERL Archives); Torres, p. 98.
- Supercomputing – Interview with Radha; Interview with Whalin; “Interesting Facts about the ERDC MSRC.”
- Bosnia Boys – Torrie McAllister, “Corps people at work in Bosnia,” *Engineer Update* (Feb. 1996): 1; “Labs Support Bosnia Peacekeepers,” *Engineer Update* (Mar. 1996): 6-7; Interview with Bush.
- Musseled Out – WES LOY Reports, 1992-1998; Activities Summary, FY 1990-1997.
- 3D Modeling – *Highlights in Computational Science and Engineering* (Vicksburg: WES, 1998): quote on p. 6. 312.
- Recycled Materials – Lampo quoted in Ira Breskin, “Plastic lumber tested,” *Knight-Ridder* (Sun. Nov. 1, 1992); Elaine Sampson, “Experiment replaces wood with longer-lasting plastic,” *Essayons* (Jul. 9, 1998); Richard Lampo, “Federal interest gives recycled plastic lumber a leg up,” *ASTM Standardization News* (Sept. 1996): 27-31, quote on 31.
- Pentagon – Yates quoted in “The Miracle of the Pentagon,” *60 Minutes* (Nov. 28, 2001); Interview with Mosher.
- Wired Up – Andrew G. Roe, “Pulsing Charges Prove Effective Dewatering Tool,” *ENR* (Jun. 24, 2002): 16; Dana Finney, “Electro-Osmosis Dries Wet Areas,” *Installations* (Jan.-Mar. 1998): excerpt; Michael K. McInerney et al., “Using Electro-Osmotic Pulse Technology to Prevent Rising Damp and Moisture Intrusion in Historic Buildings,” *Indoor Environment Connections* (Jun. 2003): excerpt.
- Hurricane – Manders et al., “Rebuilding Hope: Task Force Hope and the U.S. Army Corps of Engineers, Mississippi Valley Division’s Response to Hurricanes Katrina and Rita,” (St. Louis: MVS, 2008): passim; Interview with Mosher; Riley quoted in Sheila Grissett, “Science stronger, Corps chief asserts,” *New Orleans Times-Picayune* (Wed., Dec. 5, 2007): online.
- Unjamming Rivers – Marie Darling, “Ice jams cause severe winter floods,” *Engineer Update* (Jan. 2001): 1-4; Julie Anderson and Joe Kolman, “Ice Jams Costly, Can be Deadly,” *Omaha World-Herald* (Jan. 11, 2001); Ellen Barry, “Breaking the Ice,” *Boston Sunday Globe* (Jan. 28, 2001); Andrew Tuthill, “Winter ice is major problem in locks,” *Engineer Update* (Feb. 2001): 1-3; “District provides technical assistance for ice jams,” *Yankee Engineer* (Feb. 2001): 1-2; “Hanover lab helps Maine in combating spring flooding,” *AP* (Feb. 5, 2001); Steve Grant, “In a Thaw, Gradual is Preferred,” *Hartford Courant* (Mar. 7, 2001): A10; Joe Kolman, “Of ice jams and raging rivers,” *Billings Gazette* (Mar. 12, 2000).



Appendix A

Biographies of Notable Scientists and Engineers¹

John J. Abert, 1814-1861

Col. John J. Abert received an appointment as a U.S. Military Academy cadet in 1808 only to resign in 1811 to serve in the War Department. After service in the enlisted ranks during the War of 1812, he was appointed a topographical engineer with the rank of major in 1814. After the war, he worked on surveys, fortifications, and river and harbor improvements before receiving appointment as Chief of the Topographical Bureau in 1829 and Chief of the Corps of Topographical Engineers in 1838. Under his leadership, the Topographical Engineers improved rivers and harbors, built lighthouses, oversaw a detailed study of the Lower Mississippi River, explored and documented the Western U.S., and conducted numerous military, border, and railroad surveys. He retired in 1861 and died in 1863.

Richard G. Ahlvin, 1949-1980

Richard G. Ahlvin joined WES as chief of the Special Projects Section of the Flexible Pavements Branch after three years of military service and two years as an engineering instructor at Purdue University. He made numerous contributions in construction and design criteria in the fields of foundation engineering, soil and rock mechanics, highway and airfield pavements, earthquake engineering, soil dynamics, and engineering geology. He served as director of the Mid-South Section and president of the Vicksburg Branch of ASCE, was recipient of the Arch T. Colwell Merit Award for contributions to the Society of American Engineers, and was a Distinguished Engineering Alumnus from Purdue University. He retired as assistant chief of the Geotechnical Laboratory in 1980.

Guy L. Arbuthnot, Jr., 1937-1972

Guy L. Arbuthnot, Jr. started his career in the WES Hydraulics Laboratory. After service in World War II, he was assigned to the Mississippi Basin Model where he contributed materially to the design, construction, and operation of the model. In 1951, he transferred to newly initiated explosion effects research and soon became a recognized expert in this field. Under his direction, the program and the team's expertise increased, giving WES a worldwide reputation in the explosion effects field. As chief of the Weapons Effects Laboratory, he served on numerous Defense Nuclear Agency committees; on the Tripartite Technical Cooperation Group involving effects on the U.S., Great Britain, Canada, and Australia; and on the Armed Services Explosives Safety Board.

¹ Given the large number of brilliant scientists and engineers associated with the Corps of Engineers for more than two centuries, it would be impossible to list them all. The individuals in this list represent top researchers identified by each ERDC lab that showed particular brilliance or played an important role in the history of Corps research and development.

Joseph Arthur, Jr., 1934-1938

Col. Joseph Arthur, Jr. was Zanesville District Engineer from 1934 to 1938. Having studied at MIT under soil mechanics pioneer Karl Terzaghi, Arthur was aware of soil issues that could undermine critical projects in the district. During construction of 14 dams on the Muskingum River, Ohio, he established soils and concrete labs in May 1934 and brought in Robert Philippe to head them. The labs proved essential for the success of the project, determining the right soil types and the degree they should be compacted and treated. On completion of the project in 1937, the labs became part of the Ohio River Division Laboratories, which later formed the core of CERL.

Andrew A. Assur, 1953-1991

Born in Estonia and raised in Germany and Poland, Andrew A. Assur received a civil engineering degree in Latvia. He taught at the University of Riga until 1944 when he moved to Hamburg as part of the German Hydrographic Service to avoid the Russian advance. It was here he gained an enduring interest in sea ice, earning his Ph.D. in physics from the University of Hamburg. He relocated to the U.S. in 1951 and gained employment at SIPRE in 1953, where he worked on ice problems encountered in construction of the Distant Early Warning line and conducted sea ice research in Labrador, Greenland, and Antarctica. CRREL assigned him as chief of the Applied Research Branch in 1961 and as Chief Scientist in 1963, a position he occupied until his retirement in 1989. He continued work in ice mechanics, conducting experiments on the *SS Manhattan* in 1970 and publishing major papers on sea ice. In 1972, he served as technical adviser to the Assistant Chief of Engineers on Cooperative Research with the Soviet Union. After retiring, he served as a CRREL consultant until his death in 1991.

Henri Bader, 1947-1961

A Swiss-born U.S. citizen and internationally recognized expert on snow and ice physics, Henri Bader began his relationship with the Corps when it hired Bader, then at Rutgers University, to study the state of polar research in Europe in 1947. Based on his recommendation, the Corps established SIPRE in 1949. He later joined SIPRE in 1953 and became chief scientist, where he led efforts to develop ice core drilling techniques, developed formulas based on Sorge's Law of Densification to date ice cores, and helped to establish Camp Century, Greenland. A member of the National Academy of Sciences committee at the International Geophysical Year in 1957, he helped establish an ice core drilling and studies program in Greenland and Antarctica. In 1961, he left for a position at the University of Miami, where he continued research on glacial ice.

James W. Bagley, 1917-1926

Lt. Col. James W. Bagley started his career as an employee of the U.S. Geological Survey, where he introduced the first improved panoramic camera in 1910 used for surveying Alaska. Bagley worked tirelessly in the years leading up to World War I to track aerial photographic equipment developed in Germany and Austria. When the U.S. entered the war in 1917, Bagley joined the Corps of Engineers as a major and developed the first aerial three-lens camera, patented in 1921. In April 1920, the Corps assigned Bagley to the Aerial Mapping Detachment at McCook Field in Dayton, Ohio, where the U.S. Army Air Service (later the Army Air Corps) conducted tests on using aerial photography in topographical mapping. The detachment later moved to Wright Field. He was the first of six chiefs to head the small detachment of five to ten men that would conduct most photogrammetric research for the Corps of Engineers until 1943. Advancing to the rank of lieutenant colonel, he left the Army in 1926, eventually becoming a lecturer at the Institute of Geographical Exploration at Harvard University. He published the content of these lectures in 1941 in *Aerophotography and Aerosurveying*.

Angel A. Baldini, 1960-1981

Chairman of the Geodesy Department at La Plata University, Argentina, to 1957 and researcher at the Georgetown University Observatory from 1957 to 1960, Angel A. Baldini joined GIMRADA in 1960, where he worked in the field of astro-geodesy. From 1962 to 1969, he developed his Theory of World Geocentric Geodetic System, known as the Baldini Theory, which expressed positions in a common system based on satellite positions against a

star background independent of gravity. Over his career, he published more than 36 reports and papers presented at more than 20 conferences. From 1974, he served as senior scientist at the ETL Research Institute.

James A. Bender, 1949-1972

A researcher, physicist, and chief of the Snow and Ice Research Branch at SIPRE, James A. Bender conducted significant investigations of the properties and methods of construction in ice and snow, contributing to development of ice runways critical for supplying the Distant Early Warning radar stations in 1955. He was also instrumental in the development of construction techniques used at Camp Century, Greenland. At the formation of CRREL in 1961, he became chief of the Research Division, where he served until 1972 when he left to pursue a degree in business.

Arne Bjerhammar, 1963-1967

Born in Bastad, Scania, in South Sweden, Arne Bjerhammar was a professor at the Royal Institute of Technology in Stockholm and geodesist best known for developing matrix algebra with generalized inverses used to determine the geoid. After serving a six-month residence at GIMRADA in 1963, he published seven major reports from 1963 to 1967 related to gravity data reduction and developing a figure of the earth based only on horizontal distances from observation, gravity, and potential differences. He also formulated a concept for an automatic electro-optical satellite triangulation system influencing modern positioning systems. He served as the director of the ETL Research Institute from 1966 to 1967.

George P. Bonner, 1961-1996

After service in the U.S. Marine Corps after 1957, George “Pat” Bonner joined the WES Instrumentation Services Division in 1961 as a physicist, where, other than brief service with the Air Force Weapons Laboratory from 1964 to 1966, he remained until his 1996 retirement. He became chief of the 100-person division in 1982. A pioneer in blast and shock instrumentation, he directed instrumentation efforts on the underground nuclear tests DISCUS THROWER and PIN STRIPE, the MIDDLE GUST explosive experiment, and the first high-explosive simulation test of missile silos. He developed a state-of-the-art self-recording data acquisition package and was the first to use magnetic tape recorders to record explosion experiments at WES.

Spencer J. Buchanan, 1933-1940

A native of Texas, Spencer J. Buchanan graduated from Texas A&M in 1926 with a degree in civil engineering, then went on to graduate studies in soil mechanics at MIT under Karl Terzaghi. In 1933, Spenser accepted a position at WES as head of the Soils Laboratory. Between 1934 and 1940, he introduced modern methods of soils research, publishing his *Manual for the Personnel of the Soil Mechanics Laboratory on Laboratory Procedure in Testing Soils and Sediment* in 1935, and developed close relations among WES, MIT, and Harvard University, taking a leading role in the First International Conference on Soil Mechanics in 1936. In October 1940, Buchanan transferred to the Mississippi River Commission before receiving a commission to serve in the Pacific theater during World War II. After the war, he joined the faculty of Texas A&M University in 1946 as Professor of Soil Mechanics and Foundation Engineering, retiring in 1969. He died in 1982.

Edwin Bucher, 1949-1960

A civil engineer, fellow snow researcher with Henri Bader, and director of the Swiss Federal Institute of Snow and Avalanche Research at Weissflujoch from 1936 to 1949, Edwin Bucher was a SIPRE consultant during its early years. He guided early research, advised establishment of a headquarters near a major university, and helped found SIPRE facilities near Northwestern University, where fellow Swiss researcher, Johannes Weertman, later became a faculty member. His continued recommendation for a stronger snow research program eventually led to the formation of CRREL. He returned to Switzerland in 1953 but continued as a consultant.

Marden B. Boyd, 1956-2000

A graduate of Mississippi State College, Marden “Burton” Boyd joined WES in 1956 working in the Hydraulic Analysis Branch and rising to section chief in the Structures Branch. After earning a graduate degree from Colorado State University in 1967 in hydraulics and mathematics, he became a leading proponent in the use of computers. Over several years, he volunteered much of his personal time to hold educational sessions with coworkers, track technology trends in literature, and help recruit computer-oriented talent. In 1968, he became one of the founding members of the Mathematical Hydraulics Branch – four engineers supervised by Garbis Keulegan to start applying numerical modeling to hydraulic engineering. He directed efforts to develop the Ship/Towboat Simulator and led the study team that developed plans for the Dredged Material Research Program that led to the establishment of the Environmental Laboratory.

Joseph M. Caldwell, 1933-1973

After graduating from Mississippi State University, Joseph M. Caldwell joined WES in 1933, eventually becoming responsible for all hydraulic model testing before leaving for service in World War II in 1942. In 1946, he joined the Beach Erosion Board’s Research Division and became its chief in 1951. There, he was instrumental in establishing hurricane research and emergency beach fill programs, developed scale model testing techniques, researched methods for predicting wave heights, and set standards for constructing deep water ports. After the formation of CERC in 1963, he served as its technical director until 1971, when he left to become chief of the Engineering Division, Civil Works, in the Office of the Chief of Engineers. Among his many accomplishments were to draft legislation for a dam safety national inspection program. He retired in 1973 and died in 1980.

Arthur P. Casagrande, 1935-1981

Arthur P. Casagrande is recognized as the world’s foremost specialist in soil mechanics and foundation engineering and their application to civil works. A student of geotechnical engineering pioneer Karl Terzaghi, he was a Harvard University faculty member from 1932 until his death and a Gordon McKay Professor in Soil Mechanics and Foundation Engineering in 1946. After 1935, he served as a principal consultant for the largest and most complex construction projects undertaken by the Corps of Engineers and a teacher of Corps officers and civilians. Among his many contributions were standardization of the liquid limit device and development of the Unified Soil Classification System. He had an impact on earth and rock fill dam and foundation engineering without parallel in the field of engineering. He died in 1981.

Frederick J. Clarke, 1937-1973

Lt. Gen. Frederick J. Clarke graduated from the U.S. Military Academy in 1937 and received his M.S. in civil engineering from Cornell in 1940. After distinguished service in World War II building airfields, he served in the Manhattan District, Atomic Energy Commission, and Armed Forces Special Weapons Project. He later served as Trans-East District Engineer from 1957 to 1959, as Engineer Commissioner of the District of Columbia from 1960 to 1963, as commandant of the Engineer School from 1965 to 1966, and as Deputy Chief of Engineers before becoming Chief of Engineers from 1969 to 1973. As Chief, he was instrumental in increasing Corps environmental cooperation and research and helping reorganize research and development.

Samuel C. Colbeck, 1970-2000

Known informally as “Dr. Snow,” Samuel C. Colbeck earned a B.S. and M.S. in petroleum engineering from the University of Pittsburg in 1962 and 1964 and a Ph.D. in Geophysics from the University of Washington in 1970. He was employed at CRREL from 1970 to 2000, rising to Senior Research Scientist in 1991 and Chief of the Office of Science and Technology from 1998-1999. Concurrently, he served as adjunct professor of engineering at Dartmouth College from 1981 to 2001. Widely recognized as an expert on snow and ice problems ranging from snowmelt to skiing to glaciology, he was a fellow of the American Geophysical Union and 1980 recipient of the Horton Award, he served as President of the International Glaciology Society, he was an honorary member of the Electromagnetic Academy, and a founding member of the American Association of Avalanche Professionals.

After his retirement in 2000, he served as a consultant on ice safety, skier accidents, and various snow, ice, and hydrology problems.

Leiland M. Duke, 1938-1995

Leiland M. Duke's career spanned more than 57 years of federal service, including 50 at WES, where he was a pioneer in the development and application of instrumentation for coastal and hydraulics structures. Starting as a junior civil engineering aide in 1938, he served in World War II in the Army, Air Corps, and Signal Corps before returning to WES in 1947 as an electrical engineer and chief of the Potamology Section. He was responsible for development, installation, and operation of instrumentation used in the Comprehensive Potamology Study, the WES Relief Well Flow Meter, and the Remote Reading Subsurface Water Velocity Direction Indicator. In 1958, he became chief of the Measurements and Testing Section and in 1970 became chief of the Operations Branch in the Instrumentation Services Division, where he would remain for the next 25 years. Over his long career, he supported data acquisition and control requirements for hundreds of programs and was responsible for instruments installed at Corps structures including the Port Allen Lock, Old River Control Structure, Arkansas River Locks and Dams, Columbia Lock and Dam, and Red River Locks and Dams.

John Q. Ehrigott, 1968-2000

John Q. Ehrigott started his career at WES as a developer of world-class laboratory test devices and facilities to support weapons effects and hardened structures research programs. He eventually ascended to the role of assistant director for the Structures Laboratory. In that capacity he oversaw the expansion of military research and development programs for fundamental weapons effects, response of structures to terrorist and advanced conventional weapons threats, and battlefield protective measures. Ehrigott designed the High-Velocity Projectile Penetration Experimental Facility, a unique ballistic range developed to investigate antipenetration shielding techniques against projectile threats that opened at WES in 1980. Ehrigott died in 2000 while employed at ERDC.

Robert M. Engler, 1973-2005

After graduating from LSU with a Ph.D. in agronomy, Robert M. Engler began his 32-year career in 1973 as a research soil scientist at WES, where he became an expert in the fields of dredged material, flooded soils, sediments, toxic substances, aquatic disposal, and domestic and international regulatory criteria. He authored more than 100 publications and provided numerous technical contributions, including to the London Convention Dredged Material Disposal Guidelines and Corps/EPA Ocean Dumping Implementation Manual. He served as a representative to a number of environmental forums, including international symposia on European and Japanese dredging, International Atomic Energy Agency, EPA's Science Advisory Board, National Research Council committees, and chairman of committees for the International Navigation Association. From 1977 to 2005, he served as a U.S. State Department representative to and from 1988 to 1991 as chairman of the London Convention. From 1996 until his retirement, he served as the first and only Environmental Senior Scientist responsible for setting the technical direction of \$35 million in environmental research. In 2005, he received the Army Meritorious Civilian Service Award and Silver Order of de Fleury medal.

Harold N. Fisk, 1940-1952

A well-known professor of geology at LSU and a researcher for the Louisiana Geological Survey, Harold N. Fisk drew worldwide attention for a series of geological investigations in the 1930s. In 1940, the Mississippi River Commission hired Fisk to conduct various studies on underseepage and sedimentation, leading to his seminal work, *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*, in 1944. The study fundamentally changed modern understanding of the composition and history of the Mississippi River, and brought attention to problems at Old River for the first time. The team he trained in the WES Baton Rouge, Louisiana, field office formed the core of the Geology Branch in the Soils Division in 1948. Fisk continued to serve as a consultant to WES for several years after his departure in 1950 to serve as research geologist for Humble Oil.

Raphael A. Franco, Jr., 1975-2003

After service in the U.S. Army, Raphael A. “Ray” Franco joined the WES Instrumentation Service Division (ISD) in 1975 as an electrical engineer. He went to graduate school at Auburn and Mississippi State Universities and was the first engineer in ISD to achieve a Ph.D. He was the first to use microprocessors, surface-mounted integrated circuits, and programmable logic arrays. He worked on underground nuclear and explosive effect tests. By integrating sensor and recording electronics into a single solid-state package, he was able to eliminate the dependency of cables having to survive harsh explosive environments. This resulted in gathering data that had eluded explosion effect researchers for decades. He developed a miniature shock-hardened recorder to gather data for defeating penetration weapons. The U.S. Air Force recognized his pioneering work, and he helped develop a smart fuse that could count floors and make a decision on when to detonate. He testified as an electrical expert in court for the U.S. Department of Justice and the State of Alabama. In 1997, he was the acting chief of ISD.

Gunther E. Frankenstein, 1954-1991

Before joining SIPRE in 1954, Guenther E. Frankenstein served in the U.S. Army from 1946 to 1948 and worked in the construction industry while earning his B.S. in forestry engineering from Michigan Technical University in 1953. He later earned his M.S. in civil engineering in 1972. An expert on ice engineering in the CRREL Applied Research Branch and later chief of the Ice Engineering Research Branch, he was intricately involved in ice-breaking experiments on board the *SS Manhattan* in 1970 and conducted important research on ice jams, ice buildup on bridges, ice removal, and prevention of ice formation. For efforts on recovery of aircraft in ice and work on the *Manhattan*, he earned two meritorious civilian service awards. He retired in 1991.

John C. Fremont, 1838-1848, 1861-1862

Explorer, politician, and Civil War general, “The Pathfinder” John C. Fremont received a commission in the U.S. Army Topographical Engineers in 1838 after attending the College of Charleston and serving on the *USS Natchez*. From 1838 to 1842, he led expeditions up the Mississippi and Missouri rivers and blazed the path that became the Oregon Trail. From 1842 to 1844, he led expeditions into Utah, New Mexico, and California, documenting the Great Salt Lake, the Sierra Nevada range, and the Alta California basin. His reports to Congress were highly demanded and widely distributed. In 1845, he led California settlers in resisting Mexican rule, sparking the Big Bear Revolt. Heading a battalion during the Mexican-American War, Lt. Col. Fremont defended California. Although later court-martialed for refusing to turn over governorship of California to the lawful agent, after which he resigned his commission in 1848, Fremont went on to serve as one of the first two U.S. senators from California, ran for president in 1856 and 1864, served as major general and commander during the Civil War, and served as governor of the Arizona Territory from 1878 to 1881. He died in 1890.

Robert E. Frost, 1949-1990

Robert E. Frost was a pioneer in interdisciplinary image analysis for engineering, military, and scientific purposes and the co-originator in concept and use of coordinated aerial survey/ground survey procedures. Frost completed all of his education at Purdue University, where in 1946 with his graduate adviser, Donald Belcher, he conceived the idea of air photo interpretation through pattern analysis to support military terrain analysis. With an increase in Purdue’s air photo consulting work, Frost became instrumental in the formation of the SIPRE, one of the forerunners of CRREL. There, Frost applied aerial photo analysis and interpretation techniques to the Arctic regions for pioneering work on siting airfields on the Alaskan North Slope, eight Distant Early Warning sites, and Thule Air Base, Greenland. In the early 1970s, he and seven others transferred to ETL. In 1974, his division took the name Center for Remote Sensing. From 1956 to 1985, Frost participated in more than 20 research projects ranging from mobility research to environmental studies, testified in eight major lawsuits, and developed 86 training courses taken by more than 2,000 personnel. He retired in 1990.

Robert W. Gerdel, 1945-1975

Robert W. Gerdel graduated from Michigan State University with degrees in physics and chemistry and earned his Ph.D. in physics from Ohio State University. He worked more than two decades for the state of Ohio and the Soil Conservation Service, becoming an expert in the impact of the freezing-thawing cycle on soil instability and erosion. In 1943, he moved to Sacramento, California, as the technical lead for the Weather Bureau's Soda Springs Research Project. In 1945 became director of the Cooperative Snow Investigations Research Program with the Corps of Engineers and established the Central Sierra Snow Laboratory in Soda Springs, California. There he pioneered use of isotopic profiling snow gauges to research snowpacks. With the formation of SIPRE in 1949, he went to work for the Corps and soon after became a permanent employee. He continued permafrost and snow research for CRREL as chief of the Environmental Research Branch in 1961, documenting climate change in Greenland using melting ice. He retired in 1965 but continued as a consultant until 1975.

Quincy A. Gillmore, 1861-1888

During the Civil War, Quincy A. Gillmore earned fame and a brevet promotion to major general by reducing fortifications with precision artillery attacks. He avenged the famous "first shot" fired at Fort Sumter, South Carolina, by coordinating the attack that led to the capture of that famous stronghold. Gillmore is considered the preeminent nineteenth-century authority on cementing materials, a reputation established by his landmark book: *Practical Treatise on Limes, Hydraulic Cement, and Mortars* (1863). In 1871, Gillmore developed the first hopper type dredge used in the United States. The following year, he had a key role in building the Cleft Ridge Span in Brooklyn's Prospect Park – the first concrete arch constructed in the United States. In 1879, President Rutherford B. Hayes appointed Gillmore as the first president of the Mississippi River Commission, a position he held until 1888.

William C. Gribble, Jr., 1941-1976

Lt. Gen. William C. Gribble, Jr., was a prominent researcher and manager before becoming Chief of Engineers from 1973 to 1976. After graduating from the U.S. Military Academy in 1941, he served in the 340th Engineer General Service Regiment, where he helped build the Alaska Highway and served in the Pacific theater. He received his M.S. in physical science from the University of Chicago. He later served in the Los Alamos National Laboratory and Atomic Energy Commission and oversaw construction of the Army nuclear power plant at Fort Greely as the Alaska District Engineer. From 1960 to 1961, he headed the Army nuclear power program. He served as director of research and development in the Army Materiel Command from 1964 to 1966 and Army Chief of Research and Development from 1971 to 1973. He also served as commandant of the Engineer School from 1969 to 1970. As Chief of Engineers, he headed major efforts to reorganize Corps research and development. He died in 1979.

Allen F. Grum, 1953-1986

During his brief tenure as the 23rd director of WES from 1985 to 1986, Brig. Gen. Allen F. Grum helped expand the Graduate Institute and played key roles in developing the Information Technology Laboratory and gaining support for establishing a supercomputer center at WES in 1989. He previously served as professor and head of the Department of Engineering at the U.S. Military Academy at West Point for more than 13 years after serving in commands in Korea, France, and Vietnam. He graduated from the U.S. Military Academy in 1953 and earned his M.S. from MIT and his Ph.D. in engineering-economic systems from Stanford University.

Heinz E. Reinhard Gruner, 1931-1936

Born in Berlin in 1897, Heinz Gruner studied photogrammetry under Reinhard Hugershoff at the Technical Institute in Dresden from 1919 to 1923 then went to work under him at the Geodetic Institute of the College of Forestry in 1925 developing photogrammetric recording instruments. After joining U.S. contractor Aerotopograph Corporation in 1928, in 1931 he became the civilian director of the Engineer Detachment at Wright Field, Ohio. During the next five years, he helped advance multi-lens photography, redesign and test stereo-mapping

equipment, and develop new equipment for camera calibration. He participated in aerial reconnaissance missions and high altitude flights to explore aerial equipment under severe environmental conditions. While lecturing widely in the U.S. and Canada, he helped establish the American Society of Photogrammetry in 1934. In 1936, he returned to Germany with Zeiss Corporation, was rescued by the U.S. Army from Soviet occupation, and in 1948 joined Bausch and Lomb and returned to the U.S. He became a U.S. citizen in 1951, retired from Bausch and Lomb in 1967, and died in 1993.

B. Lyle Hansen, 1945-1973

Bernard Lyle Hansen was a pioneer glaciologist, physicist, engineer, inventor, researcher, and author. After receiving a B.S. in physics from Brigham Young University in 1940, he went to work for the U.S. Weather Bureau, first as an instrument engineer and physicist, and later as Director of the Central Sierra Snow Laboratory in Soda Springs, California (1947-1949). As a research associate at the University of Minnesota in 1949, Lyle assisted Henri Bader in establishing the newly formed SIPRE, which he joined as head of the Technical Services Branch. In 1961, he moved to CRREL. During this period, he was instrumental in the design of instruments and equipment for the determination of the physical properties of snow, ice, and frozen ground such as borehole logging, ice sheet dynamics, infrared radiation, and deep core drilling in ice. He headed the CRREL deep drilling program whose crowning achievement was the first ever penetration of the Greenland Ice Sheet in 1966 and the Antarctic Ice Sheet in 1968 for which he received national and international acclaim. He was the Head of the Technical Services Division until his retirement in 1973. He passed away in 2003 at the age of 87.

John W. Harrison, 1967-1999

Assigned as an active duty Army officer to WES in 1967, John W. Harrison was an original member of the Mathematical Hydraulics Branch focusing on the new field of numerical and computer modeling. On leaving active duty, Harrison continued as its first civilian chief. In 1971, he was appointed Special Assistant for Environmental Coordination and Chief of the Office of Dredged Material Research, where he coordinated early environmental research and led the multiyear Dredged Material Research Program. He was instrumental in forming the Environmental Effects Laboratory in 1974, renamed the Environmental Laboratory in 1978, and served as its director until his retirement in 1999. From 1994 to 1996, he also served as the first Executive Director of the Strategic Environmental Research and Development Program, the Department of Defense's flagship environmental research program, and he served as liaison to the Director of Army Research and Technology, Executive Secretary of the Joint Engineer Management Panel for DoD Reliance, and Chairman of the Defense Scientific Planning Group for Environmental Quality Sciences.

Paul Howdyshell, 1965-2009

After several years of work with the Corps, Paul Howdyshell joined CERL in 1969, reaching the position of technical director of Facility Acquisition and Revitalization, where he was responsible for research activities that supported the planning, design, construction, and commissioning for military construction. Over his career he served as division chief, branch chief, and program manager, and conducted extensive research in construction quality control, concrete quality, alternative construction materials, and munitions storage and associated security requirements. He received his M.S. from the University of Cincinnati and a Ph.D. in civil engineering from the University of Illinois at Urbana-Champaign. He was named CERL Researcher of the Year in 1974 and was honored with the Louis R. Shaffer Award of Excellence in 2001.

Robert Y. Hudson, 1936-1971

Robert Y. Hudson served in the WES Hydraulics Laboratory for 35 years, 29 of which he was in charge of all harbor wave action and breakwater stability studies. He was chief of the Waves Water Branch from 1963 to 1971. Through his individual efforts in improving coastal engineering model techniques and procedures and in developing design criteria for coastal structures, he gained world renown as an authority in this field. For his work,

he received numerous awards, including the Society of American Military Engineers George W. Goethals Medal in 1972.

Andrew A. Humphreys, 1831-1879

Brig. Gen. Andrew A. Humphreys was a notable topographic engineer, Civil War general, and Chief of Engineers. He graduated from the U.S. Military Academy in 1831 and served in the Seminole War. After a hiatus from the Army from 1836 to 1838, he joined the Topographical Engineers, where he supervised harbor improvements, designed the first expansion of the U.S. Capitol Building, and led a survey of the Mississippi River Delta from 1850 to 1861 that resulted in a highly influential report on the river's hydrology and established a plan for flood control. He also headed the Office of Pacific Railroad Explorations and Surveys from 1854 to 1861. After a distinguished career during the Civil War, he became Chief of Engineers from 1866 to 1879. He established the Engineer School of Application and oversaw substantial expansion of the Corps' river and harbor work. He was one of the "original fifty incorporators" of the National Academy of Sciences. He died in 1883.

Mikael Juul Hvorslev, 1947-1976

Juul Hvorslev retired in 1976 after 29 years of service as a consulting engineer for the WES Soils and Pavements Laboratory. A graduate of the Technical University of Denmark, he worked on design and construction of dams, hydropower, and water supply projects in California, Washington, and Columbia, South America, for ten years. After visiting hydraulic laboratories in Europe, he engaged in soil mechanics research. He studied under Karl Terzaghi and received a Ph.D. at the Technical University of Vienna in 1936. On his return to the U.S., he became the Soils Mechanics and Foundations research engineer for ASCE and research fellow at Harvard University. His research in obtaining undisturbed soil samples culminated in the comprehensive, world-renowned, and frequently republished report, "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes." He is author or coauthor of 13 other publications dealing with cone penetrometer tests, soil sampling and testing, and methods and theories for determination of pore water pressures and soil permeability in procedures and understanding of soils sampling, and in fundamental knowledge of the shear strength of soils.

Leo F. Ingram, 1950-1982

Leo F. Ingram retired in 1982 after 36 years of federal service, 32 of which were at WES. As chief of the Explosion Effects Division, Structures Laboratory, he demonstrated exceptional technical leadership coupled with effective management ability. He was known internationally and was actively sought out for his advice. He served as technical director of the MINESHAFT series of explosion tests in 1968 conducted by the Defense Nuclear Agency (DNA) near Cedar City, Utah. He was also an adviser to DNA and sat on numerous panels to analyze complicated test results and to plan explosion tests to fulfill Army and DoD objectives.

James R. Jefferson, Jr., 1959-1989

A computer scientist in the Information Technology Laboratory, James R. Jefferson, Jr., developed sophisticated software systems for WES and other Corps offices and showed exceptional expertise in assembler languages for multiple hardware architectures. He took initiative to learn new programming languages and machine architectures without training. He served as principal investigator on projects for the Detroit and Alaska Districts, the Ohio River Division, and HQUSACE. As the first African-American professional at WES, he was a counselor, mentor, and father figure for many who followed and served in an official capacity for many years as EEO Counselor.

Douglas W. Johnson, 1929-1930

A professor of geology at Columbia University, Douglas Johnson authored a series of studies on coastal erosion that examined sea level change and coastal stability as factors for erosion, including his 1919 book *Shore Processes and Shoreline Development*. In 1924, he was instrumental in forming the Committee on Shoreline Studies under the National Research Council, serving as its first chairman. In 1929 Johnson joined the Board on Sand Move-

ment and Beach Erosion, on which he served until formation of the Beach Erosion Board in late 1930. During this time, he helped prepare plans for field studies involving more than 30 experiments, including measurements of waves, winds, currents, tides, beach profiles, sand samples, and tracer studies at Long Branch and Seaside Heights, New Jersey. Under his guidance the board made a catalog of groins and other structures between Sandy Hook and Cape May. Although he only served with the Corps briefly, he contributed greatly to its understanding of coastal erosion and helped guide the Corps in developing a beach erosion research program.

John W. Keeley, 1971-2001

John W. Keeley started his career as a research ecologist at WES in 1971 and shortly became program manager for Aquatic Disposal in the Dredged Material Research Program. In 1973, he was assigned as Special Assistant to the Director for Program Development, where he played a key role in the development of the Environmental Effects Laboratory and recruitment of environmental researchers. From 1979 to 1999 he served as assistant director and from 1999 to his retirement in 2001 as acting director of the Environmental Laboratory, during which he helped establish work for the lab and developed facilities to support it. He also led a multidiscipline team on water quality that evolved into the eight-year Environmental and Water Quality Operational Studies. He received numerous awards, including the Engineer Regiment de Fleury Medal, three Army Meritorious Civilian Awards, and the Army Decoration for Exceptional Civilian Service.

Garbis H. Keulegan, 1962-1988

Born in Armenia in 1890, Garbis H. Keulegan achieved near legendary status at WES. After graduating from Anatolia College in 1910, he immigrated to the U.S. He earned two degrees from Ohio State University and worked initially at Westinghouse Electric before volunteering for service in World War I. He became a U.S. citizen in 1918, joined the National Bureau of Standards, completed his Ph.D. in physics from Johns Hopkins University in 1928, and became a founding member of the National Hydraulic Laboratory in 1932. Conducting studies on conduits, open channel flow, waves, wind action, viscosity, and saltwater intrusion for WES and others, his work summarized in *Laws of Turbulent Flow in Open Channels* established both his reputation and that of the lab. After his retirement in 1962, he joined WES as a retired annuitant and consultant on three conditions: he would work on only what interested him, only when inclined, and only if there was a green tree outside his window. During his tenure, he helped lead adoption of numerical modeling, worked on many projects, and won multiple awards, including election to the National Academy of Engineers. He retired in 1988 at age 98 and died less than a year later.

Chester C. Langway, Jr., 1956-1975

A researcher at SIPRE and CRREL since 1956, Chester C. “Chet” Langway participated in and was responsible for field and laboratory ice core research, core sample storage, and scientific redistribution of ice core samples. After earning his Ph.D. from the University of Michigan in 1965, Langway served as chief of the Snow and Ice Research Branch of the CRREL Research Division from 1966 to 1975. Under the leadership of Henri Bader and in cooperation with Lyle Hansen, W. Dansgaard, and H. Oeschger, his work helped to introduce the new field of polar ice core science and revolutionized modern understanding of paleoclimatology and climate change. In 1975, he joined the faculty of the University at Buffalo, New York, where he continued ice core research. He retired in 1994.

Willard N. Lappin, 1945-1973

After graduating with a B.S. in chemical engineering from the University of Iowa in 1933, Willard N. Lappin entered service with the Corps of Engineers during World War II and in 1950 began work as a chemist for the Rock Island District. When he retired in 1973, he was chief of the Paint and Corrosion Laboratory (afterwards the Paint Technology Center at CERL), which developed paint for the lock and dam systems of the Mississippi, Missouri, Ohio, and Columbia rivers. During his tenure, he was instrumental in standardizing use of V766, the first long-lasting vinyl paint developed for hydraulic structures, estimated in 1968 along with other research to have saved the Corps more than \$1.2 million per year.

Robert D. Leighty, 1956-1992

Robert D. Leighty began government service with the Corps in 1956 performing photo interpretation research under Robert Frost at SIPRE. In 1970, he transferred with the Photo Interpretation Research Division to the ETL, joined the ETL Research Institute in 1971, and became its director in 1983. His innovative research included applying emerging technology to the problem of extracting terrain information from aerial photography. He initiated ETL's program in coherent optics and artificial intelligence. He pioneered new concepts in computer-assisted photo interpretation research and initiated work in computer image generation and terrain visualization. He expanded programs with DARPA and was instrumental in formulating the DoD Strategic Computing Program.

Lewis E. Link, 1968-2009

After completing his B.S. at North Carolina State, Lewis "Ed" Link began his career as a geophysical engineer at WES in 1968. He received his M.S. from Mississippi State in 1973 and a Ph.D. from Pennsylvania State in 1976 while progressing to assistant chief of CERC in 1983; chief of the Environmental Systems Division, Environmental Laboratory in 1984; and director of CRREL in 1986. In 1996, he became director of Research and Development at HQUSACE, where he spearheaded efforts to reorganize Corps laboratories as ERDC. From 1999 to 2000, he served as the acting director of ERDC. After his retirement in 2002, he served in various consulting positions before taking a position as Senior Research Engineer at the University of Maryland in 1995. The same year, the Corps appointed him the president of the Interagency Performance Evaluation Task Force investigating performance of Corps works after Hurricane Katrina, where he served with distinction through 2009.

Stephen H. Long, 1808-1863

Col. Stephen H. Long was an explorer, engineer, inventor, and military officer. He led expeditions through the American West in areas acquired in the Louisiana Purchase following the Lewis and Clark Expedition. After graduating from Dartmouth College in 1808, he taught mathematics at the U.S. Military Academy and led a series of scientific explorations, covering 26,000 square miles in five expeditions. Among his accomplishments were exploring the Great Plains (which he famously described as the "Great American Desert"); discovering the sources of the Red, Platte, and Arkansas rivers; and establishing the 49th parallel as the northern border of the U.S. He served as the chief engineer for western river improvements, was the chief surveyor of most western railroads, and from 1861 to 1863 served as the last Chief of Topographical Engineers.

William McAnally, 1969-2001

William McAnally joined WES after graduating from Arizona State University in 1969 as part of the Nuclear Weapons Effects Division. In 1971, he moved to the Estuaries Branch of the Hydraulics Division. He was a leading proponent of computing in estuary modeling. While studying under Emmanuel Partheniades at the University of Florida, from which he graduated with an M.S. in 1973, he began to experiment with hybrid modeling. From 1974 to 1976, he helped to develop hybrid physical and numerical models of Kaneohe Bay, Hawaii; Los Angeles Harbor, California; and Columbia River, Washington. In addition, in 1984 he helped to spearhead the development of the TABS-2 application, the first application to provide sophisticated 2-D models of complex river sedimentation later used for modeling the Atchafalaya Bay. He would later play a role in the development of the super flume built by ERDC in 2001.

Jerome L. Mahloch, 1974-2000

Jerome L. Mahloch began his career with the Corps in 1974 as Special Assistant in the Environmental Engineering Division, Environmental Laboratory. From 1977 to 1988, he served as program manager for the \$30 million Environmental and Water Quality Operational Studies, in which he developed technology transfer procedures used widely today in the Corps. He oversaw development of and helped transfer the Site Characterization and Analysis Penetrometer System, which saved millions of dollars in remediation costs. In 1988, he joined the Information Technology Laboratory, where he led software development efforts that led to the subsequent creation of the Corps of Engineers Financial Management System (CEFMS). In 1992, he became Special Assistant to the

director of WES on CEFMS, and from 1994 to 1999 served as Program Manager and Deployment Officer for the CEFMS deployment team. He personally wrote hundreds of scripts to ensure the integrity of CEFMS and directed consolidation of four CEFMS databases during the standup of ERDC.

William F. Marcuson, 1970-2000

William F. Marcuson started his career at WES as an Army captain, where his work on liquefaction, soil dynamics, and microseismic wave propagation resulted in changes to Corps design guidance that saved millions of dollars. In 1981, he became director of the Geotechnical Laboratory. As leader of the Project Reliance Civil Engineering Team, he guided development of tri-services plans for 29 technology areas. He served on numerous committees for the National Science Foundation, National Research Council, and National Academy of Engineers. He was instrumental in developing the world's most powerful centrifuge at the Army Centrifuge Research Center in 1995. In 1997, he received the ASCE Norman Medal and in 1999 delivered its Terzaghi Lecture. After his retirement in 2000, he continued as Director Emeritus of the Geotechnical Laboratory and in 2006 served as president of ASCE.

Bryant Mather, 1941-2000

Known informally as "Captain Concrete," Bryant Mather began his career soon after graduating from John Hopkins University with a degree in geology working part-time for the U.S. Geological Survey. On passing the civil service exam, he began federal service in 1941 with the Central Concrete Laboratory at the U.S. Military Academy at West Point, then part of the Corps North Atlantic Division. In 1946, he joined WES, retiring as the Director of the Structures Laboratory in 2000. Over his nearly 60-year career, he authored or co-authored more than 600 technical papers or reports. In 1978, he received an honorary doctorate from Clarkson University. In addition to being an internationally recognized concrete expert, in his spare time he studied the butterflies and moths of Mississippi, documenting more than 120 species. Seven species of insects were given the name *matheri* in his honor. After his retirement, he served as Director Emeritus of the Structures Laboratory, where he continued to publish and participate in technical societies until his death in 2001.

Malcolm Mellor, 1959-1991

Born in England and educated in Ireland, Malcolm Mellor was employed in the Australian Antarctic Division while earning his M.S. from Melbourne University. In 1959, he began work as a contractor for SIPRE, switching to full-time employment in 1961. A prolific writer, he published more than 150 papers on avalanches, snow and ice mechanics, drifting snow, sea ice, ocean engineering, drilling, tunneling, explosives, and excavation, all while earning a Ph.D. in engineering from Sheffield University and a Ph.D. in science from Melbourne. He died in 1991.

Donald L. Neumann, 1957-1980

Donald L. Neumann pioneered the application of computer technology in scientific and engineering design and analysis. Having earned a civil engineering degree from the University of Illinois, he entered the Junior Engineering program at St. Louis District in 1955. When IBM announced its 650 computer, Neumann learned computer programming. In 1957, WES invited Neumann to establish the Shared Computer Center in Vicksburg. Following the devastating fire of 1960 that destroyed the entire WES library and computer center, Neumann and his staff obtained replacement parts for the damaged IBM 650 computer and returned the center to operation at a temporary location within 10 days of the fire. Neumann continued as director of the WES Computer Center through 1980 where he and his staff contributed more than 65 engineering design and analysis programs to the engineering community. Upon his retirement in 1980, Neumann became the chief technology officer for DATA-PAK, Inc.

Morrrough P. O'Brien, 1929-1978

The Board on Sand Movement and Beach Erosion hired Morrrough P. O'Brien, then assistant professor of mechanical engineering at the University of California at Berkeley, in 1929. With the formation of the Beach Erosion Board in 1930, O'Brien continued examination of the Pacific Coast, which resulted in the 1931 seven-volume *Report on Sand Movement and Beach Erosion along the Pacific Coast of the United States* and, among other things, documented the existence of littoral drift. At the same time, he developed what became the preeminent graduate and research program for coastal engineering at UC. In 1938, the board offered O'Brien, now department head and later dean, a position as civilian member of the board. He would serve on the board and with CERC for the next 40 years. During his time with the board, O'Brien published numerous technical reports, with his most important work on oscillatory waves in 1941. When CERC formed in 1963, O'Brien continued in that organization and served also on the Coastal Engineering Research Board until his retirement in 1978.

Thomas R. Patin, 1967-2005

After graduating from the University of Southwestern Louisiana with a degree in agricultural engineering, Thomas R. Patin began his career at the Environmental Effects Laboratory at WES in 1973, where he became an expert in the beneficial uses of dredged material. From 1973 to 1980, he served as assistant program manager in the areas of habitat development and beneficial uses. From 1980 to 1990, he served in the Dredging Operations Technical Support Program and Long-Term Effects of Dredging Operations Program, which provided support for dredging projects in 500 harbors and 25,000 miles of waterways in the Corps navigation program. He was a member of the Western Dredging Association, International Navigation Association, and Dredging Operations and Environmental Research Program and served as delegate to the Joint International Exchanges with the Netherlands and Japan. From 2001 to 2004, he served as the acting deputy director of the Environmental Laboratory and retired in 2005.

Margaret Petersen, 1947-1952, 1964-1977

Margaret Petersen began her career with the Rock Island District as a draftsman in 1942. After graduating from the University of Iowa with a B.S. in civil engineering, she took a job at WES in 1947. From 1947 to 1949, Petersen reviewed and analyzed hydraulic, hydrographic, and topographic data for designs of testing programs and headed several research projects. In 1949, she became the first female administrator in the Corps, reaching the position of Chief, Research Sub-Section, Mississippi Basin Model Operations. After leaving WES from 1952 to 1964, she returned as chief of the Water Waves Branch before moving on to the Sacramento District. After her retirement in 1977, she taught at the University of Arizona, publishing *River Engineering* in 1986. In 1987, the University of Iowa awarded her the Distinguished Alumni Achievement Award, and in 1990, she became the second woman given honorary membership in ASCE. She retired in 1997, but continued to serve as a guest lecturer worldwide.

Robert R. Philippe, 1934-1968

Having studied at MIT under Karl Terzaghi, the father of geotechnical research, Robert R. Philippe became director of the Zanesville District Soils Laboratory in 1934, moved to the Ohio River Division Laboratories in 1941, and became its director in 1946. In this capacity, he led rigid pavement research efforts at ORDL during World War II. In 1950, he transferred to the Office of the Chief of Engineers as the chief of the Special Engineering Branch, where he helped establish research efforts in Greenland and the Antarctic. In 1962 to 1968, he served as chief of the Environmental Sciences Branch in the Army Materiel Command Research and Development Directorate.

Narayanaswamy Radhakrishnan, 1968-1999

N. Radhakrishnan (known as Dr. Radha) was born in India and received his B.S. and M.S. at the Technical Institute of Bombay before immigrating to the U.S. and receiving his Ph.D. in civil engineering in 1969 at the University of Texas. Immediately on his graduation, he went to work as a Research Civil Engineer in the Automated Data Processing Center at WES, where he served as a consultant and project manager aiding researchers in

developing numerical models. In 1976, he initiated the Computer Aided Structural Engineering effort to develop and standardize structural engineering applications. In 1983, he became chief of the Automation Technology Center and in 1986 became the first director of the Information Technology Laboratory and CIO of WES. During his tenure, he was instrumental in starting the DoD High Performance Computing Shared Resource Center at WES, developing the Tri-Services CADD/GIS Technology Center, overseeing efforts to update engineering manuals, and growing the lab's research program to more than \$110 million per year. On leaving WES in 1999, he served as director of the Computational and Information Sciences at the Army Research Laboratory and became Vice Chancellor for Research at North Carolina A&T State University in 2003.

Jack N. Rinker, 1957-1992

Jack N. Rinker conducted exploratory and basic research in remote sensing and associated technologies for over 40 years of federal service. He served as subject matter expert for remote sensing, spectral sensing, and terrain analysis science and technology programs. After World War II service in the U.S. Navy, he completed his education at Purdue University completing a Ph.D. in Bacteriology in 1957. He joined the Photo Interpretation Research Branch of SIPRE where he developed remote sensing and image analysis techniques for military and civil applications. He went on to conduct research and development on a wide range of remote sensing technologies (photo, infrared thermal, radar, multispectral, hyperspectral) and to teach these subjects to Army and Air Force teams. He came to ETL in 1977 to serve as team leader on the remote sensing group that by 1992 had expanded into the Center for Remote Sensing in the Research Institute. The *Remote Sensing Field Guide – Desert* and online guide produced by this group remains the authoritative source on desert terrain.

Roger T. Saucier, 1961-1999

Roger T. Saucier, one of the most influential geologists of the twentieth century, began his career work at the Coastal Studies Institute at Louisiana State University in 1952. In 1961 he became a research geographer in the Soils Division at WES, while continuing his education, eventually earning his Ph.D. in Geography and Anthropology in 1968. In 1974, he transferred to the WES Environmental Laboratory, where he spent the remainder of his career mapping the alluvial deposition and soils in the lower Mississippi Valley, conducting engineering, liquefaction, and geologic investigations, and providing geomorphological data for numerous cultural resource studies. In 1994, Saucier published *Geomorphology and Quarternary History of the Lower Mississippi Valley*, a synthesis of the broad spectrum of geologic and geomorphic information that he had collected throughout his career that revealed the complex story of the development of the region. Saucier passed away in 1999.

Thorndike Saville, Sr., 1929-1963

In 1929, the Corps appointed Thorndike Saville, Sr., then professor of hydraulic and sanitary engineering at the University of North Carolina and Chief Engineer of the North Carolina Department of Conservation and Development, as an adviser to its Board on Sand Movement and Beach Erosion. He had previously conducted numerous studies for the State Board of Health and Geological and Economic Survey. In 1930, he became a permanent member of the Beach Erosion Board, where he guided the development of Corps coastal research until 1963. In 1947, he became dean of engineering at New York University and chairman of the ASEE Engineering College Research Council. He died in 1969.

Thorndike Saville, Jr., 1949-1981

Son of the prominent Beach Erosion Board member, Thorndike Saville, Jr., graduated with a B.S. in physics from Harvard University in 1947 and an M.S. in hydrological engineering in 1949. After conducting a study of sediment transport for the Navy in 1949, the Corps hired him as a researcher for the Beach Erosion Board, where he conducted pioneering work in wave hindcasting and run-up. He served as technical director of CERC from 1973 to 1981, retiring after 32 years of service. He is a recipient of the Huber Research Prize and the Moffatt-Nichol Harbor and Coastal Engineering Award from ASCE. In 1977, he was elected to the National Academy of Engineers.

William D. Severinghaus, 1976-2009

William D. "Bill" Severinghaus joined CERL in 1976 after earning an M.S. from Memphis State University in 1969 and a doctorate from the University of Illinois at Urbana-Champaign and in mammalian systematics. His early work focused on contributions to the environmental impact computer system and research on cause-and-effect relationships of training impacts on small mammals and birds, which led to his managing development of the Integrated Training Area Management program, the land management suite of tools used throughout the Army. An internationally recognized ecologist, he served on the NATO Committee on Challenges to Modern Society and has received research awards from the American Society of Mammalogists and the North America Ornithological Society. He retired as a technical director in the Environmental Quality/Installations business area.

Louis R. Shaffer, 1969-1994

After receiving his B.S. in engineering from Carnegie Mellon University in 1950 and M.S. and Ph.D. degrees in civil engineering from the University of Illinois at Urbana-Champaign, Louis R. Shaffer served as professor from 1957 until his appointment as technical director of CERL in 1969. From 1961, he was responsible for building the Department of Civil Engineering's academic program, recognized as one of the most outstanding in the country. An author of more than 50 articles, papers, and texts on construction engineering and management focusing on the systems approach, operations research, and computer applications, he was a widely recognized expert on construction research and served on the NAS Building Research Advisory Board that advised the Corps of Engineers on the formation of CERL. In 1991, he received the Carnegie Mellon Alumni Achievement Award. He served as technical director then director of CERL until his death in 1994.

Woodland G. Shockley, 1938-1980

Woodland G. Shockley joined WES in 1946 after working eight years for the Soils and Pavements Section of the Little Rock District of the U.S. Army Corps of Engineers. He served in various supervisory capacities until he was appointed chief of the Mobility and Environmental Division in 1963, which later became the Mobility and Environmental Systems Laboratory. The laboratory studied the effects of environmental parameters on all military activities, including mobility. During Shockley's tenure, he initiated, managed, and supervised technical programs that supported Army civil works and military projects for the Corps, DARCOM, Air Force, NASA, Navy, and other federal agencies. In 1978, Shockley was appointed to a special staff position as Program Manager for Military Engineering, the position from which he retired in 1980. He continued to actively support the American Society for Testing Materials and ASCE. He is listed in *Who's Who in Engineering* and in *American Men of Science*.

Henry B. Simmons, 1940-1984

Henry B. Simmons was one of the foremost U.S. authorities in the field of tidal hydraulics. During his career, he was responsible for developing most instruments, techniques, and operating procedures used in physical estuary modeling. He personally perfected resistance elements used to reproduce the vertical and lateral distribution of current velocities and salinities, leading to capabilities for studying saltwater intrusion, diffusion, dispersion, and flushing of pollutants. Under his leadership as chief, the Hydraulics Laboratory expanded mathematical modeling through establishment of the Mathematical Hydraulics Branch and initiated the first programs to investigate physical aspects of water quality in reservoirs that formed the bases for the Environmental and Water Quality Operational Studies Program. He was also involved in the conception of the Dredged Material Research Program. He authored more than 80 technical publications and received numerous awards before his retirement in 1984.

Russell F. Theriot, 1974-2004

A native of Louisiana, Russell F. Theriot earned an international reputation for research in wetland delineation and functional evaluation, biological control technology for pest management, and aquatic plant control. After receiving a B.S. in wildlife management in 1972 and an M.S. in botany in 1974 from Northwestern State University, he began his career as a wetlands biologist for the Florida Department of Natural Resources. In 1976, he transferred to the WES Environmental Laboratory and served on several national and international committees

involving aquatic and wetland ecosystems research. In 1992 Theriot earned his Ph.D. in aquatic and wetland ecology from the University of Florida. The following year, he served on the White House Office on Environmental Policy Committee, an interagency group that addressed legitimate concerns with federal wetlands policy. In this capacity, he helped to develop the Clinton Administration Wetlands Plan, which streamlined the wetlands permit program, responded to concerns of farmers and small landowners, and improved protection and restoration of wetlands. Theriot retired from ERDC in 2004, while serving as director of the Wetlands Research and Technology Center. He died in 2008.

William A. Thomas, 1957-1993

Throughout his 35-year career, William A. Thomas was a pioneer in numerical river and sediment transport modeling. After gaining a reputation for developing computer models at the Corps Hydrologic Engineering Center, California, he transferred to WES in 1977 as part of the Hydraulic Mathematical Division and served as a senior research hydraulic engineer in the Hydraulics Laboratory until his 1993 retirement. In 1985, the University of Iowa listed his HEC-6 code as one of the “Ten River Engineering Achievements that Shook the World.” He was the principal developer of the widely used TABS-2 sediment model and led development of the SAM model for small flood control projects. In 1993, he received the coveted ASCE Hans Einstein award, held at the time by only six researchers worldwide.

Joseph G. Totten, 1808-1864

After graduating from the U.S. Military Academy in 1805 and serving briefly as a surveyor, Joseph G. Totten reentered the Corps of Engineers in 1808 and served with distinction during the War of 1812. As a member of the Board of Engineers for Coastal Defense from 1816, he experimented widely with concrete and other fortification and construction technologies. Appointed Chief Engineer in 1838 and promoted to Brigadier General, he served in that position until his death in 1864, providing leadership during the Mexican War and Civil War. He was a regent of the Smithsonian Institute and cofounder of the National Academy of Sciences.

Willard J. Turnbull, 1941-1968

Willard J. Turnbull assumed leadership of the WES Soils Division in 1941 when soil mechanics was in its infancy. During his tenure and as a direct result of his managerial and technical expertise, the Soils Division tripled in size both in personnel and budget. The most noteworthy achievement developed under his direction was the Corps method for flexible pavement design, which has been used more on a worldwide basis than any other method. He was an active member of many professional societies, and his outstanding achievements have been recognized by the Secretary of the Army and Secretary of Defense and by his receipt of an honorary Ph.D. in civil engineering from the University of Nebraska.

Charles Linwood Vincent, 1974-1999

After receiving a B.A. in mathematics and M.S. and Ph.D. in environmental sciences from the University of Virginia from 1969 to 1973, Charles Linwood Vincent began a 25-year professional career as a research physical scientist at WES in 1974, eventually becoming chief of the Coastal Branch in the Hydraulics Laboratory working on coastal wave climates and tidal inlets. He transferred to CERC at Fort Belvoir, Virginia, and moved back to WES in 1983, becoming Senior Scientist for Coastal Hydrodynamics in 1991. In 1999 he accepted a position at the Naval Research Laboratory as a Navy Senior Scientist for Nearshore Hydrodynamics, eventually rising to Director of Ocean, Atmosphere, and Space Research with appointment to Senior Executive Service in 2007. He received the Walter L. Huber Prize of the ASCE in 1984. He received the U.S. Army Decoration for Meritorious Civilian Service in 1989.

Herbert D. Vogel, 1929-1954

The first commander of WES, Herbert D. Vogel graduated from the U.S. Military Academy in 1924, received an M.S. from the University of California at Berkeley in 1928 and earned his Ph.D. from the *Technische Hochschule*

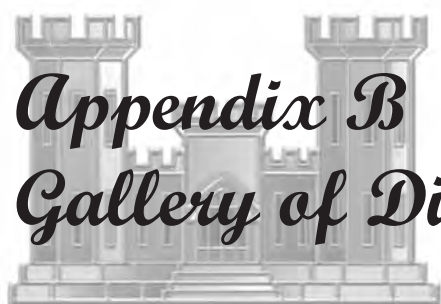
in Berlin in 1929. Immediately on his return to the U.S., he received assignment to WES. Although only a lieutenant, he was responsible for planning and construction of the facilities, recruitment of employees, and attracting projects. When he left in 1934, WES had more than 200 employees and some 20 active projects. Vogel later served as an instructor at Fort Belvoir, Virginia, and as the Pittsburg District commander until 1939. During World War II, he rose to the rank of brigadier general as the Chief of Staff to the Sixth Army, where he planned logistics for the invasions of Leyte and Japan. After the war, he served as the Buffalo District commander, lieutenant governor of the Panama Canal, Mississippi River Commission member, and the Southwest Division commander. He retired from the Army in 1954, after which he served as Chairman of the Board of the Tennessee Valley Authority until 1962. He died in 1984.

Robert W. Whalin, 1967-1998

During his 31-year career, Robert W. Whalin served in positions ranging from branch and division chief to the last technical director of an independent CERC to the first civilian director of WES. As chief of the Wave Dynamics Branch and Division and director of CERC, he championed coastal research and numerical modeling while guiding relocation of CERC to WES. As technical director and director of WES from 1985 to 1998, he grew the research program from \$100 million to \$350 million, expanded its Graduate Institute, improved recruiting and retention, established the Information Technology Laboratory, and sought the best equipment and facilities to keep WES at the forefront of research. He was instrumental in establishing the first Department of Defense High Performance Computing Center, Army Research Centrifuge, Mobile Ballistic Research System and Projectile Penetration Facility, Heavy Vehicle Simulator, Hazardous Waste Research Center, the TeleEngineering Operations Center. Under his leadership, WES received four Army Research and Development Organization of the Year and many other awards.

Jonathan Williams, 1801-1812

A grandnephew of Benjamin Franklin, Col. Jonathan Williams was the first Chief Engineer of the permanent Corps of Engineers and first Superintendent of the U.S. Military Academy at West Point, New York. As a companion to Franklin and commercial agent from 1770 to 1785 and a member of the American Philosophical Society after 1788, he wrote widely about scientific subjects. Appointed as a major in the Corps of Artillerists and Engineers and the Army's inspector of fortifications in 1801, President Thomas Jefferson selected him as Chief Engineer and Superintendent in 1802. He was instrumental in establishing scientific education in the Corps and founded the U.S. Military Philosophical Society. He later served as a Pennsylvania congressman from 1814 until his death in 1815.



Appendix B

Gallery of Distinguished Civilians

Hanover, New Hampshire, Campus¹

Dr. George Swinzow
Dr. Jerry Brown
Eunice V. Salisbury
Stephen L. Pike
Lillian G. Meier
Kenneth A. Linell
James R. Hicks
B. Lyle Hansen
Robert W. Gerdel
Francis C. Gagnon
W. Keith Boyd
Sandra J. Smith
Dr. Lewis E. "Ed" Link, Jr.
John H. Rand
Dr. Devinder S. Sodhi
Walter B. Tucker III
Dr. Samuel C. Colbeck, Jr.
Ben Hanamoto
Dr. Wilford F. Weeks
Frederick E. Crory
J. Frank Paul
Wayne N. Tobiasson
Rodney F. Poland, Jr.
Donald E. Garfield
Albert F. Wuori
Stephen L. Bowen
Barbara L. Ragan
Dr. Andrew Assur
Edward F. Lobacz
Paul V. Sellmann
Herbert T. Ueda
Dr. Malcolm Mellor

Arnold R. Goerke
Thomas L. Marlar
Gilbert A. Currier
Edward F. Lutz
Michael A. Billelo
Sylvia A. Marsters
John F. Linehan
Guenther E. Frankenstein
Sherwood C. Reed
Dr. Anthony Gow
Stephen F. Ackley
Donna R. Valliere
Edward W. Perkins
Dr. George D. Ashton
Louise E. Judd
Dr. Ronald A. Liston
Armando J. Roberto, Jr.

Humphreys Engineering Center, Virginia, Campus

William C. Cude, 1970
John T. Pennington, 1970
Randall D. Esten, 1971
Melvin C. Shetler, 1972
Robbins G. Hickson, 1974
Gilbert G. Lorenz, 1976
James W. Halbrook, 1983
Robert G. Livingston, 1984
Robert P. Macchia, 1988
Lawrence F. Ayers, 1989
Howard O. McComas, 1990
William H. Carr, 1991
Robert D. Leighty, 1992
Walter E. Boge, 1998
George N. Simcox, 1998
F. Raye Norvelle, 1998
Jack N. Rinker, 2008

¹ The Champaign, Illinois, Campus did not maintain a distinguished civilian gallery. Other sites varied in data maintained.

Olin W. Mintzer III, 2008

Robert E. Frost, 2008

Vicksburg, Mississippi, Campus

George W. Vinzant, 1943-1965

Frank J. Musil, 1930-1960

Charles R. Warndorf, 1932-1957

George B. Fenwick, 1933-1965

Thomas B. Kennedy, 1946-1965

William L. Bache, Jr., 1946-1966

Frank B. Campbell, 1951-1967

Audley A. Maxwell, 1936-1969

Willard J. Turnbull, 1941-1969

Joseph B. Tiffany, Jr., 1933-1969

Eugene P. Fortson, Jr., 1932-1970

Katharine H. Jones, 1940-1972

Guy L. Arbuthnot, Jr., 1937-1972

Luther C. Marsalis, Jr., 1946-1972

Robert Y. Hudson, 1937-1972

John J. Franco, 1933-1973

Thomas E. Murphy, 1935-1973

Charles R. Kolb, 1949-1973

John J. Kirschenbaum, Jr., 1935-1973

Mikael J. Hvorslev, 1947-1976

Stanley J. Johnson, 1956-1977

James P. Sale, 1942-1980

Richard G. Ahlvin, 1949-1980

Woodland B. Shockley, 1938-1978

Alan G. Skelton, 1947-1979

Marie Spivey, 1972-1980

Count G. Evans, 1947-1981

Jane C. Cotton, 1946-1982

Leo F. Ingram, 1946-1982

Francis P. Hanes, 1973-1982

Walter C. Sherman, Jr., 1975-1980

Katharine Mather, 1942-1982

William Flathau, 1955-1984

Garbis H. Keulegan, 1963-1988

Henry B. Simmons, 1940-1984

Frederick R. Brown, 1969-1985

George C. Downing, 1973-1985

John L. Grace, Jr., 1958-1986

David A. Crouse, 1947-1986

Charles W. Brasfield, 1935-1973

Ellen Louise H. Garner, 1943-1988

James R. Jefferson, Jr., 1959-1989

Clifford J. Nuttall, Jr., 1972-1986

Paul K. Senter, 1962-1991

Marden B. Boyd, 1957-1992

William A. Thomas, 1957-1993

John Guy Jackson, Jr., 1960-1993

Paul F. Hadala, 1962-1994

Frank A. Herrmann, Jr., 1959-1995

Joseph Lewis Decell, 1962-1995

Donald L. Robey, 1963-1996

August J. Breithaupt, 1961-1996

Leiland M. Duke, 1938-1995

Jimmy P. Balsara, 1966-1998

George P. Bonner, 1961-1996

Mary C. Landin, 1970-1997

N. Radhakrishnan, 1969-1999

Bryant Mather, 1978-2000

Robert W. Whalin, 1967-1998

H. Lee Butler, 1973-1997

Charles C. Calhoun, Jr., 1963-1998

Claude E. "Gene" Chatham, 1963-1999

John Q. Ehrgott, 1968-2000

John Harrison, 1967-1999

Jerome L. Mahloch, 1974-2000

E. Clark McNair, Jr., 1962-1999

John F. George, 1972-2002

John W. Keeley, 1971-2001

William F. Marcuson III, 1970-1999

Behzad Rohani, 1967-2001

Billy C. Bridges, 1982-2002

William H. McAnally, 1969-2002

Billy H. Johnson, 1971-2001

James E. McDonald, 1961-2003

Lawson M. Smith, 1977-2002

Billy T. Waltman, 1971-2002

David R. Coltharp, 1974-2001

H. Roger Hamilton, 1985-2004

Thomas J. Pokrefke, Jr., 1966-2004

Carlos H. "Jim" Pennington, 1978-2005

Robert M. Engler, 1973-2005



Secondary Sources

- Andrews, Richard. *Environmental Policy and Administrative Change: Implementation of the National Environmental Policy Act*. Washington, D.C.: Lexington Books, 1976.
- _____. *Managing the Environment, Managing Ourselves*. New Haven: Yale UP, 1999.
- Alley, Richard B. *The Two-Mile Time Machine: Ice cores, abrupt climate change, and our future*. Princeton: Princeton UP, 2000.
- Armstrong, John M. and Ryner, Peter C. *Coastal Waters: A Management Analysis*. Ann Arbor, Mich.: Ann Arbor Science Publishers, 1978.
- Arnold, James R. and Wiener, Roberta. *The U.S. Army Corps of Engineers and Natural Resources Management on Army Installations, 1941-1987*. Fort Belvoir: CEHO, 1989.
- Aspray, William. Ed. *Engineers as Executives: An International Perspective*. New York: IEEE, 1995.
- Bagley, James. *Aerophography and Aerosurveying*. NY: McGraw-Hill, 1941.
- Baldwin, William C. *A History of the U.S. Army Engineer Studies Center, 1943-1982*. Ft. Belvoir: CEHO, [1983].
- Barney, Patrick E. "The Programmatic Environmental Impact Statement and the National Environmental Policy Act Regulations." *Land and Water Law Review* 16:1 (Win. 1981): 1-31.
- Barry, John. *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America*. NY: Simon and Schuster, 1997.
- Bedini, Silvio. *Thinkers and Tinkers: Early American Men of Science*. New York: Charles Scribner's Sons, 1975.
- Bennett, Ira. *The History of the Panama Canal*. Washington, D.C.: Historical Publishing Co, 1915.
- Bergin, Thomas J. Ed. *50 Years of Army Computing from ENIAC to MSRC*. Aberdeen Proving Ground: Army Research Laboratory, 1996.
- Biden, John and Stroup, Richard L. Ed. *Bureaucracy vs. Environment: The Environmental Costs of Bureaucratic Governance*. Ann Arbor: Michigan UP, 1981.
- Birkemeier, William A. and Holland, K. Todd. "The U.S. Army Corps of Engineers Field Research Facility: More than Two Decades of Coastal Research."
- Boorstin, Daniel J. *The Republic of Technology: Reflections on our Future Community*. New York: Harper and Row, 1978.
- Brooks, C.E.P. *Climate Through the Ages: A Study of the Climatic Factors and Their Variations*. 2nd Ed. London: Ernest Benn, Ltd., 1950.
- Brower, David J. and Carol, Daniel S. *Coastal Zone Management as Land Planning*. Washington, D.C.: NPA, 1984.
- Bush, Vannevar. *Modern Arms and Free Men: A Discussion of the Role of Science in Preserving Democracy*. New York: Simon and Schuster, 1949.
- _____. *Science Is Not Enough*. New York: William Morrow and Company, 1965.

- Butterfield, H. *The Origins of Modern Science, 1300-1800*. New York: Macmillan Co., 1953.
- Camillo, Charles A. and Percy, Matthew T. *Upon Their Shoulders: A History of the Mississippi River Commission from Its Inception through the Advent of the Modern Mississippi River and Tributaries Project*. Vicksburg: Mississippi River Commission, 2004.
- Campbell-Kelly, Martin, and Aspray, William. *Computer: A History of the Information Machine*. New York: Basic Books, 1996.
- Ceruzzi, Paul E. *A History of Modern Computing*. Cambridge, Ma.: MIT Press, 2003.
- _____. "An Unforeseen Revolution: Computers and Expectations, 1935-1985." Corn, Joseph J. Ed. *Imagining Tomorrow: History, Technology, and the American Future*. Cambridge: MIT, 1986. 188-201.
- Channell, David. "Engineering Science as Theory and Practice." *Technology and Culture* 29:1 (Spring 1988): 98-103.
- Cohen, I. Bernard and Welch, Gregory W. Ed. *Makin' Numbers: Howard Aiken and the Computer*. Cambridge: MIT, 1999.
- Cold Regions Research and Engineering Laboratory: Retrospective, 1986-1991*. N.P. CRREL, N.D.
- Collins, Craig. "200 Years at West Point," *Duty, Honor, Country: The Bicentennial of the United States Military Academy*. West Point: USMA, 2002.
- Cooling, L.F., et al. Ed. *A Century of Soil Mechanics: Classic papers on soil mechanics published by the Institution of Civil Engineers, 1844-1946*. London: Institute of Civil Engineers, 1969.
- Cotton, Gordon. *A History of the Waterways Experiment Station, 1929-1979*. Vicksburg: WES, 1979.
- Cox, John D. *Climate Crash: Abrupt Climate Change and What It Means for Our Future*. Washington: Joseph Henry Press, 2005.
- Demma, Vincent H. *Department of the Army Historical Summary, Fiscal Year 1989*. Washington: Center of Military History, 1998.
- Desai, Chandrakant S. and Abel, John F. *Introduction to the Finite Element Method: A Numerical Method for Engineering Analysis*. NY: Von Nostrand, 1972.
- Dillow, E.L. *Methods of Science: An Introduction to Measuring and Testing for Laymen and Students*. New York: Universe Books, 1970.
- Ezell, Edward C. *ETL History Update, 1968-1978*. Fort Belvoir: ETL, 1979.
- Fatherree, Benjamin. *The First 75 Years: History of Hydraulics Engineering at the Waterways Experiment Station*. Vicksburg, Miss.: USACE, Engineer Research and Development Center, 2004.
- _____. *The History of Geotechnical Engineering at the Waterways Experiment Station, 1932-2000*. Vicksburg, Miss.: Engineer Research and Development Center, 2006.
- Fine, Lenore, and Remington, Jesse A. *The Corps of Engineers, Construction in the United States*. Washington, D.C.: Office of Chief of Military History, U.S. Army, 1972.
- Fores, Michael. "Transformation and the Myth of 'Engineering Science': Magic in a White Coat." *Technology and Culture* 29:1 (Spring 1988): 64-81.
- Foresman, Timothy W., ed. *The History of Geographic Information Systems: Perspectives from the Pioneers*. Upper Saddle River, N.J.: Prentice Hall, 1998.
- Fowle, Barry, ed. *Builders and Fighters: U.S. Army Engineers in World War II*. Fort Belvoir, Va.: CEHO, 1992.
- Frazier, Arthur. *Water Current Meters in the Smithsonian Collections of the National Museum of History and Technology*. Washington, D.C.: Smithsonian Institution Press, 1974.
- Fukuyama, Francis. *The End of History and the Last Man*. New York: Free Press, 1992.
- Garrison, Ervan G. *A History of Engineering and Technology: Artful Methods*. Boca Raton: CRC Press, 1991.
- Goetzmann, William. *Army Exploration in the American West, 1803-1863*. New Haven, Conn.: Yale University Press, 1959.

- Graves, Gregory. *Pursuing Excellence in Water Planning and Policy Analysis: A History of the Institute for Water Resources, U.S. Army Corps of Engineers* (Fort Belvoir: IWR, 1995).
- Hacker, Barton C. "Engineering a New Order: Military Institutions, Technical Education, and the Rise of the Industrial State." *Technology and Culture* 34:1 (Spring 1993): 1-27.
- Haggard, Robert. "The Nicola Affair: Lewis Nicola, George Washington, and American Military Discontent during the Revolutionary War," *Proceedings of the American Philosophical Society* 146:2 (June 2002): 139-169.
- Hagwood, Jr., Joseph. *Commitment to Excellence: A History of the Sacramento District, U.S. Army Corps of Engineers, 1929-1973*. Sacramento: USACE, 1976.
- Hamilton, Andrew and Hellman, Robert. *A History Update of the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, 1979-1983*. Fort Belvoir: ETL, N.D.
- Hays, Samuel P. *Beauty, Health, and Permanence: Environmental Policy in the United States, 1955-1985*. NY: Cambridge UP, 1987.
- _____. *Conservation and the Gospel of Efficiency: The Progressive Conservation Movement, 1890-1920*. Cambridge, Mass.: Harvard UP, 1959.
- _____. *A History of Environmental Politics Since 1945*. Pittsburg: Pittsburg UP, 2000.
- Hellman, Robert. *A History Update of the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, 1984-1988*. Fort Belvoir: ETL, 1994.
- Henriksen et al., ed., *The Use of Artificial Satellites for Geodesy* (Washington, D.C.: American Geophysical Union, 1972).
- Heuvelmans, Martin. *The River Killers*. Harrisburg, Pa.: Stackpole Books, 1974.
- Hewes, Jr., James E. *From Root to McNamara: Army Organization and Administration*. Washington, D.C.: Center of Military History, 1975.
- Heidish, Louise S. *A History of the Huntsville Division, U.S. Army Corps of Engineers, 1977-1981 Update*. Huntsville, Alabama: HND, 1983.
- Hill, Forest G. *Roads, Rails and Waterways: The Army Engineers and Early Transportation*. Norman, Oklahoma: University of Oklahoma Press, 1957.
- Hindle, Brooke. *The Pursuit of Science in Revolutionary America, 1735-1789*. Chapel Hill: University of North Carolina Press, 1957.
- Historical Summary, World War II to 30 June 1950*. 2nd ed. Fort Belvoir: ERDL, 1950.
- History of the Board of Engineers for Rivers and Harbors*. Fort Belvoir, Va.: BERH, 1980
- History of the U.S. Army Nuclear Cratering Group*. Livermore, Ca.: Lawrence Radiation Laboratory, 1969.
- Idorn, Gunnar M. *Concrete Progress from Antiquity to the Third Millennium*. London: Thomas Telford, 1997.
- Jacobs, W.A. and Woodman, Lyman. *The Alaska District, United States Army Corps of Engineers, 1946-1974*. Elmendorf Air Force Base, Aka.: Alaska District, 1976.
- Jennings, Todd, et al. *Currents of Change: A History of the Portland District, U.S. Army Corps of Engineers, 1980-2000*. Portland, Ore.: Portland District, 2003.
- Johnson, Leland. *The Ohio River Division, U.S. Army Corps of Engineers: A History of a Central Command*. Cincinnati: USACE, ORD, 1992.
- Kemp, Emory L. *Stemming the Tide: Design and Operation of the Bonnet Carre Spillway*. Chicago: Public Works Historical Society, 1990.
- Kirby, Richard, et al. *Engineering in History*. New York: McGraw-Hill, 1956.
- Kaufmann, E. and Idzikowski, Tomasz. *Fortress America: The Forts that Defended America, 1600 to the Present*. Cambridge, Mass.: De Capo Press, 2004.
- Lamb, H.H. *Climatic History and the Future*. Vol. 2. Princeton: Princeton UP, 1977.

- Larson, John L. *Internal Improvement: National Public Works and the Promise of Popular Government in the Early United States*. Chapel Hill: University of North Carolina Press, 2001.
- Layton, Edwin. "American Ideologies of Science and Engineering." *Technology and Culture* 17:4 (Winter 1976): 688-701.
- _____. *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession*. Baltimore, Md.: Johns-Hopkins University Press, 1986.
- _____. "Science as a Form of Action: The Role of the Engineering Sciences." *Technology and Culture* 29:1 (Spring 1988): 82-97.
- Lewis, Emanuel. *Seacoast Fortifications of the United States: An Introductory History*. Washington, D.C.: Smithsonian Institution Press, 1970.
- Lindberg, David C. *The Beginnings of Western Science: The Empirical Scientific Tradition In Philosophical, Religious, and Institutional Context, 600 B.C. to A.D. 1450*. Chicago: University of Chicago Press, 1992.
- Livingston, Robert. *Impact of the USAETL Field Office and Its Predecessors on Military Mapping Research and Development*. Fort Belvoir: TEC, 1992.
- Losee, John. *A Historical Introduction to the Philosophy of Science*. New York: Oxford University Press, 2001.
- _____. *Manual of Photogrammetry*. 2nd ed. Washington, D.C.: American Society of Photogrammetry, 1952.
- Marr, Alan. Ed. *A History of Progress: Selected U.S. Papers in Geotechnical Engineering*. Vol. 1 Reston, Va.: ASCE, 2003.
- McFadden, Terry, and Bennet, Lawrence. *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers*. New York: Wiley and Sons, 1991.
- McNichol, Dan. *Paving the Way*. Lanham, Md.: National Asphalt Pavement Association, 2005.
- Merritt, Raymond. *Creativity, Conflict, and Controversy: A History of the St. Paul District, U.S. Army Corps of Engineers*. St. Paul, Minn.: St. Paul District, 1979.
- Mighetto, Lisa and Homstad, Carla. *Engineering in the Far North: A History of the U.S. Army Engineer District in Alaska, 1867-1992*. N.P.: Historical Research Associates Inc., 1993.
- Moore, Jamie W. and Dorothy P. *History of the Coastal Engineering Research Center, 1963-1983*. Vicksburg, Miss.: U.S. Army Engineer Waterways Experiment Station, 1991.
- Moore, David. *The Roman Pantheon: The Triumph of Concrete*. Online. 1995.
- Moore, Kenneth. "The Engineer School," *The Military Engineer (TME)* (Jan.-Feb. 1935): 9-13.
- Moreau, Renee. *The Computer Comes of Age: The People, the Hardware, and the Software*. Cambridge, Mass.: MIT Press, 1984.
- Morgan, Arthur E. *Dams and Other Disasters: A Century of the Army Corps of Engineers in Civil Works*. Boston: Porter Sergeant. 1971.
- Morrison, James. *'The Best School in the World': West Point and the pre-Civil War Years, 1833-1866*. Kent, Oh.: Kent State University Press, 1986.
- Nash, Stephen. Ed. *A History of Scientific Computing*. New York: ACM Press, 1990.
- Parkman, Aubrey. *Army Engineers in New England: The Military and Civil Work of the Corps of Engineers in New England, 1775-1975*. Waltham, Mass.: New England Division, 1978.
- Pennington, John. *History of the U.S. Army Engineer Topographical Laboratories (1920 to 1970)*. Fort Belvoir, Va.: USAETL, 1973.
- Prelini, Charles. *Dredges and Dredging*. NY: D. Van Nostrand Co.: 1911.
- Quinn, Mary-Louise. *The History of the Beach Erosion Board, U.S. Army, Corps of Engineers, 1930-63*. Fort Belvoir, Va.: Coastal Engineering Research Center, 1977.
- Rae, John, and Volti, Rudi. *The Engineer in History*. New York: Peter Lang, 2001.

- Reuss, Martin. "Andrew A. Humphreys and the Development of Hydraulic Engineering: Politics and Technology in the Army Corps of Engineers, 1850-1950." *Technology and Culture* 26 (January 1985): 1-33.
- _____. "The Art of Scientific Precision: River Research in the Army Corps of Engineers to 1945." *Technology and Culture* 40:2 (April 1999): 292-323.
- _____. "Coping with Uncertainty: Social Scientists, Engineers, and Federal Water Resources Planning." *Natural Resources Journal* 32:1 (Win. 1992): 101-135.
- _____. *Designing the Bayous: The Control of Water in the Atchafalaya Basin 1800-1995*. Alexandria, Va.: Office of History, USACE, 1998.
- _____. *Shaping Environmental Awareness: The United States Army Corps of Engineers Environmental Advisory Board, 1970-1980*. Fort Belvoir: CEHO, 1982.
- Reynolds, Terry S. Ed. *The Engineer in America: A Historical Anthology from Technology and Culture*. Chicago: Chicago University Press, 1991.
- Rosnay, Joel de. *The Macroscopic*. NY: Harper and Rowe, 1979.
- Rouse, Hunter. *Fluid Mechanics for Hydraulic Engineers*. New York: Dover, 1938.
- Rouse, Hunter, and Ince, Simon. *History of Hydraulics*. Ann Arbor, Mich.: State University of Iowa, 1957.
- Sackman, Harold. *Computers, System Science, and Evolving Society: The Challenge of Man-Machine Digital Systems*. New York: John Wiley and Sons, 1967.
- Schubert, Frank N., ed. *The Nation Builders: A Sesquicentennial History of the Corps of Topographical Engineers, 1838-1863*. Fort Belvoir, Va.: Office of History, USACE, 1988.
- _____. *Vanguard of Expansion: Army Engineers in the Trans-Mississippi West, 1819-1879*. Washington, D.C.: Historical Division, Office of the Chief of Engineers, N.D.
- Schwarzbach, Martin. *Climates of the Past: An Introduction to Paleoclimatology*. NY: D. Van Nostrand and Co., 1963.
- Shallat, Todd. *Structures in the Stream: Water, Science, and the Rise of the U.S. Army Corps of Engineers*. Austin: University of Texas Press, 1994.
- _____. "Building Waterways, 1802-1861: Science and the United States Army in Early Public Works." *Technology and Culture* 31:1 (Jan. 1990): 18-50.
- Smyth, Albert Henry. Ed. *The Writings of Benjamin Franklin*. Vol. 2. NY: Macmillan, 1905.
- Snyder, Frank and Guss, Brian. *The District: A History of the Philadelphia District, U.S. Army Corps of Engineers, 1866-1971*. Philadelphia: USACE, 1974.
- Stellar, Gary A. *CERL: A History of the U.S. Army Construction Engineering Research Laboratory, 1968-1974*. Champaign, Ill.: CERL, [1975].
- Suid, Lawrence. *The Army's Nuclear Power Program: The Evolution of a Support Agency*. NY: Greenwood Press, 1990.
- Sutherland, R.J.M. et al. *Historic Concrete: Background to Appraisal*. Reston, Va.: Thomas Telford, 2001.
- _____. *The U.S. Army Corps of Engineers: A History*. Alexandria, Va.: Office of History, USACE, 2006.
- Taylor, David Watson. *The Speed and Power of Ships: A Manual of Marine Propulsion*. NY: J Wiley and Sons, 1911.
- Tiffany, J.B. *History of the Waterways Experiment Station*. Vicksburg: WES, 1968.
- Torres, Louis. *A History of Huntsville Division, U.S. Army Corps of Engineers: 1982-1987 Update*. Huntsville: HND, 1990.
- _____. *A History of the U.S. Army Construction Engineering Research Laboratory (CERL), 1964-1985*. N.P.: USACE CERL, N.D.
- Truck, J.A.V. *Origin of Modern Calculating Machines*. Chicago: Western Society of Engineers, 1921.
- Tucker, Todd. *Atomic America: How a Deadly Explosion and a Feared Admiral Changed the Course of Nuclear History*. NY: Free Press, 2009.

- Walker, Paul K. *Engineers of Independence: A Documentary History of the Army Engineers in the American Revolution, 1775-1783*. Fort Belvoir: CEHO, 1981.
- Waugh, E.D.J. *West Point: The Story of the United States Military Academy Which Rising from the Revolutionary Forces Has Taught American Soldiers the Art of Victory*. New York: Macmillian Books, 1944.
- Wiegall, Robert L. and Saville, Thorndike, Jr. "History of Coastal Engineering in the USA." Kraus, Nicholas C. ed. *History and Heritage of Coastal Engineering*. Long Beach, CA: ASCE, 1996: 513-600.
- Wilde, Robert E. *ACI: A Century of Progress*. NP: American Concrete Institute, 2003.
- Wright, Edmund A. *CRREL's First 25 Years, 1961-1986*. Hannover, N.H.: CRREL, 1986.

Primary Sources

File and Archival Material¹

- Airfield Pavement. CEHO MIL R&D Eng. Board Studies VI-11-2.
- Army Geospatial Center. ICDT Study. Presentation. Announcement. News Releases. ERDC Archives TEC-1.
- Beach Erosion Board. Correspondence. History. Project Failure. CEHO GEN 119A-1-1; Weapons testing. CEHO GEN 119A-16.
- Board of Engineers on Experimental Towboats. Correspondence. NARA RG 77, Entry 103, Box 1826, Folder 76542; Box 1944, Folder 80137; Box 1826, Folder 76542; Box 2093, Folder 85607; and Box 2989, Folder 132967.
- Board of Engineers on Water Hyacinth Obstructions. Correspondence. NARA RG 77, Entry 103, Box 672, Folder 30674.
- Coastal Engineering Research Center. Ecological Program. Correspondence. CEHO GEN 119-11 and 119-20.
- Cold Regions Research and Engineering Laboratory. Correspondence. CRREL. Drawer 3, Folder, Bender; Drawer 4, Folder, Lobnez – Move to Hanover; Drawer 4, Folder, Experts, Professional and Technical, SIPRE; Drawer 4, Folder, SIPRE Personnel – Bender. Foundation. CRREL Drawer 3, Folder, Bender; Folder, Philippe – Earth Sciences Lab; Drawer 4, Folder, Dr. Gerdel's Historical Files; Drawer 4, Folder, SIPRE Personnel – Bender; Drawer 4, Folder, Lobnez – Move to Hanover; Drawer 4, Document Collection, "Establishment of CRREL," Assembled May 13, 1959. Computing. ERDC Archives.
- Construction Engineering Research Laboratory. Organizational charts. Reorganization. Small Problems Program. ERDC Archives; Paint Technology Center. CERL Folder, Beitelman Paint Newsletter Article; Correspondence. Studies. Establishment. Site Selection. Folder, Construction Engineer Research Lab Concept and Staff Study; "Construction Engineering Research Laboratory History," a documentary collection (CERL); Briefings. Folder, ECR Laboratory; Construction Research Lab – Planning; Folder, Construction Research Program.
- Corps of Engineers. Role in Research and Development. NARA RG 77, Entry 103, Box 86, Folder 50734; CERL Archives.

¹ Documentary material is listed by subject and location. For the specific document, see the end notes. The location of the specific archives are CEHO: Corps of Engineers History Office, Kingman Building, Humphreys Engineering Center, Virginia; CERL: Historical Files, Michael Golish, Construction Engineering Research Center, Illinois; CRREL: Vertical Files, Cold Regions Research and Engineering Laboratory Library, New Hampshire; ERDC: Archival Boxes, Engineering Research and Development Center, Mississippi. Boxes are divided by laboratory. Collation of files is still ongoing; NARA: National Archives and Record Administration, Washington, D.C., and Maryland.

- Department of Army Laboratories. Correspondence. NARA RG 77, Entry 103, Box 1612, Folder 66893; Box 2429, Folder 99541; Box 50, Folder 1870. AMC Laboratory Meeting at CRREL. CRREL Archives.
- Engineer Board. CEHO MIL R&D Eng. Board Reports, VI-1.
- Engineer Equipment. Correspondence. NARA RG 77, Entry 103, Box 1084, Folder 45253; Box 2731, Folder 118329; Entry 109, Box 50, Folder 1870.
- Engineer Research and Development Center. Establishment. Macro-plans. Organization Chart. PMB Minutes. Plans. Presentations. ERDC Archives. News releases. Fact Sheets. ERDC Web site; ERDC Archives.
- Environmental Laboratory. Establishment. ERDC Archives EL-1. Scaled Ecosystem Modeling. Aquatic Plant Control Research Program. Military Research. ERDC Archives EL-2. Dredged Material Research Program. ERDC Archives EL-3. Environmental Policy. CEHO CW IV-18-8 Environmental Policy.
- Fortifications. Correspondence. NARA RG 77, Entry 103, Box 265, Folder 12417; Box 674, Folder 30708; Box 855, Folder 37210 and 12958; Box 930, Folder 39705; Box 993, Folder 42566; Box 1408, Folder 58067; Box 2038, Folder 83720; and Box 2435, Folder 99735. Reports. CEHO Archives, MIL GEN Coast Defense, Box 1-4, Folder 9-1.
- Franklin, Benjamin. Correspondence. American Philosophical Society. Albert Henry Smyth, ed. *The Writings of Benjamin Franklin*. Vol. 2. NY: Macmillan, 1905. Hydraulic Modeling. No. 471 and 513. Smyth. Vol. V, 1767-1772. NY: Macmillan Co., 19Geotechnical and Structures Laboratory. Soil Mechanics. CEHO MIL R&D Eng. Board Studies VI-11-2. Structural Engineering Center. GSL. ERDC Archives GSL-1.
- Hydraulics research and development. CEHO MIL R&D Eng. Board Studies VI-11-2 Articles and Memoranda. Modeling. ERDC Archives CHL-1.
- Information Technology Laboratory. Establishment. Timeline. Correspondence. A-76 Competition. ERDC Archives ITL-1.
- Manhattan Project. Correspondence. Reports. NARA MD RG 77 ENT 390 Row 1, Comp 11, Shelf 05, Box 2; Maj. Gen. Leslie R. Groves Biography. CEHO BIO-IND, box GRE-GUY.
- Mississippi River Commission. Revetment, groin, dredging, and dike research on the Mississippi River. MRC Archives: Drawer 1-1, Bank Protection, File 24, 38, 45; Drawer 2-1, Discharges, File 85, 87; and Drawer 1-5, Discharges, File 46. Revetment research correspondence. NARA RG 77, Entry 103, Box 26, Folder 7036.
- National hydraulics laboratory debate. Correspondence. NARA RG 77, Entry 103, Box 3014, Folder 134377; Entry 109, Box 50, Folder 1850.
- Office of Chief of Engineers. Civil Works R&D. CEHO MIL R&D VI-1. Research and Development Reorganization, Studies, and Policy. Lab Director Meetings. ERDC Archives; Organization Charts. CEHO, MIL R&D VI-1, GEN 105-2.
- Office of Research and Technology Application. ERDC Archives ITL-1.
- Ohio River Division Laboratories. Accomplishments. CERL Archives, Folder Staff Study Development of CE Constr. R&D Program. Correspondence. NARA MD RG 77 Entry 109, Box 50, Folder 1870.
- Permafrost Research. Correspondence. CEHO MIL R&D Eng. Board Historical Studies, VI-11; CEHO MIL R&D Eng. Board Hist. Studies VI-11; CRREL Archives, Drawer 4, Folder Dr. Gerdel's Historical Files.
- Reliance. ERDC Archives.
- Remote sensing. Assignment of ETL as lead laboratory. ERDC Archives TEC-1.
- Snow, Ice, and Permafrost Research Establishment. Greenland. CRREL. Drawer 5, Greenland-Arctic R&D Reference Papers. Early Research. Drawer 4, CSI-SIPRE Conference, 1950-1954; Drawer 4, SIPRE Personnel – Bender; Correspondence. CRREL Drawer 4, Folder, Gerdel; Drawer 4, Folder, Dr. Gerdel's Historical Files; Drawer 4, Folder, SIPRE Personnel – Bender. Early Activity. CRREL Drawer 3, Folder, Memo to CO; Drawer 4, File, CSI-SIPRE Conference, 1950-1954; Drawer 4, Dr. Gerdel's Historical Files; Drawer 4, Folder, SIPRE Personnel – Bender; Drawer 5, Folder, Greenland-Arctic R&D Reference Papers.
- Topographic Engineering Center. Organizational Chart. Establishment. ERDC Archives TEC-1.

Waterways Experiment Station. ADP Coordinator Office. ERDC Archives ITL-1. Establishment. CEHO GEN123-1-1; MRC Archives. Finances. MRC Historical Files, Drawer 3-2, General A16 Section, File 28; ERDC Archives. POW Reports. NARA RG 77, Entry 103, Folder 2658, 2501, 4012504; Box 2502, 4012503, 4012002, 4012004. Copy at ERDC Archives. Organization Charts. Reorganization. ERDC Archives.

Interviews

Adiguzel, Ilker R. and Topudurti, Kirakumar V. By Damon Manders and Charles Camillo. Dec. 1, 2008
Balbach, Hal. By Damon Manders. Oct. 22, 2008.
Barr, Sam. By Damon Manders. Nov. 18, 2008.
Beitelman, Al. By Damon Manders. Nov. 12, 2008.
Benton, John. By Damon Manders. Nov. 20, 2008.
Bonner, Pat. By Damon Manders. July 8, 2008.
Bush, Al. By Damon Manders. July 7, 2008.
Caldwell, Doug. By Damon Manders. Jun. 19, 2008.
Clairain, Buddy. By Damon Manders. Apr. 22, 2009.
Cullinane, John. By Damon Manders. Jul. 9, 2008.
Davis, Robert and Hansen, Lance. By Damon Manders and Marie Darling. Sept. 17, 2008.
Flathau, Bill. By Damon Manders. Jul. 21, 2009.
Fontanella, Joseph. By Damon Manders and Charles Camillo. Nov. 18, 2008.
Golish, Michael. By Damon Manders. Oct. 23, 2008.
Grum, Allen. By Damon Manders. May 19, 2009.
Harrison, John et al. By Damon Manders. May 13, 2008.
Herrmann, Richard. By Damon Manders. Nov. 20, 2008.
Hoge, Gregg. By Damon Manders. June 2, 2009.
Howdyshell, Paul. By Damon Manders. Oct. 22, 2008.
Holland, Jeffery P. By Damon Manders and Charles Camillo. Aug. 27, 2009.
Houston, James R. By Damon Manders. May 14, 2008.
_____. By Damon Manders and Charles Camillo. Aug. 27, 2009.
Karpiscak, John. By Damon Manders. Nov. 20, 2008.
Landin, Mary. By Damon Manders. Feb. 26, 2009.
Link, Jun. 16 and 23, 2009
McAnally, William. By Damon Manders. Aug. 11, 2008.
Marcuson, William. By Damon Manders. Jun. 10 and 15, 2009.
_____. By Peggy Price. [March 2001].
Mather, Bryant. By Peggy Price. Mar. 22, 2001. ERDC Archives.
Mosher, Reed. By Damon Manders. Jul. 9, 2008.
O'Connor, Michael J. By Damon Manders. Oct. 22, 2008.
Pazak, Robert. By Damon Manders. Nov. 20, 2008.
Pennington, Jim. By Damon Manders. July 8, 2008
Pofrefke, Thomas. By Damon Manders. July 8, 2008.
Radhakrishnan (Radha), Narayanaswamy. By Damon Manders. Apr. 27-28, 2009.
Roper, William E. By Damon Manders. Oct. 21, 2009

Rinker, Jack. By Damon Manders. Mar. 22, 2009.

Schmidt, Wayne. By Damon Manders. Apr. 7, 2009.

Sherwin, Chalmers W. By John Bryant. June 12, 1991. Boston: Rutgers University and IEEE History Center, 1991.

Shine, James. By Damon Manders. Jun. 19, 2008.

Tillman, Russ. By Damon Manders Jul. 8, 2008.

Vogel, Herbert. By Public Works Historical Society. Nov. 10, 17, 24, Dec. 1, 1976.

_____. By Charles Crawford. Memphis State University. Jan. 9, 1970. CEHO Oral History, Career Interview, Vogel, Herbert.

Whalin, Robert W. By Damon Manders. Mar. 31, 2009.

Manuscripts, Unpublished

Pendergrass, Lee and Bonnie. "Mimicking Waterways, Harbors, and Estuaries: A Scholarly History of the Corps of Engineers Hydraulics Laboratory at WES, 1929 to the Present." Vicksburg: WES, 1979.

Peyton, Billy Joe. "A History of Hydraulic Instrumentation Used at Waterways Experiment Station, Vicksburg, Mississippi." Washington, D.C.: Historic American Engineering Record, 1987.

Manders, Damon, et al. "Rebuilding Hope: Task Force Hope and the U.S. Army Corps of Engineers, Mississippi Valley's Response to Hurricanes Katrina and Rita." Vicksburg: MVD, 2008.

Schulz, Brig. Gen. John W.N. "Research in the Corps of Engineers." CEHO MIL-R&D-Engineer Board Studies VI-11-6.

Vogel, Brig. Gen. Herbert D. "Conception, Birth and Development of the U.S. Waterways Experiment Station." CEHO GEN 123-6.

Pursell, Carroll and Willingham, William. "Protecting the Nation's Waterways: A History of the U.S. Army Corps of Engineers' Regulatory Responsibilities, 1899-1999. CEHO 1998.

Non-Technical Publications

Abbot, Henry. "Early Days of the Engineer School of Application." Occasional Papers, No. 14. Washington, D.C.: U.S. Army Engineer School of Application, 1904.

Activities Summary FY 1969-1997. 28 Vol. Vicksburg: WES, 1969-1997.

Allen, John; Grantham, Rodney; and Nichols, Donald. *The DoD Laboratory Utilization Study*. Washington, D.C.: ODDR&E, 1975.

"Army Corps of Engineers Tames Nature with GE-420 Time Sharing System." Application Profile. N.P: GE, 1969.

Army Science and Technology Master Plan, 1997. Washington, D.C.: ASA-RDA, 1997.

Banks, Don et al. *A U.S. Army Engineer Research and Development Command – A Feasibility Study*. WES, 1979.

"The Bendix G-15 CPM/PERT Program." Brochure. Los Angeles: Bendix, N.D.

Cairns and Humphrey, "A Water Resources Ecology Capability for the Waterways Experiment Station and Corps of Engineers." Vicksburg: WES, 1969.

"Capabilities for Evaluating Environmental Effects on Military Operations." Brochure. Vicksburg: WES, 1963.

"Construction Engineering Research Laboratory." Brochure. Champaign, Ill.: CERL, 1974.

Corps Laboratory Study. Washington, D.C.: OCE-RDO, 1978.

Cold Regions Research and Engineering Laboratory. *Army Research and Development Laboratory of the Year Award, FY 1997-1998*. 2 Vol. Hanover: CRREL, 1997-1998.

- Construction Engineering Research Laboratory. *Army Research and Development Laboratory of the Year Award, FY 1998*. Champaign: CERL, 1998.
- "Dual Use Technology: A Defense Strategy for Affordable, Leading-Edge Technology." Washington, D.C.: OASD-ES, 1995.
- Engineering Foundation. *Hydraulic Laboratories in the United States of America*. NY: Engineering Societies Building, 1922.
- Engineer Research and Development Center. *Army Research and Development Laboratory of the Year Award, FY 1999-2005*. 7 Vol. Vicksburg: ERDC, 2000-2006.
- The ERDC Road Ahead*. Vicksburg: ERDC, 2007.
- "FY87 Annual Report." Hanover: CRREL, 1987.
- "The Genealogy of ARL." N.P.: ARL, 1993.
- Harrison, John. "Plan of Action for a More Centralized Management of WES Environmental Projects." 3 Vol. Vicksburg: Special Advisor for Environmental Coordination, 1972-1974.
- Institute for Water Resources. *The Role of the U.S. Army Corps of Engineers in Water Quality Management*. Springfield, Va.: IWR, 1970.
- Long-Range Master Plan for the Waterways Experiment Station*. Vicksburg: WES, 1965.
- Naval Research Advisory Committee. *Science and Technology: Community in Crisis, May 2002*. Washington, ASNRDA, 2002.
- Peixotto, *Exit Report*. Vicksburg: WES, 1973.
- Priscoli, Jerry et al. *Research and Development Prioritization Study*. NP: IWR, [1980].
- "Remote Sensing/GIS Center, Hanover, New Hampshire." Brochure. CRREL, N.D.
- "Report of First through Sixth Conference of Hydraulics Consultants Board." 6 Vol. Vicksburg: WES, 1964-1970.
- "Report of Seventh Meeting of the Corps of Engineers Working Group on Terrain Analysis." Vicksburg: WES, 1962.
- Research for Civil Works: A Progress Report*. Washington, D.C.: OCE-CW, 1968.
- "Study of Retirement Patterns of Waterways Experiment Station Organizations." Vicksburg: WES Personnel Office, 1967.
- "Summary of Environmental Research Capabilities." Brochure. Vicksburg: WES, N.D.
- "Ten Years of Accomplishment." [Champaign, Ill.]: CERL, [1979].
- Topographic Engineering Center. *Army Research and Development Laboratory of the Year Award, FY 1991-1998*. 2 Vol. Fort Belvoir: TEC, 1992-1999.
- Vincent, Mary K. "Loss of Doctorates from WES, 1980-1987." Vicksburg: WES, 1987.
- Wang, Mark et al. *Technology Transfer of Federally Funded R&D: Perspectives from a Forum*. Santa Monica, Ca.: Rand Corp., 2003.
- Waterways Experiment Station. *Army Research and Development Laboratory of the Year Award, FY 1991-1998*. Vicksburg: WES, 1992-1999.
- WES '82 Study Group. *Functions and Organization, 1977-1982*. Vicksburg: WES 1977.

Orders and Regulations

- General Order No. 9. Change in Jurisdiction of Waterways Experiment Station, Vicksburg, Mississippi. HQDA. Jul. 29, 1949.
- General Order No. 46. Transfers of Installations and Activities to the U.S. Army Materiel Command. HQDA. Jul. 25, 1962.
- General Order No. 34, IV. HQDA. Aug. 28, 1967.

Improving the Common Stock of Knowledge

General Order No. 17. Organization of the U.S. Army Construction Engineering Research Laboratory. HQDA. Sept. 9, 1968.

Permanent Orders 5-1. USACE Coastal Engineering Research Center. DA-USACE. Mar. 21, 1983.

Standard Operating Procedure. for Acquisition of Automated Data Processing Equipment and Support Services. USACRREL. May 1, 1984.

WES Supplement 1 to Army Regulation No. 18.

Periodicals

Alaska.

Army Research and Development News.

Associated Press.

ASTM Standardization News.

Australian Civil Engineering Transactions.

Beach and Shore.

Billings Gazette.

Chemical Progress.

Civil Engineering.

Courant (Hartford).

DG Insight.

Engineering News-Record.

Engineer Update.

Environmental Affairs.

ERDC Information Bulletin.

ERDC MSRC Resource.

Essayons.

Experiment Station Hydraulics Bulletin.

Federal Facilities Environmental Journal.

FedTech.

Federal Times.

Fuel Cells Bulletin.

GIS World.

Ice Engineering.

Indoor Environment Connections.

Information Exchange Bulletin (WES).

Installations.

Journal of Forest History.

Knight-Ridder.

Military Affairs.

New Orleans District Riverside.

NYT.

Oregon Journal.

Science.

Ski.
Smithsonian.
Sunday Globe (Boston).
Technology Development and Transfer Report.
The Military Engineer.
Times-Picayune (New Orleans).
USA Today.
Vicksburg Evening Post.
Vicksburg Sunday Post.
World-Herald (Omaha).
World Ports.
Yankee Engineer.

Technical Publications

ACIA. *Arctic Climate Impact Assessment*. NY: Cambridge UP, 2005.

"Application of ADCIRC 2DDI to Masonboro Inlet, North Carolina: A brief numerical modeling study." N.P.: WES, 1991.

Ashton, George D. "Ice Deterioration." *Proceedings of the Great Lakes Ice Research Workshop*. Ann Arbor, Mich.: Great Lakes Environmental Research Laboratory, 1984.

_____. Ed. *River Lake Ice Engineering*. Highlands Ranch, Col.: Water Resources Pub., 1978.

Balbach, Hal, and Kirby, Patricia M. Ed. "Red-cockaded Woodpecker Research at ERDC/CERL." Champaign: CERL, 2001.

Banks, D.C., and Palmerton, J.B. "Application of Finite Element Method in Determining the Stability of Crater Slopes: Preliminary Report." Vicksburg: WES, 1968.

Brogdon, N.J. "Galveston Bay Hurricane Surge Study." Vicksburg: WES, 1969, 1973.

"Capabilities for Performing Mathematical Modeling of Estuarine Environmental Processes." Vicksburg: WES, 1970.

Cerco, Carl F. "Chesapeake Bay Three-Dimensional Model Study." Orville T. Magoon et al. Ed. *Coastal Zone '89*. Vol. 4. NY: ASCE, 1989.

Cerco, C.F., and Cole, Thomas M. "Calibrating the Chesapeake Bay Water Quality Model." Malcolm L. Spaulding. Ed. *Estuarine and Coastal Modeling*. NY: ASCE, 1989.

_____. "Thirty-year simulation of Chesapeake Bay dissolved oxygen." JHW Lee and YK Cheung. Eds. *Environmental Hydraulics*. NY: Brookfield, 1991.

_____. "Thirty Year Simulation of Chesapeake Bay Eutrophication." Spaulding et al. Eds. *Estuarine and Coastal Modeling*. NY: ASCE, 1992.

Clark, Elmer F. "Camp Century Evolution of Concept and History of Design, Construction, and Performance." Hanover: CRREL, 1965.

Clough, Ray, and Wilson, Edward. "Early Finite Element Research at Berkele." Fifth U.S. National Conference on Computational Mechanics, Aug. 4-6, 1999 (www.edwilson.org/history/fe-history.pdf, Dec. 8, 2008).

Coleman, David. *Synthesis of railroad design methods, track response models, and evaluation methods for military railroads*. Vicksburg: WES, 1985.

Computer Simulation of Missouri River Floods, Pt. 1, Verification with Mississippi Basin Model. MRD, 1973.

Crawley, Drury. "EnergyPlus: Creating a new-generation building energy simulation program." Champaign: CERL, 2001.

- Delaney, David K., et al. *Assessment of Training Noise Impacts on the Red-cockaded Woodpecker: 1999 Results*. Champaign: CERL, 2000.
- “Disposal of Dredged Materials: Program Review and Coordination Correspondence.” Vicksburg: WES, 1972.
- Doyle, Robert D. “Potential use of native aquatic plants for long-term control of problem aquatic plants in Gunterville Reservoir, Alabama.” Rep. 1-2. Vicksburg: WES, 1993-1995.
- Feasibility Study: Dredging/Nearshore Disposal Plan, Oregon Inlet, N.C.* Wilmington, N.C.: Wilmington District, 1983.
- Foster, J.E. *History and Description of the Mississippi Basin Model*. Vicksburg: WES, 1971.
- Freeman, John R. Ed. *Hydraulic Laboratory Practice*. New York: American Society of Mechanical Engineers, 1929.
- Friedkin, Capt. J.F. *Results of Laboratory Study of the Meandering of Alluvial Rivers*. Vicksburg: MRC, 1946.
- Gatto, Lawrence W. “Ground Freezing Effects on Soil Erosion of Army Training Lands.” Pt. 1-2. Hanover: CRREL, 1997-1998.
- George, K.P. “Return-On-Investment On Paver.” Champaign, Ill.: CERL, 1982.
- Gow, A.J. et al. Ed. *International Symposium on Antarctic Glaciological Exploration (ISAGE), Sept 1968, Hanover, NH*. Hanover: International Association of Scientific Hydrology, 1970.
- Hall, James. “Comparative study of nondestructive pavement testing, WES NDT methodologies.” Vicksburg: WES, 1985.
- Highlights in Computational Science and Engineering*. Vicksburg: WES, 1998.
- Houston, J.R. “Los Angeles Harbor and Long Beach Harbor: Finite Element Numerical Model of Harbor Resonance.” *Ports '77* (ASCE 1977): 119-137.
- Humphreys, Andrew, and Abbot, Henry. *Report upon the Physics and Hydraulics of the Mississippi River*. Washington, D.C.: USACE, 1861.
- Jones, Randolph A. “Limited evaluation of the operational envelope of the M2 BFVS in ingressing / egressing water obstacles.” Vicksburg: WES, 1992.
- Ketcham, Stephen A. et al. “FDTD Seismic Simulation of Moving Tracked Vehicle.” Hanover: CRREL, 2000.
- Kitchens, Clarence W. “Interim Report: Computer, Survey, Electric, IBM, Project 8-35-04-001.” Fort Belvoir: ERDL, 1949.
- Langway, Chester C. “The History of Early Polar Ice Cores.” Hanover: CRREL, 2008.
- Lawson, Daniel, et al. “Geological and Geophysical Investigations of the Hydrogeology of Fort Wainwright, Alaska.” Pts. 1-2. Hanover: CRREL, 1996-1998.
- Lee, Charles R. et al. *Highlights of Research on Overland Flow for Advanced Treatment of Wastewater*. Vicksburg: WES, 1976.
- Link, Jr., L.E. “Thermal IR Techniques: A Possible Reconnaissance Tool for Roof Maintenance,” Apr. 1975. ERDC Archives.
- Louque, Jr., Robert E., and Graves, Eugene A. *Flood Routing Procedure for the Lower Mississippi River*. Vicksburg: MRC, 1972.
- Lyon, John Grimson. *Practical Handbook for Wetland Identification and Delineation*. Boca Raton: Lewis Publishing, 1993.
- McAnally, William, et al. *Columbia River Estuary Hybrid Model Studies*. Rp. 1. Vicksburg: WES, 1983.
- _____. “Columbia River Hybrid Modeling.” *ASCE Journal of Hydraulic Engineering* 110:3 (Mar. 1984): 300-311.
- _____. “Application of Columbia Hybrid Modeling System.” *ASCE Journal of Hydraulic Engineering* 110:5 (May 1984): 627-643.
- McMath, Robert E. “Relation Between Stage and Mean Velocity,” Mar. 14, 1881. Miscellaneous Papers of the MRC, Vol. II.

- Miscellaneous Articles on Experiment Station Work* (Vicksburg: WES, N.D.
- Murphey Newell R., and Lessem, Allan S. "Stresses in M1 tank tracks." Rps. 1-4. Vicksburg: WES, 1987-1991.
- Palermo, Michael R. and Engler, Robert M. "Thirty Years of Dredging Research at the USACE Waterways Experiment Station." *Proceedings Western Dredging Association 22nd Technical Conference and 34th Annual Texas A&M Seminar* (Denver Co.: WEDA, 2002).
- Pater, Larry L. "Getting started guide for the small arms range noise assessment model (SARNAM)." Champaign: CERL, 1999.
- Parchure, T.M., et al. "Objectives of Proposed Large Scale Experimental Facility." *Coastal Dynamics '94* (NY: ASCE, 1994): 808-814.
- Perovich, Donald K. "SHEBA: The Surface Heat Budget of the Arctic." *Arctic Research of the U.S.* 17:1 CRREL, 2001.
- Perovich, Donald K., et al., "Seasonal changes in Arctic sea-ice morphology," *Annals of Glaciology* 33 (2001): 171-176.
- Pickett, Ellis B., et al. *Los Angeles and Long Beach Harbors Model Study*. 4 Vols. Vicksburg: WES, 1975-1977.
- "A Program for the Analysis, Implementation and Test of a Waterways Experiment Station Terrain Analysis Radar (Project WESTAR)." Vicksburg: Texas Instruments, 1961.
- Reid, Robert O., and Bodine, Bernie R. "Numerical Model for Storm Surges in Galveston Bay." *Journal of the Waterways and Harbors Division, Proceedings of ASCE* (Feb. 1968): 33-57.
- Richter-Menge, Jackie, et al. *State of the Arctic, October 2006*. NOAA, 2006.
- Rinker, Jack. *Tutorial I: Introduction to Spectral Remote Sensing*. San Diego: International Symposium on Spectral Sensing Research, 1994.
- Rooney, Dan et al. "Mapping Soils with a Multiple-Sensor Penetrometer." Fertilizer, Aglime, and Pest Management Conference. University of Wisconsin, 2001.
- Second Supplementary Report on Investigations of the Board on Experimental Towboats*. June 17, 1929. CEHO CW GEN, Box 43A, Rivers, Mississippi, Folder 3, Investigation of Board on Experimental Towboats.
- Seed, H. Bolton and Lee, Kenneth L. "Liquefaction of Saturated Sands During Cyclic Loading." *Journal of the Soil Mechanics and Foundations Division, Proceedings of ASCE* (Nov. 1966).
- Simmons, H.B. "Protection of Narragansett Bay from Hurricane Surges." Vicksburg: WES, 1964.
- Smith, J.F., and Ingram, W.F. "Development of In-House Capability for Use of the Finite Element Method of Analysis of Boundary Condition Problems." Vicksburg: WES, 1967.
- Stockstill, Richard. "Olmsted Lock Outlet, Ohio River: Hydraulic Model Investigation." Vicksburg: WES, 1992.
- Stoker, J.J. *Water Waves: The Mathematical Theory with Applications*. NY: John Wiley and Sons, 1992.
- Stoker, J.J. et al., "Numerical Solution of Flood Prediction and River Regulation Problems. NY: NYU, 1954.
- Thompson, Paul W. *Flowing Water and the Small-Scale Model*. Vicksburg, Ms.: WES, 1938.
- Tucker, Walter B. et al. "Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s." *Geophysical Research Letters* 28:14 (Jul. 15, 2001): 2851-2854
- Untersteiner, Norbert, et al. "AIDJEX Revisited: A Look Back at the U.S.-Canadian Arctic Ice Dynamics Joint Experiment, 1970-78." *Arctic* 60:3 (Sept. 2007)
- Untersteiner, Norbert. "AIDJEX Review." Robert S. Prichard. Ed. *Sea Ice Processes and Models: Proceedings of the Arctic Ice Dynamics Joint Experiment International Commission on Snow and Ice Symposium*. Seattle: Washington UP, 1977.
- _____. "A Preliminary AIDJEX Model Simulation with 1972 Data." *AIDJEX Bulletin* (Sept. 1977): 1-24.
- Weatherly, John W., and Bitz, Cecilia. "Natural and Anthropogenic Climate Variations in the Arctic." *12th Symposium on Global Change and Climate Variations*. Boston: American Meteorological Society, 2001.
- Wilson, J.R. and Van Dam, V.L. Ed. *Dredging: Technology, Environmental, Mining*. Orlando, Fla.: 12th World Dredging Congress, 1989.

U.S. Government Documents

Motteff, John D. "Defense Research: A Primer on the Department of Defense's Research, Development, Test and Evaluation (RDT&E) Program." Congressional Research Service. Washington, D.C.: Library of Congress, Jul. 14, 1999.

Office of Technology Assessment. *A History of the Department of Defense Federally Funded Research and Development Centers*. Washington, D.C.: GPO, 1995.

U.S. Congress. *An Act to amend the Stevenson-Wydler Technology Innovation Act of 1980*. 99th Cong. 2nd Sess.

_____. *An Act Authorizing the construction, repair, and preservation of certain public works on rivers and harbors and for other purposes*. 71st Cong. 2nd Sess.

_____. *An Act Authorizing the construction, repair, and preservation of certain public works on rivers and harbors for navigation, flood control, and other purposes*. 91st Cong. 2nd Sess.

_____. *An Act to establish a national policy and develop a national program for the management, beneficial use, protection, and development of the land and water resources of the Nation's coastal zones, and for other purposes*. 92nd Cong. 2nd Sess.

_____. *An Act to establish a national policy for the environment, to provide for the establishment of a Council on Environmental Quality, and for other purposes (NEPA)*. 91st Cong. 2nd Sess.

_____. *An Act to promote United States technology innovation for the achievement of national economic, environmental, and social goals, and for other purposes*. 96th Cong., 2nd Sess.

_____. *Black Warrior, Warrior, and Tombigbee Rivers, Alabama, at Jackson Lock and Dam*, H.D. 50. 86th Cong. 1st Sess.

_____. *Bridges Across the Great Kenahwa River*. S.D. 114. 48th Cong., 1st Sess.

_____. *Coast Defenses of the United States and Insular Possessions*. S.D. 248. 59th Cong., 1st Sess.

_____. *Columbia River and Tributaries, Northwestern United States*. H.D. 531. Vol. 1. 81st Cong. 2nd Sess.

_____. *Expanded Project for Aquatic Plant Control*, H.D. 251. 89th Cong. 1st Sess.

_____. *Experimental Towboats*, H.D. 857. 63rd Cong., 2nd Sess.

_____. *Experimental Towboats*, H.D. 108. 67th Cong., 1st Sess.

_____. *Flood Control in the Mississippi Valley*, H.D. 90. 70th Cong., 1st Sess.

_____. *National Hydraulic Laboratory: Hearings before the Committee on Rivers and Harbors, House of Representatives, 70th Congress, 1st Session, on S.1710*.

_____. *Ohio River Pollution Control*. H.D. 266. Pt. 1. Vol. 1. 78th Cong., 1st Sess.

_____. *Platte River and Tributaries, Missouri and Iowa*, H.D. 262. 89th Cong. 1st Sess.

_____. "Policies, Standards, and Procedures in the Formation, Evaluation, and Review of Plans for Use and Development of Water and Related Land Resources." S.D. 97. 87th Cong. 2nd Sess.

_____. *Report on the Board of Engineers on Deep Waters Between the Great Lakes and the Atlantic Tide Waters*. H.D. 142. 58th Cong., 2nd Sess.

_____. *Report of the Board of Engineers regarding obstructions in the Columbia River*. S.D. 7. 53rd Cong., 1st Sess.

_____. *A Report of the Board of Road Commissioners for Alaska of Operations for the Season of 1906*. HD 523. Jan. 17, 1907. 59th Cong., 2nd Sess.

_____. *Report of the Chief of Engineers, U.S. Army, 1922*, H.D. 422. 67th Cong., 3rd Sess.

_____. *Report of the Chief of Engineers, 1867*. H.D. 1, Pt. 2. 40th Cong., 2nd Sess.

_____. "Report to the President on Government Contracting for Research and Development," S.D. 94. 87th Cong., 2nd Sess.

- _____. *To Establish a National Hydraulic Laboratory: Hearing before a Subcommittee of the Committee on Commerce, United States Senate, 67th Congress, 2nd Session, Pursuant to S.J. Res. 209, Sept. 8, 1922.* Washington, D.C.: GPO, 1922.
- _____. *U.S. Army Corps of Engineers Proposed Reorganization Plan: Hearings before the Subcommittee on Investigations and Oversight of the Committee on Public Works and Transportation, May 6 and 11, 1993.* 103rd Cong. 1st Sess.
- _____. *Water Hyacinth Obstructions.* H.D. 91. 55th Cong. 3rd Sess.
- _____. *Water-Hyacinth Obstructions in the Waters of the Gulf and South Atlantic States,* H.D. 37. 85th Cong. 1st Sess.

Video

- “Ancient Computer?” *Ancient Discoveries.* History Channel, Thurs., Apr. 30, 2009.
- “Hot Times in Alaska,” *Scientific American Frontier.* PBS, 2004.
- “Global Warning...?” History Channel, Nov. 27, 2007.
- “The Miracle of the Pentagon.” *60 Minutes.* Nov. 28, 2001.



A

Abbot, Henry A. 3, 22, 27, 30, 31, 43, 52, 56, 72; *ADCIRC model* 260, 329, 330; *Adiguzel, Ilker R. v.* 315, 321; *Advanced Research Project Agency (ARPA)* 155, 242; *Aerial cameras* 44, 46-47, 102; *Air Corps* 47, 90-91, 97, 103, 108, 113, 120; *Air Force* 94, 112, 118, 120, 124, 126, 143, 154, 165, 169, 180, 219, 241, 250-1, 253, 260, 265, 283-285, 290, 320, 332; *AirLand Battlefield Environment (ALBE)* 180, 198, 245, 278, 294; *Air Transport Command (ATC)* 124; *Alameda Air Station, California* 105; *AMC-71 Mobility Model* 235; *American Association of State Highway Officials (AASHO)* 116, 156; *American Institute of Electrical Engineers* 33; *American Philosophical Society* 1, 15, 17, 20; *American Revolution* 14-15, 18, 35; *American Shore and Beach Preservation Association (ASBPA)* 45, 89; *American Society of Civil Engineers (ASCE)* 9, 33-34, 51-54, 78, 82, 288, 311, 320, 330; *American Society of Mechanical Engineers (ASME)* 8, 33, 53-54; *American Society of Photogrammetry* 90, 93; *American Society of Testing and Materials (ASTM)* 154, 286, 311; *AMM-75mobiltiy model* 235; *Ancient engineering* 9-11, 49; *Antiterrorism* 268,310, 313, 319-320; *Aquatic Plant Control Program* 42, 173, 192, 195, 197-198, 270, 278, 288, 328; *Arbuthnot, Guy L.* 127; *Arctic Construction and Frost Effects Laboratory (ACFEL)* 124-125, 134, 137-139, 142; *Arctic Ice Dynamics Joint Experiment (AIDJEX)* 234; *Aristotle* 9-10; *Army Ballistics Research Laboratory* 127, 217; *Army Geospatial Center* 317-318; *Army Map Service* 135, 179, 219, 280; *Army Materiel Command (AMC)* 135, 143, 162, 166,-168, 179-180, 204, 293; *Army Pollution Abatement Program* 171, 186, 189, 239; *Army Research and Development Office* 162, 164, 167; *Army Research Laboratory (ARL)* 250-251, 193, 305, 334; *Arthur, Joseph* 3, 83, 96; *Astrolabe* 102, 134; *Atomic Energy Commission (AEC)* 127-128, 162, 164; *Automated Data Processing (ADP) Center* 237, 248-250

B

Babbage, Charles 215, 217; *Bacon, Francis* 10-11; *Bader, Henri* 3, 125, 206, 335; *Bagley, James W.* 44, 46-47, 90, 93-94; *Bailey Bridge* 103; *Baker, Benjamin* 13, 81-82; *Ballard, Joe N.* 269, 291, 294-300, 303, 305, 308-311; *Bandy, John* 288, 297-298; *Banks, Don* 149; *Bartlett, William* 20; *Base Realignment and Closure (BRAC)* 291-293, 327; *Bazin, Henri-Emile* 37-38, 49; *Beach Erosion Board (BEB)* iv, 3-4, 67, 88-90, 98, 101, 106-110, 112, 114-115,126-127, 130, 143-145, 148, 176, 192-193, 223, 288; *Beach, Lansing S.* 42-43, 52, 55-58; *Beard, Roy* 163, 233; *Bell Report* 133, 166; *Bentzel, Carl E.* 78; *Beitelman, Alfred D.* 161, 285; *BLAST software* 188, 239, 275, 290, 321; *Board of Engineers* 24-25, 38-39, 42-44, 72, 126; *Board of Engineers on Engineer Equipment* 44, 47-48, 91; *Board of Engineers on Experimental Towboats* 42-43; *Board of Engineers for Rivers and Harbors* 39, 72, 144, 173; *Board of Engineers on Sand Movement and Beach Erosion* 45, 89-90; *Board of Engineers on Water Hyacinth Obstructions* 42, 173; *Bonaparte, Napoleon* 12,

19, 24, 26; *Bonneville Hydraulic Laboratories* 95, 162, 175; *Bosnian War* 261-263, 284, 289; *Bossut, Charles* 12-13, 48; *Boyd, Marden "Burt"* 229, 232; *Boyd, Keith* 116, 142; *Breakwaters* 105-106, 111-112, 146-147; *Brindley, James* 13; *Brown, Fredrick R.* 62-63, 67, 127, 130, 154, 256; *Brown, Lytle* 59, 67, 71, 89; *Buchanan, Spenser J.* 83-85, 98, 106, 335; *Bucher, Edwin* 125, 139; *Building Research Advisory Board, National Academy of Sciences* 157, 160, 238, 288; *Bureau of Mines* 149; *Bureau of Reclamation* 34, 52, 82, 86-87, 96, 124, 128, 171-175, 269, 272, 288; *Burkhardt, Robert W.* 315-318; *Bush, Vannevar* 101, 131, 217, 242; *Byrd Station, Antarctica* 142, 207-208

C

Cababa, Robin C. 298-299, 303-306, 310; *Caldwell, Joseph M.* 144-145; *California Bearing Ratio* 116-117; *Camp Century, Greenland* 126, 137, 142, 164-165, 207-209; *Camp Fistclench, Greenland* 126, 137; *Camp Humphreys, Virginia* 40, 44, 67; *Camp TUTO, Greenland* 126, 137-138; *Cannon, John L.* 148, 169, 197; *Casagrande, Arthur* 3, 83-85, 116-117, 149, 152; *Central Concrete Laboratory, North Atlantic Division* 87-88, 113, 118, 270, 310; *Central Sierra Snow Laboratory* 124-126, 137; *Centrifuge* 256, 267, 311, 326, 332; *Chemical Warfare Service* 102; *Chesapeake Bay Model* 229, 233, 254, 260, 270; *Choromokos, James* 148; *Clarke, Frederick J.* 157, 162, 167, 184-185; *Clean Air Acts* 183, 186; *Clean Water Acts* 183, 186, 193, 200-202; *Coastal and Hydraulics Laboratory (CHL)* 264, 304; *Coastal Engineering Research Board (CERB)* 144-148, 264, 329; *Coastal Engineering Research Center (CERC)* iv, 4, 133, 143-149, 184-185, 192-196, 201, 223, 233-234, 238, 255, 260-264, 275, 305, 336-337; *Coastal erosion* 44, 64, 90, 114, 146, 194; *Coastal Zone Management* 192-194, 246; *Cold Regions Research and Engineering Laboratory (CRREL)* iv, 4, 133, 140-143, 162, 166, 169, 178, 180-182, 184, 189-190, 198, 201, 205-212, 226, 260, 262-263, 271, 282-284, 303, 324-325; *Cold War* 4, 101, 112, 119, 123, 125-126, 131, 179-181, 208, 244, 259, 267-268, 283, 291, 295; *Columbia University* 45, 256; *Committee on Tidal Hydraulics* 145, 148; *Computer-aided design and drafting (CADD)* 239, 242, 246-248, 253, 278-279, 289, 333; *Computer-Aided Structural Engineering (CASE)* 237, 249, 252-254, 275, 279, 289; *Computer Applications for Geotechnical Engineering (CAGE)* 237-238, 275; *Computerized Evaluation of Utility Plans (CEUP)* 188, 238-239; *Computer, survey* 102, 217, 218-219, 223; *Comstock, Cyrus B.* 37; *Condorcet, Marquis de* 13, 21; *Concrete Laboratory, WES* 88, 153-154, 267, 289; *Condensed Army Mobility Model System (CAMMS)* 265, 275, 283; *Coolidge, Calvin* 53; *Cooperative Research and Development Agreement (CRADA)* 289-291, 294, 311, 326; *Corps of Artillerists and Engineers* 19; *Corps of Topographical Engineers* 24-29; *Cornell University* 34, 38, 50, 62, 77, 122, 244; *Construction Engineering Research Laboratory (CERL)* iv-v, 4, 95, 97, 133, 157-162, 167, 169, 184, 186-188, 190-191, 197-198, 201, 204, 211-212, 226-227, 238-242, 246-259, 254-255, 257, 271, 273-275, 278, 285-289, 293-297, 303-306, 309, 311, 315, 318, 321-323, 326-327, 334; *Construction Productivity Advancement Research (CPAR)* 266, 269, 286, 289; *Corps of Engineers Research and Development Directorate (CERD)* 167-169, 200, 252, 294-299, 304-307, 315; *Cox, Rodney E.* 157, 160; *Crozet, Claudius* 19-20; *Coulomb, Charles Augustin* 12, 81-82

D

Daggett, Larry L. 229, 232-233; *Dalecarlia Reservation, Washington, D.C.* 90, 106, 144-145; *Dartmouth College* 142, 226, 228, 307; *Da Vinci, Leonardo* 12; *Davis, Robert E.* v, 315, 318-319; *Defense Advanced Research Project Agency (DARPA)* 189, 282, 290; *Defense Environmental Restoration Program (DERP)* 201, 271, 278, 293; *Defense Intelligence Agency* 179; *Defense*

Mapping Agency (DMA) 179-181, 245-246, 280, 316; *Department of Agriculture* 50, 171, 181, 273; *Department of Energy* 189, 210, 243, 260, 267, 271; *Department of Housing and Urban Development* 160, 179; *Descartes, Renee* 10-11; *De Vauban, Sebastian Le Prestre* 12-13; *Digital Image Analysis Laboratory (DIAL)* 181, 226, 244; *Digital Terrain Elevation Data (DTED)* 180, 245-246; *Digital Topographic Support System (DTSS)* 245, 278; *Distant Early Warning (DEW)* 126, 137, 139, 143, 164, 207, 283; *Distinct element method (DEM)* 235, 274; *DrChecks* 242, 275, 321; *Dredges* 25, 37, 42-43, 198; *Dredging* 32, 69, 184, 192-193, 195-202, 264, 270, 328-329; *Dredged Material* 95, 177, 182, 192-193, 195-200, 270; *Dredged Material, Beneficial Uses of* 196-201, 328; *Dredged Material Research Program (DMRP)* 185, 195-201, 270, 335; *Dredging Research Program* 270; *Duportail, Louis L.* 18; *Dutton, George* 25

E

Eads, James 3, 32; *Eckert, J. Presper* 217-218; *Ecole Polytechnique* 12-13; 19-20, 48; *Edison, Thomas A.* 3, 34, 39, 44, 52; *EDVAC computer* 217, 220-221, 242; *Einstein, Albert* 126; *Ellet, Jr., Charles* 27, 30-31; *Ellicott, Andrew* 14, 19; *Endangered Species Acts* 183, 188, 190-191, 201; *Endicott Board* 38-39; *Engineer Board* 3-4, 44, 47, 67, 90-91, 94, 98, 101-103, 106-109, 120-121, 124, 126, 134, 218, 337; *Engineer depots* 39, 43-44; *Engineer Detachment at Wright Field, Ohio* iv, 44, 90-94, 102, 107; *Engineer Research and Development Center (ERDC)* iii-v, 3-4, 7, 258, 294, 296, 299-300, 302-337; *Engineer Research and Development Laboratories (ERDL)* 121, 126, 128, 134-135, 137, 142, 162, 164-166, 219, 223, 244; *Engineer School* v, 6, 21-23, 25, 40, 43-44, 48, 56-58, 63, 103-109, 114, 120-121, 126, 134-135, 164, 216, 218-219; *Engineer Studies Center* 280; *Engineer Topographic Laboratories (ETL)* 135-137, 162, 169, 179-182, 188, 198, 211-212, 226, 244-249, 254-257, 279-282; *Engler, Robert* 196, 270, 328; *Engels, Hubert* 14, 50, 53-54; *ENIAC* 217-218, 220-221; *Enola Gay* 117; *Environmental Advisory Board (EAB)* 185, 192, 247; *Environmental Impact Statement (EIS)* 166, 183, 185-186, 195-197, 201; *Environmental Laboratory (EL)* 4, 194-205, 211-212, 232, 260, 265, 270-273, 289, 297, 305-306, 309, 315, 318, 321, 326-328, 334; *Environmental Protection Agency (EPA)* 179, 183-184, 186, 189, 192, 196, 200-204, 239, 260, 271-274, 286, 289; *Explosive Excavation Research Laboratory* 129, 154

F

Facilities Engineering Support Agency (FESA) 162-165, 167-168, 187; *Falkner, Francis* 63, 76-77, 85, 98, 147; *Fargue, Louis* 49; *Federal Aviation Administration* 160; *Federal Highway Administration* 189, 205, 332; *Ferguson, Harley* 70, 72-73; *Field Research Facility, Duck, N.C.* 145-146, 193, 261, 264; *Finite element method (FEM)* vi, 152, 228-229, 235-235, 248, 274-275, 277; *Fish and Wildlife Service* 172-173, 175, 190-192, 201-202, 272; *Fisheries Engineering Research Laboratory* 98, 162, 174-175; *Fisk, Harold* 111, 149; *Flathau, William* v, 130, 154, 267; *Fleming, Beth* 315, 321, 328; *Flood Control Acts* 2, 54, 59; *Floods, Mississippi River* 7, 23, 27, 31, 37, 48, 50-52, 54-55, 57-58, 64, 67, 71-73, 75; *Forest Service* 102, 119, 172, 205; *Formerly Used Defense Sites* 204, 274, 279; *Fort Belvoir, Virginia* 3, 63, 90, 94, 107, 134-135, 145, 162-164, 179, 223, 293, 327; *Fort Drum, New York* 187, 285; *Fort Hood, Texas* 187, 247; *Fort Lewis, Washington* 187, 247; *Fort Peck Dam, Montana* 69, 85, 97, 128, 152; *Fort Polk, Louisiana* 187, 190, 247; *Fort Richardson, Alaska* 123, 192, 274; *Fort Stewart, Georgia* 187, 190; *Fort Totten, New York* 24, 38, 43; *Fortifications* 18, 20-21, 24, 37-39, 43-44, 56, 85, 102, 112, 126, 268; *Franklin, Benjamin* 1-4, 14-19, 336; *Franklin Institute* 24, 33-34; *Freeman, John R.* 2, 50-54, 57-58, 62-64;

Freeman scholars 53-54, 67; *Friedkin, J.F.* 81, 335; *Freitag, Dean R.* 150-151, 195; *Fremont, John C.* 26, 28; *Frost, Robert* 3, 142, 180-182, 244, 279, 281; *Fuel cells* 135, 187, 285, 290, 326

G

Galilei, Galileo 11-12; *Gerdel, Robert W.* 3, 124-126, 189; *Geodesy, Intelligence, and Mapping Research and Development Agency (GIMRADA)* 135-136; *Geographic information systems (GIS)* 182, 242-248, 253, 257, 270, 278-280, 283-284, 289-290, 306, 309, 316, 318-319, 328, 333-334; *Geographic Resources Analysis Support System (GRASS)* 188, 247-248, 278, 290; *Geotechnical and Structures Laboratory (GSL)* 311, 314-315, 319-320, 329, 332; *Geotechnical Laboratory* 152-153, 197-198, 237, 255, 265-271, 274, 305, 310; *Gilboy, Glennon* 83, 85; *Gillmore, Quincy* 37; *Global positioning systems (GPS)* 136, 200, 270, 280-281, 327; *Goethals, George* 37; *Goran, William* 248, 278, 288, 308; *Graves, Earnest* 128; *Great Lakes* 21-22, 26, 38, 145-146, 148, 193, 195, 241, 260, 329; *Greenland* 119, 122-126, 130, 137-138, 142-143, 164-165, 206-209, 257, 274, 283, 335; *Greenland Ice Sheet Program (GISP)* 142, 207, 210; *Greenville Bends* 70, 72-73, 76; *Gribble, William Jr.* 162, 166-168; *Groves, Leslie* 126-127; *Grum, Allen F.* 252; *Gruner, Heinz* 91, 93; *Guglielmini, Domenico* 12-13, 48; *Gun Foundry Board* 38; *Gunnison, John* 26

H

Hansen, B. Lyle 142, 206, 208-209, 335; *Harrison, John W.* v-vi, 195-197, 229, 232, 247, 297-298, 305; *Harvard University* 32, 47, 83, 86, 217-218, 221, 243, 247; *Hatch, Henry J.* 248, 292; *Haupt, Hermann* 21; *Hazardous Waste Research Center* 204, 271; *Headquarters of the Corps of Engineers (HQUSACE)* 94, 242, 253-254, 259, 279, 288, 292-296, 304-305, 311, 315, 317; *Herrmann, Frank A.* 229, 256, 264; *Hershel, Clemens* 50, 52; *High Mobility Multi-Wheeled Vehicle (HMMWV)* 266, 284, 287; *High Performance Computer (see also Supercomputer)* 251, 276-277, 293, 298, 333; *High Performance Computing Major Shared Resource Center* 251, 276-277, 279, 317, 333, 335; *Holland, Jeffery P.* v-vi, 254, 308, 314-315, 337; *Hollerith, Herman* 216; *Hoover, Herbert* 54, 63, 86; *Houston, James R.* v-vi, 232, 254, 264, 298, 305-306, 309-310, 314-315, 317, 334; *Hudson, Robert Y.* 106, 110, 147; *Humphreys, Andrew A.* 3, 21-23, 27, 30-32, 52, 58, 72, 172, 215; *Humphreys Engineering Center, Virginia* 40, 44, 67, 293, 296-297, 304; *Huntsville Division* 158, 188, 204, 239, 253-254; *Hurricane Study Coordinating Committee* 144; *Huval, Carl J.* 229, 232-233; *Hvorslev, Juul* 83, 111, 149; *Hydraulic laboratories* 2, 7, 14, 34-35, 37, 48-57, 59-64, 67, 76, 95, 172, 176, 220; *Hydraulic Laboratory, WES* 106-107, 110, 130, 147, 176, 195, 229-230, 233, 256, 260, 264; *Hydraulic modeling* 13-14, 16-17, 37, 55-56, 60-61, 74-77, 84, 143, 147, 163, 169, 176-177, 220, 222, 230-231, 256, 325; *Hydrologic Engineering Center (HEC)* 163, 167-168, 229, 233, 237, 246, 261, 275, 278

I-L

Information Technology Laboratory (ITL) 4, 248-255, 257, 276-279, 288-289, 305-306, 309, 314-315, 318, 328, 333, 335, 337; *Internet* v, 242, 253, 260, 262-263, 275, 280, 328, 332; *Institute for Water Resources (IWR)* 145, 163, 166-168, 184; *Integrated Training Area Management (ITAM)* 188, 247, 275; *Ippen, Arthur T.* 147, 222, 229; *Jackson, Thomas H.* 59, 67, 70, 72; *Jadwin, Edgar* 45, 53-59, 63-64, 70-71; *Johnson, Douglas W.* 45; *Keeley, John W.* 195, 306-307, 315; *Kennedy, John F.* 128, 133, 184; *Keulegan, Garbis* 3, 106, 148, 176, 229, 232, 256; *Keweenaw Field Station, Michigan* 126, 137, 143, 180; *Khobar Towers* 254, 268, 312, 320, 335; *Kingman, John J.* 106, 114; *Kirby, Robert F.* 295, 297; *Korean War* 101, 107, 110, 112, 121;

Kovel, Maxim 169, 198; *Krumbein, William* 106-107, 114-115; *Langley Field, Virginia* 116-118, 120; *LANDSAT* 181-182, 244, 279; *Langway, Chester C.* vi, 206-209, 335; *Lappin, Willard N.* 161, 225; *L'Enfant, Pierre* 18-20; *Leverenz, Donald J.* 305-309; *LIDAR* 264, 318, 332; *Link, Lewis E.* "Ed" v-vi, 261, 283-284, 294-300, 304-309, 311, 314, 330; *Liquefaction* 152; *Long, Stephen* 15, 25-28, 30; *Lowell Locks and Canals Company* 50, 56; *Lyons, L.E.* 55-56

M

McAdams, John 113; *McAnally, William H.* vi, 229-233, 256, 261, 264; *McFadden, Gayle* 116; *McKim, Harlan "Ike"* 182, 246, 284; *McMath, Robert E.* 56-57; *Mackenzie, Alexander* 48; *Mahan, Dennis* 19-20; *Manhattan Project* 101, 126, 128; *Marcuson, William v.* 255, 270, 298-299, 305-306, 311; *Marshall, Bruce* 116-117; *Mason, Martin* 106, 114-115; *Massachusetts Institute of Technology (MIT)* 32, 34, 50, 54, 57, 62, 82-84, 95-96, 101, 119, 123, 128, 147, 155, 217, 220, 222, 227; *Mather, Bryant* 3, 14, 87, 88, 153-154, 267, 270, 298, 305-306, 311; *Matthes, Gerard* 73-74, 98, 106-107; *Mathematical Hydraulics Group (MHG)* 195, 229, 232, 336; *Mauchley, John* 217-218; *Maune, David F.* 180, 279; *Merrill, William* 37; *Mexican-American War* 21, 26; *Microcomputer* 238, 248; *Middlebrooks, Thomas A.* 83, 116, 123; *Military Evaluation of Geographic Areas (MEGA)* 122, 178-179; *Mine detection* 102, 134; *Mississippi Basin Model* 71, 74-75, 87, 107, 110, 122, 229; *Mississippi Delta Survey* 27, 30, 72, 215; *Mississippi River* 7, 25-27, 30-32, 34, 37, 42, 48, 51, 53-58, 67-68, 70-77, 80, 98, 106, 110-111, 149, 161, 176, 183, 195, 197, 261, 266, 276; *Mississippi River Commission (MRC)* 28, 31-32, 37, 42-43, 52-53, 56-59, 67-73, 77, 80, 85, 87, 90, 95, 98, 106, 110-111, 229; *Mobility* 4, 9, 15, 118-123, 131, 135, 137, 149-153, 176-179, 182, 197-198, 235, 255, 257, 263-267, 269, 283-284, 294, 319, 332; *Mobility and Environmental Systems Laboratory* 123, 150, 177-178, 197, 235, 289; *Mobility Environmental Research Study (MERS)* 123, 179, 235; *Morris, John W.* 163, 169, 184; *Mosher, Reed v.* 312, 315; *Munitions* 61, 192, 198, 268, 271, 274, 327, 332

N

National Academy of Sciences 156, 206, 238, 288; *National Academy of Engineers* 153, 311; *National Aeronautics and Space Administration (NASA)* 16, 97, 149, 150-151, 156, 181-182, 210, 226-227, 243-244, 248, 282, 288; *National Bureau of Standards* 2, 34, 50, 102, 106, 146, 176; *National Center for Supercomputing Applications* 242; *National Defense Research Committee (NDRC)* 101-102, 126; *National Environmental Policy Act (NEPA)* 4, 166, 183-185, 192, 327; *National Oceanic and Atmospheric Administration (NOAA)* 47, 92-93, 181, 196, 210, 233-234, 246, 260, 264, 272, 274, 289; *National Research Council* 9, 45, 54, 275, 330; *Naval Facilities Engineering Command* 187, 248, 253, 287; *Naval Research Laboratory* 2, 52, 102, 181; *Neumann, Donald L.* 222-223, 225, 227, 249; *Newcomer, Henry C.* 42, 45, 56; *Newton, Isaac* 11, 49, 67; *New York University* 119, 144, 221; *Nichols, Kenneth D.* 63, 77, 126-127, 164; *Normandy Invasion* 103, 106, 112, 115; *North American Aerospace Defense Command (NORAD)* 156, 162; *North Atlantic Division* 67, 87, 126; *North Atlantic Treaty Organization (NATO)* 198, 235, 265, 319; *Northway Field, Alaska* 124, 137; *Nuclear Cratering Group* 128-130, 228, 267

O-P

O'Brien, Morrough P. 45, 90, 106, 125, 148, 176; *O'Connor, Michael J. v.* 288, 295, 298-299, 305-306, 308, 311, 315; *Ockerson, John* 52-53, 55-58; *Office of the Chief of Engineers (OCE)* 4, 42, 63, 71, 83, 85, 87, 91, 97, 103, 107, 110, 114, 116, 119, 122-128, 134-135, 139, 142-148,

156-157, 160-164, 166-169, 177, 179, 181-182, 184-185, 187-188, 192-198, 201, 222, 225, 229, 233, 237, 239, 246, 249, 280; *Office of Naval Research* 145, 210, 261; *Ohio River* 25, 37, 56, 68-69, 176, 222; *Ohio River Division Laboratories (ORDL)* v, 3, 83, 87, 95-97, 113, 116, 118-119, 123, 153, 155-157, 160, 226; *Ordnance* 38, 327; *Ordnance Department* 39, 102, 118, 126, 218; *Paint and Corrosion Laboratory* 161; *Paint Technology Center* 285, 326; *PAVER software* 228, 240-241, 275, 290, 326; *Peixotto, Ernest D.* 168, 195, 259; *Penetrometer* 119, 265-266, 284; *Permafrost* 4, 40, 123-125, 131-132, 137, 139, 142-143, 180, 182, 189, 210, 274, 332, 336; *Permafrost Division, St. Paul District* 124-125, 137; *Philippe, Robert R.* 83, 96-97, 116, 119, 142; *Photogrammetry* iii, 3-4, 67, 92-93, 136-137, 169, 181, 243-244, 257, 259, 335; *Pike, Zebulon* 26; *Pillsbury, George B.* 40-41, 45; *Pittman, David W.* 94, 314, 319; *Pitot, Henri De* 12, 48, 50, 78-79; *Porter, O. James* 116-117; *Price, William G.* 37, 78-79, 95; *Project Reliance* 290, 293-294; *Puget Sound Navy Yard, Washington* 105, 166; *Purdue University* 119, 124, 137, 161, 180-181, 244; *Putnam, Rufus* 18

R

Radhakrisnan, N. v-vi, 237, 249-254, 256, 298, 305, 307, 314; *Rapid Combat Mapping Systems (RACOMS)* 245; *Rankin, William* 13, 81; *Ransdell, Joseph* 51-54, 58; *Reclamation Service (See Bureau of Reclamation)*; *Red-cockaded woodpecker* 189-191, 274, 328; *Redstone Arsenal, Alabama* 173, 237; *Rehbock, Theodor* 53-54; *Remote Sensing/GIS Center* 182, 246, 279, 284, 289, 306, 318; *Rensselaer Polytechnic Institute* 21, 32; *Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Program* 154, 266, 269; *Research and Development Office, OCE* 167, 198; *Research, Development, Test, and Evaluation (RDTE&E)* 290, 307, 310, 318, 336; *Resio, Donald T.* 148, 230, 323; *Resource Conservation and Recovery Act* 183, 201; *Reybold, Eugene* 71, 74-75; *Reynolds, Osborne* 49, 88; *Rhine River* 76, 103, 106, 109, 112; *Richardson Highway* 40-41; *Richardson, Thomas* 264, 315, 328-329; *Rittenhouse, David* 14-15; *Rivers and Harbors Acts* 25, 39, 42-43, 172-173, 195; *Rock Island District* 161-162, 246; *Rock mechanics* 149, 153, 162, 167, 235-236, 306; *Roessler, Solomon W.* 39; *Roper, William E.* v, 280, 294-295, 298, 305-306; *Roosevelt, Franklin D.* 126; *Roosevelt, Theodore* 39, 172; *Rouse, Hunter* iv, 64, 147, 155; *Royal Society of London* 1, 13, 15; *Rutledge, Phillip* 116, 125;

S

SAFEGUARD 154, 158, 160; *SAGE* 220, 236; *Saltwater intrusion* 110, 176; *Sand Inventory Program* 144, 146; *San Juan Harbor, Puerto Rico* 105, 233, 276; *Saville, Thorndike, Sr.* 3, 45, 89, 144; *SCR-625 Mine Detector* 102-103; *Sequential Collation of Range (SECOR)* 136, 280; *Shake table* 158-159, 257; *Shanks, Fletcher* 161, 335; *Sheng, Y. Peter* 233, 260; *Ship-Tow Simulator* 233, 274, 329; *Shreve, Henry M.* 3, 25; *Shaffer, Louis A.* 3, 157, 238, 288; *Signal Corps* 34, 46, 102, 135, 219; *Simulated ecosystem modeling (SEM)* 195, 197, 328; *Simmons, Henry B.* 110, 229; *Site Characterization Analysis Penetrometer System (SCAPS)* 265, 271; *Skidmore, Herrol J.* 110, 127; *SM-1 Nuclear Power Plant* 135, 161, 164-165; *Smeaton, John* 13, 56, 86; *Soil mechanics* vi, 4-5, 13, 81-85, 123, 139, 149, 152, 193, 215, 255, 265, 267, 311, 329, 334-336; *Soil Mechanics Laboratory* 106, 113 *Soils and Pavements Laboratory* 153-154, 235, 264-267; *Sotirin, Barbara* 295, 298, 305-306, 309-310, 315; *Snow, Ice, and Permafrost Research Establishment (SIPRE)* 125-126, 132, 137-142, 178, 180, 206, 226, 284, 337; *S.S. Manhattan* 140-141; *Steele, Byram* 87; *Stevin, Simon* 12; *St. Louis District* v-vii, 95, 223, 239, 253; *Stoker, J.J.* 221, 229; *Strategic Environmental Research and Development Program* 271, 291; *Structures Laboratory, WES* 150, 154, 160, 261, 265, 267-270, 310-311; *Supercomputer* 226, 234, 249, 250-254, 256, 276-277, 279,

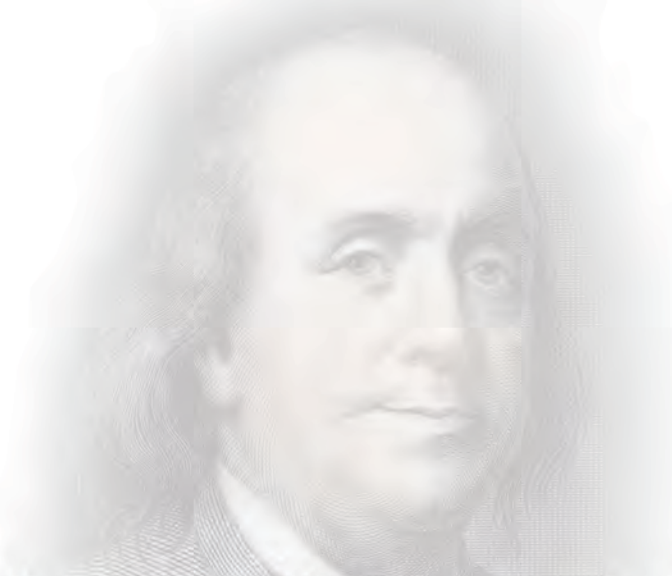
313, 333; *Superfund Act* 183, 192, 201, 204, 271, 327-328; *Surface Heat Budget of the Arctic Ocean (SHEBA)* 210, 234; *Swart, Peter* 298; *Swift, Joseph* 21

T-U

T-series cameras 46-47, 91, 102; *TABS software* 223, 237, 260, 275-276; *Taft Board* 39, 126; *Taft, William H.* 39, 48; *Tank-Automotive Command* 178, 235, 250, 253, 266, 282; *Tank* 102-104, 108-109, 118, 134, 149, 177-178, 266, 286-287, 328; *Terrain Analysis Center (TAC)* 179-180, 257, 279; *Terzaghi, Karl von* 13, 81-85, 96, 111, 117, 149, 311; *Thayer, Sylvanus* 19-21; *Theodolite* 102, 134, 136, 220; *Thierry, George Henry de* 53; *Thompson, Paul* 63, 76-77, 80, 98, 106, 336; *Tocqueville, Alexis de* 15; *Topographic Engineering Center (TEC)* 3, 262-263, 278, 280-282, 289, 293-298, 303-306, 309, 315-319, 333; *Topudurti, Kirankumar V. v.* 315, 334-335; *Totten, Joseph G.* 24-25, 38; *Townsend, Curtis* 56-58; *Trafficability* 118-123, 126, 149, 151, 177, 198; *Trans-Alaska Pipeline* 141, 143, 189; *Tri-Service CADD/GIS Technology Center* 248, 253, 279, 333; *Truman, Harry S.* 164, 193; *Tundra Biome Project* 189; *Unexploded Ordnance (UXO)* 204, 271, 308, 327; *Universal Automatic Map Compiler Equipment (UNAMACE)* 244, 235; *United Nations (U.N.)* 179, 211, 262; *UNIVAC computer* 217, 219-222, 226-227, 244; *University of California at Berkeley* 45, 59-60, 95, 119, 144, 230, 247-248, 330; *University of Illinois at Champaign* 97, 157, 226, 237, 241, 288, 304, 326; *U.S. Civil War* 20-24, 27, 31-32, 38, 44, 46, 86, 92; *U.S. Coast and Geodetic Survey* 45, 92; *U.S. Geological Survey* 44, 46, 50, 95, 115, 124, 171, 181-182, 189, 261, 264, 272, 275, 280, 288, 291, 324; *U.S. Military Academy* 2, 6-7, 12-14, 19-28, 32, 37, 59, 87, 92, 97, 310; *U.S.S. Sturgis* 163-165

V-Z

Vicksburg District 62, 70, 303; *Vietnam War* 101, 107, 110, 121, 123, 130-131, 154, 179-180, 186; *Vincent, C. Linwood* 148, 230, 232; *Vogel, Herbert D.* 3, 57, 59-63, 67-68, 70, 72-73, 76-77, 80, 84-85, 98; *Von Neumann, John* 217, 220-221, 242; *War of 1812* 20, 25; *Waterways Experiment Station (WES)* iii, 2, 7, 36, 59-64, 66-81, 84-85, 8-89, 94-95, 98, 101-107, 110-113, 116-123, 127-131, 133-134, 137-139, 142, 147-155, 162, 169, 172-173, 176-179, 194-205, 211-212, 222-225, 227-238, 246-257, 259-279, 289-291, 293-300, 303-306; *Water Resource Development Acts* 200, 289, 329; *Weapons Effects Laboratory* 130, 235; *Weather Bureau* 124-125, 144; *Weather Service* 324; *West Point* (see *U.S. Military Academy*); *Whalin, Robert W.* v-vi, 148, 155, 232, 250-252, 255-25, 259, 264, 294-295, 298-299, 305-306; *Whistler, George* 20-21, 25; *Wilby, Francis B.* 59, 71; *Willeys Point, New York* 21-25, 38-39, 92; *Williams, Jonathan* 19; *Wilson, Walter K.* 144, 156, 163; *Worcester Polytechnic Institute* 34, 50, 274; *World War I* 38-39, 41-46, 82, 93, 95; *World War II* 3-4, 8, 60, 67, 70, 74-75, 85, 87, 93, 97-99, 101-121, 123-124, 126, 127, 131, 133-134, 137, 155, 164-166, 171, 176-177, 180, 183, 192-193, 215-217, 243, 262, 265, 280, 292, 337; *Wright brothers* 46, 93; *Wuerpel, Charles E.* 87-88; *Zackrisson, Harry B.* 97, 156-157



Research and Development in the
U.S. Army Corps of Engineers:

Improving the Common Stock of Knowledge



Making the Nation Safer & Better