REPORT DOCUMENTATION PAGE

OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
May 95

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
A Risk mitigation methodology for Solid Waste Landfills

5. FUNDING NUMBERS

6. AUTHOR(S)
William Brent Nixon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFIT Students Attending:
University of South Florida

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/CI/CIA
95-012D

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DEPARTNEMT OF THE AIR FORCE
AFIT/CI
2950 P STREET, BDLG 125
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release IAW AFR 190-1
Distribution Unlimited
BRIAN D. GAUTHIER, MSgt, USAF
Chief Administration

12b. DISTRIBUTION CODE

DTIC
SELECTE
JUN 19 1995
S D
F

13. ABSTRACT (Maximum 200 words)

19950615 064

14. SUBJECT TERMS

15. NUMBER OF PAGES
178

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

DTIC QUALITY INSPECTED 5

95-012D

ABSTRACT

Several recent models have attempted to simulate or assess the probability and consequences of the leakage of aqueous contaminant leakage from solid waste landfills. These models incorporate common factors, including climatological and geological characteristics. Each model, however, employs a unique approach to the problem, assigns different relative weights to factors, and relies upon extrapolated small-scale experimental data and/or subjective judgment in predicting the full-scale landfill failure mechanisms leading to contaminant migration. As a result, no two models are likely to equally assess a given landfill, and no one model has been validated as a predictor of long-term performance.

The United States Air Force maintains a database for characterization of potential hazardous waste sites. Records include more than 500 landfills, providing such information as waste, soil, aquifer, and monitoring location data, and the results of sample testing. Through analysis of this information, nearly 300 landfills were assessed to have sufficiently, partially, or inadequately contained hazardous constituents of the wastes placed within them.

In comparing long-term containment among these landfills, only a few factors employed in existing models--primarily landfill size, seismic activity, freeze/thaw cycling, and potential evaporation relative to precipitation--were found statistically significant. An empirical model of landfill failure was thus constructed to categorize landfills as "high," "moderate," or "low" relative risk. The model classified 42 percent of tested landfills of known performance as exceptional ("high" or "low" risk), with an overall efficiency of 85 percent.

UNIVERSITY OF SOUTH FLORIDA
Graduate School

SUCCESSFUL DEFENSE OF THE PH.D./ED.D. DISSERTATION

The undersigned verify that the final oral defense of the dissertation of William Brent Nixon, has been successfully completed and that the dissertation is ready to submit to the Graduate School.

Title of Dissertation: A Risk Mitigation Methodology for Solid Waste Landfills

Major Field of Study: Environmental Engineering

Department: Civil Engineering & Mechanics

Examining Committee:

	Typed Name	Signature
Chairperson of Defense:	Dr. O. Geoffrey Okogbaa	O. Geoffrey Okogbaa
Major Professor:	Dr. R. Jerry Murphy	[signature]
Member:	Dr. Robert P. Carnahan	Robert P. Carnahan
Member:	Dr. Richard Ian Stessel	[signature]
Member:	Dr. Richard O. Mines	Richard O. Mines
Member:	Dr. Anita L. Callahan	[signature]
Member:	Dr. Henry L. Vacher	H. Vacher

March 31, 1995
DATE

sucdef.frm

Graduate School
University of South Florida
Tampa, Florida

CERTIFICATE OF APPROVAL

Ph.D. Dissertation

This is to certify that the Ph.D. Dissertation of

WILLIAM BRENT NIXON

with a major in Civil Engineering has been approved by
the Examining Committee on March 31, 1995
as satisfactory for the dissertation requirement
for the Doctor of Philosophy in Civil Engineering degree

Examining Committee:

Robert J. Murphy

Major Professor: Robert J. Murphy, Ph.D.

Robert P. Carnahan

Member: Robert P. Carnahan, Ph.D.

Member: Richard I. Stessel, Ph.D.

Richard O. Mines Jr.

Member: Richard O. Mines, Jr., Ph.D.

Member: Anita L. Callahan, Ph.D.

H L Vacher

Member: Henry L. Vacher, Ph.D.

A RISK MITIGATION METHODOLOGY
FOR SOLID WASTE LANDFILLS

by

WILLIAM BRENT NIXON

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Civil Engineering
Department of Civil Engineering and Mechanics
University of South Florida

May 1995

Major Professor: Robert J. Murphy, Ph.D.

DEDICATION

To my parents, William Brown Nixon and Louise Emerson Nixon, who provided the foundation within me upon which this work could be constructed. They continue to steadfastly encourage me, spiritually and intellectually, in my daily life and in the pursuit of my aspirations.

ACKNOWLEDGMENTS

I wish to express my gratitude to my Major Professor, Dr. Robert J. "Jerry" Murphy, and the other five members of my committee: Dr. Robert P. Carnahan; Dr. Richard I. Stessel; Dr. Richard O. Mines, Jr.; Dr. Anita L. Callahan; and Dr. Henry L. "Len" Vacher. Collectively and individually, these six professors inspired, guided and encouraged me throughout the evolution of this dissertation. Their influence will be always reflected in my future academic and professional accomplishments.

I am also grateful to my many friends throughout the United States Air Force. In particular, I thank the Air Force Institute of Technology's Department of Engineering and Environmental Management for their sponsorship of my degree and the Civilian Institutions personnel who administered the program, the Armstrong Laboratory Environics Division for providing funding for this research effort, the staff of the Air Force Center for Environmental Excellence who assisted me in accessing their database and other resources, the Air Combat Command Civil Engineering staff, the Cadre of AFROTC Detachment 158, and the many personnel at MacDill Air Force Base who provided administrative and other services. I am grateful, as well, to the staff of the University of South Florida's Department of Civil Engineering and Mechanics for their assistance.

Most of all, I thank my wife, Sumie, for her understanding and her selfless support throughout this endeavor. I could not have completed this degree without her unwavering commitment and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AFI	Air Force Installation Information (IRPIMS table)
ANOVA	Analysis of Variance (statistical procedure)
AOC	Area of concern
ARAR	Applicable or relevant and appropriate requirements
ASD	Air/soil dust
ASTM	American Society for Testing and Materials
ASV	Air/soil volatiles
Br^-	Bromine
BOD_5	5-day biochemical oxygen demand
C	Celsius
CAL	Calculated Hydrologic Parameters (IRPIMS table)
CDD	Construction and demolition debris
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act of 1980
CERCLIS	Comprehensive Environmental Response, Compensation and Liability Information System
CHF	Contaminant Hazard Factor
cm	Centimeter

CMI	Corrective Measures Implementation
CMS	Corrective Measures Study
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
CTB	Chemical time bomb
da	Day
DERP	Defense Environmental Restoration Program
DL	Detection limit
DOD	United States Department of Defense
DOE	United States Department of Energy
DOT	United States Department of Transportation
DPM	Defense Priority Model
DRASTIC	A standardized system for evaluating ground water pollution potential developed by the National Water Well Association
DWS	Debris Washing System
EHQ	Ecological Hazard Quotient
E/P	Evaporation-to-Precipitation ratio
EPA	United States Environmental Protection Agency
ESC	Expedited Site Characterization
F	Fahrenheit or F-value (a measure of statisical significance)
FS	Feasibility Study
gal	Gallon
GPO	United States Government Printing Office
GSI	General Site Information (IRPIMS table)
GW	Ground water

GWD	Groundwater Level Data Information (IRPIMS table)
HARM	Hazard Assessment Rating Methodology
HELP	Hydrologic Evaluation of Landfill Performance
HHE	Human health and the environment
HHQ	Human Health Hazard Quotient
hr	Hour
HRS	Hazard Ranking System
HW	Hazardous waste
ID	Identifier
IRP	Installation Restoration Program
IRPIMS	Installation Restoration Program Information Management System
K	Hydraulic conductivity
l	Liter
LDI	Location Definition Information (IRPIMS table)
LF	Landfill
LOD	Limit of detection
LTD	Lithologic Descriptions Information (IRPIMS table)
m	Meter
mg	Milligram
MILL	Model Investigation of Landfill Leachate
mm	Millimeter
M.M.	Modified Mercalli (seismic scale)
mo	Month
MPF	Migration Pathway Factor

MSW	Municipal solid waste
MULTIMED	Multimedia Exposure Assessment model
NCAPS	National Corrective Action Prioritization System
NCP	National Oil and Hazardous Substance Pollution Contingency Plan
NDVI	Normalized Difference Vegetative Index
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priorities List
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
P	Octanol-water partition coefficient
PA	Preliminary Assessment
PAR	Protection of Aquifer Rating
PCLTF	Post-Closure Liability Trust Fund
PVC	Polyvinyl chloride
r	ratio (refers to E/P Ratio)
RA	Remedial Action
RD	Remedial Design
RCRA	Resource Conservation and Recovery Act of 1976
RelRisk	Relative Risk Site Evaluation Concept
RES	Analytical Results Information (IRPIMS table)
RF	Receptor Factor
RFA	RCRA Facility Assessment
RFI	RCRA Facility Investigation
RI	Remedial Investigation

ROD	Record of Decision
RTC	Response to Comments
s	second or seismic (refers to Seismic Impact Zone)
S	Waste solubility
SA	Surface area
SAM	Environmental Sampling Information (IRPIMS table)
SARA	Superfund Amendments and Reauthorization Act of 1986
SB	Statement of Basis
SCC	Site Contaminant Classifications (IRPIMS table)
SCS	Soil Conservation Service
SERI	Solar Energy Research Institute
SETAC	Society of Environmental Toxicology and Chemistry
SI	Site Inspection or Seismic Impact (refers to Relative Landfill Failure Risk model)
SIA	Surface Impoundment Assessment
SLB	Shallow land burial
SLI	Site-Location Cross-Reference Information (IRPIMS table)
SOILINER	A deterministic hydrologic computer model developed for the USEPA Office of Solid Waste
SW	Surface water
t	Temperature (refers to Minimum Monthly Temperature)
TC	Toxicity Criteria
TDS	Total dissolved solids
TES	Sample Testing and Analysis Information (IRPIMS table)
T_{max}	Maximum temperature

T_{min}	Minimum temperature
TOC	Total organic carbon
TOT	Time of travel
U.S.	United States
USAF	United States Air Force
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VOC	Volatile organic compounds
WCEF	Waste Containment Effectiveness Factor
WCI	Well Completion Information (IRPIMS table)
WQF	Waste Quantity Factor
wt	Weight
yd	Yard
yr	Year
α	Area beyond the critical value in the tail of a distribution (a measure of statistical uncertainty)
η	Mean
ν	Degrees of freedom
σ	Standard deviation
Σ	Sum
μg	Microgram
$\mathbf{X}^2$	Chi-square (statistical procedure)

A RISK MITIGATION METHODOLOGY FOR SOLID WASTE LANDFILLS

by

WILLIAM BRENT NIXON

An Abstract

Of a dissertation submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy in Civil Engineering
Department of Civil Engineering and Mechanics
University of South Florida

May 1995

Major Professor: Robert J. Murphy, Ph.D.

Several models have been developed in recent years to simulate or assess the magnitude, probability and consequences of the leakage of aqueous environmental contaminants from solid waste landfills. These models incorporate many common factors, including local climatological and geological characteristics. Each model, however, employs a unique approach to the problem, assigns different relative weights to the various factors, and relies upon extrapolation of small-scale experimental data and/or subjective judgment in predicting the various mechanisms of full-scale landfill failure that lead to contaminant migration. As a result, no two models are likely to yield the same assessment of a given landfill, and no one model has been validated as a predictor of long-term landfill performance.

The United States Air Force maintains a computer database for the characterization of potential hazardous waste sites on its installations. Records in the database include more than 500 landfills, providing such information as coordinates, waste content, years of operation, soil and aquifer data, monitoring location data, the dates and types of sampling, and the results of sample testing. Through analysis of this information, nearly 300 landfills, virtually all unlined and now closed, were assessed to have sufficiently, partially, or inadequately contained the hazardous constituents of the wastes long ago placed within them.

In comparing the long-term containment performance among these landfills, only a few of the various factors employed in the many existing models--primarily landfill size, local seismic activity, freeze/thaw cycling, and potential evaporation relative to average precipitation--were found statistically significant. An empirical model of landfill failure was thus

constructed to categorize similarly characterized landfills as "high," "moderate," or "low" relative risk. The model distinguished 42 percent of landfills of known performance as exceptional (either "high" or "low" risk) with an overall efficiency of greater than 85 percent.

Abstract Approved: ______________________

Major Professor: Robert J. Murphy, Ph.D.
Associate Professor,
Department of Civil Engineering and Mechanics

Date Approved: 31 MAR '95

CHAPTER 1

INTRODUCTION

Major General James McCarthy, The Civil Engineer, United States Air Force (USAF), reported in 1993:[1]

> The Air Force has built its environmental programs to comply with today's standards, to prevent future pollution, to protect our natural and cultural resources, and to clean up waste sites resulting from past practices. Despite experiencing eight consecutive years of budgets with declining purchasing power, the Air Force is putting its money behind these programs, with a current-year allocation of $1.8 billion. We have generally made good progress in achieving our environmental goals, except for our efforts to clean up the 4,000+ hazardous waste sites for which the Air Force is responsible. The bill for the studies, designs, and cleanup has grown dramatically -- too much. We, together with the environmental firms and the regulators, must bring our talents and innovations to bear; it is imperative that we drive down the cost of cleanup. Our fellow citizens expect it and our nation needs it."

Of these 4,000+ sites, over 500 are landfills, which for many years were used as repositories for the solid and hazardous wastes resulting from day-to-day Air Force mission activities. Around the same time that communities across the country began to own and operate municipal solid waste (MSW) landfills, the Air Force found disposal into on-base landfills to be a practical and cost effective approach in dealing with the tons of solid waste -- domestic as well as hazardous -- generated every

[1] James E. McCarthy. "Meeting the Future." The Military Engineer Mar-Apr 1993: 54-58, p 56.

week at its many bases. Constructed in the same way as the municipal landfills of their day, most were long ago filled and are now closed.

The more stringent state and federal environmental regulations in recent years have caused a reassessment of MSW disposal practices by the Air Force and most city and county agencies. New requirements for liners, daily covers, recordkeeping, siting approval, etc., have driven up the demand for manpower and money to operate landfills. Restrictions on the types of materials that may be dumped have also raised the legal stakes associated with landfill management. As a result, on-base solid waste landfills were increasingly viewed as avoidable, yet very real, sources of potential liability for installation commanders.

With a few exceptions, bases' solid waste collection and disposal functions are now performed by service contractors who carry the refuse off-base, most often to a nearby municipal or private disposal facility. Hazardous wastes are handled in accordance with a host of regulations, administered by the United States Environmental Protection Agency (EPA), Department of Transportation (DOT), Occupational Safety and Health Administration (OSHA), and their state and local counterparts.

Unfortunately, the legacy of closed on-base landfills remains, in the form of "Installation Restoration Program" (IRP) sites of known or potential environmental consequence. Nearly all USAF landfills were designed, constructed and operated long before current regulations were enacted. Many now-closed landfills may well present an imminent threat to the ecology of the area, as well as an enormous financial liability for the Air Force, for as long as the waste remains buried. This liability is at the heart of General McCarthy's stated concern. Remediation of these landfills will inevitably divert resources intended to support the Air Force in carrying out its mission for many years to come. A need exists, then, for a method of determining the likelihood of failure of these existing landfills, and to predict the timing and magnitude of such a failure.

Purpose of the Study

The primary objective of this research is to develop a risk-based, empirical decision model to assist USAF environmental managers in the optimization of investments in monitoring and remediation of more than 500 closed USAF solid waste landfills within the United States and its territories. The model is intended as a tool in the application of limited financial and management resources to achieve the greatest tangible benefit, either in mitigating environmental damage resulting from release of contaminants or in preventing future releases, by identifying those landfill characteristics which are most likely to lead to failure.

By determining the degree to which a number of measurable parameters are associated with contaminant releases identified in the USAF Installation Restoration Program Information Management System (IRPIMS) database, as well as those characteristics associated with long-term landfill integrity, the methodology will serve as a framework for identifying landfills which have not yet shown signs of failure, but may pose the greatest ecological threat in the long term. Thus, the most probable timing and severity of a contaminant release, the optimal scope and scheduling of any preventive measures, and the anticipated cost and magnitude of remediation may be forecast.

Identifying the factors most predictive of failure in the long-term, and comparing those factors with the characteristics of any given landfill should yield failure risk with respect to time. Conversely, factors most predictive of long-term stability should yield a measure of viability over time. These functions are the desired output of the model.

History of USAF Landfills

The USAF functions in many respects as an industrial enterprise--900,000 employees, operating and maintaining over 7,000 aircraft, and a vast inventory of equipment, vehicles, and facilities. These various activities are managed through an administrative organization at the "base" or "wing" level, with standards and objectives established at the "headquarters" or "command" level. One necessary consequence of these many people and their endeavors is the generation of a large volume of waste materials. Landfills have long been seen as a cheap, expedient, and safe instrument for the ultimate disposal of virtually anything found in the waste stream. Since before the Air Force was established as a separate department in 1947, defense activities have managed their wastes largely by land disposal, the method most commonly practiced by both businesses and government entities at all levels since World War II.

Only in the past twenty or so years have the potential dangers of landfilling been closely examined. Chemicals from within some fills have been discovered deep in the underlying soil matrix, in ground water, in nearby surface water bodies, and even in the atmosphere around many of these sites. Military landfills, in particular, are of concern for several reasons: the waste deposited in these facilities is likely to comprise a broad variety and high concentration of dangerous chemicals, from the heavy metals and petroleum distillates found in machinery maintenance residues to the explosive and exotic materials unique to various weapons systems. Further, prior to the Federal Facilities Compliance Act of 1992, the regulatory oversight of military and other federal agencies' landfills was likely to have been less rigorous than that given sites operated by businesses and local governments, who were not exempt from penalties for noncompliance.

A series of additional federal, state, and local regulations has been promulgated in recent years to ensure that safeguards are incorporated into future landfills to prevent the escape of chemical contaminants into the environment. The most recent EPA regulations, published in 1991, distinguish between landfills for MSW and those for hazardous waste (HW), but in both cases they require such design features as cap and liner systems combining clay and geomembrane materials, a leachate control system, a gas control system, and a network of monitoring devices to quickly detect any failure of the containment systems.

The vast majority of the existing 8,000 landfills throughout the United States,[2] including virtually all of the over 500 USAF-owned sites, do not meet the new EPA design and performance criteria. In fact, most have no leachate or gas control systems and only a clay, if any, liner system. And most were only recently retrofitted with monitoring wells to detect ground-water contamination beyond their perimeters.

[2] Charles A. Wentz. Hazardous Waste Management. New York: McGraw-Hill, 1989, p 387.

Several closed landfills have found their way onto the National Priorities List (NPL) of contaminated sites, where the Superfund provided for by the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) is available to pay for site remediation. Furthermore, nearly every USAF landfill in the United States is now being monitored and maintained under the provisions of the Resource Conservation and Recovery Act of 1976 (RCRA), at significant annual cost to the Air Force and with no foreseeable end to the process. RCRA Subtitle C regulates HW treatment, storage and disposal, and was the impetus for the Air Force to discontinue on-base land disposal of HW. RCRA Subtitle D governs MSW land disposal.

The post-closure care requirements for MSW landfills include the monitoring of ground water; monitoring, recovery and management of landfill gases; collection and treatment of leachate; maintenance of the final cover; and financial assurance that the required maintenance and necessary remediation work can continue for at least the next 30 years. Responsible parties who remain financially solvent after the minimum 30-year period continue to be liable indefinitely, facing the possibility of eventual remediation costing tens of millions of dollars.

Several closed USAF landfills have already been found in need of remediation. A 1988 report noted that 294 landfills at 116 USAF bases had already been identified as having "Hazard Assessment Rating Methodology (HARM) scores greater than or equal to 50,"[3] suggesting a

[3] M. D. Kilroy and E. Heyse. Assessment of Contamination Problems and Remedial Alternatives for Air Force Landfills. ESL-TR-87-64, Dynamac Corporation report to USAF, Mar 1988, p 4.

need for further investigation of these sites in particular. Situations will likely arise where years of monitoring and analysis will be followed by years of far more costly soil and ground-water remediation. Indeed, an increasing proportion of the USAF budget will undoubtedly be required for environmental restoration as these sites continue to deteriorate.

Defining Landfill Failure

The failure of a landfill is a complex event to analyze because the mechanisms at work are neither observable nor entirely understood. In general, failure may be regarded as the release to the environment of one or more of the substances contained within the landfill facility. In the case of landfills constructed without many of the modern control and containment systems now required by law, however, a degree of "failure" by this definition will have certainly occurred even as the fill material was still being deposited.

An alternative definition, tied to contaminant concentrations and the associated risk to exposed populations, is more appropriate in determining whether a failure is of sufficient magnitude to warrant remediation. This definition parallels the approach described in RCRA Subtitles C and D for determining whether the primary liner in a modern landfill has failed, and it is the basis for determining the scope of site remediation requirements prescribed by CERCLA.[4] Therefore, "failure" in

[4] U.S. EPA. Conducting Remedial Investigations/Feasibility Studies for CERCLA Municipal Landfill Sites. EPA/540/P-91/001. Washington: GPO, 1991.

the context of this study is defined as a contaminant release of sufficient quantity and duration to warrant remedial action.

Contaminant Fate and Transport

Essentially the same mechanisms at work in the release of contaminants from the boundaries of a landfill are responsible for the movement of those same contaminants through external environmental media. The greatest difference is that the natural media more readily facilitate contaminant transport than do even failed engineered barriers. The hydrologic cycle persists, relatively unimpeded in the atmosphere and in the native soil. Vapors and particulates entrain and disperse in the ambient air. Leachate flows with the same ease as infiltrating water from surrounding terrain, in accordance with Darcy's Law. Regardless of their phase (solid, liquid, or gas) these contaminants create a Gaussian plume in the affected medium, where they may biodegrade, chemically react, otherwise transform, or merely enervate over time.[5]

For the purposes of this study, it is important to note that contaminant transport need take place only from the point of release from a given landfill to the point at which its presence is discovered, most often a subsurface monitoring well. It is assumed that any detected ground-water contaminant concentration exceeding statutory limits constitutes "failure" of the landfill containment system, as defined earlier.

[5] Michael D. LaGrega, *et al.* Hazardous Waste Management. New York: McGraw-Hill, 1994, pp 147-214.

CHAPTER 2

REVIEW OF THE LITERATURE

The proposed risk mitigation methodology must consider issues founded in both the natural and the societal environment in which the landfills under study exist. The methodology requires an awareness of the known mechanisms by which contaminants may be released from a landfill, the state of understanding that exists with regard to the causes and the likelihood of these failure mechanisms, and a way of measuring the environmental and financial consequences of such a release.

Contaminant Release Mechanisms

Contaminant concentrations may be measured in the soil matrix around and beneath the landfill site, in the adjacent ground and surface waters, and in the air above and downwind of the site. Most of the older landfills of concern in this study relied solely on the soil matrix to serve as a "liner" barrier, as a daily cover, and as a cap upon closure. Thus, assessment of long-term suitability of soil barriers in the containment of fill materials is pertinent to any analysis of landfill performance. A multitude of studies have been performed to determine the field hydraulic conductivity or permeability of various natural and amended soils used as landfill liner and cap barriers.

Professor David E. Daniel is perhaps the most prolific researcher of geotechnical aspects of soil barriers. His work appears often in technical publications, and his research dating back to the early 1980s is often referenced by others, including many of those cited below.

Suter, *et al.*, found that compacted soil barriers are susceptible to initial construction flaws, shrink-swell and freeze-thaw cycles, erosion, subsidence, root and animal intrusion, any of which may significantly increase barrier permeability with age. In the absence of perpetual care and monitoring, natural processes may not jeopardize the integrity of either cap or liner within the first 30 to 50 years of a landfill's life, but "can be expected to cause barriers to fail in the long term (>100 yr)."[6]

The researchers recommend a final cover of at least 0.15 m over a low-permeability infiltration barrier or "cap" of sufficient thickness to extend below the frost line and to exceed the typical rooting depth of native plants (usually at least 3 m). Suter, *et al.*, acknowledge, however, that this guidance has been seldom practiced.

Nineteen "key factors" that affect the permeability of compacted clay liners have been identified by Elsbury, *et al.*[7] These factors were categorized according to the stage in the life of the landfill in which they apply -- Design, Construction, or Postconstruction -- and then grouped according to an approximate ranking in order of importance. The list of factors as proposed by Elsbury, *et al.*, is given in Table 1.

[6] Glenn W. Suter II, Robert J. Luxmoore, and Ellen D. Smith. "Compacted Soil Barriers at Abandoned Landfill Sites are Likely to Fail in the Long Term." Journal of Environmental Quality 2 (1993): 217-26.

[7] Bill R. Elsbury, *et al.* "Lessons Learned from Compacted Clay Liner." Journal of Geotechnical Engineering 11 (1990): 1641-60.

Table 1. Key Factors that Influence Permeability of Compacted Clay Liners. (Bill R. Elsbury, *et al.* "Lessons Learned from Compacted Clay Liner." Journal of Geotechnical Engineering 11 (1990): 1641-60.)

Principal Group (1)	Key Factors (2)
(*a*) Design Stage	
Soil type	Workability Gradation Swell potential
Other considerations	Overburden stress Liner thickness Foundation stability
(*b*) Construction Stage	
Basic compaction objectives	Destruction of clods Interlift bonding
Essential choices (to achieving the basic compaction objectives)	Lift thickness Water content of soil Type and weight of roller Number of passes and coverages Size of clods
Supporting elements (that are included in or subsidiary to essential choices)	Dry density Degree of saturation
Other considerations	Soil preparation Construction quality assurance
(*c*) Postconstruction Stage	
Environmental influences	Desiccation Freezing

The influences of all the listed factors have already occurred in a closed landfill. To the extent these factors can be measured at a given site, however, its suitability as a waste containment facility may be qualitatively assessed. That is, a poorly designed and/or constructed landfill is distinguishable from a better one in a similar environment.

A substantial research program at Los Alamos National Laboratory has focused on landfills of "mixed" (HW and low-level radioactive) wastes in semiarid and arid regions. These studies, extensively documented in a series of reports published throughout the 1980s, found cover-barrier failure, biointrusion, subsidence, and soil erosion to be the major causes of problems in the long-term performance of landfills or "shallow land burial (SLB) sites."[8] Each of these failure mechanisms permits the infiltration of water into, and percolation through, the buried wastes and ultimately leads to mobilization of waste components. Precipitation and other climatological impacts on SLB cover barriers were found to be exacerbated by deep-rooting plants and burrowing animals, as well as by settlement of the containment structure as the fill materials compact and decay, and as the overburden erodes or slumps. Optimizing the slope, material and thickness of the barrier, cover vegetation, and other design parameters was determined to be a function of the climatologic -- and especially the hydrologic -- environment in which the landfill is located. In every case examined by the Los Alamos researchers, SLB site problems resulted from water entering from above; the permeability of

[8] J. W. Nyhan. Hydrologic Modeling to Predict Performance of Shallow Land Burial Cover Designs at the Los Alamos National Laboratory. LA-11533-MS. Los Alamos, NM: LANL, 1989c.

the liner beneath the buried waste was, therefore, never addressed as critical to long-term viability of SLB sites in arid or semiarid regions.[9,10]

Another effort found that the deterioration of clay liners is an extremely long-term process. Sai and Anderson's study at one hazardous waste landfill yielded no significant increase in permeability over a two-year period.[11] A study of clay-lined landfills in Wisconsin found that the clay, properly constructed in relatively thin lifts, retains a fairly uniform field hydraulic conductivity on the order of 10^{-7} cm/s, even 15 years after emplacement.[12] Citing the work of Daniel and others into the performance of clay, however, the Wisconsin study's authors recommend installation of detection wells above the liner to measure leachate levels and collection basin lysimeters below the liner to allow for measurement of the barrier layer's hydraulic conductivity after exposure to leachate.

In documenting a field-scale study, the EPA voiced skepticism of laboratory hydraulic-conductivity measurements, stating that they are "not a good indicator of the clay liner behavior."[13] This effort found that

[9] J. W. Nyhan, *et al.* Development of Corrective Measures Technologies for the Long-Term Stabilization of Shallow Land Burial Sites in Semiarid Environments. LA-10778-MS. Los Alamos, NM: LANL, 1989b.

[10] J. W. Nyhan. Development of Technology for the Long-Term Stabilization and Closure of Shallow Land Burial Sites in Semiarid Environments. LA-11283-MS. Los Alamos, NM: LANL, 1989a.

[11] Joseph O. Sai and David C. Anderson. "Long-Term Effect of an Aqueous Landfill Leachate on the Permeability of a Compacted Clay Liner." Hazardous Waste and Hazardous Materials 4 (1991): 303-12.

[12] Mark E. Gordon, Paul M. Huebner, and Thomas J. Miazga. "Hydraulic Conductivity of Three Landfill Clay Liners." Journal of Geotechnical Engineering 8 (1989): 1148-60.

[13] A. S. Rogowski. Relationship of Laboratory- and Field-Determined Hydraulic Conductivity in Compacted Clay Liner. EPA/600/S2-90/025. Washington: GPO, 1990.

even slight perforations or swelling of the clay matrix can dramatically increase water movement through the liner. The EPA suggested the use of a conservative tracer, such as bromine (Br^-), and water breakthrough measurements as more accurate methods of estimating field hydraulic conductivity. The overall performance of the landfill liner system may be thus evaluated with greater confidence.

Modern, double-lined MSW and HW landfills differ from the older landfills examined in this effort with regard to the generation and control of leachate. Leachate sources in all landfills include the precipitation infiltrating the cap, moisture in the cover soil, and moisture in deposited wastes. Even in a modern, fully lined landfill, leachate typically leaks past the primary liner at a rate of 22 gal/acre/da. The waste constituent concentrations approach equilibrium solubility as the water is retained within the fill for many years before it is collected.[14]

On the other hand, unlined or clay-lined facilities are less able to contain the infiltrating water. Leachates from these facilities are, as a result, likely to be far greater in volume. But with the increased volumes come proportionately lower contaminant concentrations than are found in leachates from geomembrane-lined fills.

MSW typically averages 30 percent moisture by weight, whereas the moisture content of ash in a typical monofill is about 6 percent,[15] and the moisture content of HW varies widely with the nature of each waste, its containment method, and the degree of treatment or stabilization it

[14] LaGrega, 1994, p 144-145.

[15] George Tchobanoglous, Hilary Theisen, and Samuel Vigil. Integrated Solid Waste Management. New York: McGraw-Hill, 1993, p 442.

received prior to disposal. MSW leachate tends to be higher in total organic carbon and more biologically active than HW leachate, but with fewer petroleum by-products and other volatile organic compounds (VOC) and fewer heavy metals, as shown in Table 2. A facility's leachate volume and composition, then, must be determined by on-site measurement.

Cureton, *et al.*, recirculated leachate at two landfills in Ontario, Canada, in order to test the stress on cover vegetation species. In the process of this two-year study, the researchers found no evidence of pore clogging in the clay cover barrier. This response was surmised to result from "[v]olumetric shrinkage ... due to physicochemical incompatibility with applied leachates containing organic solvents and salts."[16] Similar results have been obtained in studies of soil bottom-barrier layers.

The hydrologic cycle's effect on barrier performance was studied in Florida and Canada. In the Florida study, compacted barrier layers of 60- to 105-cm thickness were constructed of carbonate silt tailings from a limestone mine and of a an admixture of bentonite (30 metric tons per acre) and sand. The saturated hydraulic conductivities were determined to be 2.4×10^{-6} and 3.6×10^{-7} cm/s, respectively. Each material was deemed adequate in "minimizing leachate generation," allowing no more than 0.2 percent of precipitation to infiltrate the cover barrier, with no measurable difference with respect to liner thickness.[17]

[16] P. M. Cureton, P. H. Groenevelt, and R. A. McBride. "Landfill Leachate Recirculation: Effects on Vegetation Vigor and Clay Surface Cover Infiltration." Journal of Environmental Quality 20 (1991): 17-24.

[17] Olaf L. Weeks, Robert S. Mansell, and Scott W. McCallister. "Evaluation of Soil Top-Cover Systems to Minimize Infiltration into a Sanitary Landfill: A Case Study." Environmental Geology and Water Science 2 (1992): 139-52.

Table 2. Typical Leachate Constituents and Concentrations.

Leachate Constituent	MSW Landfills (mg/l)[18,19,20,21,22]		HW Landfills[23] (mg/l)
	New (<2 yr)	Mature (>10 yr)	
BOD_5	2,000 - 55,000	100 - 200	-
TOC	1,500 - 30,000	80 - 160	10.9 - 8,700
Calcium	200 - 3,000	100 - 400	-
Chloride	200 - 3,100	100 - 400	-
Iron	50 - 1,700	20 - 200	-
Organic Nitrogen	10 - 800	80 - 120	-
Phosphate	5 - 130	5 - 10	-
Potassium	200 - 1,000	50 - 400	-
Sulfate	25 - 1,000	20 - 50	-
Arsenic	0.01 - 70		0.01 - >10,000
Cadmium	0.03		0.05 - 8.2
Chromium	<0.1 - 0.21		0.01 - 208
Cyanide	<0.01		0.05 - 14
Lead	1.3 - 14.0		0.3 - 19
Nickel	0.01 - 0.80		0.02 - 48
VOC	<0.01 - 0.34		<590

18 Tchobanoglous, 1993, p 418.

19 Cureton, 1991.

20 Vasillos Gounaris, Paul R. Anderson, and Thomas M. Holsen. "Characteristics and Environmental Significance of Colloids in Landfill Leachate." Environmental Science and Technology 7 (1993): 1381-87.

21 Ramanathan Manoharan, *et al.* "Inferred Metal Toxicity during the Biotreatment of High Ammonia Landfill Leachate." Water Environment Research 7 (1992): 858-65.

22 U.S. EPA. 1991a, p 3-11.

23 LaGrega. p 144-145.

Uppot examined the effects of a variety of organic and inorganic permeants on two common liner clays--montmorillonite and kaolinite. Inorganic aqueous solutions (containing aluminum, magnesium, sodium, calcium, barium, or strontium) were found to minimally affect the clays' permeability, as the loss of mass of clay due to seepage was offset by precipitation of metals. Ion exchange and ionic size impacts also were found to be negligible. Acidic and neutral polar permeants (acetic acid and methanol, respectively) were found to increase the permeability of montmorillonite by a factor of two to three, while minimally affecting kaolinite. Basic and neutral nonpolar permeants (aniline and xylene), on the other hand, tended to reduce the permeability of kaolinite, with little effect on montmorillonite. Chelating agents and their salts appeared to have little effect on either of the clays tested.[24]

Warith and Yong similarly found natural clays to be effective in containing a variety of contaminants, especially heavy metals, but the clay may at the same time release other contaminants through desorption. Clay's buffering capacity was found especially limited when exposed to acidic or organic wastes, regardless of liner thickness.[25]

These representative studies all indicate that natural soil barriers are useful barriers, but far from perfect and vulnerable to attack by both leachate and natural water. The above research examined only vertical flow of leachate through the soil cover and liner barriers. Peyton and

[24] Janardanan O. Uppot. A Study of the Permeability of Clays Subjected to Organic and Inorganic Permeants. Ph.D. Dissertation, University of Missouri-Rolla, 1984.

[25] Mostafa A. Warith and Raymond N. Yong. "Landfill Leachate Attenuation by Clay Soil." Hazardous Waste and Hazardous Materials 2 (1991): 127-41.

Schroeder explain, however, that "[t]he objective in soil-liner design is to maximize the ratio of lateral drainage to vertical percolation ... to reduce vertical percolation to acceptable levels."[26] Peyton and Schroeder learned that the fraction of infiltration volume which percolates through the soil liner increases as total influent decreases. The relatively unimpeded lateral flow is directly proportional to the influent flow. The percolation rate, on the other hand, remains primarily a function of the substantially lower (by five to seven orders of magnitude) saturated hydraulic conductivity of the soil liner, even at values of 10^{-7} to 10^{-8} cm/s.

In summary, whether the flow of water into and through a soil-lined landfill is examined from a hydrological or geotechnical perspective, three attributes are generally expected: the quantity of leachate able to escape from the landfill through its bottom liner is highly influenced by the permeability of the top cover; the hydraulic conductivity of the entire containment system is likely to begin at no smaller than 10^{-8} cm/s and increase from that level as the landfill ages; and the leachate generated by any soil-lined landfill, MSW or HW, likely contains a variety of organic and inorganic substances capable of penetrating the liner system and contaminating nearby surface- and ground-water sources. The greatest risk factors for containment-system failure of these landfills appear to be excessive seepage of precipitation and surface runoff through inadequate cover barriers, close proximity to the ground water (relative to the permeability of the surrounding soil matrix), and structural failure of the landfill walls and cap due to surface erosion and/or fill settlement.

[26] R. Lee Peyton and Paul R. Schroeder. "Evaluation of Landfill-Liner Designs." Journal of Environmental Engineering 3 (1990): 421-37.

Another aspect of the environmental risk associated with older landfills is the potential for release of gas-phase contaminants from the containment system. The gas management systems installed on modern landfills are designed to capture for use, vent, or burn off the mixture of gases generated within. Methane and carbon dioxide are produced by anaerobic digestion of organic wastes, and other gases, including trace VOC, are also present. This mixture is usually flammable and potentially explosive, and is thought to be a significant anthropogenic contributor to the worldwide buildup of greenhouse gases in the troposphere and consequent global warming.[27] Due to their lower concentrations of organic matter, HW landfills generally produce somewhat less gas than do MSW landfills, but gas management is an important consideration in either case.[28] Older landfills are, therefore, often retrofitted with passive ventilation systems.

The rate of methanogenesis and the consequent duration of the methane-fermentation phase of a MSW landfill's existence have been examined thoroughly.[29] Despite substantial flow of leachate through a typical landfill, several studies have found that the fill material is seldom saturated, and so is less than optimum for microbial methanogenesis.[30] This conclusion strongly supports the earlier supposition that leachate

[27] Penny Eastwood. Responding to Global Warming: An Examination of the Prospects for Effective Action. New York: Berg, 1991, pp 6-11.

[28] LaGrega, p 800.

[29] Tchobanoglous, pp 382-94.

[30] K. Rao Gurijala and Joseph M. Suflita. "Environmental Factors Influencing Methanogenesis from Refuse in Landfill Samples." Environmental Science and Technology 6 (1993): 1176-81.

retention time in soil-lined landfills is minimal; the influent water tends to pass rapidly through the fill, neither readily available to the anaerobes nor suffused with contaminants, as it drains out through the bottom.

CERCLA remedial actions with regard to landfill gases tend to emphasize removal of the explosive threat posed by migration to adjacent buildings, as opposed to any environmental threat due to long-term exposure.[31] Thus, while an issue of safety and a potential source of odor around a landfill, the emission of gas-phase pollutants is not generally a major aspect of the long-term viability of landfills. Many of the same failure mechanisms that allow release of liquid-phase contaminants, however, may also facilitate the release of gas-phase contaminants: cover-soil desiccation, subsidence, biointrusion, and erosion. Some VOC diffusion through the soil matrix may also occur, but is "insignificant when compared with the convecting gas."[32]

Landfill Risk Analysis

Dozens of research efforts have been devoted to determining the rate and consequence of aqueous leakage from landfills, and several methods and computer models have been developed to deal with the unique set of conditions at any given waste site. These efforts fall into three general categories: deterministic water-balance methods, relative environmental-risk approaches, or stochastic failure-risk models.

[31] U.S. EPA, 1991a, pp 2-22 - 2-30.

[32] LaGrega, p. 137.

The Deterministic Water Balance

Analytical water-balance approaches were tried as early as 1957 by Thornthwaite and Mather, and in 1975 by Fenn, *et al.* Both these efforts attempted to predict the quantity of leachate generated at waste disposal sites as a function of water infiltration and cell design.[33] The manual predecessors to the many computerized models now in use, these early efforts were conceived to assist landfill designers rather than owners or remediators of older landfills.

HELP. Perhaps the best known of deterministic water-balance models is the Hydrologic Evaluation of Landfill Performance (HELP).[34] Developed at the U.S. Army Corps of Engineers' Waterways Experiment Station by Paul R. Schroeder, *et al.*, HELP employs several commonly accepted analytical equations, approximations and assumptions to predict leakage through a series of cover, fill and liner layers in a given climatological setting. Though intended as a tool for designers of new landfills, HELP may be useful in estimating the leachate leakage out of existing landfills and in evaluating the relative impacts of contemplated remedial actions.

HELP models the infiltration, evapotranspiration and subsurface routing of water, vegetative growth, and climatological effects at specified

[33] Dennis G. Fenn, Keith J. Hanley, and Truett V. DeGeare. Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites. EPA Report No. 168. Cincinnati: EPA, 1975.

[34] Paul R. Schroeder. "HELP Model for Design and Evaluation of Liquids Management Systems." Seminars - Design and Construction of RCRA/CERCLA Final Covers. CERI 90-50. Washington: GPO, 1990.

locations. It is capable of accepting input data for up to 12 layers, each layer one of 15 natural soil types, 2 barrier soils, MSW with daily cover, or 2 user-defined media. Synthetic daily weather can be generated data for 139 cities, and 5-year weather data are stored for 102 default cities.

The HELP model is limited in its application to existing landfills, however, because it assumes homogeneity and isotropy within layers, idealized barrier-layer compaction (reducing the saturated hydraulic conductivity by a factor of 20), and placement of the landfill above the water table. These assumptions preclude the assessment of many of the very irregularities in the containment system most suspect in a specific facility's failure. Furthermore, given a proper mix of layers and other conditions, the model will yield a theoretical (desired) zero-leakage result. As noted earlier, this ideal result is not attainable in actual construction.

CREAMS. Perrier and Gibson, also at the Waterways Experiment Station, had previously applied the U.S. Department of Agriculture's (USDA) Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model and the USDA Soil Conservation Service (SCS) runoff curves to develop the Hydrologic Simulation on Solid Waste Disposal Sites (HSSWDS) computer model for the EPA. CREAMS predicts evapotranspiration, seepage and soil moisture, given specific input soil and climatological parameter values, while the SCS curve numbers relate rainfall, runoff and retention of water at a given site.[35] The HELP model is largely a refinement of the HSSWDS concept.

[35] Eugene R. Perrier and Anthony C. Gibson. Hydrologic Simulation on Solid Waste Disposal Sites (HSSWDS). EPA/SW-868. Washington: GPO, 1980.

Researchers at Los Alamos National Laboratory also applied the CREAMS model in their studies of the hydrologic impacts on SLB landfill facilities in arid and semiarid regions. The model reasonably predicted water movement in experimental landfill cells, but was highly sensitive to the input values for the soil layers' saturated hydraulic conductivities, which can be determined with sufficient precision only by measurement in the field, and is incapable of accounting for extreme climatic, seismic, or other failure events, offering limited benefit in predicting the long-term performance of a given landfill.[36]

SOILINER. In 1986, the EPA Office of Solid Waste introduced the SOILINER computer model for predicting the rate of leachate flow through clay liners, given the liner's saturated hydraulic conductivity, hydraulic gradient, and effective porosity. The output of the SOILINER model is a contaminant time of travel (TOT) over a 100-foot horizontal distance.[37]

Daniel, *et al.*, attempted to validate the model in 1991, but found it overpredicted TOT in some cases by a factor as high as 52. They surmised that the source of this error is the model's assumption that the liner's actual and effective porosities are equal, while in fact the effective porosity of a compacted clay may vary with hydraulic gradient.[38]

[36] Nyhan, 1989c, pp 7-13.

[37] U.S. EPA. SOILINER Model. EPA/530/SW-86/006. Washington: GPO, 1986b, pp 3-5.

[38] David E. Daniel, *et al.* Project Summary: Rate of Flow of Leachate through Clay Soil Liners. EPA/600/S2-91/021. Cincinnati: GPO, 1991.

Refinements and Applications. Rust examined the effects of water percolation, runoff and storage on various landfill final covers during high-precipitation, low-evapotranspiration events. He then proposed refinements of the water-balance models to account for those effects.[39] In 1991, Mack attempted to account for current standards of landfill construction and the differential effects on open and closed landfill cells in a computer program, Model Investigation of Landfill Leachate (MILL).[40] Still, long-term performance of an actual landfill is not well predicted by any available water-balance computer model, since the full spectrum of system failures, contaminant-release and transport mechanisms is not addressed.

Despite their limitations, these models have been used as input data generators for other environmental risk models developed by the U.S. EPA. One such model accepts the output from the deterministic SOILINER model discussed earlier, then simulates the fate and transport of the contaminant in the subsurface at a RCRA site. A contaminant's TOT in the unsaturated zone is presumed to be inversely related to the vulnerability of local hydrogeologic conditions. A TOT of less than 100 years indicates the hydrogeological setting is vulnerable to contamination from that source.[41]

[39] Richard Reynolds Rust. Estimation of Percolation from Landfill Final Covers Based on Extreme Climatic Events. Ph.D. Dissertation, Texas A&M University, 1986.

[40] Mary Jessica Mack. MILL: (Computer) Model Investigation of Landfill Leachate. Ph.D. Dissertation, University of Delaware, 1991.

[41] U.S. EPA. Criteria for Identifying Areas of Vulnerable Hydrogeology under the Resource Conservation and Recovery Act: A RCRA Statutory Interpretive Guidance. EPA/530-SW-86-022. Washington: GPO, 1986a.

More recently, the U.S. EPA developed the Multimedia Exposure Assessment (MULTIMED), yet another environmental fate-and-transport risk model. Using leachate leakage data output from the HELP model, MULTIMED yields a predicted "point of compliance," the location at which the contaminant concentration no longer exceeds the Maximum Contaminant Level (MCL) allowed under the Clean Water Act. Given the depth of the uppermost aquifer, the hydraulic conductivity of the adjacent soil matrix, specific storage and geological makeup of the site, as well as the specific contaminant and its initial concentration at the point of release, a two-dimensional representation of the spread of actionable levels of contaminants may be constructed.[42] MULTIMED simulates effects of biodegradation, adsorption, advection, volatilization, and diffusion into the aquifer. The model is somewhat deterministic and is unable to deal with the complexities of many natural soil media, but represents the ongoing attempt of regulators to predict the potential environmental harm due to land disposal of wastes.

Relative Environmental-Risk Methods

Several environmental hazard rating systems were developed in the early 1980s, mostly in response to specific, local needs. These systems typically yield a value on a synthetic ordinal-number scale, which allows for relative comparisons between two or more sites or situations. Many of the parameters evaluated in these models could not be directly measured

[42] U.S. EPA. Project Summary: Subtitle D Landfill Application Manual for the Multimedia Exposure Assessment Model (MULTIMED). Washington: GPO, 1993c.

or mathematically derived, so their designs necessarily involve a degree of subjective, reasoned judgment. The subjective valuation of parameters does not invalidate a model, but suggests that calibration of the model must be performed. The selected parameters and their valuations must reasonably reflect the processes they are simulating, and the predicted result must be both accurate and precise enough to be useful.

The Michigan Department of Natural Resources developed a 2000-point "Site Assessment System" rating scale for comparing the risk of environmental contamination posed by various sites in Michigan. Five parameters were measured: contaminant release potential, environmental exposure, targets, chemical hazard, and existing exposure.[43]

An assessment of environmental risk at waste disposal sites in two Illinois counties led to the development of a similar rating system. In this model, a 100-point ordinal scale illustrated the relative severity of the combined influences of four parameters: health risk associated with the waste and mode of handling, at-risk population, proximity to wells or aquifers, and aquifer susceptibility to contamination.[44]

Hutchinson and Hoffman developed a hazard rating system for the New Jersey Geological Survey. Their method involves evaluating eleven parameters of site geology and eight parameters of the waste material, then summing these two scores for a site's overall hazard rating.[45]

[43] Michigan Department of Natural Resources. Site Assessment System (SAS) for the Michigan Priority Ranking System under the Michigan Environmental Response Act. Lansing, MI: MDNR, 1983.

[44] Linda Aller, *et al.* DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. EPA/600/2-87/035. Ada, OK: EPA, 1987, p 6.

[45] *ibid.*

LeGrand/DRASTIC. A broader approach was taken by LeGrand, who developed a rating system for the relative ranking of hydrogeologic settings in terms of their vulnerability to contamination from waste sites. He identified four "key parameters" to evaluate: distance to a water supply, depth to water table, hydraulic gradient, and soil matrix permeability-sorption.[46]

The LeGrand method consists of a four-stage, ten-step process whereby a given waste type (*e.g.* solid waste) imposed on a given hydrogeologic setting, defined as a "situation," is rated numerically according to the "degree of seriousness" of the resulting ground-water contamination hazard potential. This rating may then be compared with a standard "Protection of Aquifer Rating" (PAR) to grade the situation's "probability of contamination and degree of acceptance." Both the natural setting and the effects of any proposed modifications to the setting, such as a liner system, may be so assessed.

The EPA adopted and modified the LeGrand method in its Surface Impoundment Assessment (SIA) methodology. SIA emphasizes site monitoring, however, yielding a "monitoring priority" as its result.[47]

Another derivative of the LeGrand site evaluation system, and also a product of the National Water Well Association, is DRASTIC. Similar in its approach to the LeGrand method, the evaluation parameters and the roots of the DRASTIC acronym are: *d*epth to water, net *r*echarge, *a*quifer

[46] Harry E. LeGrand. A Standardized System for Evaluating Waste-Disposal Sites. 2nd ed. Worthington, OH: National Water Well Association, 1983, pp 20-22.

[47] U.S. EPA. Surface Impoundment Assessment National Report. EPA/570/9-83/002. Washington: GPO, 1983, pp 3-4.

media, soil media, topography (slope), impact of the vadose zone, and conductivity (hydraulic) of the aquifer. They are the same parameters proposed by LeGrand, with refinement of the soil matrix permeability-sorption characteristic. DRASTIC parameter weightings and appropriate valuation ranges are given in Table 3. Actual parameter values applied in each case depend on the subjective judgment of the model user.

The DRASTIC methodology expands the province of the LeGrand approach, as well, by implementing a 15-region classification system, as developed by Heath for the U.S. Geological Survey (USGS), slightly modified to enhance serviceability within the DRASTIC framework to generally describe the differing hydrogeologic conditions throughout the United States:

1) Western Mountain Ranges
2) Alluvial Basins
3) Columbia Lava Plateau
4) Colorado Plateau and Wyoming Basin
5) High Plains
6) Nonglaciated Central Region
7) Glaciated Central Region
8) Piedmont and Blue Ridge
9) Northeast and Superior Uplands
10) Atlantic and Gulf Coastal Plain
11) Southeast Coastal Plain
12) Hawaiian Islands
13) Alaska

Table 3. Assigned Weights and Rating Ranges for DRASTIC Parameters. (Aller, Linda, *et al.*, DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings, EPA/600/2-87/035, April 1987.)

DRASTIC Parameter	Assigned Weight	Rating Range	Range of Values & Units*
Depth to Water	5	10 - 1	(0 - 5) to 100+ feet
Net Recharge	4	1 - 9	(0 - 2) to 10+ inches
Aquifer Media	3	1 - 10	"Massive Shale" to "Basalt"/"Karst Limestone"
Soil Media	2	10 - 1	"Thin or Absent"/"Gravel" to "Nonshrinking and Nonaggregated Clay"
Topography	1	10 - 1	(0 - 2) to 18+ percent slope
Impact of the Vadose Zone Media	5	1 - 10	"Confining Layer" to "Basalt"/"Karst Limestone"
Hydraulic Conductivity of the Aquifer	3	1 - 10	(1 - 100) to 2000+ gallon per day per square foot

*** The relationship between a measured parameter value and the rating associated with that value is generally nonlinear, and often includes a range of appropriate ratings for a given parameter value. For example, a "Basalt" aquifer media may be rated from 5 to 10, depending upon the evaluator's judgment, whereas "Karst Limestone" ratings may range from 9 to 10. This table is intended only as a representation of the nature of the DRASTIC evaluation process, and should not be used as a substitute for the tables and graphs from which it was derived.**

Heath's "Alluvial Valleys" were reincorporated into other regions; "Puerto Rico and the Virgin Islands" was omitted in the development of DRASTIC. These 13 regions were then subdivided into "mappable ... hydrogeologic settings" within which "typical geologic and hydrologic configurations" are described in the context of their vulnerability to pollution.[48]

Using the description for a site's hydrogeologic setting, refined and amplified with data obtained from investigation at the site, appropriate ratings are applied to each parameter. A site's "DRASTIC Index," or pollution potential rating, is determined by summing the rating-and-weight products for each of the seven parameters. The DRASTIC Index for a given site has a theoretical range from 23 to 226, with a higher score indicating higher susceptibility to contamination. Environmental and human health risks associated with a site's DRASTIC Index depend upon the toxicity and loading of the contaminant, its travel time and distance, and the size and composition of the exposed population.

HRS. In response to the 1980 passage of CERCLA, the EPA contracted with MITRE Corporation to develop the Hazard Ranking System (HRS). The intent was to provide a standard method for deciding whether a contaminated site should be among those deemed to pose the greatest "relative risk or danger to public health or welfare or the environment,"[49] and thus be placed on the National Priorities List (NPL) for remediation under the Superfund program. The HRS was promulgated as Appendix A

[48] Aller, pp 13-16.

[49] U.S. Congress. The Comprehensive Environmental Response, Compensation and Liability Act. Washington: GPO, 1980, Section 105(8)(A).

of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) on July 11, 1982.[50]

The HRS was designed to use data gathered in the preliminary assessment/site inspection (PA/SI) to assess several factors which may characterize the potential of a contaminant release to harm human health and the environment (HHE), including: proximity to population, nature of contaminants, and potential pathways to the at-risk population and ecosystems.[51] The individual HHE factor scores are combined into a site score between zero and 100, corresponding to a relative measure of risk. Initially, any site with a score equal to or above the threshold value of 28.50 was placed on the NPL, thereby assuring the NPL to comprise at least 400 of the some 700 HW sites recorded in the CERCLA Information System (CERCLIS). HRS scores, designations as a state's top priority, and advisories by the U.S. Public Health Service had inflated the NPL to 1,189 sites when the final list was promulgated on February 11, 1991.[52]

The original HRS model was modified in response to the Superfund Amendments and Reauthorization Act (SARA) of 1986. HRS was revised on December 14, 1990,[53] in order to correct deficiencies. Unfortunately, these revisions also increased both the model's complexity and the effort required to determine a site's HRS score. Furthermore, many sites that ranked below 28.50 under the earlier HRS criteria were scored above the

[50] U.S. EPA. Fact Book: National Priorities List Under the Original Hazard Ranking System 1981-1991. EPA 540-R-93-079. Washington: GPO, 1993b, p 3.

[51] LaGrega, p. 55-56.

[52] U.S. EPA, 1993b, pp 1-3.

[53] *ibid.*, p 3.

threshold when reassessed using the revised criteria, whereas a lesser number of sites received lower revised scores.[54]

HARM. A similar site evaluation scheme was developed in the early 1980s jointly by CH2M Hill and Engineering-Science, Inc., based on a document produced for the EPA Office of Hazardous Waste Enforcement by JRB Associates, Inc.[55] The Hazard Assessment Rating Methodology (HARM) was intended to assist in the prioritization of USAF sites in the Department of Defense (DOD) Installation Restoration Program (IRP), Phase I. Parameters of evaluation were grouped into four categories: waste characteristics, management practices, receptors, and pathways of contaminant migration from point of release to the receptors. A factor rating, usually between zero and three, and a multiplier yield a score for each factor within a category. Factor scores are summed and normalized to a 100-point scale, and a subscore for each category is determined. The four subscores are then multiplied by their respective weighting factors to produce a HARM score between 30 and 100. HARM evaluation factors, their associated rating ranges and their multipliers are given in Table 4.

The factor evaluation process, however, was limited to a records search at each installation, without benefit of systematic analyses of environmental media. Testing was to be conducted, with deference to the

[54] U.S. EPA. Field Test of the Proposed Revised Hazard Ranking System (HRS). EPA/540/P-90/001. Washington: GPO, 1990, p 9.

[55] CH2M Hill. Installation Restoration Program Records Search for MacDill Air Force Base, Florida. Report to USAF, Nov 1981, p 1.

relative ratings given by HARM, as funding permitted in IRP Phase II. Research efforts, as necessary, were to be accomplished in Phase III, with remedies to be designed and implemented in Phase IV. The advance of environmental regulation has since altered this sequence somewhat; the IRP persists, but is now patterned after an amalgam of the CERCLA and RCRA processes, addressed elsewhere in this chapter.

Table 4. Assigned Rating Ranges and Multipliers for HARM Parameters. (Engineering-Science, Inc., Installation Restoration Program Phase 1, MacDill AFB, Florida, Report to USAF, 1985.)

HARM Parameter	Rating Range	Factor Multiplier	Range of Values & Units*
Waste Characteristics:		0.24	
Judgmental Hazardous Rating	30 - 100	1	"Closed landfill, old site, no known HW" to "Known large quantities of HW"
Management Practices:		0.24	
Record Accuracy and Ease of Site Access	0 - 3	7	"Accurate, no dumping" to "No records, no barriers"
HW Quantity	0 - 3	7	<1 to >20 ton
Total Waste Quantity	0 - 3	4	(0 - 10) to >250 acre-ft
Waste Incompatibility	0 - 3	3	"None" to "Present & posing an immediate hazard"
Absence of Liners or Confining Strata	0 - 3	6	"Both present" to "Neither present"
Use of Leachate Collection Systems	0 - 3	6	"Adequate collection and treatment" to "None"
Use of Gas Collection Systems	0 - 3	2	"Adequate collection and treatment" to "None"
Site Closure	0 - 3	8	"Impermeable cover" to "Abandoned site, no cover"
Subsurface Flows	0 - 3	7	">5 feet above high GW level" to "Below mean GW level"

(Continued on next page.)

Table 4. (Continued.)

HARM Parameter	Rating Range	Factor Multiplier	Range of Values & Units*
Receptors:		0.22	
Affected Population	0 - 3	4	0 to >100 ft
Distance to Nearest Drinking Water Well	0 - 3	15	"Greater than 3 mi" to "0 - 3,000 ft"
Distance to Reservation Boundary	0 - 3	6	"Greater than 2 mi" to "0 - 1,000 ft"
Land Use/Zoning	0 - 3	3	"Completely remote" to "Residential"
Presence of Critical Environments	0 - 3	12	"Not critical" to "Major habitat of endangered species; recharge area"
Quality of Nearest Surface-Water Body	0 - 3	6	"Agricultural/Industrial" to "Potable water supplies"
Pathways:		0.30	
Evidence of Water Contamination	0 - 3	10	"None" to "Positive proof from laboratory analyses"
Level of Water Contamination	0 - 3	15	"None" to "High, >MCL or EPA drinking water stds"
Contamination Type (Soil/Biota)	0 - 3	5	"None" to "Severe"
Distance to Nearest Surface Water	0 - 3	4	"Greater than 1 mi" to "0 - 500 ft"
Depth to Ground Water	0 - 3	7	"Greater than 500 ft" to "Less than 10 ft"
Net Precipitation	0 - 3	6	"Less than -10 in" to "Greater than +20 in"
Soil Permeability	0 - 3	6	"Greater than 50% clay ($<10^{-6}$ cm/s)" to "Less than 15% clay ($>10^{-2}$ cm/s)"
Bedrock Permeability	0 - 3	4	"Impermeable ($<10^{-6}$ cm/s)" to "Very permeable ($>10^{-2}$ cm/s)"
Depth to Bedrock	0 - 3	4	"Greater than 60 ft" to "Less than 10 ft"
Surface Erosion	0 - 3	4	"None" to "Severe"

* Relationships between parameter values and the ratings associated with those values are generally nonlinear. This table provides only a representation of the nature of the HARM process, and is not a substitute for the tables from which it was derived.

By 1986, HARM scores had been calculated for nearly 2,000 USAF IRP sites, at least 434 of which were landfills. Over half of those ratings were 50 or above, suggesting a need for further investigation of those sites.[56] The installations upon which those landfills are sited have since implemented monitoring programs and remedies as required to maintain compliance with environmental regulations, but a vast number of USAF landfills remain unremediated and of undetermined consequence.

The HARM model is no longer executed in prioritizing USAF sites. Before it was discontinued, however, data from 77 IRP Phase I studies served as the basis for yet another risk model. The Hazardous Materials Technical Center developed a multiple regression equation of potential contamination at USAF installations. Suggested as a prioritization tool for site remediation, the proposed model was found too uncertain to be serviceable.[57]

EPA has assigned HRS scores to many of the same USAF sites scored under the HARM model. Sites ranked above the 28.50 HRS threshold (and potentially others meeting the supplemental NPL criteria) have led to the addition of several USAF installations to the NPL Federal Section. Three bases--McClellan AFB CA, Wright-Patterson AFB OH, and Mountain Home AFB ID--are in NPL Group 2, placing them among the top 100 priorities nationally. In all, 31 current and former USAF bases and USAF contractor-operated plants are included on the NPL.

[56] Kilroy, *loc. cit.*

[57] Hazardous Materials Technical Center. Review and Analysis of Phase I Installation Restoration Program Reports for Selected Air Force Facilities. Report to USAF, Feb 1985, p 18.

DPM. In addition to HARM and HRS scores, many IRP sites where the CERCLA Remedial Investigation/Feasibility Study (RI/FS) has been conducted were evaluated again via the Defense Priority Model (DPM). In acknowledging differences between ecological risks and human health risks, DPM isolated assessments for exposure to contaminants in surface water, ground water, volatiles in air and soil, and dust in air and soil.

The pathway parameters evaluated in the DPM, their rating ranges, and associated physical values are given in Table 5; the model's health and ecological hazard and receptor parameters are summarized in Table 6. The pathway, hazard and receptor subscores for each parameter in each of the four media are summed, normalized and multiplied by a waste containment factor and a waste quantity factor. These results are summed to yield an overall site score between 0 and 100 on an ordinal scale. As in the other models discussed, the site score represents a relative ranking wherein a higher value translates to a higher priority for available remediation funding. DPM also employs "confidence factors" to represent uncertainty in the scoring process.[58] Many parameters, the scoring ranges and weights, and the various adjustment and confidence factors in the DPM scoring procedure remain subjective, however.

In its 1992 review, the National Research Council (NRC) expressed several concerns about the DPM. Specifically cited was the substantial reliance on the judgment of both the designers and the user, and the resultant degree of uncertainty introduced to the final scores. Additional

[58] Earth Technology Corporation and ERM Program Management Company. User's Manual for the Defense Priority Model. FY 93 Version. Interim Draft prepared for Office of Deputy Assistant Secretary of Defense (Environment), Apr 1992, pp 1-5.

Table 5. Assigned Rating Ranges and Multipliers for DPM Contaminant Pathway Parameters. (Earth Technology Corporation and ERM Program Management Company. User's Manual for the Defense Priority Model, FY 93 Version. Interim Draft prepared for the Office of the Deputy Assistant Secretary of Defense (Environment), April 1992.)

DPM Parameter	Rating Range	Factor Multiplier	Range of Values & Units
Surface Water Pathway:			
Detected Release in Surface Water	0 or 100	1	If "yes," bypass all other SW pathway parameters
Nearest Surface Water	0 - 3	4	>1.0 to ≤0.13 mi
Net Precipitation	0 - 3	1	<-10 to >+20 in
Surface Erosion Potential	0 - 3	4	"None" to "Severe: ≥15% slope, poorly vegetated or ≥6% slope, unvegetated"
Rainfall Intensity	0 - 3	4	<1.0 to >3.0 in (1-yr, 24-hr or 2-yr, 6-hr event)
Hydraulic Conductivity	0 - 3	3	"$\geq 10^{-2}$ cm/s (gravel, *etc.*)" to "$<10^{-6}$ cm/s (clay, *etc.*)"
Flooding Potential	0 - 3	10	"Beyond 100-yr floodplain" to "Floods annually"
SW Waste Containment Effectiveness Factor (SW WCEF)		0.1 - 1.0	"Contaminant removed"/ "Landfill capped, graded" to "Contaminant exposed"
Waste Quantity Factor (WQF)		0.1 - 1.0	Depth/Area: "<3 ft & <5 acre" to ">100 & >20"
Ground Water Pathway:			
Detected Release in Ground Water	0 or 100	1	If "yes," bypass all other GW pathway parameters
Distance from Bottom to Seasonal High GW	0 - 6	10	">500 ft & no discrete features" to "Saturated"
Permeability of the Unsaturated Zone	0 - 3	5	Hyd. Cond./Thickness: $<10^{-8}$ to $>10^{-4}$ cm/s-ft
Infiltration Potential	0 - 3	5	"Waste is solid & net precipitation <-10 in" to "Free Liquid & >20 in"
Geochemical Properties of the Vadose Zone	0 - 3	5	">30% clay, >1.0% organic, pH 5-9" to "Acid forming; <15% clay, <0.4% organic"

(Continued on next page.)

Table 5. (Continued.)

DPM Parameter	Rating Range	Factor Multiplier	Range of Values & Units
Ground Water Pathway: (continued)			
GW Waste Containment Effectiveness Factor		0.1 - 1.0	"Contaminant removed" or "Landfill capped, lined" to "Liner absent/perforated"
Waste Quantity Factor		0.1 - 1.0	Same as WQF, above
Air/Soil Volatiles Pathway:			
Volatiles Detected in Air	0 or 100	1	If "yes," bypass all other ASV pathway parameters
Volatiles Detected in Surface Soil	0 or 6	12	If "yes," add to other ASV pathway subscores
Average Summer Soil Temperature	0 - 3	2	"<0°C, 32°F" to ">25°C, 75°F"
Net Precipitation	0 - 3	2	Same as in SW, above
Wind Velocity	0 - 3	2	"<5 m/s, 11.2 mi/hr" to ">8 m/s, 17.9 mi/hr"
Soil Porosity	0 - 3	2	"<0.10" to ">0.40" [total porosity, not effective]
ASV Waste Containment Effectiveness Factor		0.1 - 1.0	"Vegetated clay cap and VOC control system" to "No cap"/"No daily cover"
Waste Quantity Factor		0.1 - 1.0	Same as WQF, above
Air/Soil Dust Pathway:			
Non-volatile Contaminants Detected in Air	0 or 100	1	If "yes," bypass all other ASD pathway parameters
Non-volatile Contaminants Detected in Surface Soil	0 or 3	12	If "yes," add to other ASD pathway subscores
Net Precipitation	0 - 3	2	Same as in SW, above
Wind Velocity	0 - 3	2	"<5 m/s, 11.2 mi/hr" to ">8 m/s, 17.9 mi/hr"
Days/yr with >0.25 mm (0.01 in) Precipitation	0 - 3	2	">150 da" to "≤50 da"
Site Activity	0 - 3	2	"None" to "Heavy vehicles, daily"/"Excavation, *etc.*"
ASD Waste Containment Effectiveness Factor		0.1 - 1.0	Same as ASV WCEF, above
Waste Quantity Factor		0.1 - 1.0	Same as WQF, above

Table 6. Assigned Rating Ranges and Multipliers for DPM Hazard and Receptor Parameters. (Earth Technology Corporation and ERM Program Management Company. User's Manual for the Defense Priority Model, FY 93 Version. Interim Draft prepared for the Office of the Deputy Assistant Secretary of Defense (Environment), April 1992.)

DPM Parameter	Rating Range	Factor Multiplier	Range of Values & Units
Contaminant Hazard:			
Detected Releases (Repeated for each pathway--SW, GW, ASV, and ASD)			
Human Health Hazard	0 - 6	1	Sum of Hazard Quotients (ΣHHQ): <0.1 to ≥10,000*
Ecological Hazard	0 - 6	1	ΣEHQ: <0.01 to >1,000
Nondetected Releases (Repeated only for SW and GW pathways)			
Human Health Hazard	0 - 9	1	Use Highest Value per Toxicity, Bioaccumulation Factors (DPM Appendix E)
Ecological Hazard	0 - 6	1	Highest Value, as above
Receptors:			
SW-Human Health Receptors			
Population downstream obtaining affected SW	0 - 3	3	"≤50 people @ >4 mi" to ">10,000 @ <3 mi"
Use of SW body/bodies	0 - 3	3	"None/>3 mi" to "Drinking"
Population within 1/2 mile of site	0 - 3	1	"≤25 people @ >1/4 mi" to ">1,000 @ <1/10 mi"
Distance to boundary	0 - 3	1	">2.0 mi" to "<0.50 mi"
Land use/zoning within 2 miles of site	0 - 3	1	"Remote" to "Residential within <1.0 mi"
SW-Ecological Receptors			
Importance/sensitivity of nearby biota/habitats	0 - 3	5	"None/SW ephemeral, *etc.*" to "Critical, <3 mi down or 1 mi any direction"
"Critical" environments within 1.5 miles of site	0 - 3	1	"Absent" to "<1 mi"
GW-Human Health Receptors			
Mean GW travel time to drinking water wells	0 - 3	9	"<5 yr" to ">100 yr"
Mean GW travel time to SW as drinking water	0 - 3	5	">100 yr and ≥3 mi" to "<5 yr and <3 mi"
Use of the uppermost aquifer	0 - 3	4	"None/not used" to "No alternate water source"
Population at GW-risk	0 - 3	1	">2.0 mi" to "<0.50 mi"

(Continued on next page.)

Table 6. (Continued.)

DPM Parameter	Rating Range	Factor Multiplier	Range of Values & Units
Receptors: GW-Human Health Receptors (continued)			
Population within 1/2 mile of site	0 - 3	1	"≤25 people @ >1/4 mi" to ">1,000 @ <1/10 mi"
Distance to boundary	0 - 3	1	">2.0 mi" to "<0.50 mi"
GW-Ecological Receptors			
Mean GW travel time to downgradient habitat	0 - 3	3	">100 yr and ≥3 mi" to "<5 yr and <3 mi"
Important/sensitive nearby biota/habitats	0 - 3	3	"None/SW ephemeral, *etc.*" to "Critical, <3 mi down or 1 mi any direction"
"Critical" environments within 1.5 miles of site	0 - 3	1	"Absent" to "<1 mi"
Air/Soil-Human Health Receptors			
Population within 4-mile radius	0 - 30	1	"None" to ">10,000 people @ 0.25 mi radius"
Land use		2	"≥1 mi (commercial use)/ ≥2 mi (park/residential)" to "<0.25 mi (either)"
Distance to boundary	0 - 3	1	">2.0 mi" to "<0.50 mi"
Air/Soil-Ecological Receptors			
Distance to important biota and habitats	0 - 3	2	">2 mi (coast)/>1 mi (freshwater/habitat)" to "<0.5 mi (coast)/<0.1 mi (freshwater)/<0.25 mi (critical habitat)"
"Critical" environments within 1.5 mile of site	0 - 3	1	"Absent" to "<1 mi"

* Human Health Hazard Quotients (HHQ) and Ecological Hazard Quotients (EHQ) are computed individually for each contaminant's detected and nondetected (but potential) releases into surface water (SW) and ground water (GW), as well as for detected releases to air/soil of volatiles (ASV) and dust (ASD).

For detected releases into water and air/soil, the HHQ and EHQ are functions of each contaminant's concentration, average daily intake, bioaccumulation factors, and effects benchmarks. HHQ and EHQ for potential but nondetected releases into water are provided by the DPM's developers based on the characteristics of each contaminant.

points raised in the NRC report questioned some of the logic in the model's design (particularly its method of assigning and combining subscore values and its contaminant fate and transport algorithm) and argued that DPM requires further documentation and validation.[59]

RelRisk. The DPM was replaced in late 1994 by the Relative Risk Site Evaluation Concept (RelRisk) as a means of categorizing sites in the Defense Environmental Restoration Program (DERP). RelRisk is similar in its methodology to DPM, but its objective is to place sites and areas of concern (AOC) into one of three relative risk categories: High, Medium, or Low, "to help in the sequencing of remedial work."[60]

Using available site information, RelRisk determines a contaminant hazard factor (CHF), migration pathway factor (MPF), and receptor factor (RF) for each of three media: groundwater, surface water/sediment, and surface soils. Factors are combined to yield three Media-Specific Risk Ratings, the highest of which equals the Overall Site Category.

At each site rated "Medium" or "Low" for human health risk, the entire process is repeated in consideration of ecological risks. The media ratings are again compared such that the Overall Site Category reflects the highest value, provided it exceeds the highest human health rating.[61] Table 7 outlines the RelRisk framework and its rating methodology.

[59] National Research Council. The Department of Defense Priority Model: An Independent Assessment of Methods, Assumptions, and Constraints. Interim Report to DOD, Jun 1992, pp 3-5.

[60] Office of the Under Secretary of Defense (Environmental Security). The Relative Risk Site Evaluation Concept, Executive Summary. Washington: DOD, undated, p 1.

[61] Office of the Under Secretary of Defense (Environmental Security). Relative Risk Site Evaluation Primer. Interim Edition. Washington: DOD, Summer 1994, pp 6-16.

Table 7. RelRisk Factors, Ratings, and their Definitions. (Office of the Under Secretary of Defense (Environmental Security). Relative Risk Site Evaluation Primer. Interim Edition. Washington: DOD, Summer 1994.)

RelRisk Factor	Rating	Definition
Groundwater:		
Contaminant Hazard (CHF)	Significant	Sum of Max/Std* ratios > 100
	Moderate	Sum of ratios = 2 to 100
	Minimal	Sum of ratios < 2
Migration Pathway (MPF)	Evident	Movement from source seen
	Potential	Possible/Too little information
	Confined	Migration limited or controlled
Receptor (RF)	Identified	Class I or IIA aquifer is down-gradient and threatened
	Potential	Class IIB aquifer, no wells
	Limited	Class III aquifer, no wells
Surface Water/Sediment:		
Contaminant Hazard (CHF)	Significant	Sum of ratios > 100
	Moderate	Sum of ratios = 2 to 100
	Minimal	Sum of ratios < 2
Migration Pathway (MPF)	Evident	Movement to point of exposure
	Potential	Possible/Too little information
	Confined	Migration limited or controlled
Receptor (RF)	Identified	Receptors have access to SW
	Potential	Possible SW/Sediment access
	Limited	Little or no potential for access
Soils:		
Contaminant Hazard (CHF)	Significant	Sum of ratios > 100
	Moderate	Sum of ratios = 2 to 100
	Minimal	Sum of ratios < 2
Migration Pathway (MPF)	Evident	Movement toward exposure pt.
	Potential	Possible/Too little information
	Confined	Migration possibility is low
Receptor (RF)	Identified	Access to contaminated soil
	Potential	Possible receptor access
	Limited	Little or no potential for access

* "Max/Std" is the ratio of the maximum concentration of a contaminant detected at a site to the RelRisk Concentration Standard for that contaminant. (The Concentration Standards are derived from EPA Region IX Preliminary Remediation Goals and EPA HRS benchmarks for radionuclides.) The Max/Std ratios for all the contaminants are summed to yield the CHF rating for each of the three media.

NCAPS. The three-category scheme employed in RelRisk is not unique. The EPA's recently-developed National Corrective Action Prioritization System (NCAPS) was conceived along similar lines. NCAPS is the current relative risk assessment model for RCRA corrective action sites, whereas the revised HRS remains the model for sites under CERCLA regulation.

According the the EPA, "NCAPS generates a High, Medium or Low ranking for each facility ... based on an evaluation of four pathways of actual or potential contamination ... and nationally-established criteria for determining High/Medium/Low."[62] The information required for the NCAPS process is expected to be obtained during a site's RCRA Facility Assessment (RFA). Most of the affected sites were ranked by the end of 1993, but remain subject to revision due either to changing conditions or NCAPS refinements.

Careful examination of available NCAPS documentation, however, reveals that the model applies the three-category rankings are actually an interpretation of a normalized 100-point scoring system, as outlined in Table 8. A site's score is one-half of the square-root of the sum of squares of the four pathway subscores.[63] In this respect, NCAPS more resembles DPM than DOD's current RelRisk model. Numerical scores are then converted to a site ranking, revealing the parallel to RelRisk. Each model deals with inherent uncertainty, and avoids addressing confidence limits, by presenting final output as a discrete, qualitative value.

[62] U.S. EPA. Environmental Fact Sheet: The National Corrective Action Prioritization System. EPA/530-F-92-027. Washington: GPO, 1993a, p 2.

[63] PRC Environmental Management, Inc. RCRA National Corrective Action Prioritization System Guidelines, Revised. Draft prepared for EPA, Aug 1992, p B-11.

Table 8. NCAPS Parameters, Rating Ranges, and Associated Values. (PRC Environmental Management, Inc. RCRA National Corrective Action Prioritization System Guidelines, Revised. Draft prepared for U.S. EPA, Aug 1992.)

NCAPS Parameter	Rating Range	Range of Values & Units
Ground Water Route:		
Observed Release	0 or 10 or 45	"No"/"Possible"/"Yes"
Depth to Aquifer	0 - 6	"150+ ft" to "0-20 ft"
Net Precipitation	0 - 6	"<-10 in" to ">+15 in"
Physical State	0 - 3	"Stable Solid" to "Liquid, Gas, Sludge"
Containment[a]	0 - 3	"Very Good" to "Poor"
Waste Toxicity/Persistence	0 - 18	Per Sax[64]/EPA[65] Method
Quantity Known/Likely	1 - 8	"0-10 yd^3" to "2500+ yd^3"
Groundwater Use	0 - 5	"Not Impacted" to "Drinking Water"
Distance to Intake	0 - 4	">3 mi" to "<1/2 mi"
Surface Water Route:		
Observed Release	0 or 45	"No"/"Yes"
Permitted Outfall	0 or 5	"No"/"Yes"
Past Permit Violations	0 or 5	"No"/"Yes"
Facility Location	1 or 2 or 3	"No"/"100-yr Floodplain"/"Prone to Flooding"
24-Hr Rainfall	0 - 3	">3.0 in" to "<1.0 in"
Distance to Surface Water	0 - 6	">2 mi" to "≤1/4 mi"
Physical State	0 - 3	"Stable Solid" to "Liquid, Gas, Sludge"
Containment[b]	0 - 3	"Very Good" to "Poor"
Waste Toxicity/Persistence	0 - 18	Per Sax/EPA Method
Quantity Known/Likely	1 - 8	"0-10 yd^3" to "2500+ yd^3"
Surface Water Use	0 - 5	">3 mi" to "Drinking"
Intake or Contact Point	0 - 4	">3 mi" to "<1/2 mi"
Sensitive Environments	0 - 6	">2 mi" to "<1/2 mi"

(Continued on next page.)

[64] N. I. Sax. Dangerous Properties of Hazardous Materials. 6th ed. New York: Van Nostrand Reinhold, 1984.

[65] U.S. EPA. Uncontrolled Hazardous Waste Site Ranking Systems, A User's Manual. HW-10. Washington: EPA, 1984.

Table 8. (Continued.)

NCAPS Parameter	Rating Range	Range of Values & Units
Air Route: Observed, Unpermitted, Ongoing Release	0 or 45	"No"/"Yes"
Air Operating Permit	0 or 5	"No"/"Yes"
Violations/Odor Complaints	0 or 10	"No"/"Yes"
Air Migration Possible	0 or 3	"No"/"Yes"
Containment[c]	0 - 3	"Very Good" to "Poor"
Waste Toxicity	0 - 9	Per Sax/EPA Method
Quantity Known/Likely	1 - 8	"0-10 yd^3" to "2500+ yd^3"
Target Population	10 - 25	"All >4 mi" to "Residences within 4 mi"
Sensitive Environments	0 - 6	">2 mi" to "<1/2 mi"
On-Site Contamination: Access to Site	0 or 2 or 4	"Inaccessible"/"Limited Access"/"Unlimited"
Observed Surface Soil Contamination	0 or 25	"No"/"Yes"
Containment[d]	1 - 4	"Very Good" to "Poor"
Waste Toxicity/Persistence	0 - 3	Per Sax/EPA Method
Distance to Residential Areas	0 - 6	">1 mi" to "≤1/4 mi"
On-Site Sensitive Environments	0 or 1	"No"/"Yes"

[a] For landfills, "Very Good" = Essentially nonpermeable liner, compatible with waste, and adequate leachate collection system; "Poor" = No or incompatible liner, moderately permeable liner, or no runon control. Do not consider natural barriers, such as underlying clay layers.

[b] For landfills, "Very Good" = Slope precludes runoff, surrounded by sound diversion system, or adequate cover material; "Poor" = Not covered and no diversion system, diversion system unsound, contaminated groundwater likely to discharge to surface water, or surface soil reaches surface water through runoff.

[c] For landfills, "Very Good" = Covered; "Poor" = Open.

[d] Same guidance as for Surface Water (see note b, above).

Stochastic Failure-Risk Models

Another set of models, even more complex than those described above, are intended specifically to assess risks associated with landfills. The U.S. EPA, through various contractors, has developed several such models, which attempt to completely enumerate and quantify potential mechanisms of failure by which a contaminant may escape the landfill's containment system and migrate into the environment. These models typically also attempt to estimate the costs associated with failure.

Liner Location/RCRA Subtitle D Risk Models. The Liner Location Risk and Cost Analysis Model and RCRA Subtitle D Risk Model are stochastic simulation computer models, both developed for EPA's Office of Solid Waste. Liner Location is described in a EPA Draft Report dated January 1985,[66] and the RCRA Subtitle D model was submitted in July 1991.[67] A comparison of the documents reveals that the latter model is in fact largely a revision of the former model.

The RCRA Subtitle D model comprises three risk submodels: MSW landfill failure/contaminant release, contaminant transport, and human exposure. The failure/release submodel employs Monte Carlo simulation to yield a probability distribution for the magnitude of contaminant release resulting from a combination of landfill-failure events for 200

[66] Pope-Reid Associates. Liner Location Risk and Cost Analysis Model. Draft Report and Appendices. Washington: EPA, 1985.

[67] DPRA, Inc. Subtitle D Risk Model. Appendix A: "Failure/Release Submodel." Draft prepared for U.S. EPA Office of Solid Waste, Jul 1991.

years after initial construction. As in the other models discussed above, however, the frequency and severity of the failure mechanisms envisaged are very often subjectively defined, using "engineering judgment and agreement by consensus," due to a lack of empirical data.[68]

The various landfill-failure scenarios considered by the model are representative of a modern, geomembrane-lined, cut-and-fill or valley-fill landfill, but the older classes of unlined and clay-lined facilities are also addressed. The sequence of events leading to failure is analyzed in a fault tree, which illustrates the causal relationships between human activities, system components, and external forces responsible for failure.

Some 70 failure mechanisms are acknowledged and simulated in the Subtitle D Risk Model's failure/release submodel, as outlined in Table 9. The simulation process yields a quantitative estimate of the likelihood of occurrence for each modeled failure mechanism, which is described by one of five probability distribution types:

1) <u>Time to First Occurrence</u>. May be a Geometric (an annual probability with potential for recurrence) or Normal (a mean time to failure with a standard deviation) distribution of failure events.

2) <u>Lagged</u>. A Normal distribution with initial time lag (*i.e.*, the ordinate is greater than zero).

3) <u>Bernoulli</u>. A time-invariant proportion of a sample population.

4) <u>Conditional</u>. An intermediate event in response to one or more defining failure mechanisms.

5) <u>Performance-related</u>. A proportional contribution to the total leachate release.

[68] *ibid.*, Section 2.3.2.

Table 9. Subtitle D Failure/Release Submodel Parameters, Distributions, and their Probabilities. (DPRA, Inc. Subtitle D Risk Model. Appendix A: "Failure/Release Submodel." Draft prepared for U.S. EPA, Jul 1991.)

Failure Mechanism	Distribution	A*	B	C	D	E	F
Cover Saturates/Fails:	Conditional						
Cover Breach	Conditional						
Differential consolidation	Conditional						
Formation of cavities in fill	Conditional						
Placement of barrels	Bernoulli	0.16	0.16	0.16	0.16	0.16	0.16
Voids form around barrels	Bernoulli	0.04	0.04	0.04	0.04	0.04	0.04
Differential settlement	Conditional						
Failure of buried barrels	Conditional						
Barrel corrosion, rupture	Normal	10,5	10,5	10,5	10,5	10,5	10,5
Free liquids in waste	Bernoulli	0.05	0.05	0.05	0.05	0.05	0.05
Highly moist waste added	Bernoulli	0.02	0.02	0.02	0.02	0.02	0.02
Poorly placed bulky wastes	Bernoulli	.0225	.0225	.0225	.0225	.0225	.0225
Inadequate compaction	Normal	20,10	20,10	20,10	20,10	20,10	20,10
Settlement of landfill	Conditional						
Erosion of cover	Conditional						
Soil loss	Conditional						
Loss of Vegetative cover	Bernoulli	0.05	0.001	0.05	0.001	0.001	0.001
Slope failure	Bernoulli	0.01	0.01	0.01	0.01	0.01	0.01
Puncture by burrowing animal	Conditional						
Burrowing animals present	Conditional						
Poor subgrade sterilization	Bernoulli	0.001	0.001	0.001	0.001	0.001	0.001
No animal ingress control	Bernoulli	0.001	0.001	0.001	0.001	0.001	0.001
Inadequate liner strength	Normal	1,0	50,10	1,0	50,10	50,10	50,10
Inadequate secondary liner	Normal	1,0	1,0	1,0	1,0	1,0	50,10
Breach of cover seal	Conditional						
Improper cover seal	Bernoulli	1	0.05	1	0.05	0.05	0.05
Synthetic cover liner present	Bernoulli	0	1	0	1	1	1
Undetected liner aging	Conditional						
Synthetic liner degradation	Normal	1,0	35,10	1,0	35,10	35,10	35,10
Aging of clay cover liner	Normal	1,0	1,0	1,0	1,0	1,0	3,2
Tear in cover liner	Conditional						
Damage upon emplacement	Bernoulli	1	0.01	1	0.01	0.01	0.01
Breach due to repair activities	Conditional						
Damage during cover repair	Bernoulli	0.01	0.01	0.01	0.01	0.01	0.01
Faulty repair patch seams	Bernoulli	0.05	0.05	0.05	0.05	0.05	0.05
Inadequate repair inspection	Bernoulli	0.1	0.1	0.1	0.1	0.1	0.1
Infiltration Through Cover	Conditional						

(Continued on next page.)

Table 9. (Continued.)

Failure Mechanism	Distribution	A[a]	B	C	D	E	F
Bottom Liner System Fails:	Conditional						
Breach in Containment Liner	Conditional						
Pressure due to water table rise	Conditional						
Rise of ground water table	Per User						
Liner too thin in areas	Bernoulli	1	1	1	0.01	0.01	0.01
Inadequate liner strength	Bernoulli	1	1	1	0.05	0.05	0.05
Breach by catastrophic event	Conditional						
Earthquake event	Bernoulli	3.E-7	3.E-7	3.E-7	3.E-7	3.E-7	3.E-7
Sinkhole collapse	Bernoulli	5.E-6	5.E-6	5.E-6	5.E-6	5.E-6	5.E-6
Damage during construction	Conditional						
Tear in containment liner	Conditional						
Damage when emplaced	Bernoulli	1	1	1	0.01	0.01	0.01
Initial failure to repair liner	Bernoulli	1	1	1	0.1	0.1	0.1
Breach in faulty liner	Conditional						
Poor synthetic liner seal	Bernoulli	1	1	1	0.05	0.05	0.05
Failure to repair seal	Bernoulli	1	1	1	0.1	0.1	0.1
Puncture by physical loading	Bernoulli	1	1	1	0.05	0.05	1
Breach by burrowing animal	Conditional						
Burrowing animal present	Conditional						
Inadequate puncture resist	Geometric	0	0	0.02	0.02	0.02	0.02
Failure due to material aging	Conditional						
Aging of first (synthetic) liner	Normal	1,0	1,0	1,0	35,10	35,10	35,10
Aging of second liner	Normal	1,0	1,0	1,0	1,0	36,10	35,10
Aging of third liner	Normal	1,0	1,0	1,0	1,0	1,0	36,10
Reduced Leachate Collection System (LCS) Efficiency:	Performance						
Buffer too thin/tiles too small	Bernoulli	1	1	0.1	0.1	0.1	0.1
Clogged LCS tiles (crust, silt)	Normal	0,1	0,1	15,5	15,5	10,5	10,5
Repetitive Inspection Error	Bernoulli[b]	0.1	0.1	0.1	0.1	0.1	0.1

[a] Fields "A" through "F" represent function values for six conceptual landfill designs:
A = Unlined, with vegetated (soil) top cover only.
B = Unlined, with synthetic (geomembrane) cover and vegetated top cover.
C = Clay liner with vegetated top cover only.
D = Single synthetic liner with synthetic cover and vegetated top cover.
E = Composite liner with synthetic cover and vegetated top cover.
F = Triple-lined, with composite cover and vegetated top cover.

[b] Value is reset to 1.0 after 50 years to reflect abandonment of the site.

The user influences the submodel's estimate of the annual leachate release by inputting values for the landfill's size, active life, and such location-related data as the "infiltration region," seismic activity zone, climatic and hydrogeologic regimes, and the presence of karst limestone. Each logical progression through the fault tree, given the user's inputs and random values from the Monte Carlo routine, renders one possible outcome, simulating the combined effects of these parameter values on one modeled landfill. A set of 100 runs represents 100 identical landfills and yields a percent probability of failure of such a facility, as well as the leachate volume predicted to be released each year from such a landfill.

Once the probability of failure has been determined on a per-unit-volume basis, the submodel determines the magnitude of contaminant release via hydrologic balance analysis, accounting for facility volume, the leachate collection system's efficiency (if present), as well as the site's hydrogeologic and climatologic setting. The product of failure probability and magnitude, a normal distribution of annual leachate-release volume, is the submodel's output. This distribution is then input to the transport submodel for calculation of contaminant concentrations with respect to location. From there, human health risk is determined as a function of contaminant toxicity and the size and nature of the exposed population.

The submodel's developers acknowledge a number of assumptions, simplifications and limitations in its design. They note that the aging of clay liners differs from that of geomembrane liners, but cite a lack of data to distinguish between those processes. They assumed the landfill to be 15 feet deep; any clay liner is 2.0 feet thick, with a permeability of 10^{-7} to 10^{-8} cm/s; subgrade permeability is 10^{-1} to 10^{-7} cm/s; a 6-inch cap of vegetated top soil is present, with or without a 30-mil PVC cover. The infiltrating water mixes completely and instantly with the waste, but the moisture content of the fill materials remains equal to the initial moisture content. The modeled landfill is operated for 20 years, closed, maintained for the next 30 years, then abandoned. A one-year lag is assumed between the occurrence of a failure and its detection and repair. 200 iterations of the model is thought sufficient to characterize the failure probability distribution for a landfill's design and situation.

Error in the submodel results from "inadequacy of the data base describing the reliability of land disposal facilities," despite the citation of well over 100 reports, studies and vendor publications.[69] Estimates of annual leachate-release volumes are sensitive to uncertainty in the net infiltration of water and variability in the Leachate Collection System's efficiency. The Monte Carlo routine introduces error in the timing of failure events because the calculation depends upon a random number seed which varies from one iteration to the next.

PCLTF. Yet another EPA-sponsored effort from the same era is the Post-Closure Liability Trust Fund (PCLTF) Simulation Model. Developed by ICF Incorporated and Battelle Pacific Northwest Laboratories, under CERCLA Section 232, the model's purpose is to assist in determining and ensuring the adequacy of the trust fund "to address long-term problems at [RCRA Subtitle C] permitted HW land disposal facilities."[70]

[69] *ibid.*, Section 5.2.

[70] U.S. EPA. Post-Closure Liability Trust Fund Simulation Model. Volume I: "Model Overview and Results." Washington: EPA, 1985, p 1-1.

The PCLTF was established to remediate future failures at sites which were currently active as of October 1, 1983, whereas the CERCLA Hazardous Substance Response Fund (or "Superfund") was developed under Section 221 for the remediation of inactive sites. The PCLTF may be applied only at sites meeting several criteria, including a final permit under RCRA Subtitle C, design and performance in compliance with permit and other RCRA requirements, monitoring for five years after closure, and no indication of release of hazardous substances during the monitoring period. The Fund is intended to maintain an unobligated balance of approximately $200 million, through a tax of $2.13 per dry-weight ton of HW received.

The PCLTF Simulation Model is stochastic and computer-driven, incorporating economic and contaminant release simulation submodels. Eleven factors are considered in the overall model. Five are Basic Units:

1) The population (numbers and types) of HW disposal facilities;
2) Facility-level characterization (*e.g.*, size and design) of facilities;
3) Estimated contaminant release per year at each facility;
4) Monitoring, response and care actions, and third-party claims;
5) Funding sources to cover post-closure actions and claims costs.

Six additional factors are the interrelationships among the Basic Units:

1) Economic (supply and demand) relationships affecting disposal;
2) RCRA policies regarding final permitting and remedial action;
3) Financial relationships which augur viability of disposal firms;
4) Physical phenomena (feedback from responses to releases);
5) Cost allocation and Fund qualification policies;
6) Legal issues affecting the validity of third-party claims.

Landfills represent only one of the four facility types modeled (the others are surface impoundments, land treatment and injection wells), and their contaminant releases are modeled as a function of simulated local weather conditions, deterministic water-balance calculations, and simulated subsurface transport phenomena. The designers acknowledge that the Release submodel suffers limitations due to several simplifying assumptions (particularly in the simulation of contaminant transport) and insufficient data (especially with respect to landfill cap and liner performance, hydrogeologic parameters, and waste characteristics).

Seven "Release Types" are modeled, but they represent methods of release detection rather than contaminant release mechanisms. Release Types include a change in an indicator parameter (TOC or TDS) in an on-site monitoring well, taste and odor thresholds in an off-site potable well or surface water, a detectable concentration or a toxic concentration in either on- or off-site receptors, and an overflow of contaminated leachate due to excessive infiltration. Specific site characteristics considered include the number, thickness and field capacity of each barrier layer, the number of years of operation and post-closure care, the number and types of stored wastes, and geographic parameters, as given in Table 10.

The PCLTF Model deals with the stochastic nature of the economic consequences of landfill failure, but it approaches long-term performance and contaminant release as the result of an essentially deterministic water balance and assumes transport to occur in a homogeneous and isotropic medium. It is, therefore, more an analytical failure model.

In summary, efforts to develop a stochastic model of landfill failure and the consequent environmental risk to date is subject to two inherent

Table 10. PCLTF Simulation Model Contaminant Release Parameters. (U.S. EPA. Post-Closure Liability Trust Fund Simulation Model. Volume III: "Model Description," Appendix B. Washington: EPA, 1985.)

PCLTF Release Submodel Parameter	Range of Values & Units*
Site Characteristics	
Site Type	7 prototype designs; 5 are landfills
Number of Barrier Layers	user or prototype defined
Synthetic Cover Failure	prototypes set at 0 & 50 yr
Clay Cover Permeability	prototypes set at 10^{-9} cm/s
Synthetic Liner Failure	prototypes set at 0 & 25 yr
Clay Liner Permeability	prototypes set at 10^{-8} cm/s
Soil Layer Thicknesses	user or prototype defined (cm)
Soil Layer Field Capacities	user or prototype defined (cm/cm)
Opening & Closure Years	user defined
Post-Closure Care Period	user defined (yr)
Latitude/Longitude	user defined
Number of Wastes	user defined
Waste Package Type & Size	"drum" or "sludge"/dimensions (m)
EPA Waste Code	indicator for S, DL, TC & P, below
Waste Solubility (S)	per available data
Detection Limit (DL)	10 µg/l organic; 20 µg/l inorganic
Toxicity Criteria (TC)	per available data
Octanol-Water Partition (P)	per available data
Environmental Factors	
Temperature Profile	40-year historic density (°C)
Precipitation Profile	40-year historic density (cm/mo)
Depth to Groundwater	EPA or user-defined data (cm)
Hydraulic Conductivity	"Water Atlas" data (cm/s)
Ratio Gradient/Porosity	"Water Atlas" data (dimensionless)
Distance to Well/Surface Water	user defined (cm)
Overburden Field Capacity	USDA data (% dry wt. of soil)
Erosion Loss Rate	USDA data, by state (ton/acre-yr)
Runoff Coefficient	4 "Hydrologic Soil Groups"
Aquifer Water Quality	"Water Atlas" data (mg/l)
Aquifer Thickness	"Water Atlas" data (cm)
Period Under Study	user defined (1-100 yr)

* **Most parameter functions are not provided in the available documents. The annual leachate release quantities are calculated via deterministic water balance.**

weaknesses. First, insufficient information is available to the designers of these models to accurately quantify either the timing or magnitude of the various failure mechanisms; instead, a series of largely subjective values must be assigned to idealized, simplified performance parameters. And second, since uncertainty in both timing and magnitude pervade these models, they are not particularly useful as tools for the planning of preventive measures to mitigate the damage caused by an actual landfill failure, the mechanism(s) for which may or may not have been modeled.

The existing models are not without value, however. Failure risk and hydrogeologic models offer some measurement of a site's relative propensity and vulnerability to contamination, information which can be applied, as by RelRisk, to categorize sites for funding. Yet these models do not appear to reduce site investigation costs or efforts. Risk analysis, by definition, invites criticism because it seeks the ideal of complete enumeration, but such criticism serves to suggest areas for research.

Although the objectives and approaches of the existing risk models vary substantially, the ultimate purpose of each is to aid in determining the potential threat to the environment posed by a site such as a landfill within a given set of boundary conditions. Whether deterministic or stochastic, specific to the design of landfills or generally applicable to sites of potential contamination, each is heavily dependent upon theoretical, idealized formulae and/or subjective judgments about the relative influences of myriad, often unseen, phenomena impacting each site. Despite their varied origins and goals, these models share a great deal of common ground in the parameters they employ. Table 11 provides a summary and comparison of these various models.

Table 11. Comparison of Landfill Risk Models

	Model / Parameter	CREAMS	HSSWDS	HELP	SOILINER	MULTIMED	DRASTIC	HRS	HARM	DPM	RelRisk	NCAPS	RCRA Std	PCLTF
Climatology:	Annual Precipitation	■	■	■	■	■	▒	■		■		■	■	■
	Max. Rainfall Event	■	■	■		■				■		■	▒	
	Evapotranspiration	▒	▒	▒		▒	▒	■				■		
	Daily Solar Radiation	■	■	■		■								
	Temperature Range	■	■	■		■				■				■
Topography:	Vegetation/Leaf Area	▒	▒	▒		▒					▒		■	
	Surface Erosion								■	■	▒		■	▒
	Slope/Runoff			▒	■	▒	■	■			▒	▒	▒	▒
	Surface Settlement										▒	▒	■	
	Seismic Activity												■	
	Elevation/Floodplain						▒	■	■	■	▒	▒	■	
Lithology:	Barrier Soil Character		■	■	■	■	■		■	■	■		■	■
	Vadose Soil Character		■	■		■	■		■	■				■
Hydrology:	Hydraulic Gradient			▒	■	▒	■				▒	▒	■	■
	Depth to Aquifer					■	■	■	■	■	▒	▒		■
	Aquifer Media					■	■		■	■				■
	GW Velocity/TOT				▒		▒	■		■	▒			▒
	Distance to SW							■	■	■	■	■		■
Transport:	Biodegradation					■		■		■		▒		
	Adsorption/Advection					■	■	■		■				
	Volatilization					■		■		■		▒		
	Diffusion					■								
	Background Level								■	■	▒			
Design:	Site Area/Volume			■		■		■	■	■	▒	■	■	▒
	Waste Character		■	■		■	■	■	■	■	■	■	■	■
	Liner System			■	■	■		▒	■	■	■	■	■	▒
	Cap & Cover System		▒	▒		▒			■	■	▒	■	■	▒
	Leachate Collection			▒		▒		▒	■	■	▒	■	■	
	Gas Collection							▒	■	■	▒	▒		
	Access Restrictions							■	■	■	■	■	■	

■ Model Input Parameter

▒ Used indirectly or calculated by model

Landfill Remediation Methods

The remediation of a contaminated landfill site is subject to two sets of constraints. In the United States, a complex web of overlapping jurisdictions regulate such environmental decision-making and record-keeping processes. In addition, remediation technologies largely remain in their infancy, so the relative costs and efficacies of various methods are often not well understood.

Regulatory Considerations

In the event an environmentally hazardous contaminant release of sufficient volume and duration is discovered at a landfill site, the release must be corrected and the site cleaned of the contaminant(s). The site, a "solid waste management unit" under RCRA, may be designated as all or part of a RCRA "corrective action management unit" for its cleanup, or placed on the NPL and remediated under the provisions of CERCLA. In either case, the scope of the required cleanup and appropriate, cost-effective technologies must then be identified. The proposed remediation approach and schedule must be approved by the regulators, and the plan must be executed, managed, monitored, and amended until the required degree of remediation has been achieved. Many of the specific requirements vary between RCRA and CERCLA, but the objectives and procedures, outlined in Table 12, are largely parallel.[71]

[71] U.S. EPA. Guidance on RCRA Corrective Action Decision Documents. EPA/540/G-91/011. Washington: GPO, 1991b, pp 1-1 - 1-8.

Table 12. Comparison of RCRA and CERCLA Objectives and Procedures.

RCRA Corrective Action[72,73]	CERCLA Site Remediation[73,74]
Objectives	
Short-term effectiveness	Short-term effectiveness
Long-term reliability, effectiveness	Long-term effectiveness
Implementability	Implementability
Toxicity, mobility, and volume reduction	Toxicity, mobility, and volume reduction
Cost effectiveness	Cost effectiveness
	Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)
	Protection of human health
	State concurrence
	Local community acceptance
Procedures	
RCRA Facility Assessment (RFA)	Preliminary Assessment and Site Investigation (PA/SI)
	Add to National Priorities List (NPL)
RCRA Facility Investigation (RFI)	Remedial Investigation (RI)
Corrective Measures Study (CMS)	Feasibility Study (FS)
Statement of Basis and Response to Comments (SB, RTC)	EPA Record of Decision (ROD)
Corrective Measures Implementation (CMI)	Remedial Design and Remedial Action (RD/RA)
	Long-term monitoring of site

72 U.S. EPA, 1991b, *loc. cit.*

73 Cynthia J. Bishop. "Implementing Corrective Action under RCRA: Past, Present and Future." Air & Waste Management Association 87th Annual Meeting and Exhibition. 94-FA152.01. Cincinnati, Jun 1994, pp 4-9.

74 LaGrega, pp 55-58.

Technological Limitations

In order to hasten and minimize the cost of site characterization and remediation, the U.S. Department of Energy (DOE) is trying to improve internal management processes and available *in situ* remediation technologies. Argonne National Laboratory has developed the Expedited Site Characterization (ESC) process to optimize monitoring locations and to select non-intrusive and minimally-intrusive sampling technologies, reducing DOE's site characterization time from "many months or years,to a matter of a few weeks."[75] Through the Ames Laboratory and Iowa State University, DOE is attempting to apply the ESC as the basis for a "derisking" procedure for introducing to the site characterization process various emerging technologies, many of which DOE is advancing.

In Situ. An *In Situ* Remediation Integrated Program was created to deal with the combination of radioactive, organic, heavy metal and explosive, buried or containerized wastes, contaminated soils, and ground water at DOE facilities nationwide. The focus is on reducing site cleanup costs, minimizing human exposure and resultant health risks, and remediating inaccessible sites.[76] Virtually all state-of-the-art and emerging *in situ* technologies are addressed among four subprograms, according to the affected waste or media: containment/immobilization, bioremediation, physical/chemical treatment, and subsurface manipulation/control.

[75] U.S. DOE. Technology Summary: Characterization, Monitoring, and Sensor Technology Integrated Program (CMST-IP). DOE/EM-0156T. Washington: DOE, 1994a, p 3.

[76] U.S. DOE. Technology Summary: In Situ Remediation Integrated Program. DOE/EM-0134P. Washington: DOE, 1994b, pp v - vii.

Table 13 presents the spectrum of *in situ* remediation technologies now available or under development. Although these methods offer the advantage of eliminating the need and cost to transport materials off-site, each is technically challenging, of limited applicability, difficult to measure and, in many cases, similar in cost to excavation and remote treatment/disposal techniques. *In situ* remediation appears best suited to shallow sites containing radioactive, explosive, or easily treatable wastes, in low-permeability soils and in arid or semi-arid regions.

Table 13. Summary of *In Situ* Remediation Technologies. (U.S. DOE, *In Situ Remediation Integrated Program*. DOE/EM-0134P. Washington: DOE, 1994.)

Waste Containment/ Immobilization	Biological/ Physical/Chemical Treatment	Subsurface Manipulation/ Process Control
Bio-immobilization	Bioremediation	Electrokinetic
Grouting	Microbes	*In Situ* Heating
Immobilization	Biomass	Soil Flushing
Chemical	Biofilters	Bioleaching
Physical	Nitrate Destruction	Auger/Jet Mixing
Reduction/Oxidation Manipulation	Permeable Treatment Barrier	
Subsidence Control	*In Situ* Oxidation	
Barriers	Chemical Oxidation	
Grout	Ozonation	
Chemical	Corona Discharge	
Cryogenic		
Electrokinetic		
Viscous Liquid		
In Situ Vitrification		

Ex Situ. Where *in situ* remediation is not technologically or economically feasible, contaminants must be extracted from the affected media and treated or replaced in a more suitable land disposal facility. Air, water and soil treatment processes have been widely reported and continue to evolve. But treatment tends to move these contaminants, dilute them, transform them, or change their state, rather than destroy them. Thus, land disposal is an inevitable part of the waste management process, despite the near certitude that the buried wastes will someday again escape containment.

Waste Degradation. Dr. William L. Rathje, *et al.*, have studyed MSW landfills and contents for over twenty years. The University of Arizona's Garbage Project has provided the best characterization to date of the contents of a typical MSW landfill, and has supported observations of others that degradation of landfilled wastes is often an extremely slow process due to the relatively dry, dark, anaerobic environment.[77]

Many recent studies have suggested that operating a landfill as a biological reactor will significantly increase the rate at which degradation occurs. The Delaware Solid Waste Authority has for more than ten years recirculated leachate into landfills as a means of providing both moisture and oxygen to encourage the naturally occurring microbes to digest the volatile components of the waste.[78] Similar projects have since been undertaken in Pennsylvania, Ohio, Maryland, Florida, and elsewhere.

[77] William L. Rathje and Cullen Murphy. Rubbish! The Archaeology of Garbage. New York: HarperCollins, 1992, pp 110-30.

[78] L. V. Miller, *et al.* Evaluation of a PVC Liner and Leachate Collection System in a 10 Year Old Municipal Solid Waste Landfill. Post, Buckley, Schuh & Jernigan, Inc., report to the Delaware Solid Waste Authority, 1990.

Landfill Reclamation. The Collier County, Florida, landfill project went on to "mine" the landfilled wastes, not only to determine the effectiveness of the aerobic process, but to separate recyclable materials, remove the enriched soil, most of which originally served as daily cover, and then return the remaining wastes to the landfill for permanent entombment. This study found that about 75 percent of the original fill volume could be removed and reclaimed from the solid waste stream, so only the remaining 25 percent needed to be returned to the landfill facility.[79]

The Collier County study further demonstrated that the reclaimed materials can be effectively separated through process trains similar to those commonly used in the solid waste management industry. Waste processing equipment in the pilot-scale train in the Collier County study included a grizzly, a trommel, an air knife, and magnetic separators.[80]

Once separated, contaminated materials must be either treated or disposed of in accordance with current regulations. The EPA has fielded a pilot-scale Debris Washing System (DWS) at two sites where metal, masonry and other solid materials had been contaminated with hazardous wastes. The relatively simple DWS water-treatment process was found to effectively clean most materials sufficiently to permit their sale or proper disposal, while producing a minimum of contaminated process water. A full-scale DWS is now planned.[81]

[79] R. I. Stessel and R. J. Murphy. "A Lycimeter Study of the Aerobic Landfill Concept." Waste Management and Research 10 (1992): 485-503.

[80] E. L. von Stein and G. M. Savage. Evaluation of the Collier County, Florida Landfill Mining Demonstration. EPA/600/R-93/163. Washington: GPO, 1993, pp 9-12.

[81] M. A. Dosani and M. L. Taylor. Technology Demonstration Summary: Design and Development of a Pilot-Scale Debris Decontamination System. EPA/540/S5-91/006. Cincinnati: GPO, 1991.

To the extent that landfilled waste materials can be returned to productive use (metals and glass recovered for recycling; plastics, rubber and paper for either recycling or conversion to fuel; cover soil and organic materials reclaimed as nutrient-enriched soil), and liquid and hazardous wastes removed for safer disposal (such as incineration), risks of long-term environmental damage presented by an obsolete landfill can be mitigated. Land once consumed by such a landfill may be reclaimed for more productive use, as well. Landfill reclamation costs are substantial, however, so a decision to take such action must be made on the basis of reasoned technical, environmental and financial risk assessment.

USAF Investigations. In a study of USAF landfills conducted from 1986 to 1988, over half of the landfills then identified were deemed to warrant further investigation and possible remedial action. That study examined eight installations' landfills in depth, but focused on water and soil treatment processes applicable after substantial site contamination has occurred. The use of "excavation" as a remediation method was limited in that report to removal of hazardous wastes, but no methods were suggested for exclusively extracting hazardous wastes from within a landfill cell.[82] No broad investigation of USAF landfills has since been conducted, but the waste stream of several bases is now under study.[83] Data from those studies may prove to be useful in characterizing already-landfilled wastes for site remedial investigation and design processes.

[82] Kilroy, pp 68-71.

[83] Law Environmental, Inc. Solid Waste Characterization Study, MacDill AFB, Florida. Report to USAF, Mar 1994.

CHAPTER 3
METHODOLOGY

Given the broad range of parameters discussed in various studies, landfill models and hazard assessment methodologies, examination of a multitude of characteristics appears to be essential to any measurement or forecast of the performance of a particular landfill facility. Clearly, the supposition of most knowledgeable observers of landfill performance is that certain of these characteristics--an unlined HW fill in a sandy soil matrix near the coast of Florida, for example--are virtually manifest indicators of trouble. Other attributes may hold strong correlations with the actual long-term performance of landfills, but without so apparent a causal link or so easily quantifiable consequences.

Access to data from a large number of landfills, spanning a long period of observation, and recording a broad spectrum of properties, is essential to such a performance analysis. The lack of this kind of data is precisely the reason the multitude of hazard models (DRASTIC, HARM, HRS, DPM, *etc.*) all rely so heavily upon subjective judgment in selecting the various measurement parameters and in assigning relative weights to those parameters as they attempt to assess the risks of landfill failure and/or resultant environmental damage.

The purpose of this study is not to implement, validate or critique the risk and hazard assessment models now available. Rather, it is intended that a set of quantified risk factors of the kind identified in those models will be empirically developed, such that estimations rooted in supposition, opinion and consensus may be replaced with values derived from actual, measurable experience.

The probability that a given landfill will fail over time to adequately contain the hazardous substances placed within it may be ascertained by assessing the correlations between observable characteristics of similar landfills and their established long-term performance. The sensitivity of each parameter and the interdependence between parameters may then be measured, ultimately leading to an empirical, definitive algorithm of landfill performance. That algorithm, or model, may be applied by environmental managers to forecast the risks associated with a specific landfill, allowing them to make more informed decisions regarding long-term maintenance, preventive and remedial measures. Anticipating and budgeting for failure prevention and remediation activities will permit limited USAF resources to be better utilized, both by aiding in the prioritization process and by potentially preventing or minimizing the environmental damage caused by landfill containment breaches.

The Empirical Database

The Air Force Center for Environmental Excellence (AFCEE) at Brooks AFB, Texas, maintains an Oracle-driven relational database for the characterization and monitoring of IRP sites at USAF installations throughout the Continental United States, Alaska, Hawaii, and United States territories where there is a USAF presence. This database, the IRP Information Management System (IRPIMS), currently contains data on more than 500 landfills, as well as thousands of other sites where petroleum products and other chemicals have leaked or spilled from tanks, drums, pipelines, firefighter training facilities and the like.

Many of the monitoring well samples from landfill sites indicate undetectable concentrations of regulated contaminants, and still more samples contain contaminants below actionable levels, but the remaining IRPIMS sampling data confirm that the potential for significant levels of contamination to escape from USAF landfills is a reality. In fact, several landfill sites have already been found in need of remediation, and many sites which have been found to be presently satisfactory remain subject to continued monitoring and eventual re-evaluation. As the contents and condition of these landfills continue to degrade, situations will arise where the years of costly monitoring and analysis may be followed by years of far-more-costly soil and water remediation.

All but a few solid waste landfills on USAF installations in the United States are now closed. Nearly all were designed, constructed and operated without the liners and other systems required by RCRA Subtitle D standards in 1991, and required of HW landfills under Subtitle C since 1984.[84] All landfills in the United States accepting MSW as of October 1994 must comply with Subtitle D, regardless of their date of inception.

Due to the minimal protection to the surrounding environment offered by these older USAF landfills, they have been uniformly included in the IRP and routinely investigated for potential remediation under

[84] Several states have imposed higher and/or earlier standards on the design and construction of new landfills than those required under RCRA Subtitles C and D. In any case, no USAF landfills in the IRPIMS database and the subject of this research were constructed since the imposition of these more stringent standards.

either RCRA or CERCLA. Most bases have further ensured that relevant information about these sites was loaded into the IRPIMS.

The information stored in the IRPIMS has served as a regulatory compliance tool and historical record for USAF environmental managers at base level, command level and AFCEE, but no other broad analyses of these data have been yet undertaken. IRPIMS records of landfill leachate composition, contaminant concentrations, soil properties, and other characterizations of the landfills in the USAF inventory thus remain an untapped source of insight to the failure mechanisms from which the sampling data are derived. In other words, the IRPIMS data on over 500 USAF landfills represent a "reference distribution" with which the performance of a given landfill may be statistically compared.[85]

Access to IRPIMS data is necessarily limited to authorized federal government agencies and their contractors. Although not "classified," the data are generated and maintained for official use only, and are continually subject to updates and corrections. For this reason, no raw IRPIMS data are presented in this document. All IRPIMS records employed in this study were extracted from the USAF database between March and October 1994, and input to an IBM-compatible personal computer in a Borland® Paradox® for Windows™ (Release 4.5) relational database environment. Some of the statistical analyses were performed via SPSS® for Windows™ (Release 6.0).

[85] Reference distributions, typically comprising at least 200 samples, have been used extensively in experimental and geostatistical analysis. See George E.P. Box, *et al.* Statistics for Experimenters. New York: Wiley, 1978.

Database Adjustments and Additions

The IRPIMS is designed to permit cross-referencing between "sites" such as landfills and "locations" from which those sites are monitored. Further cross-referencing, as to the dates and methods of construction of monitoring wells, the geologic and hydrologic conditions at well locations, samples drawn from monitoring locations, tests performed and results of such testing, are also accessible.

Only records for sites identified by their Site Type Code as landfills, their associated monitoring locations, and the available cross-referenced information were utilized. Some records were further eliminated, where certain parameter values indicated the record to be irrelevant to the proposed analysis (*e.g.*, test results on samples identified as laboratory blanks). The applicable IRPIMS records, as provided by AFCEE, were divided among 12 "flat-file" data tables. These data tables, the number of records in each, their key fields and other fields relevant to the analysis are provided in Table 14.

Unfortunately, not every record in every table nor every field in every record has been yet input. Most notably, a small number of USAF installations' data are virtually absent, so the 549 documented landfill sites represent a substantial fraction, but not all, of the landfills in the USAF inventory. For other installations, site-to-location cross-references are inadequate or missing entirely; location descriptions are occasionally lacking; well completion and lithologic descriptions are often missing; and four sites identified as landfills clearly are not, in light of the other descriptive information provided on those sites.

Table 14. IRPIMS Tables, Fields and Records Extracted for Analysis

Table Name (Acronym) Key Fields/Other Relevant Fields	Number of Records
Air Force Installation Information (AFI) AFI ID Code/AFI Name, County, State, Climate Classification	132
Analytical Results Information (RES) AFI ID, Location ID Code, Log Date, Sample Matrix, Upper & Lower Sample Depths, Sample Type, Analytical Method, Run No., Analyt/ Test Result Value, Units of Measure, Uncertainty, Results Qualifier	345,989
Calculated Hydrologic Parameters (CAL) AFI ID, Location ID, Log Date, Parameter Source (Aquifer/Tracer)/ Test Result Value, Units of Measure	200
Environmental Sampling Information (SAM) AFI ID, Location ID Code, Log Date, Sample Matrix, Upper & Lower Sample Depths, Sample Type/Sampling Method, Log Time, Lot No.	5,605
Groundwater Level Data Information (GWD) AFI ID, Location ID, Log Date, Log Time/Static GW Depth, Pump Production Rate, Highest & Lowest Dynamic GW Depths, Recovery Time, Sounding to Well Bottom	4,236
General Site Information (GSI) AFI ID, Site ID Code/Site Name, Site Type, Topographic Setting, Co-ordinates, Surface Area, HARM & HRS Scores, Status, Description	549
Lithologic Descriptions Information (LTD) AFI ID, Location ID, Upper & Lower Depths of Lithologic Stratum/ Lithologic & Visual Descriptions, Stratum Order, ASTM Class Code	1,199
Location Definition Information (LDI) AFI ID, Location ID/Location Type, Coordinates, Elevation, Drilling or Excavation Method, Depth, Diameter, Description, Completion Date	2,236
Sample Testing and Analysis Information (TES) AFI ID, Location ID, Log Date, Sample Matrix, Upper & Lower Sample Depths, Sample Type, Extraction & Analysis Methods, Run Number/ Laboratory ID Code, Extraction Date & Time, Analysis Date & Time	41,908
Site Contaminant Classifications (SCC) AFI ID, Site ID, Class of Contaminant Present or Suspected/none	3,230
Site-Location Cross-Reference (SLI) AFI ID, Site ID, Location ID/Site-to-Location Hydraulic Relationship	2,222
Well Completion Information (WCI) AFI ID, Location ID/Well Type, Construction Method, Date of Casing Installation, Hydrologic Description, Sole Source Aquifer Code, Seal Depth, Seal-to-Bottom Distance, Total Depth, Reference Elevation, Casing Material & Diameter, Screen & Slot Dimensions, % Open	1,063

To the extent possible, compensations have been made for the data discrepancies described above. For example, where the IRPIMS SLI table fails to provide a needed site-to-location cross-reference, the WCI table Remarks field may specify the site for which a monitoring well was constructed. In order to include such cases in the analysis, it was necessary to build an expanded SLI table which includes data records missing from the original IRPIMS SLI table. The site-to-location cross-referencing remains incomplete, however, even with the additions from the WCI table.

In the same way, additional information was obtained for analysis (and the four non-landfill sites were removed from consideration) via a careful examination of the Site Description, Location Description, and Visual Description fields for each record in the GSI, LSI, and LTD tables, respectively. The additional data obtained through this procedure includes years of operation for many sites and types of wastes believed to be present in the fill.

Additional fields were created where appropriate to supplement the IRPIMS data fields for ease of analysis. These additional fields contain data which were either provided only in "Remarks" fields within the IRPIMS structure (as in the dates of operation and nature of the fill material at specific sites) or obtained from sources other than the IRPIMS database.

Many parameters of interest in this study are not among the data gathered for the IRPIMS. It was, therefore, necessary to consult a variety of other sources, described in Chapter 4, to obtain additional data on local climatic conditions, solar radiation values, average wind speeds, vegetation densities, potential water infiltration and runoff rates, seismic risk and impact zones, *etc.*, from sources external to the IRPIMS. This information was then entered into each appropriate landfill site record in one of several newly-created data fields. The total body of gathered data was finally assembled into a new "flat-file," or matrix, of 545 sites by 31 analytical parameters.

The Empirical Approach

Development of the landfill risk mitigation methodology consisted of a four-step process, following the traditional "Scientific Method:"[86]

1) Determination of parameters associated with either the long-term viability or failure of the USAF landfills in the IRPIMS database,

2) Construction of an empirical algorithm (or model) which reflects the correlation of specific parameters with landfill performance over time,

3) Testing of the algorithm to determine its validity and accuracy in predicting the performance of a particular landfill, and

4) Analysis of the sensitivity of the model to variations in the parameter values and the algorithm functions.

Candidate landfill viability parameters were selected through an examination of the parameters identified in the existing water-balance, relative environmental-risk, and landfill failure-risk models, as listed in Chapter 2, Table 11. The effects over time, in terms of overall landfill age and period of operation, were also addressed in the analysis.

[86] Barry Render and Ralph M. Stair, Jr. Quantitative Analysis for Management. Boston: Allyn and Bacon, 1982.

Parameters that can be measured quantitatively, such as the depth from the fill to an underlying aquifer or the hydraulic conductivity of the intermediate soil matrix, may be applied directly as a function in any mathematical algorithm or decision model. Qualitative parameters, such as lithological descriptions and fill material characterizations, may also apply to the extent that an adequate statistical correlation exists between a general description and an ensuing landfill condition.

If, for instance, a karst limestone base is strongly correlated with contaminant migration but a sandy soil of similar hydraulic conductivity is not, then lithology may be evaluated mathematically via a "scoring function" which yields a "worth score" for each soil matrix considered.[87] Such qualitative parameters may be thus measured quantitatively and objectively, without reliance on the modeler's judgment. Alternatively, a decision model may represent the algorithm so that potentially complex mathematical formulae may, too, be avoided. Such decision models are routinely applied as fault trees, the logical basis for stochastic models, and can be constructed to explain the logical processes of the relative environmental-risk analytical methods discussed above.

The IRPIMS data were reviewed to determine those parameters for which measurable values or meaningful descriptions are available. In combination with the data collected from other sources, a series of statistical analyses were then performed to correlate these parameters with ground water, surface water, and soil sampling and testing results as evidence of long-term performance. Further analyses were conducted to

[87] James R. Miller, III. Professional Decision-Making. New York: Praeger, 1970.

determine the significance of any interdependence between parameters. Those distributions that are highly correlated with landfill performance (whether positive or negative) were then studied to ascertain the nature of causal relationships between the measured values and the apparently related phenomena.

Construction of the model algorithm consisted of selecting a set of relevant parameter functions. Such an empirical algorithm reflects the correlation of specific parameters with long-term landfill performance, connecting the performance response to the most significant causal effects of the modeled parameters. The algorithm may thus serve as a basis for predicting performance over time of any landfill for which the modeled parameters are known.

The algorithm was tested to determine the accuracy of its results. It was also tested against known landfills to validate those results. This effort ensures that the algorithm reasonably predicts a landfill's failure in cases where similar conditions have historically resulted in failure, and so reveals the conditions under which failure is most likely to occur.

Finally, the sensitivity of the algorithm's output to such factors as the input values, the underlying assumptions, and potential for user bias must be examined. Should a small change in an input value or in the algorithm itself result in a dramatic fluctuation in the output value, further refinement and testing of the algorithm may be required. At the same time, the inherent uncertainty associated with landfills may result in a significant performance variation within a set of essentially identical sites. The algorithm, therefore, may be so inherently insensitive as to be unable to distinguish among somewhat similar sites.

The implications of the results must be examined by the user to ensure response to a predicted performance is reasonable. For example, a landfill predicted by the model to have a high probability of failure may in actuality remain intact. Thus, implementation of the methodology may consist of increased monitoring, programming for remediation funding, and/or elevation of the site's remediation priority. But the model's output alone is insufficient to warrant an emergency response.

Evaluation of Landfill Performance

The performance of a vessel or a containment system such as a landfill is simply its ability to hold its contents within its walls without leaking or spilling. More precisely, a landfill's long-term performance may be characterized by the detection of waste constituents which have been released into the environment beyond its perimeter. Landfill Status is the variable used in this analysis to measure the apparent relative performance of the landfills under study.

Landfill Status was interpreted from the IRPIMS data, primarily through an analysis of available sampling results, cross-referenced to the site for which the monitoring location was established, the contaminant's MCL, and the media involved. In cases where sampling results were not available, the GSI table CLSCODE field provided insight to a landfill site's status. For example, CLSCODEs "SC01" and "SC02" indicate that the site has been studied and was determined during IRP Phase 1 or Phase 2, respectively, to satisfactorily contain any substances of concern. No further investigation or remedial action is anticipated at such sites.

In general terms, a landfill has failed when it has permitted a hazardous constituent of contained wastes to escape in a concentration which exceeds the permissible level. Lower concentrations may be cause for concern, but it may not necessarily lead to an eventual need for site remediation. Since many closed landfills were already decades old by the time monitoring began, detection of a low concentration of a regulated contaminant may indicate the end or the middle of many years of slow, steady release, rather than the early phases of a growing problem. Thus, the two Landfill Status categories and their respective subcategories are:

Viable: Intact. Evidence of study, with determination that contaminant migration has not occurred or remains below detection limits.

Leaking. Evidence of contaminant migration, but concentration has remained below actionable levels (see Appendix A).

Failing: Metals. Evidence of heavy metal migration at a concentration in excess of its federal MCL in the affected media.

Metals +.[88] As above, plus pesticide, organic and/or radioactive compounds exceeding standard or human health benchmarks.

The following statistical analysis was conducted with consideration of both broad--"Viable" *vs.* "Failing"--categories and their subcategories, in recognition of the inherently discrete and subjective nature of their definitions, and the experimental bias those definitions might otherwise have introduced. Performance was evaluated against essentially the

[88] No site was identified as having failed due to exclusively non-metal contaminants. This may be due to the sequencing of tests, beginning with metals and moving on to other contaminants only after a significant metals concentration is detected. Complex organics and other compounds are also subject to degradation over time; thus their concentrations may be somewhat reduced in the relatively old landfills that are the primary focus of this study.

same parameters employed in the myriad landfill risk models which precede this study, plus two measures of aging effects. Many of the 31 parameters are external to the landfill systems themselves (lithology, climate, *etc.*), while others are typically perceived as defining internal aspects of the tested distribution of landfill sites.

Definition of Analytical Parameters

The parameters observed in this study are described in generally the same order as they were addressed in Chapter 2, Table 11:

1) Annual Precipitation[89,90,91] (inches). A universally applied parameter in deterministic water-balance models and also used in many of the relative and stochastic risk models. Precipitation is a primary factor, along with surface drainage and countered by evapotranspiration, in the influent water loading on a landfill, as well as in the recharge of the underlying aquifer.

2) Maximum [24-Hour] Rainfall Event[92] (inches). Also widely applied in water-balance models, the maximum short-term precipitation event relates to the peak influent loading on a site and may correspond to cyclical fluctuation of the water table.

[89] USAF Air Weather Service. International Station Meteorological Climate Summary. Version 2.0. CD-ROM. Washington: USAF, 1992.

[90] Hydrosphere, Inc. CLIMATEDATA. "Summary of the Day." CD-ROM. Washington: NOAA, 1990.

[91] Earth Technology Corporation, Appendix B.

[92] USAF Air Weather Service, *loc. cit.*

3) Annual Potential Evaporation[93] (inches). A function of solar radiation, wind and temperature. The potential for evaporation exceeds total annual precipitation in arid and many semi-arid locales, minimizing percolation of water into the subsurface, except during and immediately following major precipitation events.

4) Average Potential Infiltration[94] (inches). A method of accounting for the opposing phenomena of precipitation and evaporation, infiltration is a measure of the vertical percolation of water through the subsurface.

5) Daily Solar Radiation[95] (Langleys). The average global solar radiation on a horizontal surface at a site is commonly applied in water-balance models in determining the average evaporation rate, which is a mitigating factor in the net loading of influent precipitation and drainage.

6, 7) Maximum and Minimum Daily-Mean Temperatures[96] (°F). The 24-hour-mean temperature extremes at a given location approximate the full range of temperatures imposed on the site. Wide temperature swings may contribute to failure through expansion/contraction or freeze/thaw cycling of a landfill's cap and cover barrier soils.

8, 9) Maximum and Minimum Monthly-Mean Temperatures[97] (°F). Less broad in range than daily-mean temperatures, these intermediate-

[93] Earth Technology Corporation, *loc. cit.*

[94] A. A. Fungaroli. Pollution of Subsurface Water by Sanitary Landfills, Volume 1. SW-12rg. Washington: EPA, 1971, pp 124-25.

[95] Solar Energy Research Institute. Insolation Data Manual. SERI/SP-755-789. Golden, CO: SERI, 1980, pp 2-249.

[96] USAF Air Weather Service, *loc. cit.*, and Hydrosphere, Inc., *loc. cit.*

[97] *ibid.*

term values may be more representative of the cyclical influences on the waste and soil matrices deeper in the subsurface, where unobservable contaminant release pathways are most likely to occur.

10, 11) Maximum and Minimum Annual-Mean Temperatures[98] (°F). The longest-term, narrowest range of temperature values is related to average evaporation at a site (which mitigates the impact of precipitation loading), as well as the near-constant subsurface temperatures of soil and ground water (which may affect the mobility of contaminants).

12, 13) Latitude and Longitude[99] (degrees). Clearly not parameters of landfill failure, as such, but a site's map coordinates may be useful in identifying trends due to general geological or climatological variations across the Continent. These coordinates were also used to assist in the specification of parameter values from various maps, as noted.

14) Normalized Difference Vegetation Index (NDVI)[100] (dimensionless). NDVI is a depiction and characterization of the "quantity and vigor of live vegetation," in eleven gradations from thin/weak (<.07) to dense/ vigorous (≥.60) which represent the full range of vegetation types found in climatic conditions from deserts and tundra to forests and crops. Vegetation type and density affect the average rate of soil erosion, water percolation and runoff, as well as the propensity for biointrusion (roots and burrowing animals) through the landfill cap.

[98] *ibid.*

[99] *ibid.*

[100] J. C. Eidenshink. The North American Vegetation Map. Washington: USGS, 1992, p 1.

15) Mean Annual Wind Speed [averaged through the afternoon mixing layer][101] (m/sec). Associated in relative risk models with both air pollution and surface erosion, mean wind speed may be correlated with contamination of surface soils and/or ground and surface water around a landfill site. Contaminant migration through the air and surface erosion due to winds are likely to be more pronounced at sites where vegetation is sparse.

16) Average Annual Runoff[102] (inches). A function of the combined effects of precipitation, vegetation, and surface soil type and texture. Runoff has been related to the rate of surface soil erosion through the USDA universal soil loss equation (USLE).[103] Surface erosion is, in turn, associated in many existing environmental models with the release and migration of contaminants.

17) Seismic Risk Zone.[104] A standard parameter in the building design and construction industry, four zones characterize the relative earthquake intensity and resultant structural damage experienced throughout the United States. The four Seismic Risk Zones are defined as: (0) No Damage; (1) Minor Damage [intensity V to VI on the 1931 Modified Mercalli (M.M.) scale]; (2) Moderate Damage [M.M. VII]; and (3) Major Damage [M.M. VIII].

[101] Earth Technology Corporation, p 53.

[102] DPRA, Inc., Sections 3.2.1.3 and 4.1.1.

[103] U.S. EPA. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867. Washington: GPO, 1982, p 37.

[104] S. T. Algermissen. "Seismic Risk Studies of the United States." Proceedings of the Fourth World Conference on Earthquake Engineering. Santiago, Chile (1969): pp 14-27.

18) Seismic Impact Zone[105] (percent probability). An alternative method of predicting seismic effects, adopted by the U.S. EPA for the siting and design of RCRA Subtitle D landfills. Seismic Impact Zones are defined according to the probability that an earthquake will yield a maximum horizontal acceleration in lithified rock in excess of 0.1 g (or 0.1 times the force of Earth's gravity) within a 250-year period.

19) Elevation [above mean sea level][106] (feet). Site elevation is somewhat correlated with the average depth to ground water, and is inversely related to mean atmospheric pressure. Therefore, a site's elevation may indirectly indicate either the probability of landfilled waste components to leach into the underlying aquifer or their propensity to volatilize and escape into the air, reducing their concentration as aqueous contaminants.

20) Most Resistive Soil Media [between fill and aquifer].[107] An approximate quantitative assessment of the hydraulic conductivity of the barrier soil in the vadose zone below a landfill, roughly equated to its "liner" quality. Thickness of the barrier layer diminishes in importance as its resistivity increases. Table 15 outlines the relationships between soil types, hydrologic groups, and approximate hydraulic conductivities. Hydraulic conductivity, a function of both the soil media and the fluid, may be directly correlated with intrinsic permeability, a property of the media only, assuming the fluid is essentially typical of ground water.

[105] U.S. EPA. Seminar Publication: Design, Operation, and Closure of Municipal Solid Waste Landfills. EPA/625/R-94/008. Washington: GPO, 1994, pp 7-11.

[106] *ibid.*

[107] IRPIMS data, interpreted in accordance with the information in Table 15.

Freeze and Cherry[108] note that conversion of hydraulic conductivity (cm/sec) to permeability (cm^2) can be accomplished by multiplying by a factor of 1.02×10^{-5}. That is, a sand media through which natural water passes, with measured hydraulic conductivity of 1.0 cm/sec, is expected to have a permeability of approximately 1.02×10^{-5} cm^2.

Table 15. Characterization of Surface and Subsurface Soils.

Physical Description	ASTM Soil Classification[109]	Hydrologic Group[110]	Hydraulic Conductivity (**K**, cm/sec)[111,112]
Gravel	GP, GW	1.0	10^{2} - 10^{-1}
Sand	SP, SW	2.0	10^{0} - 10^{-3}
Silty Mixtures	SM, GM, GC, ML	3.0	10^{-1} - 10^{-5}
Silt, Loess	MH, OL	4.0	10^{-3} - 10^{-7}
Glacial Till, Clay	OH, CH, CL	5.0	10^{-6} - 10^{-10}

108 R. A. Freeze, and J. A. Cherry. Groundwater. Englewood Cliffs NJ: Prentice Hall, 1979, p 29.

109 As recorded in the IRPIMS database. The ASTM Soil Classification System is labeled the "Unified Soil Classification System" (USCS) in some texts.

110 Hazardous Materials Testing Center, p B-2.

111 Freeze, *loc. cit.*

112 LeGrand, p 30.

21) Depth to Aquifer[113] (feet). An obvious parameter in assessing environmental vulnerability. The vertical travel distance of contaminants may offer an indirect measure of a landfill's containment and buffering capacities (*i.e.*, the thickness of the bottom barrier), or it may represent a hindrance to detection of a breach, since most monitoring is conducted through well water sampling around the site's perimeter.

22) Hydraulic Conductivity of the Aquifer[114] (cm/sec). A factor in the rate and degree of potential damage resulting from a failure, rather than a parameter of the failure itself. The aquifer's hydraulic conductivity may be related, however, to the likelihood that contaminant seepage through a landfill breach will be detected at the monitoring well.

23) Prevalent Aquifer Media.[115] At sites where quantitative data (such as the hydraulic conductivity) are not available, an approximation grounded in the conversions shown in Table 15 or a simple, qualitative description of the aquifer may provide similar insight.

24) Modified Heath Ground Water Region.[116] From the DRASTIC model, a classification of the geology, geomorphology, and hydrogeology of a site. The 13 Heath Ground Water Regions may be subdivided into "Hydrogeologic Settings" to more precisely describe local features, but available data are insufficient to adequately assign a Hydrogeologic Setting to each site as a part of this effort.

[113] IRPIMS data.

[114] IRPIMS data.

[115] IRPIMS data, interpreted in accordance with information in Table 15.

[116] Aller, p 13-16.

25) Landfill Surface Area[117] (acres). Commonly applied as a variable in water-balance and other environmental risk models, the surface area of the waste containment system may affect both the likelihood and the magnitude of a contaminant release.

26) Type of Waste in Landfill.[118] A qualitative assessment of the nature of the waste materials expected in the landfill. In this analysis, waste types were categorized in accordance with industry terminology and in order of increasing hazardous constituents concentration: Construction and Demolition Debris (CDD); Municipal Solid Waste (MSW) as defined and regulated by RCRA Subtitle D, including industrial and commercial non-hazardous wastes, as well as the contents of older landfills described as "General" where no known hazardous materials were dumped; and Hazardous Waste (HW), including RCRA Subtitle C, low-level radioactive, and munitions materials.

27) Period of Landfill Operations[119] (years). May be representative of various influences on performance related to an extended operational period where the site and the deposited wastes are exposed without a cap. The degree to which the site was disturbed during those operations, the total volume of disposed wastes, and the likelihood that wastes were spilled or improperly placed may also be proportional to the length of time the site was open to operations.

[117] IRPIMS data, manually extracted from GSI table SITEDESC field.

[118] IRPIMS data, manually extracted from GSI table SITEDESC and SITENAME fields.

[119] IRPIMS data, manually extracted from GSI table SITEDESC field.

28) Age of Landfilled Waste[120] (years). The stage of degradation of the disposed wastes may affect the propensity of waste constituents to leach out of the waste matrix and into the surrounding soils and ground water. Older landfills may also have been operated with little regard for the potential hazards they pose, and so may be more closely correlated with contaminant migration.

29, 30) HARM and HRS Scores.[121] Intended as measures of the relative environmental hazard posed by a site, HARM and HRS scores should strongly correlate to the probability of contaminant release at a site, as well as the relative vulnerability of the environmental setting.

31) NPL Group.[122] The federal sites included on the NPL are considered to be among those most in need of remediation. A site's presence on the list suggests a high probability and magnitude of contaminant release, while its position (by Group Number) on the NPL should be suggestive of its relative severity among listed sites.

Parameters 1 through 31, above, or some variation on the same concepts, have been applied in one or more of the existing risk models discussed in Chapter 2. The permutations used in various models are clearly exemplified by Annual Precipitation: HELP and the Subtitle D Risk Model rely on synthesized annual precipitation (which varies about the annual mean value); the PCLTF Model uses a monthly probability distribution; and DRASTIC employs precipitation and evapotranspiration

[120] IRPIMS data, manually extracted from GSI table SITEDESC field, measured against the current baseline year of 1995.

[121] IRPIMS data.

[122] U.S. EPA, 1993b, pp 49-51.

data in whatever form is available to calculate an annual "net recharge" value for a given location.

In every prior application, however, each of these parameters was evaluated on the basis of either an idealized, theoretical formula or a relative scale founded primarily in opinion. In this study, the long-term performance of over 500 landfills is evaluated, and that performance is correlated with each parameter. The actual individual and cumulative effects of these parameters are then empirically determined, enhancing performance predictions for other appropriately specified landfills.

Additional parameters used in some of these models either are not applicable to the purpose of this study or do not apply to the specific landfill sites here under study. For instance, ground-water velocity and distance to the nearest drinking water source may be meaningful in a discussion of receptors of a contaminant after its release, but they are irrelevant to the mechanisms leading to that release. On the other hand, effectiveness of leachate and gas collection systems would be relevant to this study except that they are not present at the landfills discussed herein. Also of importance to public exposure, access restrictions are approximately equivalent among all landfills on military installations.

CHAPTER 4

FINDINGS AND DISCUSSION

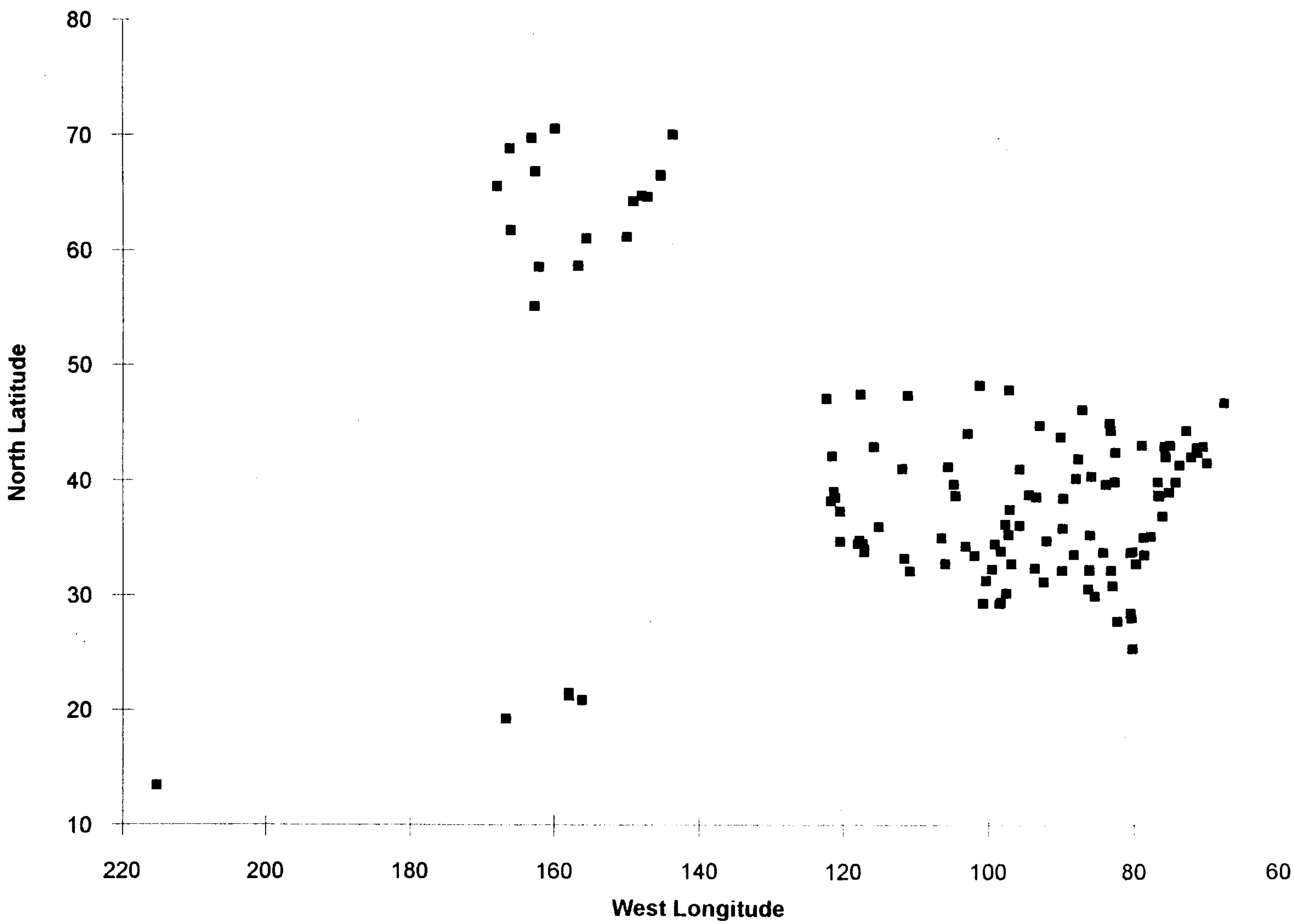
All observations of landfill performance employed in this study may be assumed to be random and independent, and so are subject to common statistical analysis methods. The relevance of normality varies with the test performed, but many tests are quite robust with respect to non-normality.[123] No sequential observations, with respect to either location or time, are included. No attempt was made to serialize or group landfills, nor are the observations concentrated in any one region of the country. As is apparent in the plot of sites provided at Figure 1, the 48 contiguous United States, Alaska, Hawaii, and the Pacific Islands are all represented in the database. (Because IRPIMS data are "For Official Use Only," general locations are provided in lieu of specific coordinates.)

Reference Distributions of Parameter Values

Valuations obtained from the 545 landfills in the IRPIMS database constitute the full range of expected values for each of the observed parameters. Consequently, 31 separate external reference distributions are possible--one for each variable--and a mean and confidence interval

[123] For a complete discussion of the requirements of randomness and normality in statistical analyses, see Paul Mac Berthouex, and Linfield C. Brown. Statistics for Environmental Engineers. Boca Raton, FL: Lewis, 1994, pp 13-49.

Figure 1. Plot of IRPIMS Landfill Sites.



may be obtained for each reference distribution. The values of individual or groups of observations may then be compared to the reference set, rather than to an idealized normal distribution, in order to determine whether an observation is exceptional.[124] The 31 reference distributions and their summary statistics are listed in Table 16. Those parameters for which mean values were correlated with performance are presented in Table 17. At this point, any potential cumulative and confounding effects were not identified, but had to be isolated through further testing.

Comparing mean and standard deviation values for each reference distribution with the means of the subset of landfills whose status has been defined revealed that every subset is statistically representative of the entire population. Further, the relatively broad standard deviations for both the reference distribution and the defined subset, and the fact that no one mean value among the "viable" or "failing" cases was found to be exceptional, demonstrate that no single parameter is so significant as to unilaterally foretell the viability (or failure) of a landfill.

Certain trends appear to have surfaced among the mean values in Table 17. Mean and maximum event values for precipitation appear to correlate directly with long-term landfill failure in a general way, as does a reduction in the solar radiation which aids in the evaporation of that precipitation. All of these findings suggest a trend in the association of these parameters in keeping with intuition. And yet, the values for wind speed, runoff, evaporation, and potential infiltration all run counter to intuition.

[124] *ibid.*, pp 49-55.

Table 16. External Reference Distributions for Primary Parameters.

Parameter Label	Units of Measure	Mean (η)	Standard Deviation (σ)		Number of Observations
1 Precipitation	in/yr	33.34	17.70		539
2 Max. Rainfall	in/da	5.68	2.96		419
3 Evaporation	in/yr	45.96	13.15		461
4 Infiltration	in/yr	2.19	13.57		467
5 Solar Radiation	Langley	369.7	84.6		545
6 Max. Day Temp	°F	103.52	8.14		539
7 Min. Day Temp	°F	-6.31	24.29		539
8 Max. Mo. Temp	°F	85.80	10.79		539
9 Min. Mo. Temp	°F	26.70	18.99		539
10 Max. Yr. Temp	°F	65.88	13.98		539
11 Min. Yr. Temp	°F	46.60	13.37		539
12 North Latitude	degree	38.8	10.3		539
13 West Longitude	degree	104.7	27.6		539
14 Vegetation Index	none	0.269	0.115		528
15 Wind Speed	m/sec	6.57	1.03		468
16 Runoff	in/yr	9.27	8.02		468
18 Seismic Impact	% prob.	15.79	19.48		523
19 Site Elevation	ft	1044	1461		538
21 Depth to Aquifer	ft	39.47	87.54		179
22 Conductivity	cm/sec	0.011	0.020		48
25 Surface Area	acre	20.7	65.6		99
27 LF Operations	yr	10.6	8.7		248
28 Fill Age (@ 1995)	yr	39.1	11.3		277
29 HARM Score	none	55.47	11.70		413
30 HRS Score	none	42.7	6.0		17
	Mode	25th	50th	75th	← Percentiles*
17 Seismic Risk	1	1	1	2	470
20 Soil Media	3.0	3.0	3.0	4.0	44
23 Aquifer Media	3.0	2.0	3.0	3.0	18
24 Heath GW Region	10	--	--	--	532
26 Waste Type	MSW	MSW	MSW	MSW	339
31 NPL Group	2	5	11	17	154

* These parameters consist of nominal or ordinal values, for which units of measure, mean, and confidence interval are not meaningful. For the ordinal values, the mode and quartiles (with the median as the 50th percentile) are provided. Nominal values are characterized by the mode only. The quartiles and mode, as given, are indicators of the population, but these parameters are evaluated only by nonparametric tests and/or scoring functions.

Table 17. Correlation of Parameter Means with Landfill Performance.

	Parameter Label	"Viable" Mean Value	Defined Cases*	"Failing" Mean Value	Number of Cases
1	Precipitation	35.32	35.83	36.62	277
2	Max. Rainfall	5.81	6.09	6.51	220
3	Evaporation	45.93	44.56	42.26	243
4	Infiltration	3.71	3.16	2.26	250
5	Solar Radiation	379.2	377.6	375.2	278
6	Max. Day Temp	104.62	103.61	102.06	277
7	Min. Day Temp	-6.44	-3.41	1.19	277
8	Max. Mo. Temp	87.92	86.34	83.96	277
9	Min. Mo. Temp	28.43	29.86	32.03	277
10	Max. Yr. Temp	68.16	67.81	67.28	277
11	Min. Yr. Temp	48.37	48.73	49.27	277
12	North Latitude	37.54	37.08	36.38	277
13	West Longitude	99.04	101.07	104.16	277
14	Vegetation Index	0.280	0.277	0.272	267
15	Wind Speed	6.64	6.62	6.58	250
16	Runoff	10.13	9.89	9.48	250
18	Seismic Impact	12.61	15.84	20.88	271
19	Site Elevation	1205.3	1051.3	817.5	277
21	Depth to Aquifer	49.61	38.90	32.52	166
22	Conductivity	0.014	0.011	0.010	48
25	Surface Area	29.11	25.91	18.91	67
27	LF Operations	11.04	11.57	12.20	152
28	Fill Age (@ 1995)	40.89	40.06	39.16	172
29	HARM Score	50.65	53.94	59.41	240
30	HRS Score	38.6	41.6	44.6	12

* Defined cases are those landfill sites for which a "viable" or "failing" status has been determined. Some sites in the IRPIMS database include insufficient information on monitoring, test results, or other analyses from which this determination can be made.

All three horizons of temperature extremes also suggest trends counter to intuition, in that the ranges are consistently broader for the "viable" landfills. On the basis of the reference distribution analysis, thermal expansion/contraction of the soil matrix in a landfill's perimeter does not appear to be an overriding concern.

A site's elevation, density of vegetation, and depth to ground water all appear to support the hypothesis that long-term viability is consistent with expectations. The size of a landfill and the length of time during which wastes were received or contained do not appear to substantially affect long-term performance. The aquifer's hydraulic conductivity is not seen to impede the detection of waste migration at monitoring wells.

The ratio-number parameter most strongly correlated with long-term performance is the Seismic Impact Zone, and yet the difference in means is not significant at one standard deviation. The HARM and HRS scores also correlate well with performance, suggesting both models may generally predict the relative risk of contaminant release from these sites.

Examination of Failure by Analysis of Variance

The one-way Analysis of Variance (ANOVA) test is one method of determining whether the mean values for landfill status conditions could have been obtained from different populations with the same true mean.[125] Seismic Impact Zone was found to be the parameter most likely to reveal

[125] See George E. P. Box, William G. Hunter, and J. Stuart Hunter. Statistics for Experimenters. New York: Wiley, 1978, pp 165-75, for a complete description of the ANOVA methodology.

a significant result in an ANOVA test, just as it did in the reference distribution approach. And the variance in the means between "viable" and "failing" conditions is indeed statistically significant, even at a 99 percent confidence level ($F_{99\%}$), as demonstrated in Table 18.

Table 18. ANOVA Table: Seismic Impact Zones *vs.* Landfill Failure.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio
Between Conditions	4415	1	4415	10.54
Within Conditions	112646	269	418.8	$F_{99\%}$=6.85

A similar result was obtained when the subcategories of status ("intact," *etc.*) were applied, rather than the broader categories, as shown in Table 19.

Table 19. ANOVA Table: Seismic Impact Zones *vs.* Landfill Leakage.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio
Between Conditions	5009	3	1670	3.99
Within Conditions	112053	267	419.7	$F_{99\%}$=3.95

Of the remaining ratio- and interval-number parameters, few other statistically significant effects (at the 99 or 95 percent confidence level) were ascertained via the ANOVA procedure, given the complex set of variables present in the data. Furthermore, ANOVA does not explain the meaning of the differences in means; it merely identifies the presence of those differences within the data set. The interaction among parameters, therefore, warrants further investigation. Parameters for which ANOVA revealed a significant variance among the mean values for landfill status conditions are presented in Table 20. Significant results imply only that landfill performance was found to vary with the parameter in question despite, or conceivably owing to, the interaction of the other variables present in the data.

The degree to which the ANOVA detects these differences depends on both the confidence level specified for the result and the definition of the test conditions. Table 20 demonstrates that the broad categorization of landfill status ("viable" *vs.* "failing") yields a less definitive analysis than does the subdivision of landfill status into its four subcategories. Seven parameters were identified through consideration of "intact" and "leaking" landfills independently, but only three parameters were found to be significant in the broader analysis. A distinction among "viable" landfills was deemed appropriate in all remaining tests, therefore, as "leaking" facilities may be more closely associated with "failing" landfills than with the "viable-and-intact."

ANOVA testing of the HARM and HRS relative environmental-risk model scores available in the IRPIMS database revealed very strong correlation between HARM scores and performance, but the correlation for HRS scores is not statistically significant. Despite the obvious trend in mean values seen in Table 17, there are apparently too few HRS records with too many inconsistencies between site scores and observed failures. At a 95 percent confidence level, HRS scores are not adequately correlated with long-term performance.

Table 20. Other Significant ANOVA Test Results (95 percent confidence).

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio
Precipitation (by subcategories only*):				
Between Conditions	3385	3	1128	3.37
Within Conditions	91456	273	335.0	$F_{crit}<2.68$
Evaporation (by subcategories):				
Between Conditions	4381	3	1460	10.61
Within Conditions	32912	239	137.7	$F_{crit}<2.68$
Evaporation ("viable"/"failing" conditions):				
Between Conditions	766.9	1	766.9	5.06
Within Conditions	36527	241	151.6	$F_{crit}<3.92$
Solar Radiation (by subcategories only*):				
Between Conditions	53270	3	17757	3.29
Within Conditions	1477205	274	5391	$F_{crit}<2.68$
Vegetation Index (by subcategories only*):				
Between Conditions	0.2289	3	0.0763	5.96
Within Conditions	3.3669	263	0.0128	$F_{crit}<2.68$
Wind Speed (by subcategories only*):				
Between Conditions	10.41	3	3.470	3.58
Within Conditions	238.73	246	0.970	$F_{crit}<2.68$
Elevation (by subcategories):				
Between Conditions	2.545×10^7	3	8.483×10^6	3.45
Within Conditions	6.708×10^8	273	2.457×10^6	$F_{crit}<2.68$
Elevation ("viable"/"failing" conditions):				
Between Conditions	9.971×10^6	1	9.971×10^6	4.00
Within Conditions	6.862×10^8	275	2.495×10^6	$F_{crit}<3.92$
HARM Score (by subcategories):				
Between Conditions	12106	3	4035	42.42
Within Conditions	22452	236	95	$F_{crit}<2.68$
HARM Score ("viable"/"failing" conditions):				
Between Conditions	4314	1	4314	33.95
Within Conditions	30244	238	127.1	$F_{crit}<3.92$

* Where ANOVA results are given for subcategories ("intact," *etc.*) only, the results of the broader conditions were found to be not statistically significant.

Non-Parametric Testing of Ordinal- and Nominal-Value Parameters

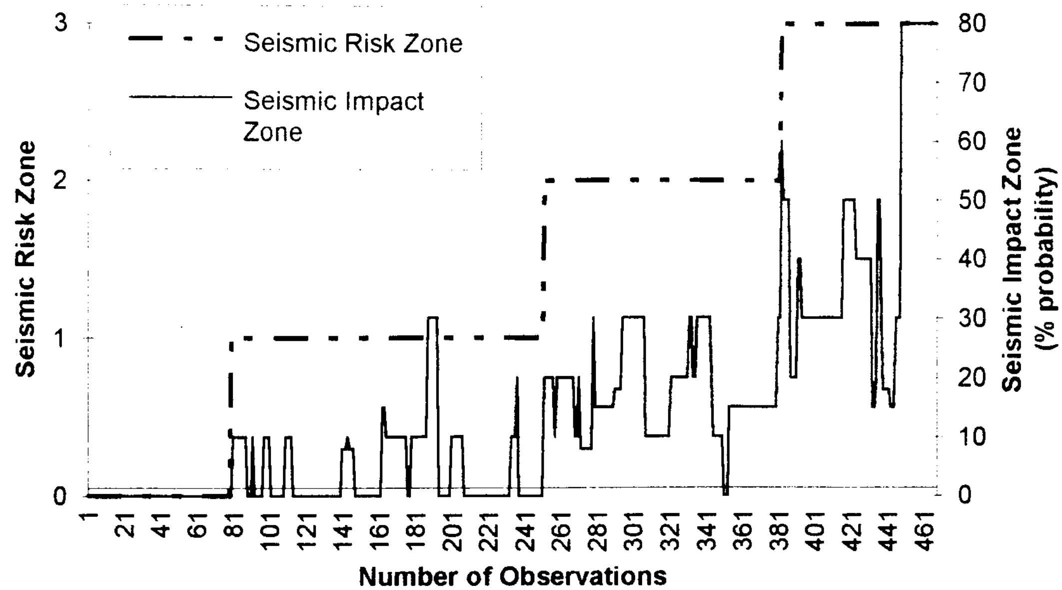
Measures such as mean and standard deviation are not applicable to an ordinal scale, since there is no specific interval between numbers. However, valuations on an ordinal scale are ranked in a relative way, and so may be analyzed statistically via non-parametric tests. An even more limited number of tests are available to nominal-scale distributions.

Of the landfill performance parameters assessed in this study, four are clearly ordinal-scale distributions: Seismic Risk Zone, Soil Media, Aquifer Media, and NPL Group. Waste Type may also be viewed as an ordinal-scale distribution, where CDD, MSW, and HW approximately represent ascending concentrations of hazardous constituents.

The Soil Media and Aquifer Media parameters could be considered grouped ratio-number data, in that the Hydrologic Groups were derived from hydraulic conductivities typical of soils within each Group. In Table 15, the average hydraulic conductivity (in cm/sec) was seen to vary by a factor of approximately 100 between Hydrologic Groups. In each case, numbers are merely an indication of order--first, second, *etc.*--but not magnitude. The Heath Ground Water Regions are nominal labels only; no ranking or magnitude is implied.

Comparison of Seismic Risk and Seismic Impact (Figure 2) revealed that the ordinal Risk scale conforms generally with the Impact scale, but lacks continuity between rankings. Non-parametric tests such as chi-square ($\mathbf{X}^2$) contingency tables may be applied in the analysis of ordinal data, as well as grouped data from interval or ratio scales. $\mathbf{X}^2$ also avoids assumption of normalcy within the tested distribution.

Figure 2. Plot of Seismic Risk Zones *vs.* Seismic Impact Zones.



A X^2 contingency table of Seismic Risk Zones *vs.* Landfill Status, as shown in Table 21, clearly illustrates the significance of seismic activity to the long-term performance of landfills. The hypothesized relationship is supported even at a 99.9 percent confidence level.

Table 21. X^2 Contingency Table: Seismic Risk Zones *vs.* Landfill Status.

Status	Zone 0	Zone 1	Zone 2	Zone 3	Total
Intact	0.11 20.51 22	0.99 35.10 41	0.12 23.67 22	1.66 19.72 14	99
Leaking	0.58 11.60 9	0.00 19.86 20	5.54 13.39 22	3.40 11.16 5	56
Failed	0.06 19.89 21	1.07 34.04 28	2.10 22.95 16	7.38 19.12 31	96
Total	52	89	60	50	251

X^2 = 23.0; 6 degrees of freedom (ν) X^2_{crit} = 22.5 at α = 0.001

The value in the upper right corner of each center block is the expected value for that combination of Zone and Status. For example, of the 99 "intact" landfills, an even distribution among zones would have 20.51 [or (99 x 52)/251] in Zone 0, as opposed to 22 actually counted. A $\mathbf{X}^2$ value for each combination is given in the upper left corner. The $\mathbf{X}^2$ value represents the squared difference between observed and expected counts divided by the expected [$(22 - 20.51)^2/20.51 = 0.11$]. Individual $\mathbf{X}^2$ contributions are then summed to obtain the overall $\mathbf{X}^2$ statistic.

A cursory assessment of landfill performance as a function of Waste Type (CDD, MSW, or HW) led to the supposition that a strong correlation exists. The bar charts at Figures 3 and 4 indicate a clear trend in the relationship between the perceived hazardous component concentrations in the various Waste Types and the probability that one or more contaminants will migrate out of the fill.

Applying the $\mathbf{X}^2$ contingency table procedure, however, muted this apparent relationship somewhat. The pattern remains clear, but Table 22 reveals it to be statistically insignificant at 95 percent confidence.

Table 22. $\mathbf{X}^2$ Contingency Table: Waste Types *vs.* Landfill Status.

Status	CDD	MSW	HW	Total
Intact	4.12 3.96 8	0.14 54.80 52	0.17 9.24 8	68
Leaking	0.35 3.03 2	0.23 41.90 45	0.61 7.07 5	52
Failed	1.81 5.01 2	0.00 69.30 69	0.94 11.69 15	86
Total	12	166	28	206

$\mathbf{X}^2 = 8.37$; 4 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 9.49$ at $\alpha = 0.05$

Figure 3. Landfill Failures by Waste Type.

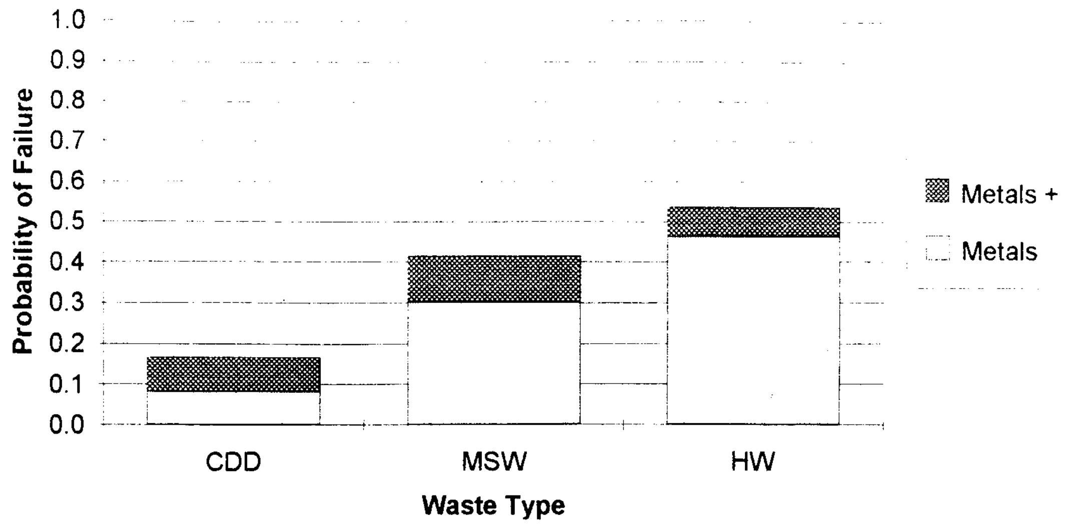
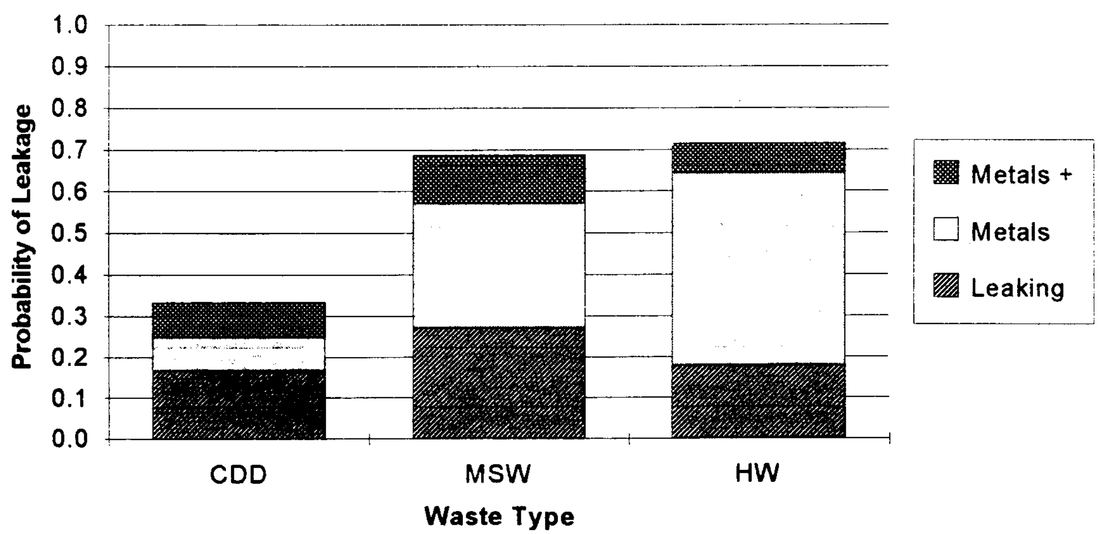


Figure 4. Landfill Failures and Leaks by Waste Type.



Soil Media, Aquifer Media, and NPL Group parameters also may be analyzed via $\mathbf{X}^2$ contingency tables. The Heath Ground Water Regions, while on a nominal scale rather than ordinal, may be similarly assessed insofar as regional differences may be revealed.

The $\mathbf{X}^2$ contingency procedure in Table 23 reflects an inverse relationship between long-term viability and the presence of the naturally resistive soils at a site, contrary to conventional wisdom. This is perhaps due to interaction with other parameters (the small population of sites for which both Soil Media and Landfill Status are known is heavily weighted toward areas of seismic activity), or it may result from heterogeneity in the subsurface soil matrix (such that the resistive soils act as a channel rather than a barrier layer). This result is also in keeping with several previous studies, discussed in Chapter 2, which suggest that the soil matrix is relevant to contaminant migration only to the extent that a large volume of infiltrating water is also present. In any event, no statistical inference as to the performance contribution of subsurface soils is possible from the limited site information in the IRPIMS database.

Table 23. $\mathbf{X}^2$ Contingency Table: Soil Media *vs.* Landfill Status.

Status	Sand (2.0)	Silty Sand (3.0)	Silt, Loess (4.0)	Glacial Till, Clay (5.0)	Total
Intact	2.14 2.63 5	0.57 7.00 9	3.50 3.50 0	0.88 0.88 0	14
Leaking	1.31 1.31 0	1.79 3.50 1	6.04 1.75 5	0.72 0.44 1	7
Failed	0.55 2.06 1	0.05 5.50 6	0.02 2.75 3	0.14 0.69 1	11
Total	6	16	8	2	32

$\mathbf{X}^2 = 17.7$; 6 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 16.8$ at $\alpha = 0.01$

The Aquifer Media is not expected to significantly correlate with the performance of the landfill itself. On the contrary, since many of the failed and leaking facilities were detected by monitoring wells, such a direct relationship could jeopardize the other results of this study.

As ground water passes below a compromised landfill site and is contaminated, a plume develops. Contaminants in the plume are then observed in water samples taken from the monitoring wells. A resistive aquifer matrix increases the time of travel (TOT), encourages precipitation and sorption of metals into the soil, and promotes the degradation of the volatile organic, pesticide, and radioactive constituents. It is conceivable, then, that some contaminants that reach the aquifer are degraded or deposited before they are detected in the monitoring well network.

Table 24 reveals, however, that no distinction can be made among Aquifer Media. The null conclusion holds even at a confidence level of less than 25 percent. Thus, water samples drawn from monitoring wells are equally likely to detect the presence of contaminants regardless of the aquifer matrix in which they are installed.

Table 24. $\mathbf{X}^2$ Contingency Table: Aquifer Media *vs.* Landfill Status.

Status	Gravel (1.0)	Sand (2.0)	Silty Sand (3.0)	Total
Intact	0.27 0.27 0	0.40 0.40 0	0.34 1.33 2	2
Leaking	0.17 0.67 1	0.00 1.00 1	0.03 3.33 3	5
Failed	0.00 1.07 1	0.10 1.60 2	0.02 5.33 5	8
Total	2	3	10	15

$\mathbf{X}^2 = 1.33$; 4 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 1.92$ at $\alpha = 0.75$

The NPL Group parameter may be viewed from two perspectives; it represents the relative ranking of all federal sites nationwide believed to be in greatest need of remediation under CERCLA, but it may also reflect the vulnerability of a site to the mechanisms of failure addressed in this study. Priority ranking of sites comprises social, economic, political and regulatory, as well as environmental and technical, considerations. As a result, relative placement on the list, and to a lesser degree placement on the list at all, might have little to do with the actual hazards posed by a site. Furthermore, the boundaries of an NPL site may encompass several sites of differing status as designated in the IRP.

NPL rankings may, however, correspond to relative risk of failure of any landfill exposed to the same climate, geology, management practices, and wastes. To this end, a site's NPL Group may serve as a predictor of problems in other landfills at the same installation, as shown in Table 25.

Table 25. $\mathbf{X}^2$ Contingency Table: NPL Groups *vs.* Landfill Status.

NPL Group	Intact	Leaking	Failed	Total
2, 4, 5	1.73 6.30 3	5.79 6.07 12	0.80 8.63 6	21
6, 7, 8	4.03 2.70 6	0.98 2.60 1	0.78 3.70 2	9
10, 11, 12	0.17 6.00 5	0.26 5.78 7	0.01 8.22 8	20
13, 15, 16	1.88 3.60 1	0.06 3.47 3	1.91 4.93 8	12
17, 18, 19	0.16 5.10 6	1.72 4.91 2	0.58 6.99 9	17
20, 21, 22	2.21 3.30 6	1.49 3.18 1	0.06 4.52 4	11
Total	27	26	37	90

$\mathbf{X}^2 = 24.6$; 10 degrees of freedom (v) $\qquad$ $\mathbf{X}^2_{crit} = 23.2$ at $\alpha = 0.01$

Table 25 verifies that NPL ranking is, indeed, correlated with the likelihood of leakage, and leakage to the point defined as failure, of the landfills at a listed installation. At a confidence of 99 percent, the higher an installation's placement on the NPL (*i.e.*, the lower the Group number) the more probable landfills at that installation are to leak.

The modified Heath Ground Water Region designations adopted in the DRASTIC methodology characterize general hydrogeology, lithology, and geomorphology throughout the United States. More specific details are presented in the 13 main regions' subcategories, or "hydrogeologic settings." While these more specific characterizations require direct and expert knowledge of each site, the 13 regions are essentially geographic.

Table 26 presents the results of the $\mathbf{X}^2$ contingency procedure for these regions, clearly indicating that some regional differences do exist with regard to long-term performance. Region 6, the Nonglaciated Central Region (a band extending from Montana south to Texas and east to New York), and to a lesser degree Region 2, the Alluvial Basins (which make most of Nevada and California and the non-mountainous portions of several other Western states), are extraordinarily resilient to the forces leading to contaminant migration. Region 7, the Glaciated Central Region (from northern Montana to New York, and a section of central New England), is highly susceptible to leakage, but that region's rate of failure (leakage resulting in contamination that exceeds the MCL) is not exceptional, suggesting an uncommon buffering capacity despite generally unfavorable conditions. The Northeast and Superior Uplands of Region 9 are similarly predisposed to moderate leakage rates. Hawaii, Region 12, is far more susceptible to failure than any other region.

Table 26. **X**^{2} Contingency Table: Heath GW Regions *vs.* Landfill Status.

GW Region	Intact	Leaking	Failed	Total
1	0.35 8.29 10	0.05 4.49 4	0.18 8.21 7	21
2	1.04 21.3 26	3.76 11.6 5	0.17 21.1 23	54
3	0.06 0.79 1	0.76 0.43 1	0.78 0.78 0	2
4	0.39 0.39 0	0.21 0.21 0	0.95 0.39 1	1
5*	0 0 0	0 0 0	0 0 0	0
6	3.21 9.48 15	0.67 5.14 7	5.82 9.39 2	24
7	10.76 16.2 3	19.96 8.77 22	0.00 16.0 16	41
8*	0 0 0	0 0 0	0 0 0	0
9	3.31 6.71 2	3.10 3.64 7	0.27 6.65 8	17
10	0.50 21.7 25	5.16 11.8 4	0.94 21.5 26	55
11	0.74 13.8 17	0.30 7.49 6	0.21 13.7 12	35
12	1.97 1.97 0	1.07 1.07 0	4.72 1.96 5	5
13	0.45 6.32 8	0.59 3.42 2	0.01 6.26 6	16
Total	107	58	106	271

X^2 = 72.5; 24* degrees of freedom (v) **X**$^2_{crit}$ = 51.2 at α = 0.001

* **Disregarding Regions 5 and 8, within which no sites of known Landfill Status are identified, yields** ν = 20 **and X**$^2_{crit}$ = 45.3 at α = 0.001.

X^2 Analysis of Parameters by Grouping

In much the same way as Soil Media and Aquifer Media parameter values represent ranges of hydraulic conductivity, a continuous range of values may be grouped, or categorized, for analysis via a $\mathbf{X}^2$ contingency table. Where ANOVA testing of the full range of values for temperatures, infiltration, *etc.*, did not reveal a significant effect on performance, such an effect may be found within segments of the range of parameter values.

Temperature Effects

The rationale varies for the three selected temperature ranges, but the annual, monthly and daily maxima and minima are generally linearly dependent, so the monthly values may be used as surrogates for either the annual or daily distribution in the initial analysis:

$$(T_{max})_{annual} = [1.10(T_{max})_{month}] - 28.7\ °F \qquad R^2 = 0.731$$

$$(T_{max})_{month} = [1.16(T_{max})_{day}] - 34.1\ °F \qquad R^2 = 0.755$$

$$(T_{min})_{annual} = [0.667(T_{min})_{month}] + 28.2\ °F \qquad R^2 = 0.893$$

$$(T_{min})_{month} = [0.730(T_{min})_{day}] + 30.9\ °F \qquad R^2 = 0.895$$

where R^2 is the coefficient of determination; thus, 73.1 to 89.5 percent of the variation is explained by the linear model. (As an interesting aside: the minimum temperature distributions are consistently highly normal, whereas maximum temperature distributions are consistently skewed somewhat toward the higher values, while remaining more peaked than respective minimum-temperature distributions.) Six equal categories of Maximum Monthly Mean Temperature are evaluated with respect to

Landfill Status in Table 27. The effects of equal categories of Minimum Monthly Mean Temperatures are examined in Table 28.

Table 27. X^2 Contingency Table: Maximum Monthly Mean Temperature *vs.* Landfill Status

Temperature Range	Intact	Leaking	Failed	Total
>50 - 60	0.39 0.39 0	0.22 0.22 0	0.92 0.40 **1**	1
>60 - 70	1.44 8.50 5	0.66 4.77 3	3.17 8.74 **14**	22
>70 - 80	0.59 12.7 10	0.10 7.15 **8**	0.28 13.1 15	33
>80 - 90	3.87 46.4 33	2.46 26.0 **34**	0.60 47.7 53	120
>90 - 100	8.16 36.7 **54**	2.11 20.6 14	3.04 37.7 27	95
>100 - 110	3.10 2.32 **5**	0.07 1.30 1	2.38 2.38 0	6
Total	107	60	110	277

$X^2 = 33.6$; 10 degrees of freedom (v) $X^2_{crit} = 29.6$ at $\alpha = 0.001$

Table 28. X^2 Contingency Table: Minimum Monthly Mean Temperature *vs.* Landfill Status

Temperature Range	Intact	Leaking	Failed	Total
>-40 - -20	0.04 2.32 2	1.30 1.30 0	1.10 2.38 **4**	6
>-20 - 0	0.07 0.77 1	0.43 0.43 0	0.05 0.79 **1**	2
>0 - 20	2.38 28.2 20	5.36 15.8 **25**	0.03 29.0 28	73
>20 - 40	3.89 51.8 **66**	0.14 29.0 27	2.80 52.3 41	134
>40 - 60	0.22 20.1 18	2.49 11.3 6	2.66 20.6 **28**	52
>60 - 80	3.86 3.86 0	0.01 2.17 2	4.09 3.97 **8**	10
Total	107	60	110	277

$X^2 = 30.9$; 10 degrees of freedom (v) $X^2_{crit} = 29.6$ at $\alpha = 0.001$

A distinct and significant (exceeding 99.9 percent confidence) trend in the relationship between Maximum Monthly Mean Temperature and landfill performance is apparent in the exceptionally high values shown in the bold figures in Table 26. As maximum temperature increases, so does the long-term prospect of viability. This relationship is asymptotic at both extremes with critical points at around 95 °F and 65 °F.

Improved performance at the highest temperature range suggests a possible interaction with precipitation and/or infiltration, which was explored later. The trend toward leakage and eventual failure at lower temperature ranges is less indicative of interaction among parameters, however, and is more suggestive of the influences of freeze/thaw cycling, as explained by Elsbury, *et al.* (see Chapter 2).

The effect of Minimum Monthly Mean Temperature on performance is somewhat more complex, but generally conforms with the Maximum Monthly Mean Temperature results. As in Table 27, exceptionally high values are in bold in Table 28, illustrating performance degradation as minimum temperatures diminish below about 25 °F. As the minima rise above 40 °F, however, performance again rapidly declines.

An interaction between minimum temperature and precipitation and/or infiltration may again be affecting the results, since the drier areas of the desert Southwest tend toward greater temperature fluctuation than do the wetter climes of Hawaii and South Florida, areas which dominate the >40 °F minimum ranges. So, while the freeze/thaw effects may explain the performance trend at the lower end of the temperature distribution, interaction among parameters is apparent at higher temperatures.

As noted, a linear relationship between temperature extremes of different time horizons. The same conclusions with respect to correlation of temperature with performance may be drawn, therefore, from any of the six temperature distributions. However, the relative strengths of those correlations may provide insight to the nature of the effect. A higher level of confidence in the correlation of performance with annual temperatures than in the same correlation with daily temperatures would suggest that the freeze/thaw effect is a gradual process rather than sudden. Thus, a generally colder climate, rather than a more broadly varying one, would amplify the effect. This analysis cannot be achieved by merely fitting the temperature conversion equations to the Monthly Mean Temperature data, because its purpose is to detect residual error in a linear model. Using the same procedure as in Table 27, Tables 29 and 30 explore differences in performance effects given shorter and longer time horizons of maximum temperature.

Table 29. X^2 Contingency Table: Maximum Daily Mean Temperature *vs.* Landfill Status.

Temperature Range	Intact	Leaking	Failed	Total
>70 - 80	0.39 0.39 0	0.22 0.22 0	0.92 0.40 1	1
>80 - 90	0.66 3.48 5	0.00 1.95 2	0.69 3.57 2	9
>90 - 100	4.86 30.1 18	0.21 16.9 15	6.36 31.0 **45**	78
>100 - 110	0.00 52.9 53	0.37 29.7 **33**	0.21 54.4 51	137
>110 - 120	4.88 20.1 **31**	0.15 11.3 10	4.51 20.6 11	52
Total	107	60	110	277

X^2 = 24.4; 8 degrees of freedom (v) X^2_{crit} = 22.0 at α = 0.005

Table 30. X^2 Contingency Table: Maximum Annual Mean Temperature *vs.* Landfill Status.

Temperature Range	Intact	Leaking	Failed	Total
>30 - 40	0.00 3.09 3	1.73 1.73 0	1.04 3.18 5	8
>40 - 50	0.13 4.25 5	0.16 2.38 3	0.43 4.37 3	11
>50 - 60	3.20 21.2 13	0.81 11.9 15	1.22 21.8 **27**	55
>60 - 70	1.04 25.1 20	2.47 14.1 **20**	0.02 25.8 25	65
>70 - 80	5.48 44.4 **60**	3.94 24.9 15	0.71 45.7 40	115
>80 - 90	0.93 8.88 6	0.82 4.98 7	0.08 9.13 10	23
Total	107	60	110	277

$X^2 = 24.2$; 10 degrees of freedom (ν) $X^2_{crit} = 23.2$ at $\alpha = 0.01$

In both cases above, the trend toward landfill failure with declining temperature holds, at least in the mid-ranges, as shown in bold figures. Levels of confidence in the analysis are diminished from that in the monthly temperature analysis but remain in excess of 99 percent. Both daily and annual maxima, though, fail to confirm the correlation with performance at the limits of their distributions.

A cold climate alone, therefore, does not appear to explain these failures. Instead, the thermal cycling effect appears most destructive to landfill integrity where it repeatedly crosses the freezing point into the subsurface at sufficient depth to disturb the landfill's cap, and perhaps its walls. Recalling that the best results were found at those sites where minimum temperatures linger near but rarely below freezing (see Table 28), hotter days and cooler nights (low annual mean temperatures

These same conditions may also correlate with low precipitation and low or negative infiltration. Such interaction must be addressed, but further insight may first be gained by studying the remaining parameters.

The Water Balance

Infiltrating water is widely regarded as the most important pathway for contaminant migration, as discussed in Chapter 2. As water leaches through a landfill it accumulates a "witch's brew" of biological and chemical impurities, which it then carries to (and possibly through) the bottom barrier soil. Table 31 examines this relationship.

Table 31. $\mathbf{X}^2$ Contingency Table: Annual Precipitation *vs.* Landfill Status.

Precipitation Range	Intact	Leaking	Failed	Total
>0 - 20	2.52 29.4 **38**	5.47 16.5 7	0.02 30.2 31	76
>20 - 40	3.78 34.4 23	12.8 19.3 **35**	0.52 35.3 31	89
>40 - 60	0.20 36.3 39	1.43 20.4 15	0.20 37.3 40	94
>60 -	0.00 6.95 7	0.21 3.90 3	0.10 7.15 8	18
Total	107	60	110	277

$\mathbf{X}^2 = 27.3$; 6 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 22.5$ at $\alpha = 0.001$

Precipitation. Table 31 suggests that annual precipitation affects landfill performance, but the exceptionally high values in bold reveal a trend only up to 40 inches per year. The trend vanishes at higher levels, where the performance effect is expected to be at its maximum. Once again, some interaction with other parameters might be involved.

Maximum Rainfall Event. Given the randomness of performance with respect to a site's annual precipitation, the maximum rainfall event may be key to the aqueous migration of contaminants out of the cell. A $\mathbf{X}^2$ contingency table was again employed to investigate this potential relationship but, as shown in Table 32, no significant difference exists among ranges even when categorized into as little as 2-inch increments.

Table 32. $\mathbf{X}^2$ Contingency Table: Maximum Rainfall *vs.* Landfill Status.

24-Hr Rainfall Range	Intact	Leaking	Failed	Total
>0 - 2	0.58 5.26 7	0.06 2.60 3	0.89 5.14 3	13
>2 - 4	0.22 21.8 24	0.00 10.8 11	0.27 21.4 19	89
>4 - 6	2.11 20.6 14	4.53 10.2 17	0.00 20.2 20	94
>6 - 8	0.62 18.6 22	1.92 9.20 5	0.04 18.2 19	94
>8 - 10	0.02 12.5 13	2.85 6.20 2	1.11 12.3 16	11
>10 -	0.12 10.1 9	0.20 5.00 6	0.00 9.89 10	7
Total	89	44	87	220

$\mathbf{X}^2 = 15.5$; 10 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 16.0$ at $\alpha = 0.1$

Evaporation. Annual potential evaporation, determined by combining the effects of solar radiation, ambient temperature and wind velocity, should act as an indicator of performance if surface loading of water on a landfill is in fact responsible for contaminant leaching. Where potential evaporation exceeds precipitation, moisture within the landfill cell may even be extracted as vapor through the cap, carrying VOCs out with it.

Table 33 clarifies and amplifies the conclusion of the ANOVA procedure at Table 20. Annual potential evaporation is, indeed, strongly correlated with landfill performance. Although the mid-range of values is inconclusive, the high potential evaporation values typical of the desert Southwest appear to enhance performance. Conversely, the low end of the distribution, typical of the Midwest and North, promotes deterioration of landfill integrity, as precipitation and overland flow are allowed to penetrate the cap and carry contaminants out through the subsurface.

Table 33. $\mathbf{X}^2$ Contingency Table: Evaporation *vs.* Landfill Status.

Evaporation Range	Intact	Leaking	Failed	Total
20 - 30	6.40 14.7 5	3.38 7.85 **13**	1.50 13.5 **18**	36
>30 - 40	1.14 22.0 17	7.17 11.8 **21**	0.87 20.2 16	54
>40 - 50	0.23 37.1 40	4.85 19.8 10	1.40 34.1 41	91
>50 - 60	0.05 12.2 13	0.99 6.54 4	0.29 11.2 13	30
>60 - 70	4.85 8.56 **15**	0.07 4.58 4	4.37 7.86 2	21
>70 - 80	4.56 4.48 **9**	0.82 2.40 1	2.36 4.12 1	11
Total	99	53	91	243

$\mathbf{X}^2 = 45.3$; 10 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 29.6$ at $\alpha = 0.001$

Infiltration. A similar effect, then, is expected of potential infiltration. The net of precipitation and evaporation,[126] infiltration should reflect the fluid loading on a landfill's surface. Similar cap, cover and vegetation conditions should respond proportionally, but as presented in Table 34, infiltration is not a satisfactory predictor of performance.

[126] Fungaroli, *loc. cit.*

Table 34. $\mathbf{X}^2$ Contingency Table: Potential Infiltration *vs.* Landfill Status.

Infiltration Range	Intact	Leaking	Failed	Total
-20 - -10	1.04 24.9 30	1.19 14.1 10	0.03 23.9 23	63
>-10 - 0	0.13 15.4 14	1.60 8.74 5	1.83 14.8 20	39
>0 - 10	1.89 19.0 13	2.50 10.8 16	0.04 18.2 19	48
>10 - 20	0.07 32.5 34	0.70 18.4 22	0.87 31.2 26	82
>20 -	0.11 7.10 8	0.25 4.00 3	0.01 6.80 7	18
Total	99	56	95	250

$\mathbf{X}^2 = 12.3$; 8 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 13.4$ at $\alpha = 0.1$

Solar Radiation. In ANOVA testing, performance was found to vary with the level of Solar Radiation. Table 35 confirms the correlation and corresponds to the trends noted above for temperature and evaporation, but below 250 Langleys, in Alaska, other influences appear to dominate.

Table 35. $\mathbf{X}^2$ Contingency Table: Solar Radiation *vs.* Landfill Status.

Radiation Range	Intact	Leaking	Failed	Total
>150 - 250	0.55 6.16 8	0.61 3.45 2	0.02 6.39 6	16
>250 - 350	8.95 23.5 9	10.6 13.2 **25**	75.1 5.92 **27**	61
>350 - 450	0.11 64.3 67	1.36 36.0 29	0.28 66.7 71	167
>450 - 550	7.48 13.1 **23**	1.52 7.34 4	3.20 13.6 7	34
Total	107	60	111	278

$\mathbf{X}^2 = 109.8$; 6 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 22.5$ at $\alpha = 0.001$

Vegetation. The Normalized Difference Vegetation Index (NDVI), too, was found by the ANOVA procedure to hold some correlation with performance. $\mathbf{X}^2$ testing should illustrate the nature and strength of that relationship. Table 36 reveals significant differences among the NDVI categories, but the trend appears to be parabolic.

Table 36. $\mathbf{X}^2$ Contingency Table: Vegetation [NDVI] *vs.* Landfill Status.

NDVI Range	Intact	Leaking	Failed	Total
>0.0 - 0.10	0.34 9.22 11	0.80 5.00 3	0.01 8.79 9	23
>0.10 - 0.20	0.86 30.1 25	1.72 16.3 11	3.70 28.7 **39**	75
>0.20 - 0.30	2.04 33.7 **42**	0.43 18.2 21	3.84 32.1 21	84
>0.30 - 0.40	3.06 16.0 **23**	0.83 8.69 6	1.21 15.3 11	40
>0.40 -	8.00 18.0 6	5.33 9.78 **17**	1.34 17.2 **22**	45
Total	107	58	102	267

$\mathbf{X}^2 = 33.5$; 8 degrees of freedom (v) $\mathbf{X}^2_{crit} = 22.5$ at $\alpha = 0.001$

Moderate levels of vegetation correlate well with sustained landfill viability, while extreme index values foretell a poorer typical performance. Of course, very high NDVI values are suggestive of high precipitation and potential root penetration, so some interaction is likely in those cases. Very low values, on the other hand, are indicative of desert, beachfront, and permafrost environments, which are otherwise characteristically dissimilar. NDVI, therefore, has validity as a parameter of landfill performance, but is rather difficult to apply except at levels above around 0.25, where the associated degree of uncertainty begins to diminish.

Winds. Winds promote both evaporation--a positive influence on landfill performance--and soil erosion, theorized to be a negative influence. So the net correlation of mean wind speed with landfill status is not at all intuitively clear.

Table 37 presents the empirical relationship between winds and landfill performance. While differences exist (at 99.5 percent confidence), they clearly cannot be explained on the basis of wind speed alone. Other factors must be influencing performance variances at given wind speeds, such that any correlation that does exist is lost in the resultant noise.

Table 37. $\mathbf{X}^2$ Contingency Table: Mean Wind Speed *vs.* Landfill Status.

Wind Speed	Intact	Leaking	Failed	Total
4 - 5	1.09 16.2 12	0.52 9.18 7	2.63 15.6 **22**	41
6	4.13 25.7 **36**	2.15 14.6 9	0.89 24.7 20	65
7	0.19 36.4 39	0.56 20.6 24	1.03 35.0 29	92
8	3.59 20.6 12	1.67 11.6 **16**	0.89 19.8 24	52
Total	99	56	95	250

$\mathbf{X}^2 = 19.3$; 6 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 18.5$ at $\alpha = 0.005$

Runoff. Average annual runoff is also a function of a combination of other phenomena: precipitation, vegetation density, and surface soil, predominantly. Runoff contributes to erosion, and so it is expected to correlate inversely with long-term landfill viability. In the $\mathbf{X}^2$ analysis at Table 38, runoff is seen to be unreliable in predicting performance. Especially noteworthy is the utter lack of significant differences at the

20-inches-per-year level, which would logically pose the greatest threat to landfill integrity, as the precipitation and soil erosion rates are both maximized. The correlation between low runoff (0.25 inches per year) and intact landfills suggests that an underlying trend is present, but the data at higher levels of runoff are too variable to establish the remainder of the apparent trend. Other factors once again mask the overall effect.

Table 38. **X**^{2} Contingency Table: Average Annual Runoff *vs.* Landfill Status.

Runoff	Intact	Leaking	Failed	Total
0.25	4.69 14.7 **23**	2.23 8.30 4	1.19 14.1 10	37
1.0	0.12 20.6 19	3.76 11.6 5	3.40 19.8 **28**	52
10	3.18 32.1 22	10.7 18.1 **32**	0.47 30.8 27	81
20	0.34 31.7 35	0.47 17.9 15	0.01 30.4 30	80
Total	99	56	95	250

X^2 = 30.5; 6 degrees of freedom (v) **X**$^2_{crit}$ = 22.5 at α = 0.001

Other External Performance Factors

Seismic Impact. The effect of seismic activity was found significant both in the ANOVA table of seismic impact and in the **X**^{2} contingency table of seismic risk zones. A **X**^{2} contingency table of seismic impact, provided in Table 39, may add to this understanding by illustrating more precisely the nature of the correlation. Recalling that the significant findings for seismic risk were limited to Zones 2 and 3 (areas of moderate to major damage), seismic impact analysis conforms in that significant differences are found where the probability of occurrence exceeds 45 percent.

Table 39. $\mathbf{X}^2$ Contingency Table: Seismic Impact *vs.* Landfill Status.

Seismic Impact Zone	Intact	Leaking	Failed	Total
0.0	0.49 43.4 48	0.52 23.5 20	0.02 43.0 42	110
>0 - 15	0.07 29.6 31	3.01 16.1 **23**	2.37 29.3 21	75
>15 - 30	0.38 19.7 17	0.16 10.7 12	0.11 19.6 21	50
>30 - 45	0.10 4.34 5	0.05 2.35 2	0.02 4.30 4	11
>45 - 60	0.63 4.34 6	2.35 2.35 0	0.11 4.30 5	11
>60 -	5.53 5.53 0	1.33 3.00 1	10.3 5.48 **13**	14
Total	107	58	106	271

$\mathbf{X}^2 = 27.6$; 10 degrees of freedom (v) $\mathbf{X}^2_{crit} = 25.2$ at $\alpha = 0.005$

Interestingly, the rate of failure does not diminish substantially within lower levels of seismic impact. As is true for runoff, above, only conditions near one extreme act as a predictor of landfill performance.

Elevation. Site elevation offers a possible correlation with performance, as indicated in ANOVA testing, although causality for the relationship is somewhat more speculative than among other parameters. A higher elevation may be accompanied by deeper ground water, a more resistive subsurface soil matrix, and climatic differences. The elevation itself may contribute to landfill viability by enhancing release of VOCs into the atmosphere rather than into the soil and water. Table 40 shows that at high elevations performance improves, but is inconclusive below about 2500 feet. Successive elevation range limits were quadrupled in order to normalize category populations; equal ranges yield a similar trend.

Table 40. $\mathbf{X}^2$ Contingency Table: Site Elevation *vs.* Landfill Status.

Elevation Range	Intact	Leaking	Failed	Total
0 - 10	0.25 10.4 12	0.59 5.85 4	0.01 10.7 11	27
>10 - 40	0.23 6.18 5	0.62 3.47 2	1.11 6.35 9	16
>40 - 160	0.64 13.1 16	0.37 7.36 9	1.50 13.5 9	34
>160 - 640	0.26 37.1 34	0.38 20.8 18	0.91 38.1 44	96
>640 - 2560	4.37 24.3 14	6.50 13.6 **23**	0.04 25.0 26	63
>2560 -	6.58 15.8 **26**	2.68 8.88 4	1.72 16.3 11	41
Total	107	60	110	277

$\mathbf{X}^2 = 28.8$; 10 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 25.2$ at $\alpha = 0.005$

The Underlying Aquifer. The depth to ground water and the hydraulic conductivity of the aquifer are cited as important factors of contaminant migration in many of the existing models discussed in Chapter 2. The developers of DRASTIC, *etc.*, supposed that these parameters influence the rate and degree of spread and, therefore, the amount of potential environmental damage resulting from a contaminant release. In Table 41, however, IRPIMS data on depth to the aquifer yield an insignificant result. This does not refute the importance of the parameter with respect to migration, but rather supports the assumption that detection of leaky landfills is not biased by differences in ground-water depth.

As was the case for depth to aquifer, above, and aquifer media (Table 24), it is expected that the aquifer's hydraulic conductivity is insignificant as a variable in performance. Table 42 again illustrates that leak detection is generally unbiased (*i.e.*, the monitoring is effective).

Table 41. X^2 Contingency Table: Depth to Aquifer *vs.* Landfill Status.

Depth to Aquifer	Intact	Leaking	Failed	Total
0 - 5	2.52 2.52 0	0.44 4.58 6	0.10 11.9 13	19
>5 - 20	0.01 12.3 12	0.09 22.4 21	0.05 58.3 60	93
>20 - 80	2.11 5.57 9	0.44 10.1 8	0.06 26.3 25	42
>80 - 320	0.66 0.66 0	0.53 1.20 2	0.01 3.13 3	5
>320 -	0.01 0.93 1	1.02 1.69 3	0.44 4.39 3	7
Total	22	40	104	166

X^2 = 8.49; 8 degrees of freedom (ν) X^2_{crit} = 10.2 at α = 0.25

Table 42. X^2 Contingency Table: Aquifer Hydraulic Conductivity *vs.* Landfill Status.

Hydraulic Conductivity	Intact	Leaking	Failed	Total
$<10^{-5}$	0.34 9.22 0	0.80 5.00 0	0.01 8.79 2	2
10^{-5} - $<10^{-4}$	0.86 30.1 1	1.72 16.3 3	3.70 28.7 7	11
10^{-4} - $<10^{-3}$	2.04 33.7 1	0.43 18.2 0	3.84 32.1 12	13
10^{-3} - $<10^{-2}$	3.06 16.0 0	0.83 8.69 1	1.21 15.3 6	7
10^{-2} - $<10^{-1}$	8.00 18.0 2	5.33 9.78 3	1.34 17.2 10	15
Total	4	7	37	48

X^2 = 6.02; 8 degrees of freedom (ν) X^2_{crit} = 7.34 at α = 0.5

Both tables above indicate these distributions are consistent with the overall population of landfills. No bias is found in the data.

Internal Performance Factors

Surface Area. The size of a landfill, too, may be more relevant to the severity of a contaminant release than the probability that such a release will occur. A greater surface area increases the total infiltrating water quantity per unit of volume (since the depth remains relatively constant), but the ratio of floor area to waste volume is also greater in a larger landfill, so the relative buffering and sorptive capacities of the immediate perimeter/barrier soil matrix are proportionally increased. The net of these effects may favor either larger or smaller facilities. The correlation between surface area and landfill performance is examined in Table 43.

Table 43. $\mathbf{X}^2$ Contingency Table: Surface Area *vs.* Landfill Status.

Surface Area	Intact	Leaking	Failed	Total
0 - 1	5.40 **6** 2.40	2.40 0 2.40	0.65 1 2.19	7
>1 - 2	2.82 **5** 2.40	0.82 1 2.40	0.61 1 2.19	7
>2 - 10	0.34 8 6.52	0.04 6 6.52	0.10 5 5.96	19
>10 - 20	1.13 3 5.49	1.15 **8** 5.49	0.00 5 5.01	16
>20 -	4.34 1 6.18	0.54 8 6.18	2.00 **9** 5.64	18
Total	23	23	21	67

$\mathbf{X}^2 = 22.4$; 8 degrees of freedom (v) $\qquad \mathbf{X}^2_{crit} = 22.0$ at $\alpha = 0.005$

Small landfills (up to 2 acres) are far less likely to release significant contaminant concentrations than are larger facilities. Landfills of more than 20 acres are far more likely to fail. Moderate leakage is commonly found in the monitoring of those in between, as may be expected.

Period of Operations. Landfill management practices may contribute to the propensity of larger landfills to leak. Greater volume may mean more opportunities for improper introduction and placement of wastes. Poor design, inadequate daily cover, and careless vehicle operation may lead to excessive water retention in the fill or damage to walls and compacted barrier soils. The period of operations may, therefore, be an indicator of future problems. Table 44 suggests a tendency toward failure among landfills left open for 10 to 30 years, but any apparent correlation exists at less than 95 percent confidence. The reversal of the trend at sites operated over 30 years further confounds the analysis, particularly since no differences appear throughout the first 10 years. Beyond the obvious connection between a landfill's size and the span of time it is operated, no performance effect can be predicted from the available data.

Table 44. X^2 Contingency Table: Period of Operations *vs.* Landfill Status.

Period of Operation	Intact	Leaking	Failed	Total
0 - 1	0.02 2.78 3	0.42 2.07 3	0.31 4.14 3	9
>1 - 5	0.21 12.4 14	0.35 9.20 11	0.63 18.4 15	40
>5 - 10	0.30 12.1 14	0.12 8.98 10	0.50 18.0 15	39
>10 - 20	0.87 11.1 8	2.22 8.29 4	3.30 16.6 **24**	36
>20 - 30	0.96 6.49 4	0.15 4.84 4	1.15 9.67 **13**	21
>30 -	1.57 2.16 **4**	1.20 1.61 **3**	3.22 3.22 0	7
Total	47	35	70	152

$X^2 = 17.5$; 10 degrees of freedom (ν) $X^2_{crit} = 16.0$ at $\alpha = 0.1$

Age of Waste. The only variable in landfill performance which is neither constant by nature nor subject to human manipulation is the age of the facility (and its contained wastes). Continuous advancement of time translates to an inherent entropy within the landfill. The wastes degrade chemically and biologically; leachate moves through the fill along a random and unstable path of least resistance; barrier soils endure stresses caused by moisture and temperature fluctuations as well as physical movement. The phases of gas production through which the typical MSW landfill passes coincide with a multitude of characteristic changes in the fill: the material settles; the gas flux and elemental makeup vary; the acidity, oxygen demand, and metals content of the leachate rise to a peak and then taper off over the course of years.[127]

These changes all suggest the probability of a contaminant release varies as a function of landfill age. An initial period of relative stability is expected as the degradation processes slowly take hold. Eventually, fill materials dissociate and mix with infiltrating water, generating leachate. After an extended period, decomposition is so complete that the leachate is no longer any more biologically active than the infiltrating water itself. Hazardous wastes likely follow another schedule, as their degradation processes differ from the organic matter constituting much of MSW.

A $\mathbf{X}^2$ contingency table of the IRPIMS data, Table 45, yields no significant correlation of age with viability, however. Even in unlined landfills with high volumes of infiltration, the rate of waste degradation is exceedingly prolonged, evidently lasting 50 years or beyond.

[127] Tchobanoglous, pp 381-94.

Table 45. $\mathbf{X}^2$ Contingency Table: Age of Waste *vs.* Landfill Status.

Age of Waste	Intact	Leaking	Failed	Total
0 - 1	1.45 1.45 0	2.92 1.16 3	0.06 2.38 2	5
>1 - 5	0.02 8.43 8	0.24 6.74 8	0.05 13.8 13	29
>5 - 10	1.14 18.6 14	0.08 14.9 16	0.40 30.5 34	64
>10 - 20	0.27 12.2 14	2.33 9.77 5	0.45 20.0 23	42
>20 - 30	2.19 7.85 12	0.08 6.28 7	1.86 12.9 8	27
>30 -	0.21 1.45 2	0.02 1.16 1	0.06 2.38 2	5
Total	50	40	82	172

$\mathbf{X}^2 = 13.8$; 10 degrees of freedom (ν) $\mathbf{X}^2_{crit} = 16.0$ at $\alpha = 0.1$

Summary of Significant Individual Effects

The combination of reference distributions and $\mathbf{X}^2$ analyses shows 16 the proposed performance parameters to be effective measures of the likely prospects for landfills exposed to certain conditions. Significant parameters and relevant conditions are summarized in Table 46.

Many other parameters were found to be unreliable indicators of long-term landfill performance. The noise inherent in the database is caused by the interaction of an infinite number of variables at every site, masking whatever subtle effect these parameters may have. Uncertainty in the resultant model is increased by neglecting these parameters, but there is no statistical basis upon which they may be employed.

Table 46. Summary of Significant Parameters and Conditions.

Parameter Label	Units of Measure	Confidence Level (%)	Range of Significant Deviation
Precipitation	inch/year	99.9	extremes (<20 and >80)
Evaporation	inch/year	99.9	20 - 80; full range of values
Solar Radiation	Langleys	99.9	>250
Max. Day Temp	°F	99.5	90 - 120
Max. Mo. Temp	°F	99.9	50 - 110; full range of values
Min. Mo. Temp	°F	99.9	40 - -40
Max. Yr. Temp	°F	99.0	50 - 80
Vegetation Index	none	99.9	>0.10 (parabolic)
Runoff	inch/year	99.9	0.25 category only
Seismic Risk	N/A	99.9	Zones 2 and 3
Seismic Impact	% prob.	99.5	>30
Site Elevation	feet	99.5	>2560
Heath GW Region	10	99.9	Regions 2, 6, 7, 9, and 12
Surface Area	acres	99.0	0 - >20; full range of values
HARM Score	none	99.9	full range of values
NPL Group	N/A	99.0	full range of values

Establishing a Basis for Parametric Statistical Analysis

The interaction of variables is commonly examined via a factorial experimental design, wherein every combination of a high and low level for each variable is randomly tested. Each individual effect and each combination of effects is distinguished from the noise in the data by comparing each response to the normal distribution of the mean (plus or minus the standard error). A factorial design involving k variables at two levels is designated "2^k" to reflect the number of runs required to perform the experiment. Thus, three factors require eight (2^3) runs.

The factorial design identifies factors which act additively in the same way as does a classic design, varying one factor at a time. But a factorial design is more efficient in that it permits fewer runs and also identifies nonadditive interactions among factors. Even so, a complete factorial design for 31 factors would require over 2 million runs, trying to evaluate every combination of interactions. Even fractional factorial designs, in which some factor combinations are randomly omitted, can be unnecessarily unwieldy when too many factors are considered.

Further complicating the analysis of IRPIMS landfill data is the fact that no continuous, ratio- or interval-number performance response is available. In a typical experiment involving seepage, the concentration of a given substance might be measured as the outcome of each run. But in the course of this study, no single contaminant is tracked and no one concentration is applicable to the spectrum of relevant contaminants.

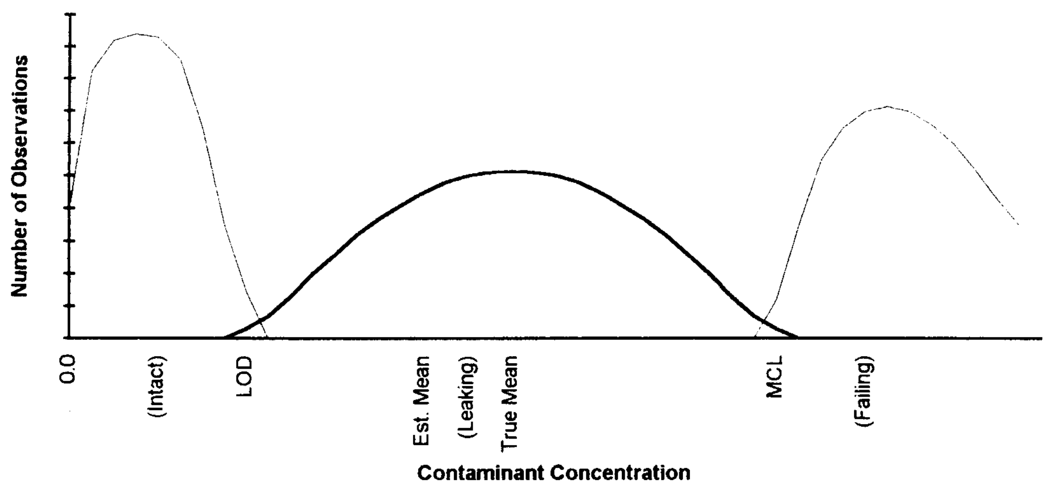
The one unifying performance standard available is the definition of actionable concentration of contaminant(s) at the monitoring location, as discussed in Chapter 1. While the contaminants and their actionable levels vary, the important aspect of a landfill's performance is whether it is adequate to avoid the need for remediation. In general, a "failing" landfill has allowed some contaminant to escape in a concentration in excess of some standard; a "leaking" landfill's contaminant migration is at a concentration between the laboratory's limit of detection (LOD) and the maximum concentration level (MCL) or similar value; any escape from an "intact" landfill has remained below the LOD.

Any value below the LOD may be treated as zero for the purposes of this study, since no risk or hazard is associated with these results. In a similar way, any value greater than the MCL may be treated as equal to that MCL, since all such values are viewed as constituting an equivalent risk or hazard, necessitating a remedial response.

"Leaking" landfills, however, present a more difficult problem. At these sites, some concentration between the LOD and the MCL has been detected. Treatment of these sites as "viable" in the same sense as "intact" (zero concentration) sites would ignore the possibility that this moderate leakage is caused by the same set of factors which resulted in a "failing" condition at another site. The consequences of leakage below the MCL, however, are not presently as severe as for a "failing" site.

It is impractical to use either a representative contaminant or the entire spectrum of detected contaminants with all their individual peak concentrations and MCLs, and all the LODs applicable to every test at every laboratory. One method of approximating the mean concentration at "leaking" sites is to assume a normal distribution of values between the LOD and the MCL. This may well be the most accurate estimate, but the nominal values for both "intact" and "failing" facilities have been approximated at less than their true means. Furthermore, the LOD is typically one or more orders of magnitude below the MCL. The estimate of the "leaking" mean, therefore, is set at 1/2 the MCL (10 percent less than the average of LOD and MCL at one order of magnitude; 1 percent less at two orders of magnitude). This conservative method of estimating the means is graphically represented in Figure 5.

Figure 5. Estimates of Contaminant Concentration by Landfill Status.



Fortunately, these approximations need not be particularly precise. Variation in the categorical response ("intact," *etc.*) to a set of conditions is far greater than any error introduced by conversion of the responses to a continuous, ratio-number scale; at several installations two seemingly identical sites differ in their performance. The more important aspect of the conversion is that it allows for comparison of the general response, given a known set of parameters shared by a large sample population. The mean response value replaces the categorical counts, permitting the use of parametric statistical methods such as factorial designs in the analysis. A hypothetical group of 30 similarly characterized landfill sites --5 intact, 10 leaking, and 15 failing--would yield a mean performance response of [(5 x 0) + (10 x 0.5) + (15 x 1.0)]/30, or 0.67, which may be compared with the mean response of any other group of sites.

While conversion of the response categories to a continuum allows the use of many more statistical procedures, it does not necessarily improve or simplify the analysis. Recalling the relatively smooth trend in the $\mathbf{X}^2$ contingency table of annual evaporation *vs.* landfill status (Table 27), the objective of conversion is to increase the sensitivity of analysis to the underlying trend. Figure 6 illustrates the erratic nature of the same parameter distribution after conversion, as well as the disparities present in both numbers of observations (distorting the confidence interval) and intervals of the primary parameter (resulting in a non-linear scale).

Through smoothing, the noise can be largely dampened, as seen in Figure 7 (which uses five-term simple moving averages), but at this point the trend is no more clearly defined than in the $\mathbf{X}^2$ contingency table. In addition, the smoothing techniques inherently reduce the span of values for which a parameter may be assessed. Five-term averaging consumes the first and last two terms, removing them from the distribution under consideration. Double averaging eliminates four terms at either end of the range, effectively reducing the annual evaporation distribution from 20-to-72 inches to 26-to-63 inches.

To be useful, the process of converting categorical performance responses to a continuum requires smoothing. But that suppression of the data's variability reduces sensitivity just as the $\mathbf{X}^2$ procedure does.

Figure 6. Annual Evaporation *vs.* Probability of Failure and Number of Observations.

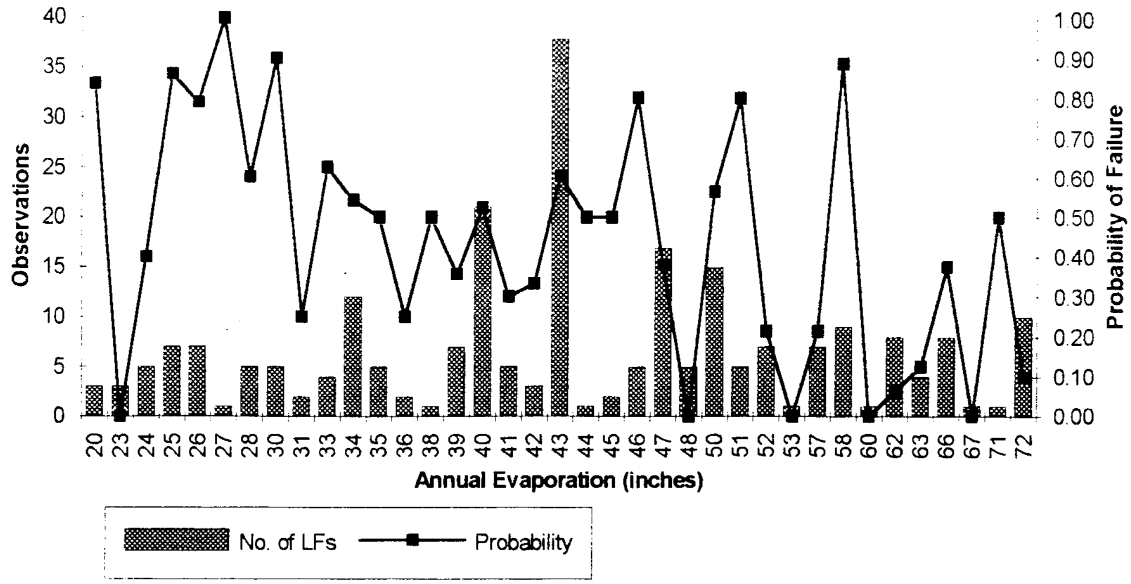
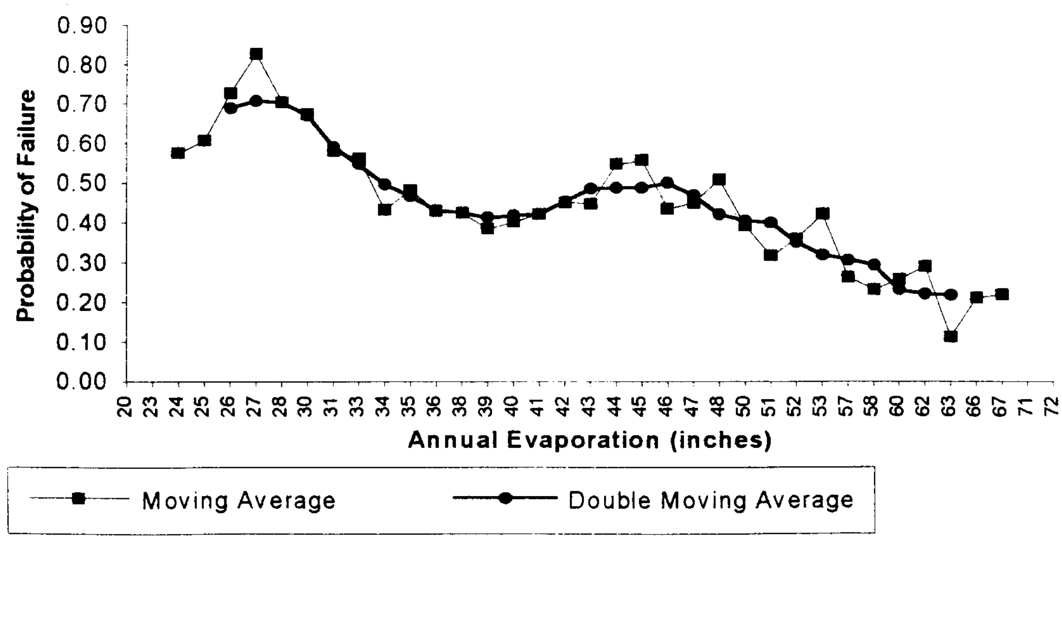


Figure 7. Annual Evaporation *vs.* Probability of Failure (Smoothed).



Analysis of the Interaction Among Parameters

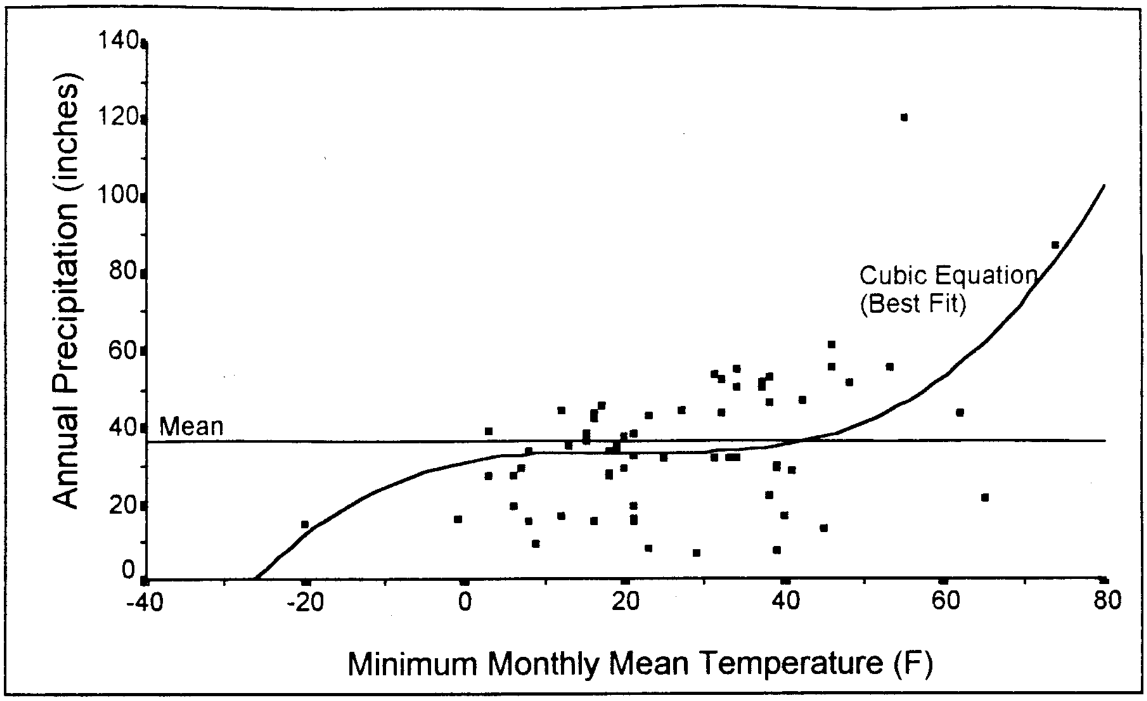
The compromises necessary to introduce parametric methods to the study of factor interactions prompted a search for a more satisfactory approach. Many interactions may be presented graphically with the advent of computerized statistical analysis programs. So, setting aside an immediate attempt to design a factorial experiment involving all of the 16 significant parameters, and relying on intuition about the additivity of some interactions, most of the apparent anomalies in the $\mathbf{X}^2$ contingency table analyses were readily explained.

The $\mathbf{X}^2$ analysis of minimum monthly temperature was the first shown with a peculiar trend in performance (Table 28). Up to 40 degrees (F), landfill performance mimics the pattern detected for all maximum-temperature profiles, but a sudden extreme rate of failure was detected above the 40-degree-minimum level.

Figure 8 illustrates the interaction of annual precipitation with minimum monthly temperature, which results in a bias in the data above 40 degrees toward sites of increasingly high rates of precipitation. The result is that minimum monthly temperatures at this level are not representative of the mean precipitation environment found among cooler sites, and so they can be directly compared only after compensation for the proportional increase in precipitation with temperature.

At temperatures below zero, precipitation diminishes rapidly but fails to enhance performance of landfills in these environments. This finding further supports concerns of Elsbury, *et al.*, about degradation by freeze/thaw cycling and soil desiccation at very cold, dry sites.

Figure 8. Minimum Monthly Temperature *vs.* Annual Precipitation.



Interaction between precipitation and evaporation is similarly seen as responsible for the unremarkable rate of landfill failures exposed to precipitation in excess of 40 inches per year (see Table 31). As shown in Figure 9, rates of annual evaporation and annual precipitation converge at 38 inches.

Above 38 inches of precipitation, the evaporation rates remain commensurate, yielding a near balance and little potential for net water infiltration. Conversely, at less than 25 inches of precipitation, the mean evaporation rate exceeds 50 inches. Thus, at a 2:1 or greater ratio of evaporation to precipitation performance is substantially enhanced, while at ratios near equality no discernible performance effect is detected at any level of precipitation.

Figure 9. Annual Precipitation *vs.* Annual Evaporation.

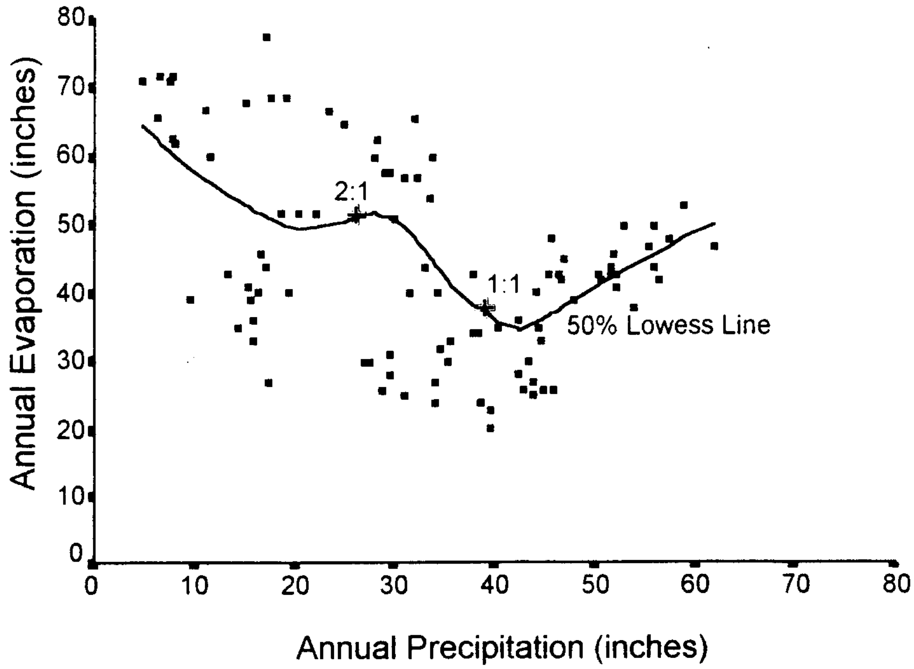


Figure 9 also facilitates the interpretation of the effect of annual evaporation on landfill performance depicted in Table 33. Evaporation rates exceeding 60 inches per year accompany without exception rates of precipitation of 32 inches or less--conditions which are found to strongly enhance performance. The 2:1 evaporation-to-precipitation ratio is again associated with this favorable result. At the other extreme, evaporation below 30 inches per year is associated with an exceptional rate of failure, and is accompanied by ratios from 1.5:1 to 1:2.

The evaporation-to-precipitation ratio is suggestive of the potential infiltration at a landfill site. Actually, infiltration also involves two other factors, runoff (or more correctly, overland flow), and transpiration (the removal of soil moisture into the atmosphere by vegetation). Infiltration is equal to precipitation minus the sum of evapotranspiration and net runoff, and is in response to transient states of the rainfall rate and the storage capacity of the subsurface soil matrix.[128]

The $\mathbf{X}^2$ contingency table (Table 34) fails to reveal any relationship between potential infiltration (as defined by Fungaroli) and performance, despite the strong evidence of such a correlation provided by both the precipitation and evaporation parameters, individually and collectively. Intuitively, it is unlikely that either runoff or vegetative transpiration, or a combination of the two, is responsible for this phenomenon. Therefore, a re-examination of the definition of potential infiltration is in order. As presented by Fungaroli, average potential infiltration is characterized by a geographic division of the 48 contiguous United States into six zones, each zone delineating a 10-inch increment (from <-10 to >30 inches). In order to apply these evaluations into the IRPIMS database analysis, a median value represents each zone ("<-10" = -15; "-10 - 0" = -5, *etc.*) The Fungaroli approximation yields a situation wherein the average potential infiltration value at a given site may no longer resemble the net of precipitation, evaporation, vegetation and runoff, determined on a more localized basis. The deviation of calculated potential infiltration values from the Fungaroli average values (disregarding any differences due to vegetative density) is presented in Figure 10.

By substituting the calculated infiltration values for Fungaroli's average values in the $\mathbf{X}^2$ contingency table, landfill performance may be more accurately assessed. Table 47 illustrates this improvement.

[128] C. W. Fetter. Applied Hydrogeology. 2nd ed. New York: Macmillan, 1988, pp 19-89.

Figure 10. Fungaroli's *vs.* Calculated Potential Infiltration Values.

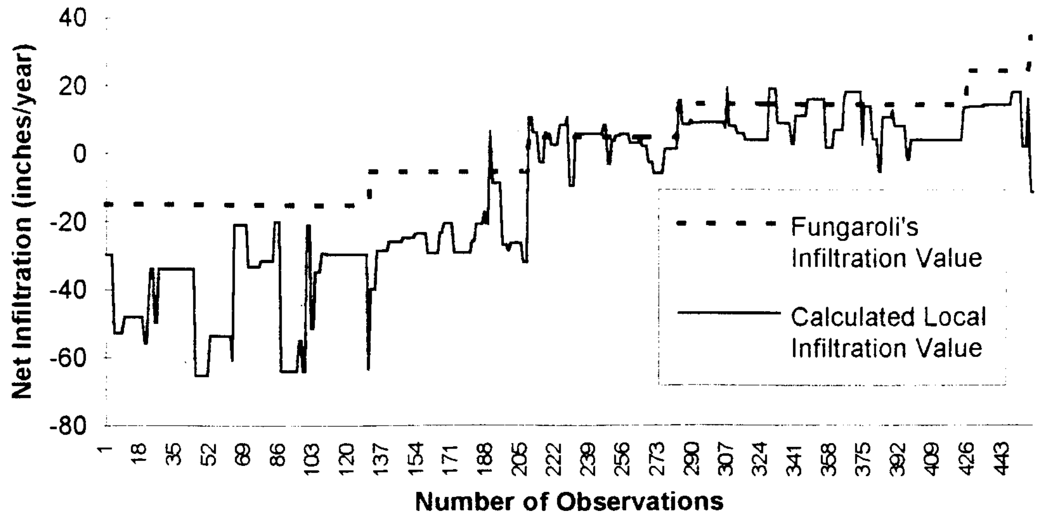


Table 47. X^2 Contingency Table: Calculated Infiltration *vs.* Landfill Status.

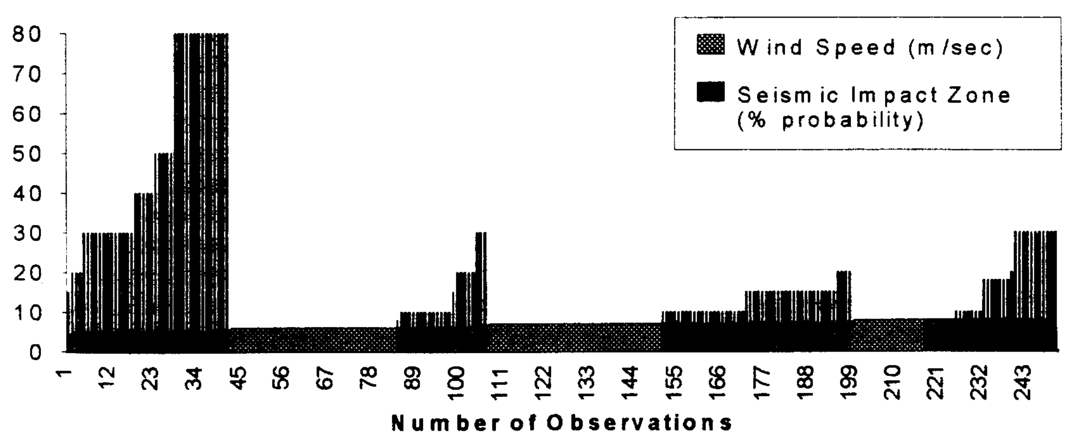
Infiltration Range	Intact	Leaking	Failed	Total
-70 - -60	4.56 4.48 **9**	0.82 2.40 1	2.36 4.12 1	11
>-60 - -50	5.97 4.07 **9**	0.64 2.18 1	3.74 3.74 0	10
>-50 - -40	0 0 0	0 0 0	0 0 0	0
>-40 - -30	2.48 6.11 10	0.02 3.27 3	2.33 5.62 2	15
>-30 - -20	2.89 24.4 16	2.84 13.1 7	9.34 22.5 **37**	60
>-20 - -10	0.81 0.81 0	0.71 0.44 1	0.08 0.75 1	2
>-10 - 0	0.73 4.89 3	4.36 2.62 **6**	0.49 4.49 3	12
>0 - 10	0.00 36.3 36	0.35 19.4 22	0.16 33.3 31	89
>10 - 20	0.20 17.9 16	0.60 9.60 12	0.02 16.5 16	44
Total	99	53	91	243

$X^2 = 46.5$; 14 degrees of freedom (ν) $X^2_{crit} = 36.1$ at $\alpha = 0.001$

Individually calculating the infiltration values for each site results in a far more sensitive analysis than was obtained from averaged values. Particularly in drier environments, the averaging method used in Table 33 substantially overestimates the water load on the landfills' cap and cover surfaces, obfuscating correlations found to exist in Table 47. Even so, the evaporation-precipitation ratio is a better predictor of landfill performance than is either formulation of potential infiltration (which represents the difference of evaporation and precipitation).

The correlation of mean wind speed with landfill performance was presented in Table 37, but revealed an erratic and illogical relationship. Winds contribute to soil erosion but also enhance evaporation, so the net effect may be positive, negative or neutral. Significant differences were found in the $\mathbf{X}^2$ analysis, but no trend was apparent. Plots of mean wind speed *vs.* temperature, precipitation and evaporation disclose no causal connection between winds and performance. One interesting correlation does exist, however: sites of 5 m/sec mean wind speed are predominant in areas of high seismic activity, as seen in Figure 11.

Figure 11. Mean Wind Speed *vs.* Seismic Impact Zone.



The performance of a landfill as measured with respect to mean wind speed, therefore, is overwhelmed by the influence of the Seismic Impact (or Seismic Risk) Zone in which it is located. Rates of failure and leakage shown in Table 39 correspond exactly with the relative number and magnitude of seismically active sites within each wind category. This finding not only negates mean wind speed as a useful parameter, it reaffirms the importance of seismic effects, and it points out the folly of equating correlation with causality. Clearly, no causal connection exists between daily winds and the probability of an occasional earthquake.

The final parameter for which significant differences with no trend were revealed in the $\mathbf{X}^2$ analysis is average annual runoff. Much like the potential infiltration estimation scheme proffered by Fungaroli, runoff values represent "Climatic Regimes" employed by the RCRA Subtitle D Risk Model. The four categories--0.25, 1.0, 10 and 20 inches--actually describe generalized quantities of precipitation which exceed immediate soil storage and evapotranspiration capacities, and so is essentially an alternate method of accounting for precipitation and evaporation.

Because it relies on gross division of the contiguous United States into only four categories, this approach is subject to the same limitations as Fungaroli's infiltration estimates, and was found in the $\mathbf{X}^2$ analysis to be equally unreliable. Figure 12 illustrates the correlation between these two parameters, while also demonstrating the inherent error in such broad categorizations of largely localized phenomena. Both parameters measure the same precipitation-evaporation relationship, so their relative values (though not necessarily their absolute values) should agree. Many significant deviations exist, however, despite the overall correlation.

Figure 12. Runoff *vs.* Fungaroli's Infiltration Values.

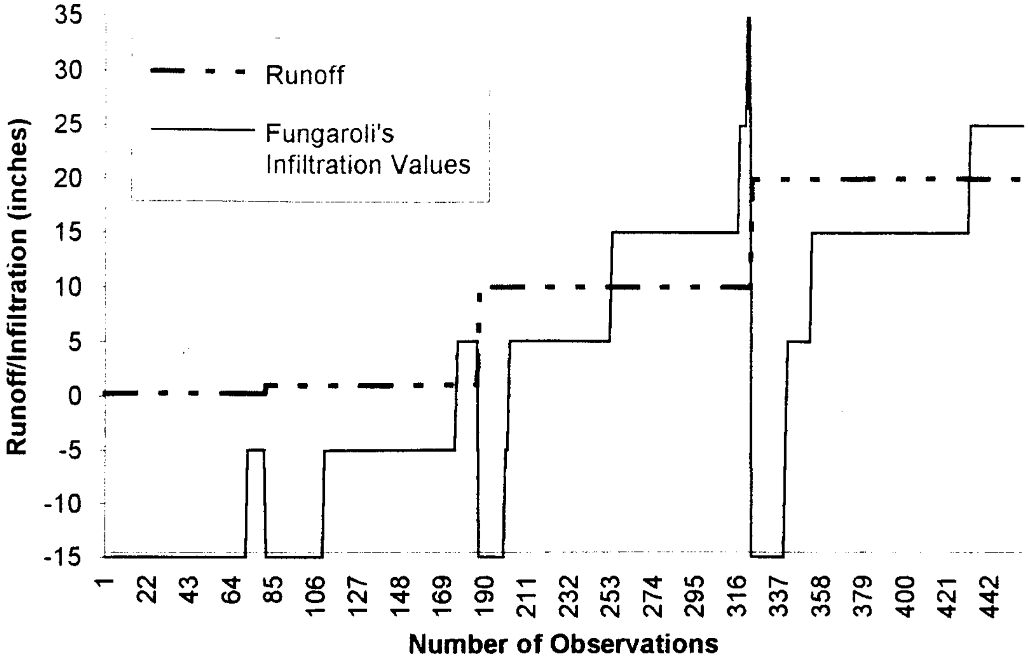


Figure 13. Runoff *vs.* Calculated Infiltration Values.

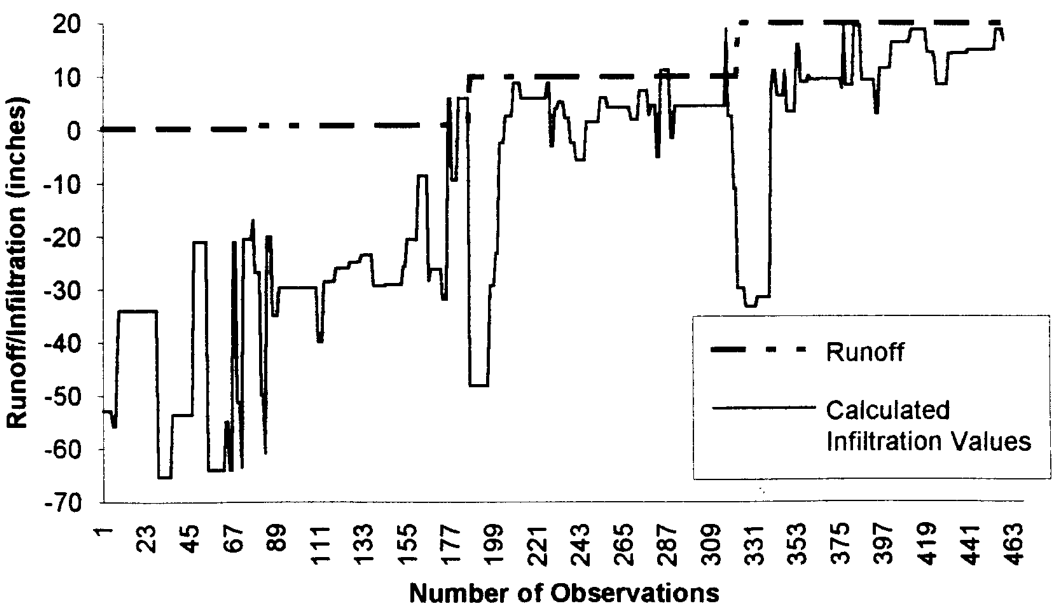


Figure 13 presents a similar comparison of average annual runoff with locally calculated infiltration values. Again the correlation is clear, but deviations are both more common and of greater magnitude than in Figure 12. Most notable is the dramatic difference in scale; the runoff values vary only between 0.25 and 20, whereas infiltration values run to less than -65, for a range of nearly 90 inches. Its limited range and its serious insensitivity to local variations conspire to make average annual runoff, as defined, an extremely poor predictor of landfill performance.

Taking into account the significant trends found through reference distributions, $\mathbf{X}^2$ contingency tables, and study of the interactions and causal relationships among variables, some prediction of the long-term viability of a landfill may be made. Such a prediction requires only that the pertinent characteristic and environmental parameters be known, but is only as reliable as the composite confidence level associated with the combination of parameters.

Development of a Predictive Model

The above analysis of parameters has shown landfill performance, on a macro-scale, to be highly influenced by its size and as few as four geophysical conditions, and may be better understood in the context of a regulatory and management environment which focuses on potential risks posed by the site. Freezing temperatures, average precipitation, the mechanisms of evapotranspiration, and the magnitude and recurrence of local seismic events all were found to contribute significantly to the failure of landfills to serve as permanent, secure depositories for the world's wastes. Efforts to assess hazards to man and the environment brought about by these failures have involved a number of deterministic and probabilistic models of the water balance, contaminant transport and fate, and even costs associated with civil and regulatory liabilities. The development of the CERCLA National Priorities List was yet another manifestation of society's desire to deal with these risks.

Having determined the significance and critical values for the five primary parameters, a geophysical predictive model of performance was relatively simple to construct. The approach chosen for development of the model's structure is in keeping with current trends in environmental risk methodologies (*e.g.* RelRisk and NCAPS), by classifying each site in accordance with its relative propensity to permit contaminant migration.

Landfills 2 acres and smaller were found significantly less likely to fail, and landfills larger than 20 acres significantly more likely, than are those in between. Of 278 landfills of known status, however, only 61 are of known surface area. In order to maximize the number of modeled sites, the middle range of surface area includes the 217 sites of unknown size. Over 50 percent of IRPIMS landfills of known size are between 2 and 20 acres, so the model ensures these mid-sized sites are rigorously tested.

Next in consistency, seismic activity correlates with performance. Seismic risk zone 3 and seismic impact zones greater than 50 result in extraordinary rates of failure. Seismic risk zone 2 and seismic impact zones of at least 30 pose a lesser, but still significant, threat to long-term landfill performance. The model is best served by the more advanced impact zone criteria, rather than applying both standards or relying on the subjective, ordinal-value risk zone structure.

Evaporation and precipitation were found to interact, such that a ratio greater than 2:1 yields a very low probability of failure, while a ratio below 1:1 often permits excessive infiltration of water into and through the buried wastes. The middle range of ratio values is inconclusive.

A critical value of Minimum Monthly Temperature was found at 20 degrees Fahrenheit, such that extended periods of time below 20 degrees result in a higher probability of leakage and failure due to freeze/thaw cycling and possible soil desiccation. At higher minimum temperatures this disruption ("frost heave") of the landfill's cap and cover is avoided.

Certain Heath ground water regions were found more prone than average to landfill leakage; higher elevations are less susceptible; and the content of a landfill have some lesser effect on its performance. HARM scores, though now obsolete, correlate well with evidence of leakage, as does an installation's NPL placement. Such secondary factors could be considered in improving the sensitivity of the model.

The parameters incorporated in the model should be tested in a factorial design of 3 x 3 x 3 x 2, in recognition of all levels involved. The IRPIMS data (see Appendix B) is insufficient to conduct a full analysis, however, so a series of smaller tests is required. Insufficiency of data is a common shortcoming of analyses employing "happenstance" or historical data.[129] The result of testing against the IRPIMS sites is given in Table 48. An optimized decision tree of the model, wherein the parameters are addressed in the order of their relative utility as predictors of landfill performance, is presented in Figure 14.

[129] Box, pp 487-98.

Table 48. Factorial Analysis of the Landfill Failure Relative-Risk Model.

Full Range of Parameter Values

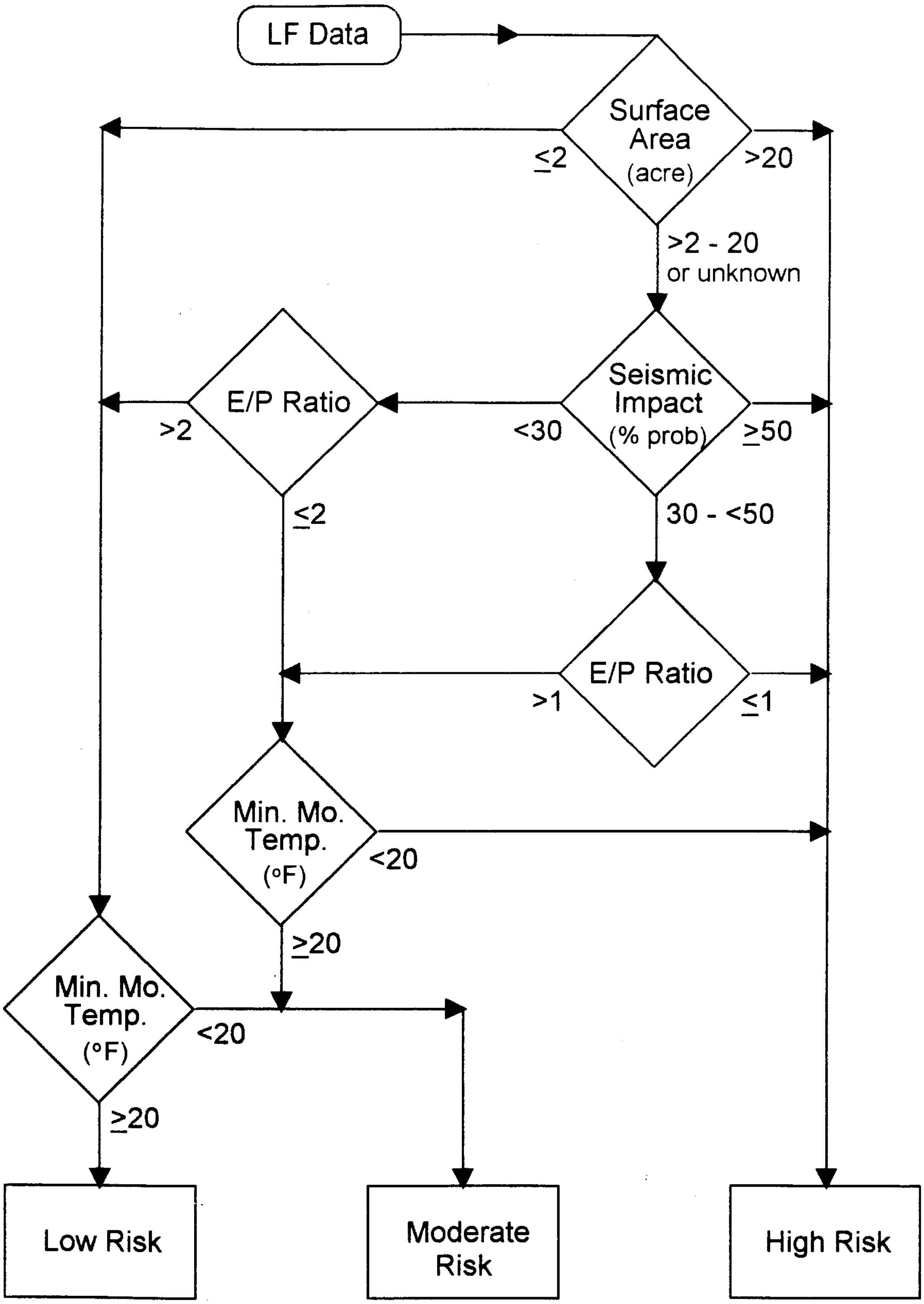
Run	Temp	Ratio	Seismic	Effect	Intact	Leak	Fail	Mean*
1	**<20**	**≤1**	**<30**	0	9	2	6	0.412
2	**≥20**	≤1	<30	t	18	6	2	0.192
3	<20	**>2**	<30	r	2	7	9	0.694
4	≥20	>2	<30	tr	47	22	32	0.426
5	<20	≤1	**≥50**	s	--	--	--	--
6	≥20	≤1	≥50	ts	9	3	20	0.672
7	<20	>2	≥50	rs	0	4	6	0.800
8	≥20	>2	≥50	trs	3	1	0	0.125
	Temp (t): Minimum Monthly-Mean Temperature (°F)							**-0.39**
	Ratio (r): Evaporation/Precipitation Ratio (unitless)							**-0.10**
	Seismic (s): Seismic Impact Zone (%)					(derived from multiple effects)		**+0.49**

Intermediate Range of Parameter Values

Run	Temp	Ratio	Seismic	Effect	Intact	Leak	Fail	Mean*
1	**<20**	**≤2**	**<30**	0	5	13	12	0.617
2	**≥20**	≤2	<30	t	54	24	41	0.445
3	<20	**>2**	<30	r	9	2	6	0.412
4	≥20	>2	<30	tr	18	6	2	0.192
5	<20	≤2	**≥30**	s	0	4	6	0.800
6	≥20	≤2	≥30	ts	4	1	4	0.500
7	<20	>2	≥30	rs	--	--	--	--
8	≥20	>2	≥30	trs	9	3	7	0.447
	Temp (t): Minimum Monthly-Mean Temperature (°F)							**-0.23**
	Ratio (r): Evaporation/Precipitation Ratio (unitless)							**-0.17**
	Seismic (s): Seismic Impact Zone (%)							**+0.22**

* Mean Values are determined in accordance with the methodology described in "Establishing a Basis for Parametric Statistical Analysis."

Figure 14. Landfill Failure Relative-Risk Model.



Of the 545 IRPIMS landfills, 278 are sufficiently characterized to determine their landfill status, as follows:

Viable: Intact - 107; Leaking - 60; Total - 167.

Failing: Metals - 80; Metals Plus - 31; Total - 111.

The model is capable of assessing the performance of all but 35 of these sites, the exceptions including one lacking temperature information and 34 lacking evaporation and/or precipitation data.

The model presumes each landfill to be "average," unless rejected by one or more of the performance parameters. A rejection efficiency can be computed at each phase and for the model as a whole, as the ratio of appropriately rejected sites to the total number of sites rejected. Rejection efficiencies are provided at Table 49. A rejection effectiveness, the ratio of properly rejected sites to the number of exceptional ("non-average") sites, cannot be meaningfully calculated because exceptions are defined by the model itself. Thus, rejection effectiveness is unity by definition.

Table 49. Landfill Failure Relative-Risk Model Exceptional-Site Rejection Efficiencies.

Node	Reject Low	Reject High
Surface Area (SA)	0.818	0.941
Seismic Impact (SI)	0.449	0.947
E/P Ratio (Low SI)	0.656	0.600
E/P Ratio (SI Pass)	0.600	0.769
Temperature (Low SA)	0.815	0.471
Temperature (E/P Pass)	0.468	0.808
Model Total	0.815	0.867

Factorial and sample testing of the Relative-Risk Model (Tables 48 and 49) demonstrate the significance of the chosen parameters and the ability of the logical structure of the model to identify landfill sites of exceptionally high or low risk of aqueous contaminant migration. The factorial design, although confounded by gaps in the IRPIMS database, provides clear statistical evidence to support the parameter selection process. In both the "full range" and "intermediate range" tests, primary parameters were consistent with respect to their relative and combined effects on landfill performance. Incorporation of secondary parameters (*e.g.*, site elevations and HARM scores) did not improve the model.

The proposed Relative-Risk Model does not attempt to identify every mechanism though which a landfill may leak; clearly, conditions and events may occur to disrupt even the most favorably situated and designed facility. The model nonetheless incorporates those factors, found through a wealth of empirical evidence, most responsible for the differences in long-term performance among unlined landfills distributed widely throughout the United States. Furthermore, the model identified 41.9 percent of the sample population as either of exceptionally low risk (11.1 percent) or of exceptionally high risk (30.8 percent), with an overall rejection efficiency of 85.3 percent.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The major deterrent historically to comprehending the dynamics of a landfill's failure has been the utter lack of empirical data on the actual long-term performance of such facilities. In the absence of any full-scale data, laboratory and pilot-scale experiments have had to suffice. Such experiments are usually conducted over relatively brief periods of time, and they fail to address the complete scenario within which an actual landfill is expected to perform. Even in light of dozens of these studies and the wealth of information in the U.S. Air Force's IRPIMS database, the internal processes of these landfills are not clearly observable or fully understood.

Prior methodologies described herein as "landfill risk models" have approached the issue of contaminant migration out of the confines of a landfill from a variety of perspectives. The deterministic water-balance methods address the impingement of atmospheric water sources on the landfill's surface and the resistive capacity of its barrier layers, implicitly assuming negative consequences of leakage. The environmental hazard and human health risk methods attempt to score or rank sites according to their relative likelihood of and vulnerability to a contaminant release, and may be applied to sites other than landfills. The stochastic landfill models try to anticipate every mechanism through which a contaminant release may occur, measure the magnitude of that release (via a water balance), and calculate the resultant environmental and human health risks and costs.

Each of the prior models suffers the same fundamental weakness. They cannot fully account for performance effects caused by the forces of nature and influences of man over the decades of life of a typical landfill. Deterministic models assume many complexities away, while the others estimate release event probabilities largely on the basis of expert opinion and consensus.

The proposed Landfill Failure Relative-Risk Model borrows from the environmental hazard and risk family of models the concept of a relative ranking system for distinguishing sites, and emulates the stochastic models' attempt to identify important release mechanisms. The proposed model differs from the others, however, in two significant respects:

1) The mechanisms of contaminant release are viewed on a macro-scale, with attention to bulk effects of various forces, rather than a micro-scale analysis. All natural soils, no matter their hydraulic conductivity or their composition, offer roughly equal protection from contaminant migration at this scale, despite substantial micro-scale evidence to the contrary.

2) Consideration of the consequences of a contaminant release is limited in context to the U.S. regulatory environment. The "Relative Risk" posed by a site describes the likelihood it will deteriorate to the point that unacceptably high contaminant concentrations will eventually be found at a legally mandated monitoring location, prompting a requirement for some remedial action. The extent of actual damage to the environment or actual costs and risks to human health are not addressed.

Significance and Application of the Research

In the nomenclature of the DOD's RelRisk evaluation system, this model decides whether a landfill site's groundwater and soil Migration Pathway Factors (MPF) should be given a "Potential" or "Confined" rating (see Chapter 2, Table 7). The fact that 13 percent of the sampled sites ranked as "High Risk" by this model currently show no evidence of aqueous contaminant migration suggests that the DOD system might benefit from further refinement.

Under the current scheme, an "Evident" MPF rating is given only where there is "analytical data or observable evidence that contamination is present at, is moving towards, or has moved to a point of exposure,...[or] away from the source."[130] Where potential receptor access exists, each of those 13 percent of sites could be evaluated as of "Low" or "Medium" risk, since the "Evident" MPF rating criteria has not been met.

The most important benefit of the proposed model is the assistance it offers to environmental managers in their planning and prioritization efforts. Early identification of sites most likely to present a future remediation problem is crucial to effective allocation of limited financial and human resources toward the organization's pollution prevention and environmental regulatory compliance objectives.

The very sites described above, the 13 percent of "High Risk" sites showing no evidence of failure, represent a lurking unspecified liability and should not be ignored. They have significant similarities to landfills

[130] Office of the Under Secretary of Defense, 1994, pp 10-12.

with an exceptional rate of failure, and so are more likely than average to exhibit signs of failure at some time in the future. An infinite number of other characteristics and factors may collectively accelerate or delay the migration of contaminants from any one of these sites, but the primary effects of seismic activity, freeze/thaw/desiccation, and persistent water infiltration conspire with the sheer size of the facility to undermine the integrity of its containment system.

Modern landfill design standards acknowledge these factors and others. The U.S. EPA will soon publish seismic design guidance for RCRA Subtitle D MSW landfills, and has recently mandated closure of facilities that do not comply with liner, leachate collection, and siting criteria. But it is virtually impossible to retrofit existing landfills; instead, their vulnerabilities and deficiencies are best addressed through recognition of the factors most likely to cause them to fail.

Careful attention to higher-risk sites contributes to attaining the organization's goals by limiting the liability generated by uncertainty, litigation and remediation. Knowing that "Site A" is significantly more likely than "Site B" to eventually release harmful contaminants to the surrounding environment permits the responsible parties to conduct technological investigations, obtain needed permits and real property agreements, and conduct preventive measures in a more orderly and cost-effective manner, and in a more cooperative regulatory, public relations, and corporate environment. Extra attention to the monitoring of "Site A" could return dividends of a hundred-fold or more if a release is detected before the contaminant is allowed to spread and a remediation plan has already been developed, approved and budgeted.

Recommendations for Future Research

The Society of Environmental Toxicology and Chemistry (SETAC) devoted a 1992 International Conference to the subject of Chemical Time Bombs (CTB). CTBs have been defined as "time-delayed and non-linear responses of soils, sediments and groundwaters to stored pollutants under changing climatic and land-use conditions."[131] CTB investigation is currently focused on Europe, where population density, reliance on ground-water sources, and a history of heavy and often poorly controlled industrial activity have already conjoined to "detonate" several CTBs.

A number of recommendations proffered at the SETAC conference specifically related to the CTB potential of solid waste landfills. SETAC members were encouraged:[132]

> (1) to form institutions responsible for the clean-up and aftercare of all landfills; (2) to set up a database in each member state including all relevant information on abandoned and existing landfills...; (3) to set up a monitoring system for all landfills--this can be preceded by tentative groundwater quality investigations; (4) to develop a simple method for the determination of the hazard potential of landfills; (5) to develop cost-effective regeneration technologies for derelict lands and landfills...; (6) to set up multidisciplinary teams in each member state (scientists, engineers, managers, and information, computer and social specialists); (7) to set up a co-operative network throughout Europe; and (8) to co-ordinate research activities.

[131] G. P. Hekstra, W. M. Stigliani, and G. R. B. Ter Meulen-Smidt. "Report of the Closing Session at the SETAC Conference, Potsdam, Germany, 24 June 1992: Chemical Time Bombs." Land Degradation and Rehabilitation 4 (1993): 199-206.

[132] D. Boels, and G. Fleming. "Chemical Time Bombs from Landfills: Appraisal and Modelling." Land Degradation and Rehabilitation 4 (1993): 399-405.

The United States leads Europe in some of these proposals. The EPA and its state-level equivalents are responsible for ensuring the clean-up and aftercare of all landfills; the IRPIMS database is a major accomplishment toward the documentation of USAF landfills (and similar databases presumably exist); and most U.S. landfills are now monitored for ground-water contamination.

The Landfill Failure Relative-Risk Model proffered herein is a significant first step toward the determination of the hazard potential of landfills. Other researchers are developing landfill, soil and water remediation technologies, as outlined in Chapter 2. Within the United States, government agencies, corporations, environmental activist groups, and universities would all benefit from a more interdisciplinary, cooperative, coordinated approach to these advances, however.

This study was possible only because the researcher was granted access to a body of sensitive information documenting the management, monitoring, and performance of a large number of landfills controlled by the U.S. Air Force. A cooperative effort among organizations must be implemented if this line of research is to progress.

Specific topics related to this research appear to warrant further study. The interaction between natural soils and leachates has been thoroughly examined, but observations over extended periods of exposure and movement have been quite limited. Soil berm and barrier design technologies to withstand thermal, moisture and seismic disturbance should be refined. The actual nature of the movement of infiltrating water through soil barriers and buried wastes is not well understood. Finally, greater attention should be given to collection of risk-related data.

Finally, greater attention should be given to collection of risk-related data. The original objective of this study was to develop a model capable of predicting not only the relative risks associated with a variety of landfills, but the change in those risks as a function of time. Unfortunately, despite the massive accumulation of data made available for this research, too little information exists to track such differences with respect to time. Thus, the most useful contribution to further this line of research may come from the corporate and government bodies who gather environmental monitoring and compliance data. Just as a landfill's liner must be relatively free of voids in order to be effective, so too must records be complete, accurate, and contain appropriate data in order to be useful in any empirical analysis.

REFERENCES

Algermissen, S. T. "Seismic Risk Studies of the United States." Proceedings of the Fourth World Conference on Earthquake Engineering, Santiago, Chile (1969): 14-27.

Aller, Linda, et al. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. EPA/600/2-87/035. Ada, OK: EPA, 1987.

Berthouex, Paul Mac, and Linfield C. Brown. Statistics for Environmental Engineers. Boca Raton, FL: Lewis, 1994.

Bishop, Cynthia J. "Implementing Corrective Action under RCRA: Past, Present and Future." Air & Waste Management Association 87th Annual Meeting and Exhibition. Cincinnati, OH (1994): FA152.01.

Boels, D., and G. Fleming. "Chemical Time Bombs from Landfills: Appraisal and Modelling." Land Degradation and Rehabilitation 4 (1993): 399-405.

Box, George E. P., William G. Hunter, and J. Stuart Hunter. Statistics for Experimenters. New York: Wiley, 1978.

CH2M Hill. Installation Restoration Program Phase 1: Records Search, MacDill AFB, Florida. Report to USAF, 1981.

Cureton, P. M., P. H. Groenevelt, and R. A. McBride. "Landfill Leachate Recirculation: Effects on Vegetation Vigor and Clay Surface Cover Infiltration." Journal of Environmental Quality 20 (1991): 17-24.

Daniel, D. E., *et al.* Project Summary: Rate of Flow of Leachate through Clay Soil Liners. EPA/600/S2-91/021. Cincinnati: GPO, 1991.

Dosani, M. A., and M. L. Taylor. Technology Demonstration Summary: Design and Development of a Pilot-Scale Debris Decontamination System. EPA/540/S5-91/006. Cincinnati: GPO, 1991.

DPRA, Inc. Subtitle D Risk Model. Appendix A: "Failure/Release Submodel." Draft prepared for U.S. EPA Office of Solid Waste, Jul 1991.

Earth Technology Corporation and ERM Program Management Company. User's Manual for the Defense Priority Model. FY 93 Version. Interim Draft prepared for Office of Deputy Assistant Secretary of Defense (Environment), Apr 1992.

Eastwood, Penny. Responding to Global Warming: An Examination of the Prospects for Effective Action. New York: Berg, 1991.

Eidenshink, J. C. The North American Vegetation Map. Washington: USGS, 1992.

Elsbury, Bill R., et al. "Lessons Learned from Compacted Clay Liner." Journal of Geotechnical Engineering 11 (1990): 1641-60.

Fenn, Dennis G., Keith J. Hanley, and Truett V. DeGeare. Use of the Water Balance Method for Predicting Leachate Generation fron Solid Waste Disposal Sites. EPA Report No. 168. Cincinnati: EPA, 1975.

Fetter, C. W. Applied Hydrogeology. 2nd ed. New York: Macmillan, 1988.

Freeze, R. A., and J. A. Cherry. Groundwater. Englewood Cliffs, NJ: Prentice Hall, 1979.

Fungaroli, A. A. Pollution of Subsurface Water by Sanitary Landfills, Volume 1. SW-12rg. Washington: EPA, 1971.

Gordon, Mark E., Paul M. Huebner, and Thomas J. Miazga. "Hydraulic Conductivity of Three Landfill Clay Liners." Journal of Geotechnical Engineering 8 (1989): 1148-60.

Gounaris, Vasillos, Paul R. Anderson, and Thomas M. Holsen. "Characteristics and Environmental Significance of Colloids in Landfill Leachate." Environmental Science and Technology 7 (1993): 1381-87.

Gurijala, K. Rao, and Joseph M. Suflita. "Environmental Factors Influencing Methanogenesis from Refuse in Landfill Samples." Environmental Science and Technology 6 (1993): 1176-81.

Hazardous Materials Technical Center. Review and Analysis of Phase I Installation Restoration Program Reports for Selected Air Force Facilities. Report to USAF, Feb 1985.

Hekstra, G. P., W. M. Stigliani, and G. R. B. Ter Meulen-Smidt. "Report of the Closing Session at the SETAC Conference, Potsdam, Germany, 24 June 1992: Chemical Time Bombs." Land Degradation and Rehabilitation 4 (1993): 199-206.

Hydrosphere, Inc. CLIMATEDATA. "Summary of the Day." CD-ROM. Washington: NOAA, 1990.

Kilroy, M. D., and E. Heyse. Assessment of Contamination Problems and Remedial Alternatives for Air Force Landfills. ESL-TR-87-64. Dynamac Corporation report to USAF, Mar 1988.

LaGrega, Michael D., *et al.* Hazardous Waste Management. New York: McGraw-Hill, 1994.

Law Environmental, Inc. Solid Waste Characterization Study, MacDill AFB, Florida. Report to USAF, Mar 1994.

LeGrand, Harry E. A Standardized System for Evaluating Waste-Disposal Sites. 2nd ed. Worthington, OH: National Water Well Association, 1983.

Mack, Mary Jessica. MILL: (Computer) Model Investigation of Landfill Leachate. Ph.D. Dissertation, University of Delaware, 1991.

Manoharan, Ramanathan, *et al.* "Inferred Metal Toxicity during the Biotreatment of High Ammonia Landfill Leachate." Water Environment Research 7 (1992): 858-865.

McCarthy, James E. "Meeting the Future." The Military Engineer Mar-Apr 1993: 54-58.

Michigan Department of Natural Resources. Site Assessment System (SAS) for the Michigan Priority Ranking System under the Michigan Environmental Response Act. Lansing, MI: MDNR, 1983.

Miller, L. V., *et al.* Evaluation of a PVC Liner and Leachate Collection System in a 10 Year Old Municipal Solid Waste Landfill. Post, Buckley, Schuh & Jernigan, Inc., report to the Delaware Solid Waste Authority, 1990.

National Research Council. The Department of Defense Priority Model: An Independent Assessment of Methods, Assumptions, and Constraints, Interim Report. Interim Report to DOD, Jun 1992.

Nyhan, J.W. Development of Technology for the Long-Term Stabilization and Closure of Shallow Land Burial Sites in Semiarid Environments. LA-11283-MS. Los Alamos, NM: LANL, 1989a.

Nyhan, J.W., *et al.* Development of Corrective Measures Technologies for the Long-Term Stabilization of Shallow Land Burial Sites in Semi-arid Environments. LA-10778-MS. Los Alamos, NM: LANL, 1989b.

Nyhan, J.W. Hydrologic Modeling to Predict Performance of Shallow Land Burial Cover Designs at the Los Alamos National Laboratory. LA-11533-MS. Los Alamos, NM: LANL, 1989c.

Office of the Under Secretary of Defense (Environmental Security). Relative Risk Site Evaluation Primer. Interim Edition. Washington: DOD, Summer 1994.

Office of the Under Secretary of Defense (Environmental Security). The Relative Risk Site Evaluation Concept, Executive Summary. Washington: DOD, undated.

Perrier, Eugene R., and Anthony C. Gibson. Hydrologic Simulation on Solid Waste Disposal Sites (HSSWDS). EPA/SW-868. Washington: GPO, 1980.

Peyton, R. Lee, and Paul R. Schroeder. "Evaluation of Landfill-Liner Designs." Journal of Environmental Engineering 3 (1990): 421-37.

Pope-Reid Associates. Liner Location Risk and Cost Analysis Model. Draft Report and Appendices. Washington: EPA, 1985.

PRC Environmental Management, Inc. RCRA National Corrective Action Prioritization System Guidelines, Revised. Draft prepared for EPA, Aug 1992.

Rathje, William L., and Cullen Murphy. Rubbish! The Archaeology of Garbage. New York: HarperCollins, 1992.

Render, Barry, and Ralph M. Stair, Jr. Quantitative Analysis for Management. Boston: Allyn and Bacon, 1982.

Rogowski, A. S. Relationship of Laboratory- and Field-Determined Hydraulic Conductivity in Compacted Clay Liner. EPA/600/S2-90/025. Washington: GPO, 1990.

Rust, Richard Reynolds. Estimation of Percolation from Landfill Final Covers Based on Extreme Climatic Events. Ph.D. Dissertation, Texas A&M University, 1986.

Sai, Joseph O., and David C. Anderson. "Long-Term Effect of an Aqueous Landfill Leachate on the Permeability of a Compacted Clay Liner," Hazardous Waste and Hazardous Materials 4 (1991): 303-12.

Sax, N. I. Dangerous Properties of Hazardous Materials. 6th ed. New York: Van Nostrand Reinhold, 1984.

Schroeder, Paul R. "HELP Model for Design and Evaluation of Liquids Management Systems." Seminars - Design and Construction of RCRA/CERCLA Final Covers. CERI 90-50. Washington: GPO, 1990.

Solar Energy Research Institute. Insolation Data Manual. SERI/SP-755-789. Golden, CO: SERI, 1980.

Stessel, R. I., and R. J. Murphy. "A Lycimeter Study of the Aerobic Landfill Concept." Waste Management and Research 10 (1992): 485-503.

Suter II, Glenn W., Robert J. Luxmoore, and Ellen D. Smith. "Compacted Soil Barriers at Abandoned Landfill Sites are Likely to Fail in the Long Term." Journal of Environmental Quality 2 (1993): 217-26.

Tchobanoglous, George, Hilary Theisen, and Samuel Vigil. Integrated Solid Waste Management. New York: McGraw-Hill, 1993.

Uppot, Janardanan O. A Study of the Permeability of Clays Subjected to Organic and Inorganic Permeants. Ph.D. Dissertation, University of Missouri-Rolla, 1984.

U.S. Air Force Air Weather Service. International Station Meteorological Climate Summary. Version 2.0. CD-ROM. Washington: USAF, 1992.

U.S. Congress. The Comprehensive Environmental Response, Compensation and Liability Act. Washington: GPO, 1980.

U.S. Department of Energy. Technology Summary: Characterization, Monitoring, and Sensor Technology Integrated Program (CMST-IP). DOE/EM-0156T. Washington: DOE, 1994.

U.S. Department of Energy. Technology Summary: *In Situ* Remediation Integrated Program. DOE/EM-0134P. Washington: DOE, 1994.

U.S. Environmental Protection Agency. Conducting Remedial Investigations/Feasibility Studies for CERCLA Municipal Landfill Sites. EPA/540/P-91/001. Washington: GPO, 1991a.

U.S. Environmental Protection Agency. Criteria for Identifying Areas of Vulnerable Hydrogeology under the Resource Conservation and Recovery Act: A RCRA Statutory Interpretive Guidance. EPA/530-SW-86-022. Washington: GPO, 1986a.

U.S. Environmental Protection Agency. Environmental Fact Sheet: The National Corrective Action Prioritization System. EPA/530-F-92-027. Washington: GPO, 1993a.

U.S. Environmental Protection Agency. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867. Washington: GPO, 1982.

U.S. Environmental Protection Agency. Fact Book: National Priorities List Under the Original Hazard Ranking System 1981-1991. EPA/540/R-93/079. Washington: GPO, 1993b.

U.S. Environmental Protection Agency. Field Test of the Proposed Revised Hazard Ranking System (HRS). EPA/540/P-90/001. Washington: GPO, 1990.

U.S. Environmental Protection Agency. Guidance on RCRA Corrective Action Decision Documents. EPA/540/G-91/011. Washington: GPO, 1991b.

U.S. Environmental Protection Agency. Post-Closure Liability Trust Fund Simulation Model. Volume I: "Model Overview and Results." Washington: EPA, 1985.

U.S. Environmental Protection Agency. Project Summary: Subtitle D Landfill Application Manual for the Multimedia Exposure Assessment Model (MULTIMED). Washington: GPO, 1993c.

U.S. Environmental Protection Agency. Seminar Publication: Design, Operation, and Closure of Municipal Solid Waste Landfills. EPA/625/R-94/008. Washington: GPO, 1994.

U.S. Environmental Protection Agency. SOILINER Model. EPA/530/SW-86/006. Washington: GPO, 1986b.

U.S. Environmental Protection Agency. Surface Impoundment Assessment National Report. EPA/570/9-84/002. Washington: GPO, 1983.

U.S. Environmental Protection Agency. Uncontrolled Hazardous Waste Site Ranking Systems, A User's Manual. HW-10. Washington: EPA, 1984.

von Stein, E. L., and G. M. Savage. Evaluation of the Collier County, Florida Landfill Mining Demonstration. EPA/600/R-93/163. Washington: GPO, 1993.

Warith, Mostafa A., and Raymond N. Yong. "Landfill Leachate Attenuation by Clay Soil." Hazardous Waste and Hazardous Materials 2 (1991): 127-41.

Weeks, Olaf L., Robert S. Mansell, and Scott W. McCallister. "Evaluation of Soil Top-Cover Systems to Minimize Infiltration into a Sanitary Landfill: A Case Study." Environmental Geology and Water Science 2 (1992): 139-51.

Wentz, Charles A. Hazardous Waste Management. New York: McGraw-Hill, 1989.

APPENDICES

APPENDIX A. REGULATED CONTAMINANT CONCENTRATION LIMITS.

REFERENCE	SECTION	PARAMETER	MATRIX	CONCEN-TRATION	UNITS
50 FR 46936	Table 12	24D	WP	.07	MG/L
25 TAC 337.2		24D	WP	100	UG/L
EPA 440/5-86-001	Public health	24D	WS	100	UG/L
22 CAC 64435	Table 3	24D	WP	.1	MG/L
40 CFR 141.12		24D	WP	.1	MG/L
40 CFR 264.94		24D	WG	.1	MG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	ACNP	WO	.5	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ACNP	WO	970	UG/L
EPA 440/5-86-001	Organoleptic	ACNP	WO	.02	MG/L
EPA 440/5-86-001	Organoleptic	ACNP	WS	.02	MG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	ACNP	WS	520	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ACNP	WS	1700	UG/L
50 FR 46936	Table 12	ACRAMD	WP	0	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	ACRL	WO	780	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	ACRL	WS	320	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ACRL	WO	55	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ACRL	WS	68	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	ACRL	WS	21	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	ACRN	WO	.065	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	ACRN	WS	2600	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	ACRN	WS	.006	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ACRN	WS	7550	UG/L
25 TAC 337.2		AG	WP	.05	MG/L
40 CFR 141.11		AG	WP	.05	MG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	AG	WS	.12	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	AG	WS	1.2	UG/L
22 CAC 64435	Table 2	AG	WP	.05	MG/L
40 CFR 264.94		AG	WG	.05	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	AG	WO	2.3	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	AG	WS	50	UG/L
50 FR 46936	Table 12	ALACL	WP	0	MG/L
50 FR 46936	Table 12	ALDICARB	WP	.009	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	ALDRIN	WO	.0079	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	ALDRIN	WS	.0074	NG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ALDRIN	WO	1.3	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ALDRIN	WS	4	UG/L
EPA 440/5-86-001	Aquatic life-fresh	ALK	WS	20	MG/L
25 TAC 337.10		ALPHA	WP	15	PCI/L
40 CFR 141.15		ALPHA	WP	15	PCI/L
50 FR 46936	Table 8	AS	WP	.05	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	AS	WO	.069	MG/L
40 CFR 141.11		AS	WP	.05	MG/L
22 CAC 64435	Table 2	AS	WP	.05	MG/L
40 CFR 264.94		AS	WG	.05	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	AS	WS	.36	MG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	AS	WS	.19	MG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	AS	WO	.036	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	AS	WO	1.75	NG/L
25 TAC 337.2		AS	WP	.05	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	AS	WS	.22	NG/L
50 FR 46936	Table 8	ASBESTOS	WP	7100000	FIBER
EPA 440/5-86-001	Humans-water & fish ingestion	ASBESTOS	WS	3000	FIBER

APPENDIX A. (Continued.)

EPA 440/5-86-001	Aquatic life-chronic-fresh	AZIPM	WS	.01	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	AZIPM	WO	.01	UG/L
EPA 440/5-86-001	Irrigation waters	B	WS	750	MG/L
50 FR 46936	Table 8	BA	WP	1.5	MG/L
40 CFR 141.11		BA	WP	1	MG/L
22 CAC 64435	Table 2	BA	WP	1	MG/L
40 CFR 264.94		BA	WG	1	MG/L
EPA 440/5-86-001	Drinking water	BA	WS	1	MG/L
25 TAC 337.2		BA	WP	1	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	BE	WO	6.41	NG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	BE	WS	5.3	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BE	WS	.37	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	BE	WS	130	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BHC	WS	.52	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	BHC	WS	100	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	BHC	WO	.34	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	BHC	WO	1.74	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	BHCALPHA	WO	.74	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BHCALPHA	WS	.22	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	BHCBETA	WO	4.5	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BHCBETA	WS	1.34	NG/L
50 FR 46936	Table 12	BHCGAMMA	WP	.0002	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	BHCGAMMA	WO	6.25	NG/L
25 TAC 337.2		BHCGAMMA	WP	4	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	BHCGAMMA	WS	2	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BHCGAMMA	WS	1.86	NG/L
40 CFR 141.12		BHCGAMMA	WP	.004	MG/L
40 CFR 264.94		BHCGAMMA	WG	.004	MG/L
22 CAC 64435	Table 3	BHCGAMMA	WP	.004	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	BHCGAMMA	WO	.16	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	BHCGAMMA	WS	.08	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BIS2CEE	WS	.003	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	BIS2CEE	WO	.136	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BIS2CIE	WS	34.7	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	BIS2CIE	WO	4.36	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	BIS2EHP	WO	50	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BIS2EHP	WS	15	MG/L
25 TAC 337.2		BZ	WP	5	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	BZ	WO	4	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BZ	WS	.066	UG/L
40 CFR 141.50		BZ	WP	0	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	BZ	WS	5300	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	BZ	WO	5100	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	BZ	WO	700	UG/L
FAC 17-22		BZ	WP	1	UG/L
40 CFR 141.61		BZ	WP	.005	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	BZD	WO	.05	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	BZD	WS	2500	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BZD	WS	.01	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	BZME	WO	424	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	BZME	WS	14.3	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	BZME	WS	17500	UG/L
50 FR 46936	Table 12	BZME	WP	2	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	BZME	WO	6300	UG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Aquatic life-chronic-marine	BZME	WO	5000	UG/L
EPA 440/5-86-001	Organoleptic	C4M2PH	WS	1800	UG/L
EPA 440/5-86-001	Organoleptic	C4M2PH	WO	1800	UG/L
EPA 440/5-86-001	Organoleptic	C4M3PH	WS	3000	UG/L
EPA 440/5-86-001	Organoleptic	C4M3PH	WO	3000	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	C4M3PH	WS	30	UG/L
EPA 440/5-86-001	Organoleptic	C6M3PH	WS	20	UG/L
EPA 440/5-86-001	Organoleptic	C6M3PH	WO	20	UG/L
50 FR 46936	Table 8	CD	WP	.005	MG/L
40 CFR 141.11		CD	WP	.01	MG/L
22 CAC 64435	Table 2	CD	WP	.01	MG/L
40 CFR 264.94		CD	WG	.01	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CD	WS	1	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CD	WS	.15	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CD	WO	43	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	CD	WO	9.3	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CD	WS	10	UG/L
25 TAC 337.2		CD	WP	.01	MG/L
50 FR 46936	Table 12	CHLORDANE	WP	0	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CHLORDANE	WS	.046	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	CHLORDANE	WO	.048	NG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CHLORDANE	WO	.09	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	CHLORDANE	WO	.004	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CHLORDANE	WS	2.4	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CHLORDANE	WS	.0043	UG/L
25 TAC 337.14		CL	WP	300	MG/L
40 CFR 143.3		CL	WP	250	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CL2	WS	19	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CL2	WS	11	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CL2	WO	13	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	CL2	WO	7.5	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CLAE	WS	238000	UG/L
50 FR 46936	Table 12	CLBZ	WP	.06	MG/L
EPA 440/5-86-001	Organoleptic	CLBZ	WO	20	UG/L
EPA 440/5-86-001	Public health	CLBZ	WS	488	UG/L
EPA 440/5-86-001	Organoleptic	CLBZ	WS	20	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CLPH2	WS	4380	UG/L
EPA 440/5-86-001	Organoleptic	CLPH2	WS	.1	UG/L
EPA 440/5-86-001	Organoleptic	CLPH2	WO	.1	UG/L
EPA 440/5-86-001	Organoleptic	CLPH3	WS	.1	UG/L
EPA 440/5-86-001	Organoleptic	CLPH3	WO	.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CLPH4	WO	29700	UG/L
EPA 440/5-86-001	Organoleptic	CLPH4	WS	.1	UG/L
EPA 440/5-86-001	Organoleptic	CLPH4	WO	.1	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CMETHB	WS	.376	PG/L
EPA 440/5-86-001	Humans-fish ingestion only	CMETHB	WO	.184	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CN	WS	200	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CN	WS	52	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CN	WS	22	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CN	WO	1	UG/L
50 FR 46936	Table 6	COLIF	WP	0	COLF/
25 TAC 337.4		COLIF	WP	1	COLF/
40 CFR 141.14		COLIF	WP	1	COLF/
25 TAC 337.14		COLOR	WP	15	COLOR

APPENDIX A. (Continued.)

40 CFR 143.3		COLOR	WP	15	COLOR
50 FR 46936	Table 8	CR	WP	.12	MG/L
40 CFR 141.11		CR	WP	.05	MG/L
22 CAC 64435	Table 2	CR	WP	.05	MG/L
40 CFR 264.94		CR	WG	.05	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CR	WS	980	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CR	WS	120	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CR	WS	170	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	CR	WO	3433	MG/L
25 TAC 337.2		CR	WP	.05	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CR6	WS	16	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	CR6	WO	50	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CR6	WS	50	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CR6	WO	1100	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CR6	WS	11	UG/L
50 FR 46936	Table 12	CRBFN	WP	.036	MG/L
25 TAC 337.2		CTCL	WP	5	UG/L
40 CFR 141.61		CTCL	WP	.005	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	CTCL	WS	.04	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CTCL	WO	50000	UG/L
40 CFR 141.50		CTCL	WP	0	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CTCL	WS	35200	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	CTCL	WO	.69	UG/L
FAC 17-22		CTCL	WP	3	UG/L
50 FR 46936	Table 8	CU	WP	1.3	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	CU	WO	2.9	UG/L
EPA 440/5-86-001	Organoleptic	CU	WS	1	MG/L
40 CFR 143.3		CU	WP	1	MG/L
EPA 440/5-86-001	Organoleptic	CU	WO	1	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	CU	WS	9.2	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	CU	WS	6.5	UG/L
25 TAC 337.14		CU	WP	.3	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	DBZD33	WO	.002	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DBZD33	WS	.001	UG/L
25 TAC 337.2		DCA12	WP	5	UG/L
40 CFR 141.50		DCA12	WP	0	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DCA12	WS	118000	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DCA12	WO	24.3	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DCA12	WS	.094	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DCA12	WO	113000	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DCA12	WS	20000	UG/L
FAC 17-22		DCA12	WP	3	UG/L
40 CFR 141.61		DCA12	WP	.005	MG/L
50 FR 46936	Table 12	DCB12	WP	.62	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DCBZ	WS	1120	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DCBZ	WS	763	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DCBZ	WS	400	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DCBZ	WO	2.6	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DCBZ	WO	1970	UG/L
25 TAC 337.2		DCBZ14	WP	75	UG/L
40 CFR 141.61		DCBZ14	WP	.075	MG/L
40 CFR 141.50		DCBZ14	WP	.75	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DCE	WS	11600	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DCE	WO	224000	UG/L

APPENDIX A. (Continued.)

25 TAC 337.2		DCE11	WP	7	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DCE11	WS	.003	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DCE11	WO	.185	UG/L
40 CFR 141.50		DCE11	WP	.007	MG/L
40 CFR 141.61		DCE11	WP	.007	MG/L
50 FR 46936	Table 12	DCE12C	WP	.07	MG/L
50 FR 46936	Table 12	DCE12T	WP	.07	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DCP	WO	790	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	DCP	WO	3040	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DCP	WS	6060	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DCP	WS	244	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DCP24	WS	3.09	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DCP24	WS	2020	UG/L
EPA 440/5-86-001	Organoleptic	DCP24	WS	.3	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DCP24	WS	365	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DCPA	WS	23000	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DCPA	WO	10300	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DCPA	WS	5700	UG/L
50 FR 46936	Table 12	DCPA12	WP	.006	MG/L
EPA 440/5-86-001	Organoleptic	DCPH23	WS	.04	UG/L
EPA 440/5-86-001	Organoleptic	DCPH23	WO	.04	UG/L
EPA 440/5-86-001	Organoleptic	DCPH25	WS	.5	UG/L
EPA 440/5-86-001	Organoleptic	DCPH25	WO	.5	UG/L
EPA 440/5-86-001	Organoleptic	DCPH26	WS	.2	UG/L
EPA 440/5-86-001	Organoleptic	DCPH26	WO	.2	UG/L
EPA 440/5-86-001	Organoleptic	DCPH34	WS	.3	UG/L
EPA 440/5-86-001	Organoleptic	DCPH34	WO	.3	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DDD	WS	.6	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DDD	WO	3.6	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DDE	WS	1050	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DDE	WO	14	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DDT	WS	.001	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DDT	WS	.0024	NG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	DDT	WO	.001	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DDT	WO	.13	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DDT	WO	.0024	NG/L
EPA 440/5-86-001	Aquatic life-acute fresh	DDT	WS	1.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DEMETON	WO	.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DEMETON	WS	.1	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DEPH	WS	350	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	DEPH	WO	1.8	G/L
EPA 440/5-86-001	Humans-fish ingestion only	DIELDRIN	WO	.0076	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DIELDRIN	WS	1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DIELDRIN	WO	.71	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	DIELDRIN	WO	.0019	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DIELDRIN	WS	.0019	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DIELDRIN	WS	.0071	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DMP24	WS	2120	UG/L
EPA 440/5-86-001	Organoleptic	DMP24	WO	400	UG/L
EPA 440/5-86-001	Organoleptic	DMP24	WS	400	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DMPH	WS	313	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	DMPH	WO	2.9	G/L
EPA 440/5-86-001	Humans-water & fish ingestion	DN46M	WS	13.4	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DN46M	WO	765	UG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Humans-fish ingestion only	DNBP	WO	154	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DNBP	WS	34	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DNP24	WS	70	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DNP24	WO	14.3	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DNT	WS	330	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	DNT	WO	590	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DNT	WS	230	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DNT24	WS	.011	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DNT24	WO	.91	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	DPHY12	WO	.056	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DPHY12	WS	270	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	DPHY12	WS	4	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	DXPH	WS	940	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	DXPH	WO	3.4	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	DXPH	WO	2944	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	DXPH	WS	3	UG/L
50 FR 46936	Table 12	EBZ	WP	.68	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	EBZ	WO	3.28	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	EBZ	WS	32000	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	EBZ	WO	430	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	EBZ	WS	1.4	MG/L
50 FR 46936	Table 12	EDB	WP	0	MG/L
FAC 17-22		EDB	WP	.02	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	ENDO	WO	159	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ENDO	WS	.22	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	ENDO	WS	.056	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ENDO	WO	.034	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	ENDO	WO	.0087	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	ENDO	WS	74	UG/L
25 TAC 337.2		ENDRIN	WP	.2	UG/L
22 CAC 64435	Table 3	ENDRIN	WP	.002	MG/L
40 CFR 141.12		ENDRIN	WP	.0002	MG/L
40 CFR 264.94		ENDRIN	WG	.0002	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ENDRIN	WS	.18	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	ENDRIN	WS	.0023	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ENDRIN	WO	.037	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	ENDRIN	WO	.0023	UG/L
50 FR 46936	Table 12	EPICLHDRN	WP	0	MG/L
25 TAC 337.2		F	WP	4	MG/L
25 TAC 337.14		F	WP	2	MG/L
40 CFR 141.51		F	WP	4	MG/L
40 CFR 141.11		F	WP	4	MG/L
40 CFR 143.3		F	WP	2	MG/L
22 CAC 64435	Table 4	F	WP	1.4	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	FE	WS	.3	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	FE	WS	1	MG/L
40 CFR 143.3		FE	WP	.3	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	FLA	WO	54	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	FLA	WO	16	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	FLA	WS	42	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	FLA	WO	40	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	FLA	WS	3980	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	HCBU	WO	5	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	HCBU	WS	.045	UG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Aquatic life-acute-marine	HCBU	WO	32	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	HCBU	WS	90	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	HCBU	WS	9.3	UG/L
EPA 440/5-86-001	Organoleptic	HCCP	WS	1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	HCCP	WO	7	UG/L
EPA 440/5-86-001	Organoleptic	HCCP	WO	1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	HCCP	WS	7	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	HCCP	WS	5.2	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	HCLEA	WS	540	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	HCLEA	WS	.19	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	HCLEA	WS	980	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	HCLEA	WO	.87	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	HCLEA	WO	940	UG/L
50 FR 46936	Table 12	HEPT-EPOX	WP	0	MG/L
50 FR 46936	Table 12	HEPTACHLOR	WP	0	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	HEPTACHLOR	WS	.52	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	HEPTACHLOR	WS	.0038	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	HEPTACHLOR	WO	.053	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	HEPTACHLOR	WO	.0036	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	HEPTACHLOR	WS	.02	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	HEPTACHLOR	WO	.02	NG/L
50 FR 46936	Table 8	HG	WP	.003	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	HG	WS	144	NG/L
25 TAC 337.2		HG	WP	.002	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	HG	WO	146	NG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	HG	WO	.025	UG/L
40 CFR 141.11		HG	WP	.002	MG/L
40 CFR 264.94		HG	WG	.002	MG/L
22 CAC 64435	Table 2	HG	WP	.002	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	HG	WS	2.4	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	HG	WS	.012	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	HG	WO	2.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	HME	WS	11000	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	HME	WO	12000	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	HME	WS	.019	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	HME	WO	1.57	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	HME	WO	6400	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	ISOP	WO	520	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ISOP	WO	12900	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ISOP	WS	117000	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	ISOP	WS	5.2	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	MALA	WO	.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	MALA	WS	.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	MIREX	WO	.001	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	MIREX	WS	.001	UG/L
25 TAC 337.14		MN	WP	.05	MG/L
40 CFR 143.3		MN	WP	.05	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	MN	WS	50	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	MN	WO	100	UG/L
50 FR 46936	Table 12	MTXYCL	WP	.34	MG/L
25 TAC 337.2		MTXYCL	WP	100	UG/L
40 CFR 141.12		MTXYCL	WP	.1	MG/L
40 CFR 264.94		MTXYCL	WG	.1	MG/L
22 CAC 64435	Table 3	MTXYCL	WP	.1	MG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Aquatic life-acute-fresh	MTXYCL	WS	.03	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	MTXYCL	WO	.03	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	MTXYCL	WS	100	UG/L
40 CFR 141.50		MVC	WP	0	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	NAPH	WO	2350	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	NAPH	WS	620	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	NAPH	WS	2300	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	NH3	WS	.0017	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	NH3	WS	.083	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	NI	WO	4.77	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NI	WS	632	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	NI	WS	1100	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	NI	WS	56	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	NI	WO	140	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	NI	WO	7.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	NNSA	WS	5850	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	NNSA	WO	3300000	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NNSBU	WS	.64	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	NNSBU	WO	58.7	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NNSET	WS	.08	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	NNSET	WO	124	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NNSM	WS	.14	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	NNSM	WO	1600	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NNSPH	WS	490	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	NNSPH	WO	1610	NG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NNSPYR	WS	1.6	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	NNSPYR	WO	9190	NG/L
EPA 440/5-86-001	Aquatic life-acute-marine	NO2BZ	WO	6680	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	NO2BZ	WS	27000	UG/L
EPA 440/5-86-001	Organoleptic	NO2BZ	WO	30	UG/L
EPA 440/5-86-001	Organoleptic	NO2BZ	WS	30	UG/L
50 FR 46936	Table 8	NO2N	WP	1	MG/L
50 FR 46936	Table 8	NO3N	WP	10	MG/L
25 TAC 337.2		NO3N	WP	10	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	NO3N	WS	10	MG/L
40 CFR 141.11		NO3N	WP	10	MG/L
22 CAC 64435	Table 2	NO3N	WP	10.2	MG/L
EPA 440/5-86-001	Aquatic life-acute-marine	P	WO	.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	P	WS	.1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PAH	WO	300	UG/L
EPA 440/5-86-001	Human-water & fish ingestion	PAH	WS	.28	NG/L
EPA 440/5-86-001	Human-fish ingestion only	PAH	WO	3.11	NG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PARA	WS	.04	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PARA	WO	.04	UG/L
50 FR 46936	Table 8	PB	WP	.02	MG/L
40 CFR 141.11		PB	WP	.05	MG/L
40 CFR 264.94		PB	WG	.05	MG/L
22 CAC 64435	Table 2	PB	WP	.05	MG/L
25 TAC 337.2		PB	WP	.05	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PB	WS	34	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PB	WS	1.3	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PB	WO	140	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	PB	WO	5.6	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PCA	WS	2400	UG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Humans-water & fish ingestion	PCA	WS	.017	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	PCA	WO	1.07	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PCA	WO	9020	UG/L
50 FR 46936	Table 12	PCB	WP	0	MG/L
40 CFR 761.125	(c)(4)(v)-nonrestricted access	PCB	SD	10	PPM
40 CFR 761.125	(c)(3)(iv)-restricted access	PCB	SD	25	PPM
40 CFR 761.125	(c)(2)(ii)-high conc. spills	PCB	SD	25	PPM
40 CFR 761.125	(b)(1)(ii)-low conc. spills	PCB	SD	1	PPM
40 CFR 761.125	(c)(4)(v)-nonrestricted access	PCB	SO	10	PPM
40 CFR 761.125	(c)(3)(iv)-restricted access	PCB	SO	25	PPM
40 CFR 761.125	(c)(2)(ii)-high conc. spills	PCB	SO	25	PPM
40 CFR 761.125	(b)(1)(ii)-low conc. spills	PCB	SO	1	PPM
EPA 440/5-86-001	Aquatic life-chronic-marine	PCB	WO	.03	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PCB	WO	10	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PCB	WS	.014	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PCB	WS	2	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	PCB	WS	.0079	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	PCB	WO	.0079	NG/L
EPA 440/5-86-001	Humans-fish ingestion only	PCE	WO	.88	UG/L
FAC 17-22		PCE	WP	3	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	PCE	WO	450	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PCE	WS	5280	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PCE	WS	840	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PCE	WO	10200	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	PCE	WS	.08	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PCLEA	WS	1100	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	PCLEA	WO	281	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PCLEA	WS	7240	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PCLEA	WO	390	UG/L
50 FR 46936	Table 12	PCP	WP	.22	MG/L
EPA 440/5-86-001	Organoleptic	PCP	WO	30	UG/L
EPA 440/5-86-001	Organoleptic	PCP	WS	30	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PCP	WS	55	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PCP	WS	3.2	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PCP	WO	53	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	PCP	WO	34	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	PHENOL	WO	5800	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	PHENOL	WS	10200	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	PHENOL	WS	2560	UG/L
EPA 440/5-86-001	Organoleptic	PHENOL	WO	.3	MG/L
EPA 440/5-86-001	Organoleptic	PHENOL	WS	.3	MG/L
EPA 440/5-86-001	Aquatic plants	PO4	WS	25	UG/L
25 TAC 337.10		RA	WP	5	PCI/L
40 CFR 141.15		RA	WP	5	PCI/L
EPA 440/5-86-001	Aquatic life-acute-fresh	S	WS	2	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	S	WO	2	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	SB	WO	45	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	SB	WS	9	MG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	SB	WS	1.6	MG/L
EPA 440/5-86-001	Humans-water & fish ingestion	SB	WS	.146	MG/L
50 FR 46936	Table 8	SE	WP	.045	MG/L
40 CFR 264.94		SE	WG	.01	MG/L
22 CAC 64435	Table 2	SE	WP	.01	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	SE	WS	260	UG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Aquatic life-chronic-fresh	SE	WS	35	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	SE	WO	410	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	SE	WS	10	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	SE	WO	54	UG/L
25 TAC 337.2		SE	WP	.01	MG/L
40 CFR 141.11		SE	WP	.01	MG/L
25 TAC 337.2		SILVEX	WP	10	UG/L
EPA 440/5-86-001	Public health	SILVEX	WS	10	UG/L
40 CFR 264.94		SILVEX	WG	.01	MG/L
22 CAC 64435	Table 3	SILVEX	WP	.01	MG/L
40 CFR 141.12		SILVEX	WP	.01	MG/L
50 FR 46936	Table 12	SILVEX	WP	.052	MG/L
25 TAC 337.14		SO4	WP	300	MG/L
40 CFR 143.3		SO4	WP	250	MG/L
50 FR 46936	Table 12	STY	WP	.14	MG/L
40 CFR 143.3		SURFACT	WP	.5	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	TC2378	WO	0	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TC2378	WS	1	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	TC2378	WS	.001	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TC2378	WS	0	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TCA	WS	18000	UG/L
25 TAC 337.2		TCA111	WP	200	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	TCA111	WO	31200	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TCA111	WS	18.4	MG/L
40 CFR 141.50		TCA111	WP	.2	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	TCA111	WO	1.03	UG/L
40 CFR 141.61		TCA111	WP	.2	MG/L
FAC 17-22		TCA111	WP	200	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	TCA112	WS	9400	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	TCA112	WO	4.18	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TCA112	WS	.06	UG/L
25 TAC 337.2		TCE	WP	5	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TCE	WS	.27	UG/L
40 CFR 141.50		TCE	WP	0	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TCE	WS	45000	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	TCE	WO	2000	UG/L
FAC 17-22		TCE	WP	3	UG/L
40 CFR 141.61		TCE	WP	.005	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	TCE	WO	8.07	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	TCLME	WO	1.57	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TCLME	WS	.019	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TCLME	WS	28900	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	TCLME	WS	1240	UG/L
EPA 440/5-86-001	Organoleptic	TCP245	WS	1	UG/L
EPA 440/5-86-001	Organoleptic	TCP245	WO	1	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	TCP246	WS	970	UG/L
EPA 440/5-86-001	Organoleptic	TCP246	WO	2	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TCP246	WS	.12	UG/L
EPA 440/5-86-001	Organoleptic	TCP246	WS	2	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	TCP246	WO	.36	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TCX	WS	9320	UG/L
25 TAC 337.14		TDS	WP	1000	MG/L
40 CFR 143.3		TDS	WP	500	MG/L
EPA 440/5-86-001	Human-welfare	TDS	WS	250	MG/L

APPENDIX A. (Continued.)

EPA 440/5-86-001	Organoleptic	TECP2346	WS	1	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	TECP2356	WO	440	UG/L
25 TAC 337.17		THM	WP	.1	MG/L
40 CFR 141.12		THM	WP	.1	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	TL	WO	48	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TL	WS	13	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	TL	WO	2130	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	TL	WS	40	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TL	WS	1400	UG/L
25 TAC 337.2		TOXAP	WP	5	UG/L
EPA 440/5-86-001	Humans-fish ingestion only	TOXAP	WO	.07	NG/L
EPA 440/5-86-001	Aquatic life-acute-marine	TOXAP	WO	.07	UG/L
40 CFR 264.94		TOXAP	WG	.005	MG/L
40 CFR 141.12		TOXAP	WP	.005	MG/L
50 FR 46936	Table 12	TOXAP	WP	0	MG/L
22 CAC 64435	Table 3	TOXAP	WP	.005	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	TOXAP	WS	1.6	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	TOXAP	WS	.013	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	TOXAP	WS	.07	NG/L
50 FR 46936	Table 6	TURB	WP	.1	NTU
40 CFR 141.13		TURB	WP	1	NTU
22 CAC 64435	Part(f)	TURB	WP	.05	NTU
25 TAC 337.3		TURB	WP	1	NTU
25 TAC 337.2		VC	WP	2	UG/L
40 CFR 141.61		VC	WP	.002	MG/L
EPA 440/5-86-001	Humans-fish ingestion only	VC	WO	52.5	UG/L
EPA 440/5-86-001	Humans-water & fish ingestion	VC	WS	.2	UG/L
FAC 17-22		VC	WP	1	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	XCLBZ	WS	250	UG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	XCLBZ	WO	179	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	XCLBZ	WO	160	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	XCLBZ	WS	50	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	XCLNAPH	WS	1600	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	XCLNAPH	WO	7.5	UG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	XNTPH	WS	230	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	XNTPH	WS	150	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	XNTPH	WO	4850	UG/L
50 FR 46936	Table 12	XYLENES	WP	.44	MG/L
25 TAC 337.14		ZN	WP	5	MG/L
EPA 440/5-86-001	Aquatic life-chronic-marine	ZN	WO	58	UG/L
40 CFR 143.3		ZN	WP	5	MG/L
EPA 440/5-86-001	Aquatic life-acute-fresh	ZN	WS	180	UG/L
EPA 440/5-86-001	Aquatic life-chronic-fresh	ZN	WS	47	UG/L
EPA 440/5-86-001	Aquatic life-acute-marine	ZN	WO	170	UG/L

APPENDIX B. PRIMARY PARAMETERS OF IRPIMS-LISTED LANDFILLS.

Record	LF Status	HARM	HRS	NPL Group	LF Operation	Age of Waste	Fill Type	Surface Area	Max Da Rainfall	Precipitation/Yr	Evaporation/Yr	Solar Radiation/Yr	Infiltration/Yr	Runoff/Yr	NDVI	Mean Wind Speed	Seismic Risk	Seismic Impact	Heath GW Region	Soil Type	Depth to Aquifer	Hyd Conductivity	Max Mo Temp	Min Mo Temp	Elevation
1										5.9		161.4			0.2			0	13				55	-34	10
2												200							13						
3										15.3		202			0.2			0	13				51	-20	10
4										14.8		208.3			0.25			20	13				71	-20	550
5										14.8		208.3			0.25			20	13				71	-20	550
6										5	71	161.4			0.2			0	13				50	-24	90
7										6.7	72	500	-15	0.25	0.15	7	1	0	2				95	29	4090
8									2.3	6.1		161.4			0.35			10	13				45	-44	10
9									2.3	6.1		161.4			0.35			10	13				45	-44	10
10									2.3	6.1		161.4			0.35			10	13				45	-44	10
11									2.3	6.1		161.4			0.35			10	13				45	-44	10
12									3.4	10.8		208.3			0.45			30	13				72	-18	440
13									3.4	10.8		208.3			0.45			30	13				72	-18	440
14									3.7	29.6	28	300	5	10	0.35	7	1	0	7				79	20	630
15									3.7	29.6	28	300	5	10	0.35	7	1	0	7				79	20	630
16									3.7	29.6	28	300	5	10	0.35	7	1	0	7				79	20	630
17									3.7	29.6	28	300	5	10	0.35	7	1	0	7				79	20	630
18									6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
19									6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
20									8.7	51.8	44	376.5	15	20	0.25	6	1	10	10				92	36	220
21									9.6	44.6	33	316	15	20	0.3	8	1	30	8				85	24	130
22									10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
23									10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
24									10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
25									10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
26		29							2.7	17.2	44	432.4	-5	0.25	0.25	6	1	0	4				86	16	6090
27		30							10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
28		35								19.2	69	425.3	-15	1	0.2	7	0	0	6				101	23	1900
29		41								52.2	41	351.4	15	10	0.35	7	1	0	10		10		88	32	110
30		41								28.1	60	380	-5	1	0.15	8	2	0	6				94	26	1310
31		43								17.6	27	325	5	1	0.2	8	1	0	7				81	-7	910
32		44							10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
33		48								28.1	60	380	-5	1	0.15	8	2	0	6				94	26	1310
34		48							6.3	23.6	67	421.6	-15	0.25	0.2	8	0	0	6				95	31	1780
35		49							7	55.4	47	375.6	15	20	0.35	6	1	0	10				92	34	330
36		50								14.8		208.3			0.4				13				71	-20	550
37		51							6.7	43.8	27	280	25	20	0.5	8	2	20	9				80	16	400
38		51							7.2	42.5	36	327.8	5	20	0.35	7	1	10	10				86	27	280
39		52								7.8		499.9	-15	0.25	0.05	5	3	60	2				103	23	2600
40		52							1.6	9.1		202			0.25			0	13				59	-12	10
41		53								47.9	39	370.5	15	20	0.45	6	3	50	10				92	31	250
42		54								47.9	39	370.5	15	20	0.45	6	3	50	10				92	31	250
43		54							1.6	6.3		207.6			0.3			30	13				72	-29	430
44		54							4.9	56	44	216.1			0.3				13				56	23	100
45		54							5.2	46.6	42	360	15	10	0.3	7	1	0	8				89	31	220
46		55								14.8		208.3			0.4				13				71	-20	550
47		55								47.9	39	370.5	15	20	0.45	6	3	50	10				92	31	250
48		55								28.1	60	380	-5	1	0.15	8	2	0	6				94	26	1310
49		55							1.7	19.8		215.3			0.3			20	13				63	6	50
50		56								27.1		198.7			0.1			0	13				53	6	460
51		56								47.9	39	370.5	15	20	0.45	6	3	50	10				92	31	250
52		56							15	34.9		466.6											88	77	10
53		57							1.7	19.8		215.3			0.3			20	13				63	6	50
54		57							1.7	19.8		215.3			0.3			20	13				63	6	50
55		58								19.2	69	425.3	-15	1	0.2	7	0	0	6				101	23	1900

APPENDIX B. (Continued.)

56		58							1.6	6.3		208.3			0.3				13				72	-29	430
57		58							1.6	6.3	66	207.6			0.25			20	13				72	-29	430
58		58							5.2	46.6	42	360	15	10	0.3	7	1	0	8				89	31	220
59		58							8.1	29	58	406.6	-5	1	0.2	7	0	0	10				95	41	690
60		59							1.6	6.3		207.6			0.3			30	13				72	-29	430
61		59							2.7	17.2	44	432.4	-5	0.25	0.25	6	1	0	4				86	16	6090
62		59							2.7	17.2	44	432.4	-5	0.25	0.25	6	1	0	4				86	16	6090
63		60							1.6	6.3		208.3			0.3				13				72	-29	430
64		60							1.7	19.8		215.3			0.3			20	13				63	6	50
65		60							9	55.5	47	399.8	15	20	0.3	6	0	0	11		7		89	46	20
66		61							4.9	52.1	41	364.9	5	20	0.45	6	2	20	6				88	32	1070
67		61							6.6	31.5	40	358.2	-5	1	0.45	8	1	10	7				87	13	1050
68		61							6.6	31.5	40	358.2	-5	1	0.45	8	1	10	7				87	13	1050
69		61							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
70		62								27.1		198.7			0.1			0	13				53	6	460
71		62										200			0.25				13						
72		62								19.7		200.1			0.35			15	13				50	-5	270
73		62								15.3		202			0.2			0	13				51	-20	10
74		62							6.6	31.5	40	358.2	-5	1	0.45	8	1	10	7				87	13	1050
75		62							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
76		63							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
77		63							6.9	45.7	48	386.8	5	10	0.35	6	1	0	10				93	36	250
78		64								42.6		205.3			0.3			0	13				53	11	540
79		64								17.2	78	411.2	-15	1	0.25	7	0	0	6				97	33	1030
80		64							7.2	42.5	36	327.8	5	20	0.35	7	1	10	10				86	27	280
81		65										200			0.25				13						
82		65							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10				95	39	790
83		65							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
84		65							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
85		66							3.2	14.4	35	342.4	-5	1	0.15	8	2	10	6				82	12	3530
86		66							6.1	42.5	36	327.8	5	20		7	1	10	10				88	28	10
87		66							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
88		67								25.6		215.3			0.35			10	13				61	-2	1590
89		67								31.1	25	282.6	15	10	0.6	8	1	0	7				75	4	1220
90		67							7	55.4	47	375.6	15	20	0.35	6	1	0	10				92	34	330
91		67							7	55.4	47	375.6	15	20	0.35	6	1	0	10				92	34	330
92		68								42.6		205.3			0.3			0	13				53	11	540
93		68								52	46	400	5	1	0.25	7	0	0	11				87	55	10
94		68							6.6	31.5	40	358.2	-5	1	0.45	8	1	10	7				87	13	1050
95		68							6.9	45.7	48	386.8	5	10	0.35	6	1	0	10				93	36	250
96		68							6.9	45.7	48	386.8	5	10	0.35	6	1	0	10				93	36	250
97		68							7.2	42.5	36	327.8	5	20	0.35	7	1	10	10				86	27	280
98		69								52	46	400	5	1	0.25	7	0	0	11				87	55	10
99		69								52	46	400	5	1	0.25	7	0	0	11				87	55	10
100		69							6.6	31.5	40	358.2	-5	1	0.45	8	1	10	7				87	13	1050
101		70								52	46	400	5	1	0.25	7	0	0	11				87	55	10
102		71										200			0.25				13						
103		71								31.1	25	282.6	15	10	0.6	8	1	0	7				75	4	1220
104		73							9.2	40.3	35	359.9	5	10	0.3	7	2	20	6				89	22	450
105		75							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
106		76								52	46	400	5	1	0.25	7	0	0	11				87	55	10
107		77								39		300		20	0.35	7	1						90	8	
108		78								28.8	26	294.6	15	10	0.5	7	1	0	7				90	-4	690
109		80								54	38	337.7	15	20	0.3	6	1	10	6	5			89	31	1080
110				12					2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
111				12					2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
112				17					2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
113		64		18					1.8	15.8	39	332	-5	10	0.2	6	2	8	1	5	18		82	21	2460
114				2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80
115				2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80
116				2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80
117				2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80

APPENDIX B. (Continued.)

118		2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80
119		2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80
120		2					5	20.5	52	445.6	-15	20	0.2	5	2	30	1				94	39	80
121		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
122		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
123		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
124		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
125		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
126		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
127		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
128		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
129		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
130		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
131		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
132		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
133		2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
134		8				4				440			0.1		1			3					
135					1		10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
136					1		10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
137	44				1		4.5	17.7	69	479	-15	0.25	0.3	8	1	0	5				91	27	3340
138	61				1		4.9	52.1	41	364.9	5	20	0.45	6	2	20	6				88	32	1070
139		17			1		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
140		17			1		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
141		7			1		2.7	15.8		227.2			0.35			60	13	2			65	8	110
142			15	20	1		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
143				35	1		5.2	46.6	42	360	15	10	0.3	7	1	0	8				89	31	220
144			15	42	1		10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
145		17	21	51	1		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
146					3			17.6	27	325	5	1	0.2	8	1	0	7				81	-7	910
147					3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
148					3		8.1	29	58	406.6	-5	1	0.2	7	0	0	10	5	11		95	41	690
149	48				3			11.1		208.3			0.3			30	13				72	-17	550
150	50				3		5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
151	51				3		2.6	33	44	367	35	10	0.25	4	1	15	1				83	21	4090
152	60				3		4.5	17.7	69	479	-15	0.25	0.3	8	1	0	5				91	27	3340
153	65				3		3	11.2	67	507.1	-15	0.25	0.05	6	2	10	2				98	40	2700
154	69				3		6.9	33.5	54	407.5	-5	1	0.15	8	2	10	6				92	21	1370
155	48	12			3		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
156	50	12			3		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
157	59	15			3			39.6	20	288.4	15	20	0.5	8	2	18	9				74	3	750
158		17			3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
159	41	17			3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
160	42	22			3		4.4	18.7	52	445.6	-15	20	0.2	5	2	30	1		72		93	38	95
161	48	22			3		4.4	18.7	52	445.6	-15	20	0.2	5	2	30	1		52		93	38	95
162	49	17			3	0.5	3.3	16.6	40	363.8	-5	1	0.35	8	1	0	1				86	12	3280
163	49		4	19	3		5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
164	54			20	3			31.1	25	282.6	15	10	0.6	8	1	0	7				75	4	1220
165	66			20	3			11.1		208.3			0.3			30	13				72	-17	550
166	42			20	3	24	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
167	51		1	22	3	6	9.4	50.4	43	370	15	10	0.25	7	2	10	10				87	37	30
168	50		3	22	3	4.5	9.6	44.6	33	316	15	20	0.3	8	1	30	8				85	24	130
169	62		3	23	3			31.1	25	282.6	15	10	0.6	8	1	0	7				75	4	1220
170	48		5	23	3	7	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
171	56		5	24	3		5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
172	52		3	25	3	3	9.6	44.6	33	316	15	20	0.3	8	1	30	8				85	24	130
173			5	25	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
174	49	17	6	25	3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
175			9	25	3	11	6.2	33.8	60	396.4	-5	1	0.2	8	2	10	6				92	28	1290
176	60			27	3	30		15.1	68	467.5	-15	0.25	0.15	7	1	0	5				89	25	4290
177			2	27	3	3	6.2	33.8	60	396.4	-5	1	0.2	8	2	10	6				92	28	1290
178	63		7	27	3			11.1		208.3			0.3			30	13				72	-17	550
179	56		1	28	3	7		15.1	68	467.5	-15	0.25	0.15	7	1	0	5				89	25	4290

APPENDIX B. (Continued.)

180	66			3	28	3	20		35.6	33	353	5	10	0.5	7	1	10	7		6		85	19	740
181	66			5	28	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
182				0	29	3	2	15	87.3		439.6											87	74	250
183				0	30	3		9.1	27.1	30	317.4	5	10	0.4	8	1	0	7				84	3	830
184				5	30	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
185				5	30	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
186	36		17	5	30	3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
187	49			6	30	3		5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
188				7	30	3		5.5	22.2	52	445.6	-15	20	0.2	5	2	20	1				94	38	110
189	55			7	30	3		6.5	35.4	30	329.6	5	10	0.3	7	1	0	7				84	13	670
190	49			5	31	3	25	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
191	64				32	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
192	35	49	5	2	32	3		2	19.6	40	434.9	-5	0.25	0.25	6	3	30	1		13		88	21	4790
193	48		11	1	33	3		6.7	43.8	25	285.6	15	20	0.45	8	2	30	9				80	16	100
194				7	34	3	16	6.2	33.8	60	396.4	-5	1	0.2	8	2	10	6				92	28	1290
195	51			4	35	3	6	9.4	50.4	43	370	15	10	0.25	7	2	10	10				87	37	30
196	60			10	35	3		6.9	33.5	54	407.5	-5	1	0.15	8	2	10	6				92	21	1370
197	51			13	35	3		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
198	54			8	36	3	9		15.1	68	467.5	-15	0.25	0.15	7	1	0	5				89	25	4290
199	64			9	36	3			11.1		208.3			0.3			30	13				72	-17	550
200	51			5	37	3			34.5	32	310	25	10	0.55	7	1	8	7				82	16	830
201	40		19	7	37	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2				93	39	1540
202	52			15	37	3	18	9.6	44.6	33	316	15	20	0.3	8	1	30	8				85	24	130
203	54			6	38	3		15	87.3		439.6											87	74	250
204	50			8	38	3		5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
205				16	38	3		2.6	8	63	497.6	-15	0.25	0.05	6	2	30	2				104	33	2160
206	74			19	38	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
207	65			1	39	3	4	9.6	44.6	33	316	15	20	0.3	8	1	30	8				85	24	130
208	57		2	13	39	3			16	36	410	-15	1	0.3	6	2	10	3		354		93	21	3000
209	53			27	39	3			25.1	65	372.5	-5	1	0.15	8	1	10	6				105	18	1380
210	40			1	40	3			25.1	65	372.5	-5	1	0.15	8	1	10	6				105	18	1380
211	57			11	40	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
212	36	49	5	12	40	3		2	19.6	40	434.9	-5	0.25	0.25	6	3	30	1		13		88	21	4790
213				0	41	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
214	64		19	20	41	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2				93	39	1540
215				2	42	3		5.7	46.9	45	380	15	10	0.3	7	1	0	11				91	42	230
216				9	43	3	8	6.2	33.8	60	396.4	-5	1	0.2	8	2	10	6				92	28	1290
217	62			5	44	3		15	87.3		439.6											87	74	250
218	72			10	44	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
219	64		7	22	44	3	17	2.7	15.8		227.2			0.35			60	13	2			65	8	110
220	46			2	45	3		4.8	32.3	57	400.1	-5	1	0.2	7	0	0	6				96	33	550
221	66			6	45	3	11	9.6	44.6	33	316	15	20	0.3	8	1	30	8				85	24	130
222	64			33	45	3		6.9	33.5	54	407.5	-5	1	0.15	8	2	10	6				92	21	1370
223	58			31	47	3		3.3	15.4	41	425.4	-5	1	0.1	6	1	0	4		7		88	16	5290
224	50			13	49	3	4		15.1	68	467.5	-15	0.25	0.15	7	1	0	5				89	25	4290
225	45			13	50	3			34.5	32	310	25	10	0.55	7	1	8	7				82	16	830
226				15	51	3		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2				68	45	370
227	55			3	52	3	4		15.1	68	467.5	-15	0.25	0.15	7	1	0	5				89	25	4290
228	66				53	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
229				3	53	3	1	6.2	33.8	60	396.4	-5	1	0.2	8	2	10	6				92	28	1290
230	42			6	53	3	17		34.4	40	362	5	10	0.45	8	1	0	7	4	8		88	19	870
231	39		19	9	53	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2				93	39	1540
232	44			12	53	3			25.1	65	372.5	-5	1	0.15	8	1	10	6				105	18	1380
233	46			16	53	3		7.5	39.8		372.5	-5	10	0.4	8	1	0	6				93	25	670
234				4	54	3		5.7	46.9	45	380	15	10	0.3	7	1	0	11				91	42	230
235				5	54	3	2.5		52.2	41	351.4	15	10	0.35	7	1	0	10				88	32	110
236	36		19	24	54	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2				93	39	1540
237			7	2	55	3		2.7	15.8		227.2			0.35			60	13	2			65	8	110
238	82	38	12	10	55	3		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
239			2	22	55	3		5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
240			2	22	55	3		5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
241			2	22	55	3		5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830

APPENDIX B. (Continued.)

242							4			17.6	27	325	5	1	0.2	8	1	0	7				81	-7	910
243		41		17			4		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
244		44	49	5			4		2	19.6	40	434.9	-5	0.25	0.25	6	3	30	1				88	21	4790
245				7			4		2.7	15.8		227.2			0.35			60	13	2			65	8	110
246				17		15	4		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
247		76		12	6	24	4		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
248		76		12	6	24	4		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
249		56			11	32	4			34.5	32	310	25	10	0.55	7	1	8	7				82	16	830
250					5	34	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2				68	45	370
251		63			9	34	4	35	8.1	29	58	406.6	-5	1	0.2	7	0	0	10				95	41	690
252					10	35	4			43.3	30	300	15	20	0.5	8	1	20	7				84	19	470
253					9	36	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2				68	45	370
254					21	36	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		36		68	45	370
255		83			3	37	4	1	8.1	29	58	406.6	-5	1	0.2	7	0	0	10				95	41	690
256		57			3	37	4	1.5	8.1	29	58	406.6	-5	1	0.2	7	0	0	10				95	41	690
257					4	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2				68	45	370
258					0	38	4		6.9	33.5	54	407.5	-5	1	0.15	8	2	10	6				92	21	1370
259		66		12	13	38	4		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
260		66		12	13	38	4		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
261		72			4	39	4		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
262		45		17	11	40	4		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
263					20	40	4	8	1.7	19.8		215.3			0.3			20	13				63	6	50
264		42		17		41	4		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
265		83			5	50	4	5.6	8.1	29	58	406.6	-5	1	0.2	7	0	0	10				95	41	690
266					26	54	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2				68	45	370
267		82	38	12	10	55	4		2.6	11.8	60	464.1	-15	10	0.2	5	2	20	1				94	38	190
268	0	30							6.2	28.2	63	412.4	-15	1	0.2	8	1	0	6				97	18	990
269	0	34								6.7	72	500	-15	0.25	0.15	7	1	0	2				95	29	4090
270	0	35							9	55.5	47	399.8	15	20	0.3	6	0	0	11				89	46	20
271	0	37								6.7	72	500	-15	0.25	0.15	7	1	0	2				95	29	4090
272	0	37							9	55.5	47	399.8	15	20	0.3	6	0	0	11				89	46	20
273	0	38							6.2	28.2	63	412.4	-15	1	0.2	8	1	0	6				97	18	990
274	0	40							5.3	52	46	400	5	1	0.2	7	0	0	11				90	48	10
275	0	41								11.1		208.3			0.3			30	13				72	-17	550
276	0	41								52.2	41	351.4	15	10	0.35	7	1	0	10				88	32	110
277	0	41								6.7	72	500	-15	0.25	0.15	7	1	0	2				95	29	4090
278	0	41								6.7	72	500	-15	0.25	0.15	7	1	0	2				95	29	4090
279	0	41							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
280	0	41							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
281	0	42							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
282	0	42							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
283	0	43							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
284	0	43							10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
285	0	44							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
286	0	45							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
287	0	45							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
288	0	46							5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
289	0	46							5.7	31.1	57	400.5	-5	1	0.2	7	0	0	10				96	39	600
290	0	46							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
291	0	47							3.2	14.4	35	342.4	-5	1	0.15	8	2	10	6				82	12	3530
292	0	47							4.8	32.3	57	400.1	-5	1	0.2	7	0	0	6				96	33	550
293	0	47							6.4	52.3	43	381	15	20	0.3	6	1	10	6				91	30	310
294	0	47							6.7	56.4	42	370	25	20	0.3	6	1	0	10				91	33	220
295	0	48							3	11.2	67	507.1	-15	0.25	0.05	6	2	10	2				98	40	2700
296	0	48							9	55.5	47	399.8	15	20	0.3	6	0	0	11				89	46	20
297	0	49							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
298	0	50							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
299	0	50							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10				86	32	10
300	0	51								52.2	41	351.4	15	10	0.35	7	1	0	10				88	32	110
301	0	53							4.8	32.3	57	400.1	-5	1	0.2	7	0	0	6				96	33	550
302	0	40		2						16	36	410	-15	1	0.3	6	2	10	3				93	21	3000
303	0	47		5						14.8		208.3			0.45			40	13	3			71	-20	550

APPENDIX B. (Continued.)

304	0	49		5						14.8		208.3			0.45			40	13	3			71	-20	550
305	0	46		7					2.7	15.8		227.2			0.35			60	13	2			65	8	110
306	0	46		7					2.7	15.8		227.2			0.35			60	13	2			65	8	110
307	0						1			46.3	43	374.1	5	20	0.35	6	1	0	10				92	38	310
308	0						1		4.8	37.9	34	304.6	5	10	0.5	7	1	10	6				85	20	810
309	0						1		4.9	50.8	42	374.4	5	10	0.4	7	3	15	10		37	1.10E-02	89	34	250
310	0			20			1		3.9	38.5	24	276.9	15	20	0.5	8	3	18	9				82	15	420
311	0	48			2	33	1		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
312	0	46		17	20	35	1	3	3.3	16.6	40	363.8	-5	1	0.35	8	1	0	1		12		86	12	3280
313	0	46			12	40	1		10.7	56	50	404.7	5	10	0.2	6	0	0	11				90	53	10
314	0	42			11	50	1		10.7	56	50	404.7	5	10	0.2	6	0	0	11				90	53	10
315	0						3			29.5	31	314.8	15	10	0.35	8	1	0	7				82	7	920
316	0	35					3		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
317	0	35					3		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
318	0	38					3			6.7	72	500	-15	0.25	0.15	7	1	0	2				95	29	4090
319	0	49					3		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
320	0	51					3		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
321	0		35	13			3			44.4	35	327.6	15	20	0.45	8	1	10	10		11		87	27	30
322	0			17			3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
323	0	37		22			3		4.4	18.7	52	445.6	-15	20	0.2	5	2	30	1		60		93	38	95
324	0	52		22			3		4.4	18.7	52	445.6	-15	20	0.2	5	2	30	1		57	7.10E-05	93	38	95
325	0	29					3	1	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
326	0	32					3	2	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
327	0	40					3	2	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
328	0	34					3	4	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
329	0	47		22	2	23	3		4.4	18.7	52	445.6	-15	20	0.2	5	2	30	1		65		93	38	95
330	0	49			6	23	3		5.7	46.9	45	380	15	10	0.3	7	1	0	11				91	42	230
331	0	34			5	25	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
332	0	28			4	27	3		10	62	47	380	25	20	0.25	6	0	0	11				91	46	190
333	0	34			5	30	3		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
334	0	58			10	30	3	53	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3	439		92	23	5330
335	0	48			3	33	3	1.5	10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
336	0	54			10	34	3		6.1	37.9	43	363.5	15	10	0.35	8	1	0	7		6		88	19	1090
337	0	60		11	10	35	3			9.8	39	404.4	-5	1	0.25	7	1	0	1		24		80	9	7270
338	0	48			6	38	3	5.5	10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
339	0			20	3	39	3	6	3.9	38.5	24	276.9	15	20	0.5	8	3	18	9		12		82	15	420
340	0	53			5	40	3	9	9.4	50.4	43	370	15	10	0.25	7	2	10	10		12		87	37	30
341	0	55			7	41	3		6.1	37.9	43	363.5	15	10	0.35	8	1	0	7		8		88	19	1090
342	0	40		17	25	42	3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
343	0	34				43	3		2.6	8	63	497.6	-15	0.25	0.05	6	2	30	2				104	33	2160
344	0	41			1	43	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11				90	53	10
345	0	51			6	43	3	2.5	10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
346	0	62			29	45	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
347	0	60		11	12	48	3			9.8	39	404.4	-5	1	0.25	7	1	0	1		10		80	9	7270
348	0	42		17	9	49	3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
349	0	48			0	50	3	0.5	7.5	45.3	43	374.4	5	10	0.35	7	3	15	10				90	36	240
350	0				7	50	3	20	6.2	33.8	60	396.4	-5	1	0.2	8	2	10	6				92	28	1290
351	0			17	20	50	3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2				97	34	2870
352	0	55			31	50	3	15	7.5	45.3	43	374.4	5	10	0.35	7	3	15	10		12		90	36	240
353	0	56	40	11	15	52	3		4	30	51	499.9	-15	0.25	0.1	5	3	50	2		58	1.40E-02	95	39	2870
354	0	50		8		53	3		8.7	59.1	53	400	5	1	0.2	7	0	0	11		7		88	59	7
355	0	39		7		53	3	15	2.7	15.8		227.2			0.35			60	13	2			65	8	110
356	0	46		22	8	53	3		4.4	18.7	52	445.6	-15	20	0.2	5	2	30	1		54		93	38	95
357	0	63			32	53	3		4.9	52.1	41	364.9	5	20	0.4	6	2	20	10		15	3.90E-04	88	32	1070
358	0	44		17	44	53	3	10	3.3	16.6	40	363.8	-5	1	0.35	8	1	0	1		22		86	12	3280
359	0	47			4	54	3	2	7.5	45.3	43	374.4	5	10	0.35	7	3	15	10				90	36	240
360	0	60		11	6	54	3			9.8	39	404.4	-5	1	0.25	7	1	0	1		26		80	9	7270
361	0	58			37	54	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
362	0	44			5	55	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11				90	53	10
363	0	56			10	55	3		4.8	32.3	57	400.1	-5	1	0.2	7	0	0	6		16		96	33	550
364	0	56			13	56	3		3.5	39.5	23	271.5	15	20	0.25	5	3	40	2				75	32	320
365	0	60		11	6	63	3			9.8	39	404.4	-5	1	0.25	7	1	0	1		8		80	9	7270

APPENDIX B. (Continued.)

366	0	36			25	78	3	5.6	8.1	29	58	406.6	-5	1	0.2	7	0	0	10				95	41	690
367	0	36			2	23	4		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
368	0	51		7	11	23	4		2.7	15.8		227.2			0.35			60	13	2			65	8	110
369	0	55		7	4	31	4	1	2.7	15.8		227.2			0.35			60	13	2			65	8	110
370	0	50			5	35	4	0.02	10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
371	0	55			21	35	4	2	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
372	0	31			4	36	4	0.1	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3			92	23	5330
373	0	39			8	37	4		2.6	8	72	505.7	-15	0.25	0.05	6	2	20	2				104	33	2160
374	0	50			1	50	4	0.25	10.2	57.5	48	374	15	20	0.35	6	1	0	10				92	38	90
375	1								3.7	29.6	28	300	5	10	0.35	7	1	0	7				79	20	630
376	1								3.7	29.6	28	300	5	10	0.35	7	1	0	7				79	20	630
377	1	56							4.8	32.3	57	400.1	-5	1	0.2	7	0	0	6		16		96	33	550
378	1	57								52.2	41	351.4	15	10	0.35	7	1	0	10		11		88	32	110
379	1	66	39	10					4.8	32.3		400.1	-5	10	0.3	7	0	0	6		8		96	25	550
380	1	73	39	10					4.8	32.3		400.1	-5	10	0.3	7	0	0	6		23		96	25	550
381	1	88	39	10					4.8	32.3		400.1	-5	10	0.3	7	0	0	6		15		96	25	550
382	1			2					5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		24		85	21	830
383	1						1	13	4.8	37.9	34	304.6	5	10	0.5	7	1	10	6				85	20	810
384	1	48				35	1	2	3.6	34.1	24	276.9	15	20	0.6	8	2	10	9				81	8	330
385	1	78				13	2			54	38	337.7	15	20	0.3	6	1	10	6	5	31	1.80E-03	89	31	1080
386	1	50		17		20	2	640	3.4	32	66	499.9	-15	0.25	0.05	5	3	40	2				98	31	2300
387	1	34					3			34.4	40	362	5	10	0.45	8	1	0	7	4			88	19	870
388	1	35					3			34.4	40	362	5	10	0.45	8	1	0	7	4			88	19	870
389	1	63					3		1.7	19.8		215.3			0.3			20	13				63	6	50
390	1	64					3		2.6	33	44	367	35	10	0.25	4	1	15	11				83	21	4090
391	1	69					3			29.5	31	314.8	15	10	0.35	8	1	0	7				82	7	920
392	1	49		15			3			39.6	20	288.4	15	20	0.5	8	2	18	9				74	3	750
393	1	55		16			3		3.9	44.8	26	280.6	25	10	0.45	8	2	8	7		20		81	12	500
394	1	74		6			3			43	26	299.6	15	20	0.4	8	3	30	9		76		78	23	50
395	1	48		11			3	3	6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		6	3.50E-05	80	16	100
396	1	72					3	20		35.6	33	353	5	10	0.5	7	1	10	7		14		85	19	740
397	1	80					3	30	3.7	29.6	28	300	5	10	0.35	7	1	0	7		17		79	20	630
398	1	39				14	3	40	5.5	22.2	52	445.6	-15	20	0.2	5	2	20	1		66		94	38	110
399	1	62			5	23	3			34.4	40	362	5	10	0.45	8	1	0	7	4			88	19	870
400	1	58			7	23	3		10	62	47	380	25	20	0.25	6	0	0	11		4		91	46	190
401	1	61			4	25	3	16		35.6	33	353	5	10	0.5	7	1	10	7		6		85	19	740
402	1	60			4	27	3		9.4	50.4	43	370	15	10	0.25	7	2	10	10		14		87	37	30
403	1	73		2	5	27	3		5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
404	1	71		2	9	27	3	16	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
405	1	82		2	3	30	3	10	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7				85	21	830
406	1	58			8	30	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		2		90	53	10
407	1	52		11	1	32	3	7	6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		8	9.20E-05	80	16	100
408	1	52			2	32	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		2		90	53	10
409	1	52			1	33	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		2		90	53	10
410	1	60		2	2	33	3	9	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		17	2.30E-02	85	21	830
411	1	65			6	33	3		3.6	45.8	26	299.6	15	20	0.45	8	2	30	9		17	4.60E-05	83	17	270
412	1	52			3	36	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		2		90	53	10
413	1			20	7	36	3	14	3.9	38.5	24	276.9	15	20	0.5	8	3	18	9		25		82	15	420
414	1	61			2	37	3		7.6	42.3	28	299.6	15	20	0.45	8	2	30	7				83	16	250
415	1	54			15	38	3		6.2	28.2	63	412.4	-15	1	0.2	8	1	0	6		6		97	18	990
416	1	52				39	3		6.3	53	50	376.5	15	20	0.25	6	1	10	10		12		91	38	170
417	1	79		2	7	40	3	13	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		8		85	21	830
418	1	71		17	20	40	3	150	3.4	32	66	499.9	-15	0.25	0.05	5	3	40	2				98	31	2300
419	1	70		2	4	43	3			16	36	410	-15	1	0.3	6	2	10	3		333		93	21	3000
420	1	76	35	13	6	43	3			44.4	35	327.6	15	20	0.45	8	1	10	10		7	2.00E-02	87	27	30
421	1	52			28	43	3	56	5.5	22.2	52	445.6	-15	20	0.2	5	2	20	1		64		94	38	110
422	1	34			1	44	3			34.4	40	362	5	10	0.45	8	1	0	7	4			88	19	870
423	1	47			6	53	3	4	5.5	22.2	52	445.6	-15	20	0.2	5	2	20	1		81		94	38	110
424	1	60			33	53	3		1.7	19.8		215.3			0.3			20	13				63	6	50
425	1	62		2	14	54	3	9	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		25		85	21	830
426	1	55		12	35	54	3		2.6	7.6	71	507.1	-15	0.25	0.05	6	2	15	2		210		102	39	1450
427	1	61		2	22	55	3	35	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		18	7.90E-02	85	21	830

APPENDIX B. (Continued.)

428	1	66			23	58	3	19		35.6	33	353	5	10	0.5	7	1	10	7		6		85	19	740
429	1	74		11	40	94	3			9.8	39	404.4	-5	1	0.25	7	1	0	1		17		80	9	7270
430	1				7	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		9		68	45	370
431	1	38			8	40	4		15	87.3		439.6									482		87	74	250
432	1	61			20	40	4	26		27.6	30	303.8	5	10	0.2	7	1	10	7	4	5		82	18	580
433	1				3	49	4	14	15	87.3		439.6											87	74	250
434	1	68			22	52	4	32	1.9	8.3	62	495.7	-15	0.25	0.3	7	2	15	2	3	396		92	23	5330
435	2								10.7	56	50	404.7	5	10	0.2	6	0	0	11				90	53	10
436	2	45							9.5	43.8		444.5						0	12				84	62	840
437	2	48							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10		6		86	32	10
438	2	48							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10		6		86	32	10
439	2	48							7	55.4	47	375.6	15	20	0.35	6	1	0	10		9	4.30E-02	92	34	330
440	2	48							9.5	43.8		444.5						0	12				84	62	840
441	2	50							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10		4		86	32	10
442	2	53							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10		11	5.70E-05	95	39	790
443	2	54							10	62	47	380	25	20	0.25	6	0	0	11		5	2.50E-04	91	46	190
444	2	57							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10		39	3.80E-03	95	39	790
445	2	59							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10		18	2.40E-04	95	39	790
446	2	64							9	55.5	47	399.8	15	20	0.3	6	0	0	11		8		89	46	20
447	2	66							9.5	43.8		444.5						0	12				84	62	840
448	2	63		18					1.8	15.8	39	332	-5	10	0.2	6	2	8	1	5	32		82	21	2460
449	2	62		20					3.9	38.5	24	276.9	15	20	0.5	8	3	18	9		38		82	15	420
450	2			8		17						440			0.1		1			3	18	6.30E-04			
451	2	55		11		38	1		6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		7		80	16	100
452	2					17	2		10.7	56	50	404.7	5	10	0.2	6	0	0	11				90	53	10
453	2			17	7	23	2		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2		91		97	34	2870
454	2	38					3		3.3	15.4	41	425.4	-5	1	0.1	6	1	0	4		13		88	16	5290
455	2	57					3			27.1		198.7			0.1			0	13		8		53	6	460
456	2	57				21	3		4.9	50.8	42	374.4	5	10	0.4	7	3	15	10		47	2.50E-02	89	34	250
457	2	60		11	13	24	3			9.8	39	404.4	-5	1	0.25	7	1	0	1		23		80	9	7270
458	2	75			8	25	3	40		27.6	30	303.8	5	10	0.2	7	1	10	7	4	5	1.50E-05	82	18	580
459	2	73		5		28	3			14.8		208.3			0.45			40	13	3	11	2.50E-02	71	-20	550
460	2	81	49	5	6	28	3	37	2	19.6	40	434.9	-5	0.25	0.25	6	3	30	1		20	8.20E-05	88	21	4790
461	2	53		7		30	3		2.7	15.8		227.2			0.35			60	13	2		2.70E-02	65	8	110
462	2	62		17	11	30	3	40	3.3	16.6	40	363.8	-5	1	0.35	8	1	0	1		24		86	12	3280
463	2	48		17	1	31	3	1	3.3	16.6	40	363.8	-5	1	0.35	8	1	0	1		20		86	12	3280
464	2	68			4	31	3	12	9.4	50.4	43	370	15	10	0.25	7	2	10	10		9		87	37	30
465	2	60			9	32	3	3	9.1	27.1	30	317.4	5	10	0.4	8	1	0	7		18	1.70E-02	84	3	830
466	2	71			11	33	3		10	62	47	380	25	20	0.25	6	0	0	11		7		91	46	190
467	2	72		16	13	35	3	22	3.9	44.8	26	280.6	25	20	0.45	8	2	8	7		13	1.30E-02	81	12	500
468	2			13	19	35	3			44.4	35	327.6	15	20	0.45	8	1	10	10		9		87	27	30
469	2	44		16	1	36	3		3.9	44.8	26	280.6	25	20	0.45	8	2	8	7		6		81	12	500
470	2				5	36	3		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		49		68	45	370
471	2	47				37	3			6.7	72	500	-15	0.25	0.15	7	1	0	2		26		95	29	4090
472	2	67			10	37	3		9.4	51.8	43	364.8	5	10	0.2	7	3	20	10		12		90	37	40
473	2	66	40	11	22	37	3		4	30	51	499.9	-15	0.25	0.1	5	3	50	2		32		95	39	2870
474	2	50		17	13	38	3		2.9	32	66	499.9	-15	0.25	0.1	5	3	30	2		109		97	34	2870
475	2	51		21	17	38	3			16.7	46	445.6	-15	10	0.2	5	3	30	2		7	4.90E-04	85	40	60
476	2	61			25	38	3			16.1	33	319.6	-5	0.25	0.25	8	1	0	7		19		81	-1	1670
477	2	59			2	39	3		9.4	51.8	43	364.8	5	10	0.2	7	3	20	10		7	1.40E-03	90	37	40
478	2	50		16	4	40	3		3.9	44.8	26	280.6	25	20	0.45	8	2	8	7		3		81	12	500
479	2	63		19	13	40	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2		20	4.10E-05	93	39	1540
480	2	68			12	42	3		6.5	35.4	30	329.6	5	10	0.3	7	1	0	7		8		84	13	670
481	2	62		19	8	43	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2		34	2.00E-03	93	39	1540
482	2	69			16	43	3			34.1	27	280.5	-5	20	0.3	8	3	20	7		2	9.00E-06	81	18	320
483	2	62		19	28	43	3		3.1	30	51	499.9	-15	0.25	0.1	5	3	50	2		17		93	39	1540
484	2	53		16	4	45	3	4.5	3.9	44.8	26	280.6	25	20	0.45	8	2	8	7		19	2.00E-03	81	12	500
485	2	61			9	45	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		3		90	53	10
486	2	63		5	10	45	3			14.8		208.3			0.45			40	13	3	9		71	-20	550
487	2	56			24	45	3		3.5	36.9		270.1	15	20	0.5	8	1	8	7		13	6.70E-03	79	15	1600
488	2	56			26	45	3		3.5	36.9		270.1	15	20	0.5	8	1	8	7		6	2.80E-04	79	15	1600
489	2				28	45	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		8		90	53	10

APPENDIX B. (Continued.)

490	2	65			27	48	3	40	15	87.3		439.6									481		87	74	250
491	2	59			5	49	3			46.3	43	374.1	5	20	0.35	6	1	0	10		21		92	38	310
492	2	63		2		50	3	23	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		9		85	21	830
493	2	50			20	50	3		9	55.5	47	399.8	15	20	0.3	6	0	0	11		5		89	46	20
494	2	50			4	53	3		15.3	21.4		444.5						0	12	4	4		87	65	4
495	2	51			9	53	3		6.3	53	50	376.5	15	20	0.25	6	1	10	10		16		91	38	170
496	2	35		21	14	53	3			16.7	46	445.6	-15	10	0.2	5	3	30	2		10	8.60E-04	85	40	60
497	2	67			15	53	3	28	8.1	29	58	406.6	-5	1	0.2	7	0	0	10		11		95	41	690
498	2	71			21	53	3		10	62	47	380	25	20	0.25	6	0	0	11		7		91	46	190
499	2	59		17	22	53	3	20	3.3	16.6	40	363.8	-5	1	0.35	8	1	0	1		20		86	12	3280
500	2	65			25	65	3	9		27.6	30	303.8	5	10	0.2	7	1	10	7	4	4	2.40E-05	82	18	580
501	2	56		2	15	70	3	6.5	5.3	38.4	34	314.9	15	10	0.25	7	2	15	7		31		85	21	830
502	2						4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		23		68	45	370
503	2				7	35	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		68		68	45	370
504	2				12	36	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		42		68	45	370
505	2				2	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		15		68	45	370
506	2				2	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		16		68	45	370
507	2				4	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		29		68	45	370
508	2				7	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		13		68	45	370
509	2				7	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		31		68	45	370
510	2				26	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		22		68	45	370
511	2				26	37	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		31		68	45	370
512	2	56			17	40	4	30	5.7	46.9	45	380	15	10	0.3	7	1	0	11		15	4.80E-04	91	42	230
513	2	83			8	45	4	15	8.1	29	58	406.6	-5	1	0.2	7	0	0	10		10		95	41	690
514	2				17	54	4		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		70		68	45	370
515	3								15	87.3		439.6									284		87	74	250
516	3	49							6.5	44.2	40	359.5	15	10	0.25	7	1	10	10		3		86	32	10
517	3	49							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10		20	1.10E-04	95	39	790
518	3	51							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10		10	5.30E-06	95	39	790
519	3	53							6.5	29.6	58	406.6	-5	1	0.2	7	0	0	10		10	5.50E-05	95	39	790
520	3	60								121.2		444.5						0	12	3	2	4.50E-02	83	55	700
521	3	71							9.4	51.8	43	364.8	5	10	0.2	7	3	20	10		8		90	37	40
522	3	86	39	10					4.8	32.3		400.1	-5	10	0.3	7	0	0	6		12		96	25	550
523	3	51		5						14.8		208.3			0.45			40	13	3	8		71	-20	550
524	3			11			1		6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		8	1.30E-04	80	16	100
525	3	55	35	13			3			44.4	35	327.6	15	20	0.45	8	1	10	10		10		87	27	30
526	3	58				22	3		10.7	56	50	404.7	5	10	0.2	6	0	0	11		4		90	53	10
527	3	54		11	2	23	3		6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		8	2.10E-05	80	16	100
528	3	51		21	5	23	3			16.7	46	445.6	-15	10	0.2	5	3	30	2		26	2.90E-04	85	40	60
529	3	47			0	30	3			46.3	43	374.1	5	20	0.35	6	1	0	10		18		92	38	310
530	3	73	52	4	13	30	3			46.3	43	374.1	5	20	0.35	6	1	0	10		21		92	38	310
531	3	60		11	11	31	3	23	6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		3		80	16	100
532	3	63		5	7	35	3			14.8		208.3			0.45			40	13	3	7		71	-20	550
533	3	80		15		39	3			39.6	20	288.4	15	20	0.5	8	2	18	9		28	1.40E-02	74	3	750
534	3	56			19	39	3		4.8	32.3	57	400.1	-5	1	0.2	7	0	0	6		26		96	33	550
535	3	57			24	40	3		3.5	36.9		270.1	15	20	0.5	8	1	8	7		6	4.20E-03	79	15	1600
536	3	68			2	42	3		9.4	51.8	43	364.8	5	10	0.2	7	3	20	10		8		90	37	40
537	3	60		11	8	42	3	7	6.7	43.8	25	285.6	15	20	0.45	8	2	30	9		10	4.10E-04	80	16	100
538	3	65			3	43	3	2	15	87.3		439.6									458		87	74	250
539	3	58			12	44	3			46.3	43	374.1	5	20	0.35	6	1	0	10		21	8.40E-04	92	38	310
540	3	66			19	45	3		5.3	52	46	400	5	1	0.2	7	0	0	11		8	9.30E-02	90	48	10
541	3	75	49	5	20	48	3		2	19.6	40	434.9	-5	0.25	0.25	6	3	30	1		17		88	21	4790
542	3	65				50	3	20	15	87.3		439.6									370		87	74	250
543	3					53	3		4.3	13.4	43	436.1	-15	1	0.15	5	3	80	2		18		68	45	370
544	3	68			14	35	4	14	7.6	42.3	28	299.6	15	20	0.45	8	2	30	7				83	16	250
545	3	65		15	4	43	4			39.6	20	288.4	15	20	0.5	8	2	18	9		18	3.30E-02	74	3	750