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**US Army Corps
of Engineers**

Hydrologic Engineering Center

Modifying Reservoir Operations To Improve Capabilities for Meeting Water Supply Needs During Drought

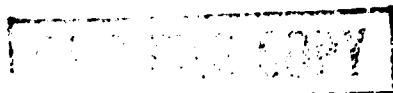
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MODIFYING RESERVOIR OPERATIONS
TO IMPROVE CAPABILITIES FOR MEETING
WATER SUPPLY NEEDS DURING DROUGHTS

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This report was prepared by Dr. Ralph A. Wurbs, Associate Professor of Civil Engineering, Texas A & M University while working at the Hydrologic Engineering Center, U. S. Army Corps of Engineers under an Inter-governmental Personnel Act (IPA) contract.

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) owns and operates over 500 reservoirs, including locks and dams, located throughout the nation. Reallocation of storage capacity between purposes and other modifications in the operation of existing reservoirs have received increased attention in recent years. Conversion of storage capacity from water quality, hydroelectric power, or flood control to municipal and industrial water supply has been particularly of concern. The benefits of improved system operations, involving coordination of water supply releases from multiple reservoirs and diversions from unregulated flows, have also been emphasized. Recent drought conditions experienced over large sections of the nation have focused attention on optimizing the effectiveness of reservoirs in dealing with droughts.

This report provides an evaluation of the role of storage reallocations and other modifications in reservoir operations in meeting water needs during drought conditions and an evaluation of capabilities for formulating, evaluating, and implementing such changes. The study documented here focuses primarily on the development of long-term water supply storage capacity and operating procedures in preparation for future droughts but also addresses emergency actions taken during droughts. The objectives of the study are:

- (1) to compile and review available pertinent information regarding storage reallocation and other operational strategies for increasing water supply capabilities of completed USACE reservoir projects,
- (2) to analyze potentialities and identify key considerations and issues in reservoir storage allocation and operations, and
- (3) to assess present capabilities and identify needs for expanded capabilities for formulating, evaluating, and implementing plans for modifying reservoir operations.

This report is organized as follows. First, legislative authority and USACE policy are outlined in regard to increasing water supply capabilities by modifying storage allocations and operating procedures for completed projects. Past studies and projects involving modifications are then reviewed. The next section provides a discussion of potentialities, issues, and considerations based largely on a review of past studies and information collected from USACE offices. A comprehensive review of the published literature has also been conducted. An evaluation of present modeling and analysis capabilities and associated research needs is covered in the last section of the report. A summary and conclusions follows.

LEGISLATIVE AUTHORITY FOR MODIFYING RESERVOIR OPERATIONS TO INCREASE WATER SUPPLY CAPABILITIES

Authority for studying and implementing storage reallocations and other changes in the operation of completed projects is contained in the basic omnibus legislation which covers federal water resources development activities in general. Optimizing the operation of existing reservoirs is an integral part of the overall USACE civil works mission. Legislation which is particularly pertinent to increasing the water supply capabilities of completed USACE reservoir projects is cited below. These acts of Congress established the general laws under which the USACE can study and implement changes in the use of available reservoir storage capacity. Initial project construction and significant structural or operational modifications of completed projects require Congressional authorization of each specific project in addition to the general policy legislation addressed here. An overview of pertinent legislation is presented below followed by selected excerpts copied verbatim from the legislative acts.

General Overview of Legislation

Authority for USACE activities in navigation is provided by a series of river and harbor acts and other legislation dating back to 1824. The Flood Control Act of 1936 and subsequent legislation established the USACE flood damage reduction programs. The Reclamation Act of 1902 initiated the Bureau of Reclamation activities in providing irrigation in the West. Numerous other statements of policy have established the concept of comprehensive multiple purpose water resources development. EP 1165-2-1 dated 15 February 1989 and entitled "Digest of Water Resources Policies and Authorities" provides a summary overview of legislation pertinent to USACE and related federal water resources development and management programs.

The Flood Control Act of 1944 (Public Law 78-534) first addressed the use of USACE reservoirs for water supply purposes. Section 6 authorized the Secretary of the Army to execute contracts for surplus water with states, municipalities, private concerns, or individuals at such prices and on such terms as he may deem reasonable. These contracts may be for domestic, municipal, and industrial uses, but not for crop irrigation, from surplus water that may be available at any reservoir under the control of the Department of the Army. Section 8 provides that USACE reservoirs may include irrigation as a project purpose upon the recommendation of the Secretary of the Interior in conformity with reclamation law. Section 8 is applicable only in the 17 western states to which reclamation law applies.

Municipal and industrial (M&I) water supply has traditionally been a nonfederal responsibility. However, the concept of comprehensive multipurpose water resources development is an integral part of the federal water program. Although M&I water supply was already being included in federal reservoirs prior to 1958, the Water Supply Act of 1958 (Title III of Public Law 85-500) established a uniform policy. Under the provisions of this law, the federal water agencies may provide additional storage capacity for M&I water supply in reservoirs to be constructed primarily for federal purposes such as navigation, flood control, and irrigation. Water supply storage capacity can be included to meet anticipated future as well as present needs or demands. Before construction or modification of any project incorporating M&I water

supply, state or local interests must agree to pay for all costs allocated to water supply. Cost allocation is based on the premise that all authorized purposes shared by a project should share equitably in the benefits of multipurpose construction. As discussed later, the Water Supply Act of 1958 includes specific requirements regarding repayment of costs allocated to water supply which were later amended by the Water Resources Development Act of 1986.

Section 216 of the River and Harbor and Flood Control Act of 1970 (Public Law 91-611) authorizes the USACE to review the operation of completed projects, when warranted by changed physical or economic conditions, and to report to Congress regarding recommendations for modifying the structures or their operation.

Section 65 of the Water Resources Development Act of 1974 (Public Law 93-251) allows water quality storage in federal reservoirs to be converted to other uses under appropriate conditions.

The Water Resources Development Act of 1986 (Public Law 99-662) was the first omnibus water bill to be passed since the Water Resources Development Act of 1976. This 10-year interval between omnibus water bills was quite lengthy compared with the typically 2-year interval between omnibus bills during the preceding several decades. The Water Resources Development Act of 1986 instituted a number of changes in water policy, the most notable being changes in nonfederal cost sharing requirements. Sections 931 and 932 of this law are particularly pertinent to a discussion of storage reallocation.

Section 931 of the Water Resources Development Act of 1986 amended Section 8 of the Flood Control Act of 1944. Section 931 authorizes interim allocation of future water supply storage for irrigation purposes.

Section 932 of the Water Resources Development Act of 1986 modified the nonfederal repayment provisions of the water supply Act of 1958. The 1986 amendments were directed to USACE projects only. The 1958 provisions are still valid for Bureau of Reclamation projects. The Water Supply Act of 1958 allowed repayment by nonfederal sponsors of costs allocated to M&I water supply, with interest, over a period not to exceed 50 years. Repayment for future water supply could be delayed for an interest-free period of up to ten years. For USACE projects, the Water Resources Development Act of 1986 limits the repayment period to 30 years and eliminates the 10-year interest-free period for future water supply. The formula for setting the interest rate was also changed. More stringent requirements were also established for payments of annual operation and maintenance costs allocated to water supply.

Section 5 of the Water Resources Development Act of 1988 (Public Law 100-662) requires that there be opportunity for public review and comment before implementing reservoir storage reallocations or other changes in operations which significantly affect any project purpose.

The legislative acts cited above provide authorization for the USACE to develop long-term water supply storage capacity and operating procedures in preparation for future droughts and also to modify the use of storage during droughts. Other legislation is directed specifically to other types of emergency actions. Section 5 of the Flood Control Act of 1941 (Public Law 77-228) authorized an emergency fund to be used for flood emergency preparation,

flood fighting, and repair and restoration of flood control works. Section 82 of the Water Resources Development Act of 1974 (Public Law 93-251) amended Section 5 of the 1941 Flood Control Act to authorize providing emergency supplies of clean drinking water when contaminated supplies are a threat to public health and welfare in a locality. This provision was directed toward water supply contamination resulting from floods. The Disaster Relief Act of 1974 Appropriations Act (Public Law 95-51) further amended Section 5 of the 1941 Flood Control Act to allow the USACE to construct wells and provide emergency water supplies during droughts. Section 917 of the Water Resources Development Act of 1986 further amends Section 5 of the 1941 Flood Control Act to authorize provision of emergency supplies of clean water, whether for drinking or other critical needs. USACE assistance in providing emergency water supplies under these authorities is contingent on emergency services not being available from any other entity.

Reproduction of Selected Sections of Legislation

The sections of public laws considered particularly pertinent to the subject being addressed by the present report are relatively short and concise and thus are excerpted below for convenient reference. The excerpts are copied verbatim from the legislative acts.

Flood Control Act of 1944 (Public Law 78-534), Sections 6 and 8

"Sec. 6. That the Secretary of War is authorized to make contracts with States, municipalities, private concerns, or individuals, at such prices and on such terms as he may deem reasonable, for domestic and industrial uses for surplus water that may be available at any reservoir under the control of the War Department: *Provided*, That no contracts for such water shall adversely affect then existing lawful uses of such water. All moneys received from such contracts shall be deposited in the Treasury of the United States as miscellaneous receipts."

"Sec. 8. Hereafter, whenever the Secretary of War determines, upon recommendation by the Secretary of the Interior that any dam and reservoir project operated under the direction of the Secretary of War may be utilized for irrigation purposes, the Secretary of the Interior is authorized to construct, operate, and maintain, under the provisions of the federal reclamation laws (Act of June 17, 1902, 32 Stat. 388, and Acts amendatory thereof or supplementary thereto), such additional works in connection therewith as he may deem necessary for irrigation purposes. Such irrigation works may be undertaken only after a report and findings thereon have been made by the Secretary of the Interior as provided in said Federal reclamation laws and after subsequent specific authorization of the Congress by an authorization Act; and, within the limits of the water users repayment ability such report may be predicated on the allocation to irrigation of an appropriate portion of the cost of structures and facilities used for irrigation and other purposes. Dams and reservoirs operated under the direction of the Secretary of War may be utilized hereafter for irrigation purposes only in conformity with the provisions of this section, but the foregoing requirement shall not prejudice lawful uses now existing: *Provided*, That this section shall not apply to any dam or reservoir heretofore constructed in whole or in part by the Army engineers, which provides conservation storage of water for irrigation purposes."

Water Supply Act of 1958 (Title III of Public Law 85-500)

"Sec. 301. (a) It is hereby declared to be the policy of the Congress to recognize the primary responsibilities of the States and local interests in developing water supplies for domestic, municipal, industrial, and other purposes and that the Federal Government should participate and cooperate with States and local interests in developing such water supplies in connection with the construction, maintenance, and operation of Federal navigation, flood control, irrigation, or multiple purpose projects.

(b) In carrying out the policy set forth in this section, it is hereby provided that storage may be included in any reservoir project surveyed, planned, constructed or to be planned, surveyed and/or constructed by the Corps of Engineers or the Bureau of Reclamation to impound water for present or anticipated future demand or need for municipal or industrial water, and the reasonable value thereof may be taken into account in estimating the economic value of the entire project: *Provided*, That before construction or modification of any project including water supply provisions is initiated, State or local interests shall agree to pay for the cost of such provisions on the basis that all authorized purposes served by the project shall share equitably in the benefits of multiple purpose construction as determined by the Secretary of the Army or the Secretary of the Interior as the case may be: *Provided further*, That not to exceed 30 per centum of the total estimated cost of any project may be allocated to anticipated future demands where States or local interests give reasonable assurances that they will contract for the use of storage for anticipated future demands within a period of time which will permit paying out the costs allocated to water supply within the life of the project: *And provided further*, That the entire amount of the construction costs, including interest during construction, allocated to water supply shall be repaid within the life of the project but in no event to exceed fifty years after the project is first used for the storage of water for water supply purposes, except that (1) no payment need be made with respect to storage for future water supply until such supply is first used, and (2) no interest shall be charged on such cost until such supply is first used, but in no case shall the interest-free period exceed ten years. The interest rate used for purposes of computing interest during construction and interest on the unpaid balance shall be determined by the Secretary of the Treasury, as of the beginning of the fiscal year in which construction is initiated, on the basis of the computed average interest rate payable by the Treasury upon its outstanding marketable public obligations which are neither due nor callable for redemption for fifteen years from date of issue. The provisions of this subsection insofar as they relate to the Bureau of Reclamation and the Secretary of the Interior shall be alternative to and not a substitute for the provisions of the Reclamation Projects Act of 1939 (53 Stat. 1187) relating to the same subject.

(c) The provisions of this section shall not be construed to modify the provisions of section 1 and section 8 of the Flood Control Act of 1944 (59 Stat. 887), as amended and extended, or the provisions of section 8 of the Reclamation Act of 1902 (32 Stat. 390).

(d) Modifications of a reservoir project heretofore authorized, surveyed, planned, or constructed to include storage as provided in subsection (b), which would seriously affect the purposes for which the project was authorized, surveyed, planned, or constructed, or which would involve

major structural or operational changes shall be made only upon the approval of Congress as now provided by law.
Sec. 302. Title III of this Act may be cited as the "Water Supply Act of 1958".
Approved July 3, 1958."

River and Harbor and Flood Control Act of 1970 (Public Law 91-611),
Section 216

"Sec. 216. The Secretary of the Army, acting through the Chief of Engineers, is authorized to review the operation of projects the construction of which has been completed and which were constructed by the Corps of Engineers in the interest of navigation, flood control, water supply, and related purposes, when found advisable due the significantly changed physical or economic conditions, and to report thereon to Congress with recommendations on the advisability of modifying the structures or their operation, and for improving the quality of the environment in the overall public interest."

Water Resources Development Act of 1974 (Public Law 93-251). Section 65

"Sec. 65. In the case of any reservoir project authorized for construction by the Corps of Engineers, Bureau of Reclamation, or other Federal agency when the Administrator of the Environmental Protection Agency determines pursuant to section 102 (b) of the Federal Water Pollution Control Act that any storage in such project for regulation of streamflow for water quality is not needed, or is needed in a different amount, such project may be modified accordingly by the head of the appropriate agency, and any storage no longer required for water quality may be utilized for other authorized purposes of the project when, in the opinion of the head of such agency, such use is justified. Any such modification of a project where the benefits attributable to water quality are 15 per centum or more but not greater than 25 per centum of the total project benefits shall take effect only upon the adoption of resolutions approving such modification by the appropriate committees of the Senate and House of Representatives. The provisions of the section shall not apply to any project where the benefits attributable to water quality exceed 25 per centum of the total project benefits."

Water Resources Development Act of 1986 (Public Law 99-662). Sections 931
and 932

"SEC. 931. INTERIM USE OF WATER SUPPLY FOR IRRIGATION.

Section 8 of the Act of December 22, 1944 (58 Stat. 891; 43 U.S.C. 390), is amended by adding at the end the following: "In the case of any reservoir project constructed and operated by the Corps of Engineers, the Secretary of the Army is authorized to allocate water which was allocated in the project purpose for municipal and industrial water supply and which is not under contract for delivery, for such periods as he may deem reasonable, for the interim use for irrigation purposes of such storage until such storage is required for municipal and industrial water supply. No contracts for the interim use of such storage shall be entered into

which would significantly affect then-existing uses of such storage."

"SEC. 932. WATER SUPPLY ACT AMENDMENTS.

(a) Section 301 (b) of the Water Supply Act of 1958 (72 Stat. 319;43 U.S.C. 390b(b)), is amended as follows:

(1) in the third proviso, after "That" insert the following: "(1) for Corps of Engineers projects, not to exceed 30 percent of the total estimated cost of any project may be allocated to anticipated future demands, and, (2) for Bureau of Reclamation projects,"

(2) in the fourth proviso, after "That" insert the following: "for Corps of Engineers projects, the Secretary of the Army may permit the full non-Federal contribution to be made, without interest, during construction of the project, or, with interest, over a period of not more than thirty years from the date of completion, with repayment contracts providing for recalculation of the interest rate at, five-year intervals, and for Bureau of Reclamation projects,"

(3) after the first sentence insert the following: "For Corps of Engineers projects, all annual operation, maintenance, and replacement costs for municipal and industrial water supply storage under the provisions of this section shall be reimbursed from State or local interests on an annual basis. For Corps of Engineers projects, any repayment by a State or local interest shall be made with interest at a rate to be determined by the Secretary of the Treasury, taking into consideration the average market yields on outstanding marketable obligations of the United States with remaining periods to maturity comparable fiscal year in which costs for the construction of the project are first incurred (or, when a recalculation is made), plus a premium of one-eighth of one percentage point for transaction costs.", and

(4) strike out "The interest rate used" and insert in lieu thereof: "For Bureau of Reclamation projects, the interest rate used".

(b) Nothing in this section shall be deemed to amend or require amendment of any valid contract entered into pursuant to the Water supply Act of 1958, or Federal reclamation law and approved by the Secretary of the Army or the Secretary of the Interior prior to the date of enactment of this Act."

Water Resources Development Act of 1988 (Public Law 100-662). Section 5

"SEC. 5. COMMENTS ON CERTAIN CHANGES IN OPERATIONS OF RESERVOIRS

Before the Secretary may make changes in the operation of any reservoir which will result in or require a reallocation of storage space in such reservoir or will significantly affect any project purpose, the Secretary shall provide an opportunity for public review and comment."

CORPS OF ENGINEERS' POLICIES

Study Authority and Funding

Studies of the feasibility of increasing water supply capabilities provided by existing reservoirs can be accomplished in various ways. For example, modifying operation of existing reservoirs may be one of many alternative plans considered during the plan formulation process of a comprehensive planning study. Alternatively, storage reallocation and other changes in operating policies may be investigated during a general review of completed projects. In other cases, local interests facing water supply problems may request a study of a specific storage reallocation plan. Modifications in reservoir operations may also be considered in drought contingency planning or during an emergency response to a water shortage situation.

Planning studies and reports provide a basis for Congressional authorization of project construction or modification of completed projects. Studies for project authorization are undertaken in response to either a study-specific authority or a standing authority. A study-specific authorization may be a resolution from the appropriate House of Representatives or Senate committee or may be included in a public law. Standing authorities are contained in legislation such as Section 216 of the 1970 Flood Control Act. As previously discussed, Section 216 authorizes investigations involving modification of completed projects or their operation. Modifications to operations of existing projects can be investigated under either study-specific authority or Section 216 authority.

Federal water resources planning is conducted in accordance with the "Economic and Environmental Principles for Water and Related Land Resources Implementation Studies," dated 3 February 1983, and "Economic and Environmental Guidelines for Water and Land Resources Implementation Studies," dated 10 March 1983. USACE planning procedures are outlined in the Planning Guidance Notebook of the engineering regulation series ER 1105-2-10, -20, -30, -35, -40, -50, and -60. Upon finalization, draft ER 1105-2-100, dated 15 May 1989 and entitled "Guidance for Conducting Civil Works Planning Studies," will replace the Planning Guidance Notebook. Requirements for developing drought contingency plans for completed projects are outlined in ER 1110-2-1971, dated 15 September 1981.

In the past, planning studies were conducted at 100% federal expense. However, the Water Resources Development Act of 1986 instituted a two phase study process consisting of a reconnaissance study followed by a feasibility study. Reconnaissance studies are conducted at full federal cost and are limited to 12 months, with a possible extension to 18 months under unusual circumstances. The primary objective of a reconnaissance study is to determine whether proceeding to the more detailed feasibility stage is warranted. The objective of feasibility studies is to investigate and recommend solutions to water resources problems. Feasibility studies are cost shared 50/50 with a non-federal sponsor. The requirement for 50% of the cost of the feasibility phase of the study to be borne by a nonfederal sponsor represents a significant change over past practice.

Authorization and funding are two separate processes. The annual

budgeting and Congressional appropriation process includes various categories of funds. Planning studies, including storage reallocation and reservoir operation studies, conducted under study-specific or Section 216 authorities are normally funded through the general investigations category of appropriations. The federal share of the feasibility phase of a reservoir modification study will normally be conducted using general investigations funds. Reconnaissance studies of reservoir modifications may be performed with either general investigations or operations and maintenance funds. For a relatively minor modification, which involves little cost and does not require detailed feasibility studies or Congressional authorization for implementation, operation and maintenance funds may also be used to complete the modification fully at federal expense.

The discussion above addressed feasibility studies which potentially could result in recommendations for Congressional authorization of construction or modification of USACE projects. Storage reallocations and other modifications in reservoir operations are normally investigated under these traditional types of study authorities. However, the USACE also has a Planning Assistance to States Program. Potentialities for increasing water supply capabilities may also be studied under this program. Section 22 of the Water Resources Development Act of 1974 authorized the USACE to cooperate with any state in preparation of comprehensive regional plans for water resources development, utilization, and conservation. Planning assistance is provided on the basis of a request from a state rather than through Congressional study authorization. Section 22 authorizes appropriation of funds for this program not to exceed \$6,000,000 annually, with not more than \$300,000 to be expended in any one year in any one state. Whereas Section 22 authority applies to all the states, several other expanded authorities have been provided for specific states or river basins. Planning assistance can be provided for New York under Section 214 of the Flood Control Act of 1965, Puerto Rico under the Flood Control Act of 1970, and the Hudson River Basin and Red River of the North Basin under Sections 49 and 50, respectively, of the Water Resources Development Act of 1988.

Implementation Authority and Cost Sharing

Authority for implementing modifications to the operation of completed projects and associated cost sharing requirements are outlined below for the following categories of authorization: (1) modifications under authority of the Water Supply Act of 1958, (2) disposal of surplus water under authority of the Flood Control Act of 1944, (3) interim use of M&I water supply storage for irrigation under authority of the Water Resources Development Act of 1986, and (4) emergency response to natural disasters under authority of Public Laws 93-251, 95-51, and 99-662. The information presented below, in regard to categories 1-3, is based upon and is discussed in greater detail by ER 1105-2-20, dated 15 May 1985, and draft ER 1105-2-100, dated 15 May 1989. Category 4 is covered by ER 500-1-1 dated 21 December 1984.

Reallocation of Storage Capacity and Other Modifications

Authority for including M&I water supply storage capacity in federal reservoirs is provided by the Water Supply Act of 1958. M&I water supply storage capacity can be included in the original project authorization and construction, or completed projects can later be modified. Major structural or operational modifications to completed projects require Congressional

authorization. Relatively minor storage reallocations or other changes in operating procedures can be made by the federal agencies without seeking Congressional approval. USACE policy, as expressed in ER 1105-2-20 and draft ER 1105-2-100, is reproduced below.

"Reallocation or addition of storage that would have a significant effect on other authorized purposes or that would involve major structural or operational changes requires Congressional approval. Providing the above criteria are not violated, 15 percent of total storage capacity allocated to all authorized project purposes or 50,000 acre-feet, whichever is less, may be allocated from storage authorized for other purposes or may be added to the project to serve as storage for municipal and industrial water supply at the discretion of the Commander, USACE. Reallocations which exceed the Commander's authority may be approved at the discretion of the Secretary of the Army if such reallocations do not require Congressional approval as described above."

Costs allocated to M&I water supply must be repaid by nonfederal sponsors. A contract for use of the reallocated storage capacity must be executed between the nonfederal sponsor and federal agency. The contract will contain a repayment schedule. Local interests are responsible for repayment of all initial investment costs and ongoing annual operation, maintenance, and replacement costs incurred specifically due to the reallocation to M&I water supply plus an equitable share of the joint cost of the original project. The joint costs for a reallocation will normally be established as the highest of the (1) benefits or revenues foregone, (2) replacement cost, or (3) updated cost of storage in the federal project.

Benefits foregone, associated with flood control or other project purposes, are estimated using standard USACE economic evaluation procedures. Revenues foregone are the reduction in revenues which would result from a reduction in hydroelectric power output.

If flood control storage capacity is being reallocated to M&I water supply, the replacement cost is the cost of implementing improvements which would provide a level of flood protection equivalent to that being lost. Similarly, if the reallocated storage is being taken from a hydropower pool, the replacement cost is the cost that the power marketing agency will incur to obtain the power from an alternative source.

The third approach for assigning a portion of the joint costs of the project to the reallocated M&I storage capacity is based on the "use of facilities" cost allocation procedure. The original project joint cost is assigned in proportion to storage capacity and then updated to current price levels using appropriate indices. The joint cost allocated to the M&I storage reallocation, and thus apportioned to the nonfederal sponsor, is computed as follows:

$$\frac{(\text{total construction cost-specific costs}) (\text{storage reallocated in acre-feet})}{(\text{total usable storage capacity in acre-feet})}$$

In this computation, usable storage does not include sediment reserve or inactive storage for hydroelectric power head. The joint cost allocated to the reallocated storage on this basis is then escalated to current price levels using the USACE Civil Works Construction Cost Index System and the

Engineering News Record Construction Index.

Draft ER 1105-2-100 outlines a recently established policy of offering nonfederal sponsors a 10% reduction in the updated cost of storage, if the sponsor is willing to pay the reduced cost up front rather than over the up to 30 year repayment period.

Disposal of Surplus Water

Section 6 of the Flood Control Act of 1944 authorizes the USACE to execute contracts with nonfederal entities for M&I use of surplus water available from USACE reservoirs. Surplus water has been interpreted to include both (1) water which is not required because the authorized need for the water never developed or the need is reduced by changes which have occurred since authorization or construction and (2) water which would be more beneficially used as M&I water than for the authorized purpose and which, when withdrawn, would not significantly affect authorized purposes over some specified time period.

An Army General Counsel opinion of 13 March 1986 states that Section 6 of the 1944 Flood Control Act empowers the Secretary of the Army to make reasonable reallocations between different project purposes. Water stored for purposes no longer necessary can be considered surplus. In addition, the Secretary may use his broad discretionary authority to reduce project outputs, envisioned at the time of authorization and construction, if the M&I use of the water is judged to be a higher and more beneficial use. Use for higher beneficial purposes would be applied with caution and only on the basis of a fixed period contract for temporary use.

Section 6 authority is pertinent in situations in which nonfederal entities request water but do not necessarily want to purchase a permanent interest in storage capacity. Permanent storage reallocations are performed under the authority of the Water Supply Act of 1958, as amended. Surplus water withdrawal or storage contracts implemented under Section 6 authority will normally be for small amounts of water and/or for temporary use as opposed to storage reallocations and a permanent right to the storage capacity. Normally, surplus water contracts will be limited to periods of 5 years or less. The annual price charged the nonfederal entities for use of surplus water would normally be determined based on the same basic concepts used to determine the annual payments in the case of a storage reallocation, as previously discussed.

The authority provided by Section 6 of the Flood Control Act of 1944 allows the USACE to be responsive to requests for water which may be generated by droughts or other emergency situations. Requests for water stored in USACE reservoirs during droughts and other emergencies affecting M&I water supplies may require immediate action.

Section 501 of the Independent Offices Appropriations Act of 1951 has also been cited in the past as providing authority for obtaining reimbursement for water supply withdrawals. However, from the perspective of USACE water management activities, this law probably provides no additional flexibility over that already available under Section 6 of the 1944 Flood Control Act.

Interim Use of M&I Water Supply Storage for Irrigation

Section 931 of the Water Resources Development Act of 1986 authorizes reallocation of storage capacity in USACE reservoirs, which is presently allocated to M&I water supply but not under contract for delivery, to interim use for irrigation until the storage capacity is required for M&I water supply. In accordance with Section 103 of the Water Resources Development Act of 1986, the cost to the non-federal sponsor would be 35% of the original project investment cost allocated to M&I water supply. A period of analysis of up to 30 years could be used for computing the annualized payments. The non-federal sponsor would also be responsible for 100% of the operation and maintenance, major replacement, and major rehabilitation cost allocated to the irrigation storage capacity.

Emergency Response to Natural Disasters

The USACE has a variety of authorities to respond to various types of natural disasters, which are outlined in "ER 500-1-1 Natural Disaster Procedures," dated 21 December 1984. However, USACE authority to provide emergency drought assistance, other than reservoir storage, is quite limited. The responsibility for providing emergency water supplies is basically nonfederal. USACE assistance in providing emergency water supplies is to be considered only when nonfederal interests have exhausted reasonable means for securing necessary water supplies, including assistance and support from other federal agencies.

The Water Resources Development Act of 1974 (Public Law 93-251) authorizes the USACE to transport water for human and livestock consumption as assistance during drought. Water can be transported by vehicle, small diameter pipeline, or other means at 100% federal cost. Equipment owned by the federal government is to be utilized to the maximum extent possible in exercising this authority to transport water. Assistance, at federal expense, can not include the purchase of water nor the cost of loading or discharging the water into or from government conveyance. Transport of water under this authority cannot be undertaken until the Secretary of the Army has made a determination that water cannot be obtained by the nonfederal applicant (for reasons other than lack of financial resources) within the time needed to prevent the applicant from suffering increased hardships from the effects of an inadequate water supply.

The Disaster Relief Act of 1974 Appropriations Act (Public Law 95-51) authorizes the USACE to construct wells, on a cost reimbursable basis, to provide water to farmers, ranchers, and political subdivisions within areas determined to be drought distressed. The USACE assistance is contingent on emergency services not being available from any other entity.

The Water Resources Development Acts of 1974 and 1986 (Public Laws 93-251 and 99-662) authorize the USACE to provide emergency supplies of clean water to localities faced with a threat to public health and welfare from a contaminated source of water. This authority does not include contamination due solely to a drought. USACE assistance in providing emergency supplies is normally limited to 30 days and is contingent on the supplies not being available from other sources.

The Federal Emergency Management Agency (FEMA) directs and administers federal disaster assistance activities upon Presidential Declaration of a disaster. The USACE may accept specified mission assignments from FEMA during

disasters. The USACE was designated the lead agency for national emergency preparedness planning for water resources in 1983. The main thrust of this planning effort is to be able to meet the nation's water needs in the event of a national emergency, including a massive nuclear attack.

USACE, Hydrologic Engineering Center (June 1988) provides a more detailed discussion of USACE emergency authorities pertinent to providing assistance during droughts.

REVIEW OF PAST STUDIES AND PROJECTS

For many years, the USACE district offices have studied and implemented storage reallocations and other modifications in reservoir operations. In some cases, reallocation and reservoir operation studies have been included in comprehensive planning reports in which the consideration of modifications was a relatively minor part of the overall study. Some reservoir modification studies have been documented by reports directed specifically to reservoir modifications. In other cases, studies have been conducted without any formal documentation.

Studies and projects, which involve increasing water supply capabilities by modifying reservoir operations, are reviewed here from two perspectives. First, the several available reports or papers which address potentialities in general are cited. These studies include identification of reallocation studies and implementations accomplished by USACE district offices for specific problems or reservoirs. Next follows a brief description of the specific-problem studies and projects which have been identified during this and prior reviews. The selected studies and projects cited below are illustrative of the USACE experience to date in reallocating storage capacity and otherwise modifying reservoir operations to enhance water supply capabilities.

Studies Addressing Potentialities in General

Holley and Kane (1974) reviewed cases of Congressional reauthorization of federal reservoir projects and examined issues particularly pertinent to developing M&I water supply from the existing Lake Lanier located near Atlanta, Georgia. Lake Lanier was originally constructed by the USACE for flood control, navigation, and hydroelectric power. The study identified seven examples of prior changes in authorized storage allocations in existing projects. The following four cases involved reallocation of flood control capacity to water supply in projects located in Texas: (1) Lake Texoma on the Red River, (2) Wright Patman Reservoir in conjunction with construction of Cooper Reservoir on the Sulphur River, (3) Grapevine Reservoir in conjunction with construction of Roanoke Reservoir in the Trinity River Basin, and (4) Lewisville Reservoir in conjunction with construction of Ray Roberts Reservoir in the Trinity River Basin. The other three cases are: (1) Alamogorda Dam and Los Esteros Lake in New Mexico involving reduction in sedimentation and transfer of irrigation storage, (2) John Martin Lake in Colorado involving the use of flood control storage for recreation and fish and wildlife, and (3) Cape Fear River in North Carolina involving a reallocation of flood control capacity to water supply.

The National Hydropower Study assessed the potential for increasing hydroelectric power production throughout the nation. Reallocation of storage capacity from flood control to hydropower was one of several potential means for increasing electric energy considered (Davis and Buckley 1984).

Pace (1982) presents "A Review of the Potential for the Expanded Use of Corps Multipurpose Reservoirs for Water Supply". Comiskey (1986) presents a discussion of "Generic Considerations in Reallocation of Water Supply Storage at Corps of Engineers Reservoirs".

Wurbs and Carriere (1988) document a university research study of: (1) the potential of storage capacity reallocation and other related modifications in operating policies as management strategies for optimizing the beneficial use of existing reservoirs in Texas and (2) modeling capabilities for formulating and evaluating such changes to operating policies. A system of 12 reservoirs operated by the USACE and Brazos River Authority in the Brazos River Basin served as a case study for formulating and testing management strategies and modeling capabilities.

HEC/IWR Studies

The Hydrologic Engineering Center (HEC) recently conducted two investigations sponsored by the Institute for Water Resources (IWR) to (1) identify lessons learned from the 1985-1986 drought in the southeastern United States (USACE, HEC June 1988) and (2) to identify opportunities for reallocation of storage capacity at USACE reservoirs (USACE, HEC July 1988).

The objective of the investigation of lessons learned during the 1985-1986 drought was to determine if the drought experience indicated a need to modify current USACE policy, as outlined in ER 1110-2-1941, regarding preparation of drought contingency plans. The lessons addressed included:

- (1) Need for a drought contingency plan,
- (2) Importance of a drought management committee,
- (3) Value of water supply and use data,
- (4) Have up-to-date water control manuals and reservoir rule curves for low-flow operations,
- (5) Use a simulation model for assessing impacts,
- (6) Open communication and public information,
- (7) Develop memoranda of agreement between USACE and other institutions,
- (8) Have a drought monitoring and response plan, and
- (9) Value of Division and District drought coordination.

All of the lessons listed above are, at least indirectly, pertinent to reservoir operations and possible modifications thereof. Several of the lessons deal very directly with reservoir operation. Prior to the 1986 drought, many of the water control manuals for reservoirs in the South Atlantic Division (SAD) had not been updated since project construction. SAD has since called for a review of water control manuals for all USACE reservoirs within the division. The 1986 drought reaffirmed the importance of having up-to-date water control manuals and drought responsive rule curves and water control plans (USACE, HEC June 1988).

The Hydrologic Engineering Center conducted an investigation, sponsored by the Institute for Water Resources, to identify opportunities for reallocation of storage capacity at USACE reservoirs (USACE, HEC July 1988). Sixteen reallocation study reports were examined. In addition, discussions were held with Corps of Engineers personnel in district and division offices where reallocation has been or is being considered. Also, a two-day workshop was held in September 1987 which brought together sixty people from various USACE offices to discuss a wide-range of topics related to reallocation of reservoir storage. The HEC report also discusses the Memorandum of Understanding between the State of Kansas and USACE.

Reports documenting the 16 reallocation studies listed in Table 1 were

examined in the HEC/IWR study. The table cites the reservoir, location by river and state, Corps of Engineers district office responsible for the reservoir, date of the report documenting the reallocation study, total storage capacity for all purposes contained in the reservoir, and proposed reallocation capacity in both acre-feet and as a percent of the total capacity. All of the reservoirs are owned and operated by the USACE. All of the studies focused on increasing M&I water supply capacity. About half involve conversion of flood control storage to water supply, with the remainder involving reallocations between different conservation purposes. The last column of Table 1 shows the purposes from which capacity was reallocated in order to increase the water supply capacity. Reallocations have been actually implemented at eight of the projects. The reallocation studies addressed single reservoirs except for the last study listed which was a basin-wide study involving a system of several reservoirs. Reports documenting these studies are included in the list of references provided at the end of the present report.

A review of the sixteen studies and subsequent discussions with Corps of Engineers personnel on other projects resulted in the development of eight general cases to describe the various opportunities which exist for reallocation of storage for M&I water supply in USACE reservoirs (USACE, HEC 1988):

- (1) Use of water supply storage not under contract,
- (2) Temporary use of storage allocated for future conservation purposes and sediment,
- (3) Storage made available by change in conservation demand or purpose,
- (4) Seasonal use of flood control space during dry season,
- (5) Reallocation of flood control space,
- (6) Modification of reservoir rule curves and method of operation,
- (7) Raising existing dams,
- (8) System operation of Corps and non-Corps reservoirs.

Studies and Implementations Addressing Specific Problems and Reservoirs

The specific-project modification studies and implementations identified in the studies cited above are described below. The reservoir modification activities discussed below are considered to be representative and illustrative of the general USACE experience to date.

Fort Worth District Projects

As indicated by Table 1, five of the 16 reallocation studies reviewed in the HEC (1988) investigation had been performed by the Fort Worth District. These and several other Fort Worth District reallocation projects are cited in the present discussion. Storage reallocations have been implemented at Belton, Sam Rayburn, and Lewisville Reservoirs. A contract has been executed for a reallocation in Waco Reservoir. A proposed reallocation for Wright Patman Reservoir may be further pursued in the future. A reallocation in Grapevine Reservoir was previously proposed. Reallocations at Bardwell, Granger, and Lake O' the Pines have been recently considered. In all cases, the actual or proposed reallocation involved a permanent conversion of flood control capacity to M&I water supply. In some cases, relatively small amounts of flood control capacity were lost to water supply. In other cases, the reallocation was accomplished or proposed to be accomplished in conjunction

TABLE 1

RESERVOIR REALLOCATION STUDIES

Reservoir	River	State	USACE District	Report Date	Total Storage Capacity (ac-ft)	Actual or Proposed Reallocation		Reallocation to Water Supply from Purpose Below
						(ac-ft)	(% Total Capacity)	
Bardwell	Trinity	Texas	Fort Worth	Dec 1985	122,392	19,329	15.8	flood control
Barren River	Barren	Kentucky	Louisville	Aug 1965	815,150	681	0.08	permanent pool
Bear Creek	South Platte	Colorado	Omaha	Nov 1984	58,400	18,400	31.5	flood control
Bloomington	Potomac	Maryland	Baltimore	Sep 1983	128,200	none		-
Chatfield	South Platte	Colorado	Omaha	Nov 1984	231,400	22,700	9.8	flood control
Cowanesque	Susquehanna	Pennsylvania	Baltimore	Jan 1985	86,700	24,335	28.1	flood control
Texoma	Red	Oklahoma & Texas	Tulsa	1985	4,281,000	77,400	1.8	hydropower
Granger	San Gabriel	Texas	Fort Worth	Oct 1986	200,100	65,950	33.0	flood control
Lake o' the Pines	Cypress	Texas	Fort Worth	Feb 1987	838,300	50,000	6.0	flood control
Rathbun	Chariton	Iowa	Kansas City	May 1985	528,000	3,340	0.6	recreation
Rough River	Rough	Kentucky	Louisville	1966 & 78	334,380	270	0.08	conservation
Sam Rayburn	Angelina	Texas	Fort Worth	Jun 1986	3,997,600	2,588	0.2	hydropower
Saylorville	Des Moines	Iowa	Rock Island	1981 & 82	676,000	14,900	2.2	flood control
Waco	Brazos	Texas	Fort Worth	Oct 1982	657,400	47,500	7.2	flood control
Wister	Poteau	Oklahoma	Tulsa	Feb 1987	410,640	4,400	1.1	conservation
*	White	Arkansas & Missouri	Little Rock	Oct 1983	-	none		-

*The White River Lakes Study, Arkansas and Missouri, includes Table Rock, Bull Shoals, Norfolk, Beaver, Greers Ferry, and Clearwater Reservoirs.

SOURCE: USACE, HEC (1988)

with construction of other reservoirs upstream. Thus, the total system flood control capacity was not reduced by the reallocation of storage in the existing reservoir combined with construction of a new reservoir.

Belton Reservoir, completed in 1954, and Proctor Reservoir, completed in 1963, are USACE flood control, water supply, and recreation projects located on the Leon River in the Brazos River Basin. The Brazos River Authority has contracted for the conservation capacity in both reservoirs. The top of the conservation pool at Belton Reservoir was raised 25 feet in 1972, reallocating flood control capacity to water supply. The reallocation was facilitated by the flood protection provided by construction of Proctor Reservoir upstream. Belton Reservoir presently contains 644,200 acre-feet of flood control capacity, 365,500 acre-feet conservation capacity, and 75,500 acre-feet sediment reserve. Proctor Reservoir has flood control, conservation, and sediment reserve capacities of 310,000 acre-feet, 31,400 acre-feet, and 32,700 acre-feet, respectively.

Ray Roberts Reservoir is a somewhat unusual USACE project because its construction, combined with the accompanying Lewisville Reservoir reallocation, provided only additional water supply and recreation. Flood control, the traditional federal purpose, remained essentially unchanged. The USACE completed construction of Lewisville Reservoir in 1954 and Ray Roberts Reservoir in 1987. Both are located on the Elm Fork of the Trinity River, with Ray Roberts Reservoir just upstream of Lewisville Reservoir. The cities of Denton and Dallas are nonfederal sponsors for both projects. The conservation capacities of the two reservoirs are used for M&I water supply and recreation. Ray Roberts Reservoir has flood control, conservation, and sediment reserve capacities of 260,000 acre-feet, 749,200 acre-feet, and 54,600 acre-feet, respectively. Lewisville Reservoir originally had flood control, conservation, and sediment reserve capacities of 525,200 acre-feet, 436,000 acre-feet, and 20,500 acre-feet, respectively. However, upon completion of Ray Roberts Reservoir, flood control capacity in Lewisville Reservoir, equivalent to the additional flood control capacity provided by Ray Roberts Reservoir, was reallocated to water supply. The reallocation was an integral part of the planning and authorization process leading up to the construction of Ray Roberts Reservoir.

Likewise, a reallocation of flood control to water supply capacity is planned for Wright Patman Reservoir upon completion of construction of Cooper Reservoir upstream, which is scheduled for 1991. In the interim, awaiting completion of Cooper Reservoir, a seasonal rule curve was implemented for Wright Patman in 1968 in which the designated top of conservation pool is raised during certain months of the year to provide additional water supply storage. Wright Patman Reservoir is located on the Sulphur River and has 2,509,000 acre-feet of flood control capacity and 145,300 acre-feet of conservation capacity. Reallocation of 120,000 acre-feet of flood control capacity to water supply upon completion of Cooper Reservoir has been proposed.

Sam Rayburn Reservoir on the Angelina River has flood control and conservation capacities of 2,531,400 acre-feet and 1,446,200 acre-feet, respectively. The conservation pool is used primarily for hydroelectric power, recreation, and sediment reserve. Construction was completed in 1965. In 1969, 45,588 acre-feet of the flood control pool was reallocated to the conservation pool, and the city of Lufkin contracted for 43,000 acre-feet of

this reallocated storage to use for M&I water supply. In 1983, the Lower Neches Valley Authority requested the Fort Worth District to study the feasibility of increasing the conservation storage space in Sam Rayburn Reservoir to supply water for the city of Huntington. A reallocation was determined to be feasible. However, it was concluded that the immediate water supply need could be met by the nonfederal sponsor contracting for the 2,588 acre-feet of storage capacity that still remained uncommitted from the 1969 reallocation (USACE, FWD 1986).

Construction of Waco Reservoir, in the Brazos River Basin, was completed in 1965. Flood control, conservation, and sediment reserve capacities are 553,300 acre-feet, 104,100 acre-feet, and 69,000 acre-feet respectively. The conservation capacity is committed entirely to supplying water for the city of Waco and adjacent smaller cities. In March 1979, the Brazos River Authority, in cooperation with the City of Waco, requested that the Fort Worth District investigate the feasibility of increasing the conservation storage capacity in Waco Reservoir to provide a greater dependable water supply yield. A subsequent study by the Fort Worth District resulted in a recommendation that 47,500 acre-feet, or 8.6 percent, of the flood control capacity be reallocated to water supply (USACE, FWD 1982). The reallocation will raise the top of the conservation pool seven feet. The proposed reallocation was approved by the Office of the Chief of Engineers in April 1983. A contract between the Brazos River Authority (BRA) and the federal government for the Waco Reservoir reallocation was executed in September 1984. An application for a water rights permit submitted by the BRA to the Texas Water Commission is presently under review. The contract provides for the BRA to reimburse the cost for relocating recreation facilities plus the allocated value of the water supply storage. The next step in the process is for BRA to provide funds in an escrow account. The Corps of Engineers will then relocate the recreation facilities as required and impound water in accordance with the raised top of conservation pool elevation.

The Fort Worth District recently investigated a reallocation of flood control to water supply capacity at Granger Reservoir in the Brazos River Basin. This investigation was a part of a study to reevaluate the feasibility of constructing the authorized South Fork Reservoir (USACE, FWD 1986). In regard to a reallocation at the existing Granger Reservoir, it was concluded that further studies should be deferred until water supply needs develop in the study area or definite interest is expressed by a local sponsor.

A study to evaluate the water resources problems and needs of the Cypress Bayou Basin was recently completed (USACE, FWD 1987). Reallocation of storage at Lake O' the Pines was investigated as an alternative water supply source. The study concluded that further studies regarding a reallocation should be deferred until water supply needs develop within the study area.

Construction of Bardwell Reservoir in the Trinity River Basin was completed in 1965. The project has flood control, conservation, and sediment reserve capacities of 79,600 acre-feet, 42,800 acre-feet, and 15,240 acre-feet, respectively. The conservation capacity supplies water for the cities of Ennis and Waxahachie. In 1984, the city of Ennis requested that the Fort Worth District study the feasibility of raising the conservation pool at Bardwell Reservoir. The Fort Worth District investigated a reallocation of 18,072 acre-feet from flood control to water supply (USACE, FWD 1985). The investigation was conducted under the Section 216 Review of Completed Projects

Program. The study resulted in a recommendation that additional funds be requested for a more detailed study.

Lake Texoma

Denison Dam-Lake Texoma, on the Red River in Texas and Oklahoma, in the Tulsa District, has the largest storage capacity of any reservoir in Texas. Construction was completed in 1944. Lake Texoma contains 2,669,000 acre-feet of flood control capacity and 1,612,000 acre-feet of conservation capacity. The project was constructed primarily for flood control and hydroelectric power, realizing that other purposes could become important in the future. For many years, the conservation capacity was used solely for hydroelectric power and recreation. Natural salt pollution in the Red River Basin has been a constraint to water supply use.

A number of reallocation plans have been studied and certain reallocations have been implemented at Lake Texoma (USACE, Tulsa District 1987). A total of 150,000 acre-feet, or 9.3%, of the conservation storage has been reallocated for municipal and industrial water supply. In August 1983, 72,600 acre-feet was reserved for water supply in an integrated hydropower and water supply conservation pool between specified pool elevations. This amount included 50,000 acre-feet which had been contracted for water supply use under the Chief of Engineer's discretionary authority and 22,600 acre-feet reserved for the city of Sherman, Texas, by Public Law 85-146, approved in August 1957. A reallocation of 77,400 acre-feet of hydropower storage to water supply storage was approved by the Assistant Secretary of the Army (Civil Works) in December 1985. A contract for 75,000 acre-feet of this storage was negotiated with the North Texas Municipal Water District. Most, but not all, of the remainder of the 150,000 acre-feet of water supply capacity has been committed by existing or pending contracts with other nonfederal entities.

The Water Resources Development Act of 1986 (Public Law 99-662) authorized the Secretary of the Army to reallocate an additional 300,000 acre-feet of storage in Lake Texoma from hydroelectric power to water supply in increments as needed. This storage is to be shared equally between the states of Oklahoma and Texas. The Act specifies that no payment is required or interest charged to water users for the reallocated storage capacity until it is actually first used for water supply. Until then, the storage may be used for hydropower production.

Other Projects Reviewed in HEC (1988) Report

In addition to the studies cited above, ten other studies are listed in Table 1 and profiled in the report of the HEC/IWR study (USACE, HEC 1988). These studies are briefly described below.

Construction of Wister Lake on the Poteau River in Oklahoma was completed in 1949 for flood control and other purposes. In 1960, 9,600 acre-feet of storage was reallocated to water supply under the discretionary authority of the Chief of Engineers. In 1974, a seasonal conservation pool was initiated to improve recreation and water quality. In 1983, the conservation pool was permanently raised creating a conservation capacity of 14,000 acre-feet. A seasonal rule curve was also implemented providing additional capacity, above the 14,000 acre-feet, during a specified period of the year. The combined permanent and seasonal reallocation of flood control storage to the conservation pool, implemented in 1983, was for the purpose of reducing adverse impacts of sedimentation and was Congressionally authorized by Public

Law 98-93. In 1987, 4,400 acre-feet of the then existing conservation pool was reallocated to releases for use by a power company for cooling water (4,053 acre-feet) and other future water supply uses (357 acre-feet).

The Cowanesque Lake project on the Cowanesque River in Pennsylvania was constructed during the period 1973-1980. Just after completion of construction, at the request of two electric generating utilities and the Susquehanna River Basin Commission, the Baltimore District conducted a restudy of the feasibility of reallocating some flood control storage to water supply (USACE, Baltimore District 1982). This reformulation study was accomplished under the original project authority. A reconnaissance study of storage reallocation had previously been completed in 1972 but not pursued further due to lack of a nonfederal sponsor to assume the costs of water supply storage. Certain basic structural provisions in the dam and outlet tower were included at the time of initial construction, though, so as not to foreclose the opportunity for water supply storage in the future. Water supply contracts were approved in 1986 to reallocate 30.1% of the flood control capacity (28.1% of total storage capacity) to water supply.

Barren River Lake in Kentucky has a flood control pool capacity of 768,590 acre-feet and a permanent pool of 46,560 acre-feet. In 1965, 681 acre-feet of the existing permanent pool was allocated to providing water supply for the city of Glasgow.

Reallocation of 15,000 acre-feet of storage capacity from recreation to M&I water supply has been recommended at Rathbun Lake in Iowa. A contract for purchase of 3,340 acre-feet of water supply storage has been executed.

Water supply contracts for M&I storage capacity in Rough River Lake, Kentucky were executed in 1966 and 1978 with the cities of Leitchfield and Hardinsburg, respectively. The reallocations for M&I water supply involved 120 acre-feet and 150 acre-feet or 0.036% and 0.045%, respectively, of the total capacity of the reservoir. Originally, the conservation (sediment) pool level was set at 465 feet. In 1966, the city of Leitchfield contracted for the storage between elevation 464.9 feet and 465 feet for water supply. Flood control storage was reallocated to recreation storage in 1969 by permanently raising the conservation pool level to 470 feet. Then in 1978, Hardinsburg contracted for water supply storage allocated from the conservation pool.

A study of the feasibility of reallocating flood control capacity to M&I water supply in Red Rock Lake and Saylorville Lake in the Des Moines River Basin, Iowa was performed by the Rock Island District under the Planning Assistance to States Program authorized by Section 22 of the Water Resources Development Act of 1974 (USACE, Rock Island District 1981). In 1983, 2.5% of the flood control storage capacity (or 2.2% of the total capacity) was reallocated to M&I water supply at Saylorville Lake.

Bear Creek Reservoir and Chatfield Reservoir are located on the South Platte River in Colorado. The Omaha District has proposed reallocations of 33% and 11%, respectively, of the flood control capacities (31.5% and 9.8%, respectively, of the total capacities) of Bear Creek and Chatfield Reservoirs to water supply. The reallocations have not been implemented to date.

The White River Lakes Study, Arkansas and Missouri (USACE, Little Rock District 1983) investigated the advisability of modifying the operation of

Beaver, Table Rock, Bull Shoals, Norfolk, Greers Ferry, and Clearwater lakes. Various operating changes, including storage reallocations, were considered. The study resulted in the recommendation that only minor operational changes be considered in the current regulating plan and that a detailed operational study be made to determine these changes relating to regulating stages and release patterns. Reallocation of storage between authorized purposes and authorization of additional purposes were found to not be economically justified or warranted.

Construction of the Bloomington Lake project, which is now called Jennings Randolph Lake, on the Potomac River in Maryland, was completed in 1981. Conversion of either water quality storage or flood control storage to M&I water supply was considered in conjunction with the Washington Area Water Supply Study (USACE, Baltimore District 1983). As discussed later, the Washington Area Water Supply Study resulted in a recommendation of no federal action since water supply needs could be satisfied through other means. Consequently, reallocation of storage in Jennings Randolph Lake has not been pursued further.

Kansas Memorandum of Understanding (MOU)

The "Memorandum of Understanding between the State of Kansas and the U.S. Department of the Army Concerning the Purchase of Municipal and Industrial Water Supply Storage" was signed by the Assistant Secretary of the Army (Civil Works) and the Director of the Kansas Water Office on December 11, 1985. A copy of the Memorandum of Understanding (MOU) is included in the USACE, HEC (1988) report. The purpose of the MOU was to facilitate reallocation of storage capacity in Corps of Engineers reservoirs from low flow augmentation for water quality purposes to M&I water supply.

The USACE has constructed 17 multipurpose reservoirs in Kansas. All the reservoirs contain flood control storage capacity. Several of the reservoirs contain conservation storage capacity for low flow augmentation to dilute pollution in the river at downstream locations. With the passage of the Federal Water Pollution Control Act Amendments of 1972, the emphasis in wastewater management shifted from dilution to point-source treatment and prevention. This lessened the need for water quality storage in reservoirs and created the opportunity to reallocate some of the existing water quality storage to other purposes. The withdrawal by irrigators and other users of water released for augmenting low flows for water quality was also a major issue in Kansas. The water quality releases from USACE reservoirs did not necessarily fulfill the intended purpose due to being depleted by diversions by irrigators and other users.

Studies by a state task force on water resources, the Corps of Engineers, and others resulted in development and execution of the Kansas Memorandum of Understanding (MOU). The MOU provides for the USACE to conduct studies on nine reservoirs to determine the feasibility of reallocating storage from water quality or other conservation purposes to water supply. The State of Kansas has a right of first refusal of all storage that may be reallocated to water supply. Under provisions of the MOU, the state established a water assurance program and an escrow account to be used for purchases of storage. The state also participates in the cost of each reallocation study.

A key provision of the MOU is that the purchase price for storage reallocated to water supply is to be computed as if it was authorized

originally as M&I water supply. This approach is different from the USACE policy of using the updated cost of storage for determining the charges to the local sponsor for a reallocation. It has been emphasized that the special cost provision in the MOU is due strictly to the unique circumstances of the Kansas water management situation which resulted in the MOU being developed. By a memorandum dated 23 December 1985, the Assistant Secretary of the Army (Civil Works) transmitted an explanation of the basis for the pricing concept adopted in the Kansas MOU.

The HEC/IWR report (USACE, HEC 1988) and Sheer (1987) discuss the background and various features and implications of the Kansas MOU.

Other Memoranda of Understanding

The Kansas MOU is a unique agreement pertaining to a particular set of circumstances. In general, such an agreement is not necessary to study and implement storage reallocations or other types of modifications. However, similar arrangements potentially could be advantageous in other circumstances as well. Subsequent to execution of the Kansas MOU, water managers in several other states have expressed interest in similar agreements for their states. As previously discussed, due to the special circumstances leading up to the Kansas MOU, the MOU specifies that the purchase price of the storage reallocated to water supply is to be based on the actual original construction cost, rather than updating to current price levels in accordance with ER 1105-2-20. This feature of the MOU is, of course, particularly attractive to nonfederal interests.

Next to Kansas, the MOU concept has probably advanced further in Texas than in any other state. In February 1986, at the Texas Water Conservation Association Annual Convention, the Assistant Secretary of the Army (Civil Works) met with several Texas water officials concerning the Kansas MOU and potential implications for projects in Texas. Shortly thereafter, several executives of river authorities, water districts, and a state agency met with the District Engineer of the USACE Fort Worth District to discuss the potential for a Texas MOU which would allow for both recovery of previous federal investments and cost savings to the nonfederal sponsor similar to the Kansas MOU. A study group of water management professionals from nonfederal and federal agencies was organized. The Fort Worth District, in coordination with the study group, drafted a document dated 15 July 1986 and entitled "Concept for a Memorandum of Understanding Between the State of Texas and Department of the Army on Reservoir Storage Reallocations in Texas", which was in the process of review at the time of this writing.

Of the various issues surfaced during development of the Kansas MOU and drafting and review of the Texas MOU concept document, two seem to be particularly important. First, to be warranted, a MOU must facilitate joint actions by state and federal agencies that effectively create new storage and cost recovery opportunities that were not available without the MOU. In general, storage reallocations can be studied and implemented without a MOU being needed. The Kansas MOU was motivated by a unique set of circumstances. Secondly, the sharing of joint cost for the original reservoir storage is a key element of a MOU. A deviation from USACE normal cost sharing policy, as outlined in ER 1105-2-20, is justified only if the MOU represents a reasonable balance of give-and-take between federal and state interests.

Metropolitan Washington Area Water Supply Study

Measures implemented to meet the water supply needs in the Washington D.C. area have been viewed nationwide as a classic example of optimizing the beneficial use of existing systems. With the exception of the previously mentioned Bloomington Lake reallocation study, the Metropolitan Washington Area Water Supply Study did not address reallocation of storage between project purposes. The final report did not recommend further consideration of storage reallocation in Bloomington Lake. The Metropolitan Washington Area Water Supply Study illustrates various other types of measures which can be taken to increase the water supply capabilities of existing facilities.

The Metropolitan Washington Area Water Supply Study Final Report (USACE, Baltimore District 1983) summarizes the USACE study authorized by the Water Resources Development Act of 1974 as well as the studies performed and actions taken by various nonfederal entities. The USACE report resulted in a recommendation of no further federal action since the water supply needs could be satisfied by measures being implemented by nonfederal entities.

Present and projected future water needs significantly exceeded supplies for a demand area consisting of Washington, D.C., and seven adjacent counties. The water supply area consists of the Potomac River Basin and adjacent Patuxent River Basin. Relatively small portions of the overall watershed is controlled by five reservoirs, but the single largest source of supply is unregulated flows of the Potomac River. Construction of additional reservoirs had been previously proposed but concluded to be infeasible for various reasons including lack of public support.

The USACE, Interstate Commission on the Potomac River Basin, several water utilities, researchers at John Hopkins University, and several committees and task forces all played key roles during several years of studies resulting in development of the plan finally implemented to meet the water supply needs of the area. The implemented regional water supply plan included a number of components involving: (1) system operation based on coordination of unregulated flows and withdrawals from the existing five reservoirs, (2) long-term and emergency demand management measures, and (3) construction of a small downstream re-regulating reservoir to facilitate improved operation of existing upstream reservoirs. Various systems analysis techniques including the Potomac River Interactive Simulation Model (PRISM) were used in developing the plan. Several contracts and agreements between the various water management agencies were required to implement the plan. Certain key contracts and agreements were signed in 1982.

Case Studies of Modifying Reservoir Operations During Droughts

All of the operational modification studies and implementations cited so far in the present report were performed prior to and in preparation for future droughts. Kelly (1986) investigated experiences in modifying reservoir operations during droughts in response to impending water shortages. Kelly reviewed reservoir operations in the Potomac and Delaware River Basins during the record severe drought in the Northeast which occurred during 1962-1967 and in California during the record severe drought which occurred in the Great Plains and West Coast states during 1976-1977. Site-specific modifications in operations of several reservoir systems and individual reservoirs were made as drought conditions worsened. The droughts also motivated later development of contingency plans and operation improvements in order to be better prepared

for future droughts.

Kelly (1986) identified four types of deviations from normal operating procedures implemented during the droughts in the selected regions: (1) water supply loans, (2) consolidation of storage, (3) minimum pool releases, and (4) project purpose changes. Each modification was site specific in nature.

Water supply loans occurred in California during the 1976-1977 drought. The Central Valley Project is a federal system managed by the U.S. Bureau of Reclamation. The State Water Project is a state system managed by the California Department of Water Resources. The two separate major water storage and conveyance systems contain a common reservoir, San Luis Reservoir, shared by both. Temporary loans of water from one project to the other, as needed, were facilitated by the common reservoir. Thus, loans were accomplished by institutional arrangements without constructing or altering physical facilities.

The Orland Project, which is a system of three reservoirs on a tributary of the Sacramento River in California, provides an example of consolidation of storage. Releases in the two upstream reservoirs were made to consolidate the storage in the downstream reservoir in order to decrease evaporation, seepage, and instream losses.

Many reservoirs contain water in a pool near the bottom of the reservoir which is never released under normal operation. This may be referred to as a minimum pool. Hidden Reservoir and Eastman Reservoir are USACE flood control and irrigation projects in the San Joaquin Valley of California with minimum pools which provide fish habitat, recreation, and water supply including fire protection for the project facilities. Water was released from the minimum pools for irrigation purposes during the drought.

Federal flood control reservoirs and private hydroelectric power facilities in the Delaware River Basin were operated for water supply during the 1962-1967 drought. In California, reservoir operations at several federal and state projects were altered to use navigation and recreation storage for water supply purposes. Coordination of interactions between project purposes was a key concern during the drought conditions for several of the reservoir systems.

POTENTIALITIES, ISSUES, AND CONSIDERATIONS

Storage Allocation and Reservoir Operations

Reservoir operation is based on the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space available for storing future flood waters to reduce downstream damages. Common practice is to operate a reservoir for either flood control only, conservation only, or a combination of flood control and conservation with separate pools designated for each. Conservation pools may be shared by various purposes, such as navigation, water supply, hydroelectric power, and recreation, which involve both complementary and conflicting interactions. Withdrawals and releases from water supply storage capacity may serve various types of uses including municipal, industrial, steam electric power cooling water, irrigation, and maintenance of instream flows for navigation, fish and wildlife, freshwater inflows to bays and estuaries, or dilution of pollution. For a given type of water use, such as M&I or irrigation, many different users are supplied from the same reservoir or multiple reservoir system.

Institutional arrangements for constructing and operating reservoirs are based on project purposes. The USACE retains overall responsibility for operation and maintenance of the reservoir projects it constructs. The USACE is responsible for flood control operations at Bureau of Reclamation projects as well as at its own reservoirs. The USACE is also totally responsible for navigation operations. Hydroelectric power generated at USACE reservoirs is marketed to electric utilities by the five regional power marketing administrations of the Department of Energy. Releases from conservation storage capacity allocated to water supply are made by the USACE as directed by the nonfederal sponsors which have contracted for the storage capacity.

In some cases, under the disposal of surplus water authority of Section 206 of the 1944 Flood Control Act, the USACE has contracted with local interests for withdrawals of water from storage capacity controlled by the USACE. However, most typically, water supply provided in USACE reservoirs is storage capacity for which local interests have contracted in accordance with the Water Supply Act of 1958. The local sponsor is provided a designated storage space or volume. Facilities may be included in the project structure for the release or withdrawal of stored water for water supply purposes. Releases are made by the USACE at the discretion of the nonfederal sponsor which has contracted for the storage volume. The nonfederal sponsor is responsible for obtaining water rights necessary for the use of the stored water and for providing treatment facilities to assure adequate water quality.

Reservoir release policies or operating procedures are based on dividing the total storage capacity into designated pools. A typical reservoir consists of one or more of the horizontal zones, or pools, illustrated by Figure 1.

Water releases or withdrawals are normally not made from the inactive pool, except through the natural processes of evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest outlet or, in the case of hydroelectric power, by conditions of operating efficiency for the turbines. An inactive pool may also be contractually set to

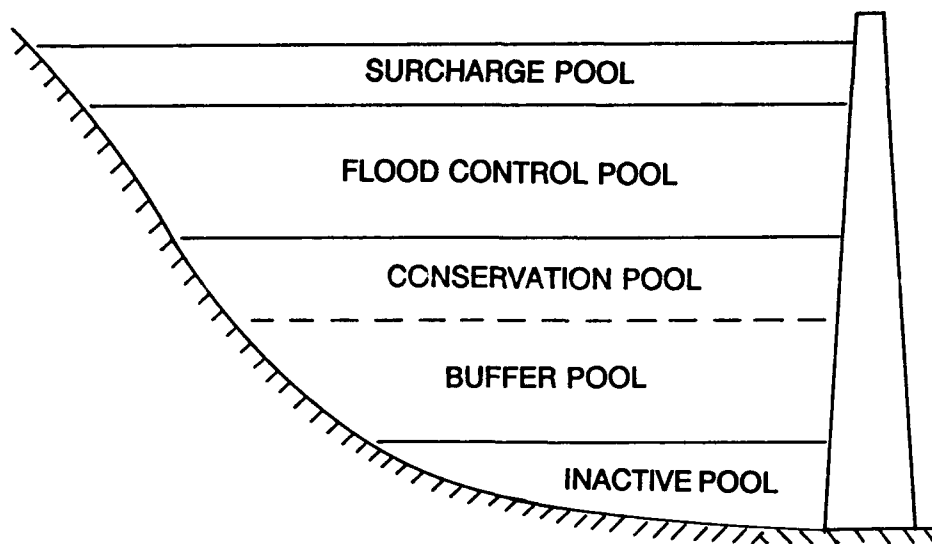


FIGURE 1 - Reservoir Pools

facilitate withdrawals from outlet structures which are significantly higher than the invert of the lowest outlet structure at the project. The inactive pool is sometimes called dead storage or a minimum pool. It may provide a portion of the sediment reserve, head for hydroelectric power, and water for recreation and fish habitat.

The conservation pool supplies water for various beneficial uses. The reservoir water surface is maintained at or as near the top of conservation pool elevation as streamflows and water and/or energy demands allow. Drawdowns are made as required to meet water supply and/or hydropower needs. Reservoir operation strategies may include designation of one or more buffer zones. Full demands are met as long as the reservoir water surface is above the top of buffer zone, with certain nonessential demands being curtailed whenever the water in storage falls below this level. Water withdrawals may be made from intake structures located in a reservoir or releases may be made through outlet structures to be diverted from the river at locations which may be many miles below the dams. Releases through hydroelectric power turbines may be diverted at downstream locations for various other uses. Various approaches have been adopted to develop operating rules for conservation pools shared by hydroelectric power and M&I and/or irrigation water supply purposes.

The flood control pool remains empty except during and immediately following a flood event. The top of flood control pool elevation may be set by the crest of an uncontrolled spillway. Gated spillways allow the top of flood control pool to exceed the spillway crest elevation. The surcharge pool is essentially uncontrolled storage capacity above the flood control pool and below the maximum design water surface. Major flood events exceeding the capacity of the flood control pool encroach into surcharge storage. The maximum design water surface is an elevation established during project design from the perspective of dam safety. Reservoir design and operation is based

on assuring that the reservoir water surface will never exceed the designated maximum design water surface elevation under any conditions.

Flood control operations are based on two sets of procedures or regulation schedules. The set of procedures requiring the largest release rate controls for given flooding and storage conditions. The regular procedure, which usually controls, is based on the assumption that ample storage capacity is available to handle the flood without special precautions being necessary to prevent the water surface from rising above the top of flood control pool. Operation is switched to an alternative schedule during extreme flooding conditions when the anticipated runoff is predicted to exceed the controlled capacity remaining in the reservoir. Surge operations are based on assuring that the maximum design water surface is not exceeded and allows reservoir releases which contribute to downstream damages. Regular operations are based on evacuating the flood control pool as quickly as practical without making releases which contribute to damages at downstream locations. Non-damaging or maximum allowable discharge rates are specified for downstream index locations or control points. Flood control pools are sometimes zoned such that allowable downstream discharge rates vary as a function of the water surface elevation in the reservoir.

Seasonal rule curve operations involve a joint use pool which is used for one purpose at certain times and for a different purpose at other times. The top of conservation pool elevation can be varied seasonally and/or as a function of floodplain activities, watershed conditions, forecasted inflows, or other parameters. Likewise, top of buffer zone elevations and the elevations defining the zones within a flood control pool or maximum allowable downstream flow rates can also be varied seasonally or as a function of specified parameters.

Changing Conditions Affecting Reservoir Operation

Reservoir storage capacities and operating policies are generally established prior to construction and tend to remain constant thereafter. However, public needs and objectives and numerous factors affecting reservoir effectiveness change over time. An increasing necessity to use limited storage capacity as effectively as possible warrants periodic reevaluations of operating policies. Operating policies should be responsive to changing needs and conditions.

The period from the Flood Control Act of 1936 through the 1970's was the construction era of water resources development. In recent years, the dominant water policy emphasis has been on shifting to a greater reliance on managing flood plain land use, water demand management, and optimizing the operation of existing facilities. The best reservoir sites have already been developed. Due to a number of economic, environmental, institutional, and political factors, construction of additional new reservoir projects is much more difficult now than in the past. Consequently, optimizing the beneficial use of existing reservoirs is becoming increasingly more important.

Population and economic growth in various regions of the nation are accompanied by increased needs for flood control, water supply, energy, recreation, and the other services provided by water resources development. Depleting groundwater reserves are resulting in an increased reliance on surface water in many areas. During the 1970's, the rising cost of fossil

fuel focused attention on increasing hydroelectric power. With the water quality management focus on more stringent treatment standards during the 1970's, the emphasis shifted away from using reservoir releases to dilute pollution. Instream flow needs for fish and wildlife habitat and maintenance of fresh water inflows to bays and estuaries have received increased attention in recent years. Storage capacity has been included in multipurpose reservoirs for proposed future navigation projects which were not actually constructed as anticipated. Water related problems and needs change greatly over time, and the changes involve uncertainties. Needs may develop quite differently over the project life than was anticipated during project planning.

Watershed and floodplain conditions are dynamic. Construction of numerous small flood retarding dams by the Soil Conservation Service and other entities in the watersheds of major reservoirs have reduced flood inflows to the reservoirs. Construction of numerous small ponds for recreation or watering livestock have also decreased reservoir inflows and yields. Increased runoff caused by watershed urbanization is significantly contributing to flooding problems in certain locations. Many of the existing flood control reservoirs were planned and designed based on the expectation of ever increasing intensification of flood plain land use. However, the National Flood Insurance Program has resulted in regulation of flood plains. With stringent flood plain management, susceptibility to flooding could decrease over time as existing activities choose to leave the flood plain and regulation prevents other activities from moving into the flood plain. Reservoir sedimentation reduces available storage capacity. Predictions of reservoir sedimentation rates are necessarily very approximate, and actual sedimentation may be significantly different than that predicted during project planning. Construction of additional reservoirs, as well as other related types of projects such as conveyance facilities, flood control levees and channel improvements, and electric power plants, affect the operation of existing reservoirs.

Technological advancements in hydrologic data collection, streamflow forecasting, system modeling and analysis, and computer technology provide opportunities for refining operating policies. Real-time water control has been a major focus of data acquisition and model development efforts in recent years. Planning-type modeling and analysis capabilities have also been significantly expanded.

With an aging inventory of numerous reservoir projects with large storage capacities being operating in an environment of change and intensifying demands on limited resources, storage reallocation and other changes in reservoir operating policies can reasonably be expected to be considered more and more frequently. During drought conditions, water users and managers will naturally be particularly interested in strategies which might improve the beneficial use of available resources and facilities.

Types of Modifications

A review of past experiences in modifying reservoir operations indicates a broad range of measures which have been and/or potentially could be implemented to improve capabilities of USACE reservoirs in responding to water needs during droughts. Various types of modifications are outlined in the following paragraphs. In general, reservoir operations may be modified for a

variety of reasons such as to increase flood protection or hydroelectric power generation or to enhance recreation. The present report focuses on water supply. For purposes of the present discussion of potentialities for improving water supply capabilities, the various types of measures are organized into the following general categories (USACE, 1988).

- (1) Temporary use of storage capacity allocated for sediment reserve and future conservation purposes.
- (2) Use of water supply storage capacity not under contract.
- (3) Improved system operation of conservation storage in multiple reservoirs and/or coordination of releases with unregulated flows.
- (4) Improved coordination between surface water supplies, ground-water supplies, and demand management.
- (5) Reallocation of storage capacity between conservation purposes or between water users.
- (6) Reallocation of flood control storage capacity to water supply.
- (7) Seasonal joint use of flood control and conservation storage capacity.
- (8) Modification of flood control release rates.
- (9) Raising existing dam.
- (10) Combinations of the above.

Temporary Use of Storage Capacity Allocated for Sediment Reserve and Future Conservation Purposes

USACE reservoirs are designed with storage capacities sized to include typically 50 to 100 years of sedimentation. Sedimentation rates are highly stochastic over time and vary greatly between locations, but the sediment reserve is typically a significant portion of the total storage capacity of a reservoir for many years after initial impoundment. Flood control and conservation pool storage capacities are typically cited exclusive of designated sediment reserve. M&I water supply contracts between the USACE and local sponsors are for storage capacity allocated to water supply exclusive of designated sediment reserve. The designated water supply storage capacity may be adjusted over the project life to reflect equitable apportionment of actual sedimentation between pools. Sediment reserve capacity above the designated top of conservation pool elevation automatically provides additional flood control. Sediment reserve capacity in conservation pools, prior to filling with sediment, can serve fish habitat, recreation and water supply. Nonfederal water suppliers sometime execute temporary contracts with water users based on availability of sediment reserve storage. During water shortage conditions, sediment reservoirs may also be treated as an additional previously uncommitted source of supply.

About 3,330,000 acre-feet, or 32%, of the total M&I storage capacity in USACE reservoirs nationwide, is designated for future use (USACE, HEC, July 1988). This storage capacity was provided in the reservoirs to meet water needs anticipated to develop at some future time. Local sponsors have contracted for the future-use storage or at least provided assurances that they will contract for the storage in the future. However, until the anticipated future needs develop, the future-use storage capacity provides an opportunity for temporary reallocations.

Use of Water Supply Storage Capacity Not Under Contract

Nationwide, there are 23 USACE projects with 945,000 acre-feet of M&I water supply storage not under contract (USACE, HEC July 1988). As previously

discussed, 65% of this storage is in the Southwestern Division and the remainder is distributed among five other divisions. This storage capacity was originally included in the reservoirs based on reasonable assurance by a nonfederal sponsor that the storage would be used sometime in the future. However, investigations have shown that some of the users no longer exist or no longer intend to use the storage. Examples include a manufacturing plant that has relocated or a municipality that has chosen to develop another source of water. These changes make water available for other water users.

Improved System Operation of Conservation Storage in Multiple Reservoirs and/or Coordination of Releases With Unregulated Flows

Water supply capabilities may be enhanced by improved system operation of the conservation storage of multiple reservoirs and/or better coordination of releases from conservation storage with unregulated flows entering the river below the dams. Improvements in system operations may involve non-USACE as well as USACE reservoirs. USACE flood control regulation plans are typically developed on a system-wide basis, with release decisions at multiple USACE reservoirs being based on allowable discharges at downstream control points which are often common to two or more reservoirs. However, water supply operations are typically based on operating each reservoir individually to meet nonfederal requirements. Whereas the USACE is totally responsible for flood control operations, a number of nonfederal entities may control the conservation storage in the various federal and nonfederal reservoirs in a river basin.

System operations are pertinent in situations in which a significant proportion of the total water use is associated with users who can be supplied alternatively by more than one source, either multiple reservoirs or a reservoir combined with a non-reservoir source such as groundwater or unregulated flows from runoff entering a river below the dam. A common situation is for water users to divert water from the river at locations downstream of several dams. The downstream diversion requirements may be met by releases from either of several of the upstream reservoirs in combination with unregulated flows. System firm yields may be significantly greater than the sum of the individual reservoir firm yields because the timing of the critical low-flow periods do not perfectly coincide at the reservoir sites. Operated individually, the reservoirs empty at different times, with some reservoirs empty while significant storage still remains in other reservoirs. Unregulated streamflow may also significantly contribute to system yield in some river basins. The unregulated flows are typically highly variable with zero or relatively low flows sometimes but providing large quantities of water much of the time. The unregulated flows may have zero firm yield but provide a significant increase in system firm yield if supplemented by reservoir releases during low-flow periods.

The previously cited plan for increasing water supply capabilities in the Potomac River Basin to meet the water supply needs of the Washington Metropolitan Area illustrates the potentialities of improved system operations. Multi-reservoir system operations are also being considered in studies being conducted in conjunction with the Kansas MOU. Wurbs, Bergman, Carriere, and Walls (1988) demonstrate the significant increases in firm yield achieved by system operations of a system of nine USACE and three nonfederal reservoirs in the Brazos River Basin in Texas.

Multiple reservoir system operations can increase yields even if

relatively simple operating policies are adopted, such as basing release decisions on balancing the percentage of the storage capacity depleted in each reservoir. More complex release policies based on minimizing the likelihood of spills or minimizing evaporation and channel losses potentially can result in additional increases in yield.

Forecasting streamflow and water use is another important aspect of system operations. For a number of major reservoir systems, the majority of water use is from diversion locations one to two weeks travel time below the dams from which the water is released. Channel losses and rainfall occurring during the travel time affect the relationship between water released from the reservoirs and water actually diverted for beneficial use. Reservoir releases typically, of necessity, include a contingency factor to assure that sufficient water actually reaches the users but which results in frequent unused excess flows to the ocean. A small re-regulating reservoir constructed near the water users may significantly improve system efficiency. A re-regulating reservoir was included in the Metropolitan Washington Water Supply Plan. Expanded data collection and computer modeling techniques may also improve forecasting and thus save water.

The previously cited consolidation of storage in the three-reservoir Orland Project in California during the 1962-1967 drought illustrates a type of system operation. Most of the limited available water was stored in a single reservoir, rather than all three reservoirs, in order to minimize evaporation and channel losses. An example of USACE and nonfederal coordination occurred during the 1986 drought in the southeast where water was stored in the flood pool of Smith Reservoir, owned by Alabama Power Company, to enable the USACE reservoirs in the Apalachicola-Chattahoochee-Flint River Basin to meet low-flow needs.

Improved Coordination Between Surface Water Supplies, Ground-Water Supplies, and Demand Management

Improved coordination between ground water well pumping and surface water reservoir releases has been widely recognized for many years as being a potentially important strategy for meeting water needs in certain regions of the nation. Conjunctive management of surface and ground-water supplies has been significantly constrained by water rights and other institutional considerations. Physically and hydrologically, in situations in which common water needs can be met by alternative supply sources, conjunctive surface and ground-water management is similar to the system operation strategies discussed immediately above. Conjunctive use activities in the United States are reviewed by the USACE HEC (1984) and various elements of conjunctive use water supply are discussed by the USACE HEC (March 1988).

Demand management has been a major water policy focus during the past 15 years. Certain long-term demand management measures can be implemented independently of reservoir operations. However, most temporary or emergency demand management measures are implemented only during impending water shortages. Reservoir drawdowns trigger implementation of certain demand management measures. Coordination of reservoir operation and demand management is an important aspect of drought contingency planning.

Reservoir conservation pools may be divided into one or more designated buffer zones. Full demands are met as long as the reservoir water surface is above the top of the buffer pool, with certain demands being curtailed

whenever the water in storage falls below this level. Drought contingency plans may include implementation of specified demand management measures whenever reservoir storage contents fall below specified buffer levels.

Reallocation of Storage Capacity Between Conservation Purposes or Between Water Users

Storage capacity allocated to a specified purpose may no longer be required for that purpose due to changed conditions or the storage may be more beneficially used for another purpose. For example, water quality storage originally provided to dilute pollutants may no longer be required if advanced treatment processes are now greatly reducing the discharge of pollutants into the stream. Permanent or temporary reallocation of navigation, hydroelectric power, or recreation storage to water supply may be warranted under appropriate circumstances. Changes in conditions affecting erosion and sediment transport upstream of a reservoir might warrant a reallocation of sediment reserve to water supply.

In addition to reallocating conservation storage between purposes, water supply storage can be reallocated between users. At many USACE reservoirs, the conservation pool is shared by two or more nonfederal sponsors. Each water supply sponsor has contracted for a percentage of the storage capacity. During drought conditions, needs may not develop in direct proportion to contracted storage capacity. Some nonfederal sponsors may have alternative sources of supply while other nonfederal sponsors do not. Temporary reallocations or water transfers between nonfederal sponsors may be warranted. Likewise, water users with no prior interest in the reservoir may request to purchase water from a nonfederal sponsor of the reservoir storage capacity.

Reallocation of conservation storage capacity between purposes and improved coordination of joint use conservation storage capacity are two closely related general types of measures for optimizing the beneficial use of a fixed amount of storage capacity. Both complementary and conflicting interactions between purposes are involved. Water supply storage is often provided primarily as a long-term protection against the threat of severe droughts characterized by recurrence intervals of many years. Drastic drawdowns of water supply storage, in many reservoirs, occur very infrequently, and the storage capacity is nearly full most of the time. Thus, the water is available for in-reservoir uses such as recreation, navigation, and head for hydroelectric power most of the time. Hydropower storage capacity typically includes both an active pool from which water is released through the turbines and an inactive pool which provides head. Hydroelectric power is often a component in an electrical generating system which relies primarily upon thermal-electric power plants. Releases through the turbines are often coordinated with diversions at downstream locations for water supply. Inactive storage for hydroelectric power can provide a contingency water supply source for emergency use during infrequent drought conditions. A broad array of opportunities exist for coordinating joint-use conservation storage operations. Institutional arrangements are required to modify or refine operating plans which involve multiple purposes and thus multiple water management entities.

Several of the previously cited storage reallocation studies and implementations fall within this general category of measures. Reallocation of water quality storage to water supply in reservoirs in the Kansas, Neosho, Marais des Cygnes, and Verigris River Basins is presently being studied under

the Kansas MOU. A portion of the hydroelectric power pools in Lake Texoma on the Red River in Oklahoma and Texas has been reallocated to M&I water supply. Navigation and hydroelectric power storage and also minimum pools normally used for recreation and fish habitat were temporarily used for water supply in California during the 1965-1967 drought. Water supply loans between the Central Valley Project and State Water Project involved transfer of storage between different M&I and irrigation water users.

Reallocation of Flood Control Storage to Water Supply

Nationwide, single-purpose flood control storage capacity of 99,960,000 acre-feet accounts for 46% of the total storage capacity provided by USACE reservoirs for all purposes (USACE, HEC, July 1988). As previously discussed, conversion of flood control storage to M&I water supply has been involved in a majority of the past projects for which storage has been reallocated between project purposes. Existing flood control storage space represents a large amount of capacity which can be reallocated to water supply quite easily, at least from the perspective of typically not requiring acquisition of additional land or modification of dam and appurtenant structures.

Loss of flood control storage capacity will adversely affect the level of flood protection provided. The loss of flood control storage may either be (1) mitigated by other flood damage reduction measures, (2) treated as being so small as to be insignificant for all practical purposes, (3) justified as being of less value than the corresponding improvement in water supply capabilities, or (4) be of sufficient severity to result in the proposed reallocation being infeasible.

In the past, for several previously cited projects, flood control capacity was converted to water supply at an existing reservoir in conjunction with construction of another reservoir which provided additional flood control capacity which mitigated the capacity loss in the reallocation. In several other actual cases, the reallocated capacity was so small relative to the total flood control capacity that the adverse impacts on flood control were small enough to be considered insignificant compared to the beneficial increase in water supply.

In other hypothetical situations, reservoirs may have been conservatively sized to provide an extremely high level of flood protection. Thus, though a significant amount of flood control storage capacity is lost in a reallocation, the level of flood protection provided is still very high. Implementation of other structural or nonstructural flood damage reduction measures and/or changes in flood plain land use may have decreased the need for flood control storage. A large portion of the benefits, included in the economic evaluations performed during planning for many of the earlier projects, were associated with protecting future floodplain development. Floodplain management activities motivated by the National Flood Insurance Program have significantly reduced floodplain development. In these situations, an evaluation of beneficial and adverse impacts could possibly show a reallocation to be warranted.

The proposed and implemented reallocations of flood control capacity to water supply identified during the review of past studies and projects involved reallocations in individual reservoirs. Conceivably, in a multiple reservoir system, both the flood control and water supply effectiveness of the basinwide system could be improved by converting flood control storage to

water supply in some reservoirs while converting conservation capacity to flood control in other reservoirs.

Reservoir projects constructed by nonfederal entities typically do not include flood control storage due to difficulties in financing flood control. Nonfederal reservoirs are much more numerous, though often smaller, than USACE and Bureau of Reclamation reservoirs. Managers of nonfederal reservoirs and occupants of the flood plains downstream are often concerned about the potential impacts of the conservation reservoirs on flooding conditions. Reservoirs with no designated flood control storage are often operated to a certain extent to minimize flooding. For example, conservation storage may be drawn down several hours or days in advance of forecasted flood inflows, which may significantly impact the more frequent but less severe flood events. The USACE could conceivably play an expanded role in the future in providing technical studies and advisory support for nonfederal water managers regarding operation of conservation reservoirs from a flood damage reduction perspective. Under appropriate circumstances, nonfederal and federal reservoirs could be considered together to develop an optimal basinwide operating plan that considers interactions and tradeoffs between flood control and water supply operations.

Seasonal Joint Use of Flood Control and Conservation Storage Capacity

Whereas permanent reallocations between flood control and conservation storage capacity result in tradeoffs between purposes, the objective of seasonal rule curve operation is to simultaneously enhance both flood control and water supply or to enhance one purpose while minimizing adverse impacts on the other. Either adopting a seasonal rule curve operation or modifying a previously adopted rule curve represents another strategy which may be used to increase water supply capabilities of existing reservoirs.

Seasonal rule curve operation is based on varying the designated top of conservation pool elevation throughout the year. Storage capacity is reallocated between flood control and conservation purposes in a cyclic manner based on season of year and/or other parameters. The lowest and highest limits of the varying top of conservation pool elevation define a joint use pool which is sometimes part of the flood control pool and sometimes part of the conservation pool. Seasonal rule curve operations are common in certain regions, such as California, which have distinct flood seasons. During the dry season, the probability of flooding is very low and the joint use storage is converted to conservation storage by raising the designated top of conservation pool. Wurbs and Carriere (1988) have noted that joint use storage operations may also be beneficial in increasing water supply yields in regions, such as Texas, which experience a significant flood threat throughout the year.

In many cases, a seasonal rule curve designates the top of conservation pool elevation as a function of time of the year only. In other cases, joint use storage operations are more complex with the top of conservation pool elevation and release rates being determined as a function of watershed moisture conditions, forecasted runoff, and/or water demands as well as season of the year.

Modification of Flood Control Pool Release Rates

As previously discussed, flood control operations are based on maximum allowable discharges at downstream control points. Flood control pools are

often zoned such that maximum allowable discharges vary with reservoir storage levels. Operating plans at some reservoirs are based on evacuating storage capacity as quickly as possible without exceeding the allowable discharge rate fixed for each control point. Operating plans at other reservoirs allow the actual target discharges to be varied, up to the maximum allowable discharges, depending on considerations such as season of the year or floodplain activities.

Flood control release rates, timing of releases, and storage capacity are interrelated in providing a given level of flood protection. In discussing this interrelationship, Beard (1964) cited Folsom Dam, in California, as an example. In this example, a 12-hour delay in releasing at the start of a major flood would be equivalent to reducing the available flood space by over 25%. In other words, only 75% of the flood space in the reservoir would be required for the same protection if releases could be dependably initiated 12 hours earlier.

Streamflow forecasting in support of real-time reservoir operating decisions has been a major research and development emphasis in recent years. Technological advancements in real time precipitation and streamflow data acquisition and computer simulation modeling provide opportunities for refining reservoir operations. Such improvements could result in enhancing both flood control and water supply capabilities without reallocating storage capacity. Also, conceivably, under appropriate circumstances, flood control storage capacity might be reallocated to water supply in combination with more refined operation of the remaining flood control storage capacity.

Maximum allowable discharges specified in authorized regulation plans are established based on analyses of stages at which significant damages occur. However, in many cases, some floodplain activities will incur damages or inconvenience at discharge rates significantly below the specified allowable. Consequently, reservoir operators frequently are pressured by floodplain occupants to limit releases to levels significantly below those dictated by the authorized maximum allowable discharges. Flood control pool release rates may be reduced for other reasons as well. For example, the flood control regulation plan for Marshall Ford Reservoir in Texas was revised to allow more efficient use of flood waters to generate hydroelectric power at a nonfederal plant located just downstream. Nonfederal interests have requested that flood control releases from several reservoirs in California be reduced to facilitate groundwater recharge projects. Under certain circumstances, a lower release rate, with correspondingly longer duration, allows a larger proportion of the flood water to be used for hydroelectric power generation, groundwater recharge, or other beneficial purposes. However, reductions in release rates, just like reductions in storage capacity, can significantly reduce the level of flood protection provided by the reservoir.

Weeks or even months may be required to completely evacuate a flood control pool after a major flood. Reductions in the release rates at which wet-season flood waters are evacuated can contribute to reductions in dry-season drawdowns from conservation storage. Thus, reductions in flood control release rates could have effects similar to seasonal rule curve operations in increasing water supply capabilities. In many cases, control points are located several days travel time below a dam. Unexpected additional precipitation occurring after a release is made can result in the release contributing to flooding several days later at a downstream location. Thus,

maintaining actual target discharges at levels below the maximum allowable non-damaging discharges could simultaneously enhance conservation purposes and reduce the risk of contributing to flood damages during the more frequent but less severe flood events. Of course, the risk of an extreme flood event exceeding the storage capacity of the flood control pool is increased.

Raising Existing Dam

The various types of measures for increasing water supply capabilities of existing reservoir projects cited above can be implemented without modifying the dam or appurtenant structures. Another approach is to raise the dam to create additional storage capacity in the reservoir. A number of USACE reservoir projects have been enlarged sometime after construction was initially completed. For example, the dam at Lavon Reservoir, Texas, was raised 12 feet to create an additional 280,000 acre-feet of M&I water supply storage capacity. A study report for F.E. Walters Reservoir in Pennsylvania recommended raising the dam 30 feet to create 70,000 acre-feet of additional storage.

Combinations of the Above

The various approaches for increasing the water supply capabilities of existing reservoirs are addressed above within the framework of nine categories of measures. Categorization facilitates discussion. However, it is important to note that various combinations of approaches may be adopted in responding to a particular water need or in optimizing the operation of a particular reservoir system.

Most approaches for increasing water supply capabilities are most effective if implemented well before a drought occurs. Some measures absolutely must be implemented during wet conditions. Other measures may be specifically designed to be implemented only during drought conditions. However, many of the various types of modifications can be implemented on either a permanent long-term basis in preparation for future droughts or, perhaps somewhat less effectively, on a short-term or emergency basis during a drought. A well-formulated drought contingency plan may significantly increase the effectiveness of actions taken during the drought. Effective drought contingency planning should result in timely implementation of appropriate measures and proper coordination of water supply management and augmentation measures with demand management and conservation measures.

Key Considerations and Issues

Water resources development and management involves complex institutional, environmental, economic, financial, social, political, and technical considerations. The various considerations which must be addressed in construction of new water projects, or in regard to other aspects of water management, are also generally pertinent to reallocating storage capacity or otherwise modifying the operation of existing reservoirs. Of course, as compared with the more traditional activities in planning and construction of new projects, developing and implementing management strategies for optimizing the operations of existing reservoirs involves a somewhat different perspective and emphasis. For purposes of the present discussion, key considerations and issues are categorized as follows:

- (1) USACE authority and funding,
- (2) Nonfederal sponsorship and financing,

- (3) Water rights and other regulatory requirements,
- (4) Special institutional arrangements,
- (5) Impacts on other project purposes and the environment,
- (6) Public involvement, and
- (7) Comprehensive integrated basinwide water resources management.

USACE Authority and Funding

The USACE has played an important role in water supply for many years. As previously discussed, the Flood Control Act of 1944, as amended, authorizes the USACE to (1) sell surplus water to municipalities and other nonfederal entities and (2) include irrigation as a project purpose. The Water Supply Act of 1958, as amended, authorizes inclusion of storage capacity for M&I water supply in USACE and Bureau of Reclamation reservoir projects.

Reviewing the operation of completed projects is also a well established USACE activity. Section 216 of the River and Harbor and Flood Control Act of 1970 authorizes the USACE to review the operation of completed projects, when warranted by changed physical or economic conditions, and to report to Congress regarding recommendations for modifying the structures or their operation.

Various alternative approaches are available for funding and conducting studies of the feasibility of increasing water supply capabilities through modifications in operations of existing reservoirs. Distinctions regarding the appropriateness of alternative approaches may be subject to discussion. For example, for a specific study, questions may arise regarding what portion of the study, if any, should be funded through operation and maintenance appropriations and what portion should be conducted with general investigations funds. However, basic authority and funding mechanisms are well established for the USACE to conduct the pertinent studies.

The Water Supply Act of 1958 specifies that modifications of a reservoir project "which would seriously affect the purposes for which the project was authorized, surveyed, planned, or constructed, or which would involve major structural or operational changes shall be made only upon the approval of Congress." This and other policy statements clearly require Congressional approval for major modifications. However, relatively minor modifications do not necessarily require Congressional approval. USACE policy, as expressed in ER 1105-2-20, is that, subject to the criterion specified above, the lesser of 50,000 acre-feet or 15% of the total storage capacity may be reallocated to M&I water supply at the discretion of the Commander, USACE. Reallocations which exceed the 50,000 acre-feet or 15% criterion, but still do not have significant effect on other authorized purposes or involve major changes, may be approved at the discretion of the Secretary of the Army.

Defining the limits by which projects can be modified without going through the Congressional approval process has significant practical implications, since obtaining Congressional approval may require significant time and effort. In many cases, modifications in reservoir operations will clearly not be major and will not require Congressional approval. In some cases, Congressional approval will definitely be required. However, in still others, the appropriate level of approval will not be evident. Although still subject to the overriding, more subjective criterion of "would seriously affect the purposes...or would involve major structural or operational changes," the 15% or 50,000 acre-feet criterion provides quantitative guidance

for reallocation of storage capacity between purposes. However, similar criteria have not been established for other types of modifications to reservoir operations. It is assumed that the 15% or 50,000 acre-feet criterion does not apply to adoption of a seasonal rule curve involving reallocation to a joint-use pool rather than to a water supply only pool. Major versus minor changes and appropriate levels of approval authority may be more difficult to define for improvements in multiple reservoir system operations or other changes involving release rates rather than storage capacity designations.

Congressional authorization of major modifications can be obtained following the same procedures followed for new construction projects. However, possibilities may exist for expediting the planning, report preparation, review, and Congressional authorization process for modifications in operation of existing projects. Investigation of possibilities for expediting the process represents a significant consideration.

Nonfederal Sponsorship and Financing

M&I water supply is primarily a local responsibility. A nonfederal sponsor is required in order to provide M&I water supply storage in a new reservoir project to be constructed by the USACE or to increase or add water supply capabilities by modifying operations of existing USACE reservoirs. Studies of the feasibility of increasing water supply capabilities are typically initiated in response to requests from nonfederal entities. In accordance with the Water Resources Development Act of 1986, costs for planning studies are now shared by the nonfederal sponsors. Nonfederal sponsors are responsible for all initial investment costs and ongoing operation, maintenance, and replacement costs allocated to water supply. Costs incurred by the USACE and allocated to water supply can be repaid, with interest, by the nonfederal sponsor over a specified period of time. The Water Resources Development Act of 1986 modified the Water Supply Act of 1958 to require repayment provisions which are generally somewhat less favorable to nonfederal interests now than before.

Local interests are responsible for repayment of all initial investment costs and ongoing operation, maintenance, and replacement costs incurred specifically due to the reallocation to M&I water supply plus an equitable share of the joint cost of the original project. The joint costs for a storage reallocation will normally be established as the highest of the (1) benefits or revenues foregone, (2) replacement cost, or (3) updated cost of storage in the federal project. In some past studies, the benefits foregone were found to be difficult to estimate, and the replacement cost was found to be too high to realistically charge the nonfederal sponsor. Therefore, the joint costs were established as the updated cost of storage in the federal project. Recently established policy allows a 10% reduction in the updated cost of storage, if the sponsor is willing to pay the reduced cost up front rather than over the up to 30 year repayment period.

Cost allocation is, of course, a key issue. For reservoir projects constructed a number of years ago, the project investment costs updated to current price levels are much higher than the actual costs at the original price levels. The Kansas MOU allows joint costs allocated to reallocated M&I water supply storage to be based on the original price levels. The joint costs allocated to water supply for reallocations in the USACE reservoirs in Kansas are being computed the same as if the water supply storage was included

in the reservoir at the time of construction. It was emphasized during development and approval of the Kansas MOU that the special cost provision was due strictly to the unique circumstances which created benefits to the federal government which would not occur without the MOU. Since approval of the Kansas MOU, water management entities in other states have indicated an interest in obtaining water supply storage based on similarly favorable cost sharing arrangements. However, the USACE position has been that a deviation from normal cost sharing policy, as outlined in ER 1105-2-20, is justified only in unusual circumstances where benefits accrue to the federal government that otherwise cannot be achieved and represent a reasonable sharing of benefits and costs between federal and nonfederal interests.

Irrigation can be included as a purpose in USACE reservoirs upon recommendation of the Secretary of the Interior, under authority of Section 8 of the Flood Control Act of 1944 and the reclamation laws. Section 931 of the Water Resources Development Act of 1986 authorizes reallocation of storage capacity in USACE reservoirs, which is presently allocated to M&I water supply but not under contract for delivery, to interim use for irrigation until the storage capacity is required for M&I water supply. Section 103 of the Water Resources Development Act of 1986 specifies that 35% of the investment costs and 100% of the operation, maintenance, and replacement costs allocated to irrigation be repaid by a nonfederal sponsor. For a reallocation of M&I water supply storage to interim use for irrigation, the nonfederal sponsor would be charged for 35% of the original investment costs allocated to M&I water supply.

Federal water policy treats M&I water supply and irrigation as distinctly different purposes. Cost sharing policies are different. The Bureau of Reclamation versus USACE roles are differentiated. However, nonfederal interests do not necessarily clearly differentiate the uses of reservoir storage capacity. River authorities and water districts have contracted, under authority of the Water Supply Act of 1958, for storage in USACE reservoirs from which they sell water to numerous customers at various times over the project life, which include irrigators as well as municipalities and industries. In some cases, it may be difficult to distinguish whether the increase in water supply capabilities provided by a storage reallocation or other operational modification is for M&I use, irrigation, or both.

Under authority of Section 6 of the 1944 Flood Control Act, local interests can purchase water from USACE reservoirs, under appropriate circumstances, without contracting for storage capacity. Thus, the USACE can be responsive to requests for temporary diversions of water which may be generated by droughts or other emergency situations.

Water Rights

The USACE normally does not get involved with water rights. The nonfederal sponsors which contract for the conservation storage in USACE reservoirs are responsible for obtaining the appropriate water rights permits. However, water rights can be a key consideration in reallocating storage capacity or otherwise modifying reservoir operations. The water rights system may provide the mechanism necessary to protect or assure that the increased water supply envisioned can actually be achieved. Reservoir inflows may have to be protected from upstream diverters to assure maintenance of anticipated reservoir yield and reliability levels. Also, without a regulatory mechanism, reservoir releases to be diverted at downstream locations for specified users

may be taken by other diverters prior to reaching the intended users. On the other hand, water rights may represent a constraint to reallocating storage capacity or otherwise modifying reservoir operations. An application for a permit to increase water supply capabilities may be denied if senior water rights are adversely impacted or if various requirements are not met. Inflexibilities in a water rights system may constrain innovative approaches to improving reservoir operations. For example, a water rights system based on permitting individual reservoirs may not recognize the benefits of multiple reservoir system operations.

Getches (1984) provides a general overview of the development and application of basic principles of water law. Rice and White (1987) treat water law from an engineering perspective. Generally, in the United States, legal rights to the use of streamflow are based on two alternative doctrines, riparian and prior appropriation. The basic concept of the riparian doctrine is that water rights are incidental to the ownership of land adjacent to a stream. The prior appropriation doctrine is based on the concept "first in time is first in right." In a prior appropriation system, water rights are not inherent in land ownership, and priorities are established by the dates that users first appropriate water. Water law in 29 eastern states is based strictly on the riparian doctrine. Nine western states have a pure prior appropriation system. Ten other western states originally recognized riparian rights but later converted to a prior appropriation or permit system while preserving riparian water rights. Two other states also have hybrid systems incorporating the two doctrines in a somewhat different manner.

Creation, allocation, and administration of water rights is the responsibility of the individual states. Water rights in the eastern riparian states are totally different from water rights in the western appropriation states. In some eastern states with abundant streamflow, water development and use is subject to little or no regulation by the state. In certain water-short western states, water development and use is very strictly regulated. Also, significant variations exist between the permit systems administered by the prior appropriation states. The various individual riparian states also view water rights differently.

Special Institutional Arrangements

In most cases, modifying reservoir operations to increase water supply capabilities involves only those institutional considerations normally associated with USACE multiple purpose reservoirs. However, special institutional arrangements may be either highly advantageous or absolutely required in certain situations. The agreements and programs developed in conjunction with the Kansas MOU and the Washington Metropolitan Area Regional Water Supply Plan are examples of special institutional arrangements which may be needed to develop and implement innovative water management plans.

The stated purpose of the Kansas MOU was to establish a federal/state partnership to take advantage of a unique opportunity to solve specific water management problems, while simultaneously increasing the economic benefits to be derived from the system of USACE reservoirs in Kansas, increasing the level of dependable water supplies to meet the needs of municipalities and industries in Kansas, and increasing the level of recovery of past federal investments in water resources development. The MOU outlined the mechanisms by which storage reallocations would be studied and implemented. Cost sharing provisions allowed deviations from established USACE policy. The State of

Kansas agreed to pursue establishment of a Water Assurance Program and also, if necessary, obtain state legislation to facilitate protection of water quality inflows and releases prior to the purchase of storage under the MOU.

Under the terms of the MOU, the State of Kansas Legislature adopted the Kansas Water Assurance Act in 1986 as a means of assuring reliable municipal and industrial water supply and strengthening its comprehensive water management program. The Act allows the establishment of water assurance districts as a means of managing the water in each basin. The districts will sell M&I water supplies to users under low flow conditions.

The other example of special institutional arrangements is the regional water supply plan for the Washington, D.C., area which was implemented by nonfederal entities. A key element of this plan was system operations involving coordination of releases from multiple reservoirs and diversions of unregulated flows. Implementation of the plan required contractual agreements between the several entities that owned and operated the reservoirs and other elements of the basinwide water supply system.

Impacts on Other Project Purposes and the Environment

Environmental and social impacts of reallocating storage capacity or otherwise modifying reservoir operations are typically minor relative to the impacts of constructing new reservoir projects but may still be quite significant. Environmental and social impact assessment is an integral part of the plan formulation and evaluation process of feasibility studies for increasing water supply capabilities of existing reservoirs.

Impacts on other project purposes is a major consideration in formulating and evaluating plans for modifying operations of existing reservoirs. Increases in water supply may be accompanied by adverse impacts on flood control, hydroelectric power, recreation, and other purposes. Thus, two key interrelated issues are (1) optimizing multiple purpose operations from the perspective of the overall general public welfare and (2) identifying and compensating individual entities who suffer losses for the public good. For example, a reallocation of flood control storage capacity to M&I water supply may be warranted from the perspective of enhancing the overall public welfare, but certain individuals may be subjected to a higher risk of flooding.

Hydrologic and economic analysis capabilities for quantifying water supply improvements and for evaluating interactions and tradeoffs between project purposes are addressed in a later section of this report.

Development of mitigation or compensation mechanisms for project beneficiaries who may be adversely impacted by a modification and also associated implications of potential litigation are issues which could be of significant concern. The review of past studies and projects identified little work accomplished in this area to date.

Public Involvement

Public involvement is an integral component of essentially all water resources development and management activities. Various interest groups and the general public can be expected to have a broad range of concerns regarding modifications to reservoir operations. Section 5 of the Water Resources Development Act of 1988 states the requirement to provide an opportunity for public review and comment before making changes in the operation of any

reservoir which involves a reallocation of storage space or significantly affects any project purpose.

Comprehensive Integrated Basinwide Water Resources Management

The potentialities of moving toward more comprehensive integrated water management have been emphasized in the technical literature and statements of water policy. The general concept includes improved integration or coordination of multiple project purposes, water quantity and quality, ground water and surface water sources, water supply augmentation and demand management, and new construction projects and improved operation of existing facilities. A river basin, or region, should be viewed as an integrated system.

Storage reallocations and other modifications of reservoir operations, in many cases, involve a relatively simple change in the operation of an individual reservoir. However, in other cases, comprehensive integrated basinwide water resources management will be important. The studies and actions associated with the Kansas MOU and Washington Metropolitan Area Water Supply Plan are illustrative of this broader approach to meeting water supply needs. Innovative management strategies and institutional arrangements may be required to fully realize the water supply potentialities of a river basin.

MODELING AND ANALYSIS METHODS

This section presents an overview of the state-of-the-art of modeling and analysis capabilities and outlines research needs pertinent to formulation, evaluation, and implementation of plans for reallocating storage capacity or otherwise modifying operations of completed reservoir projects to increase water supply capabilities. Water resources planning investigations, including studies dealing with modifications at completed reservoir projects, involve a broad range of analyses including institutional analyses, projections of water needs, environmental and social impact evaluations, and engineering studies involving geotechnical, structural, hydraulic, and civil design considerations. However, the present discussion is limited to hydrologic and economic evaluation of reservoir operations.

Analysis of Completed Projects as Compared with Analysis of Proposed Construction Projects

An array of modeling and analysis methods are routinely used to support a variety of decisions made during the planning, design, implementation, and real-time operation of water projects. In the past, development of modeling and analysis methods focused largely upon supporting planning and design efforts related to proposed construction projects. Supporting real-time reservoir release decisions has also become a major emphasis in recent years. Modeling and analysis methods developed and applied in either of these two arenas are also pertinent to formulating, evaluating, and implementing operational modifications at completed projects.

Extensive experience in sizing storage capacities and establishing operating rules for proposed new reservoir projects has been accumulated over several decades. Traditionally in the past, new construction projects were the focus of USACE water resources planning activities. Formulating and evaluating plans involving storage reallocation or other modifications in the operation of completed projects is similar, in many respects, to formulating and evaluating plans for construction of new reservoir projects. In general, the same modeling and analysis methods are applicable for either type of study. However, there are also significant differences. Several aspects of these differences are listed below and discussed in the following paragraphs.

- (1) Tradeoffs between project purposes,
- (2) Refinements and incremental differences,
- (3) Level of detail of water supply modeling and analysis,
- (4) Expanded data availability,
- (5) Advances in computer technology, and
- (6) Modeling and analysis costs relative to total study costs and to implementation costs.

Tradeoffs Between Project Purposes

The first three aspects listed above involve a difference in focus or level of emphasis in the modeling and analysis effort. For example, tradeoffs between project purposes typically will be a significantly greater emphasis in a reallocation study than in a feasibility study of a proposed new reservoir construction project.

A reservoir is operated for either flood control only, conservation

purposes only, or a combination of flood control and conservation with separate pools designated for each. Planning, design, and operating problems associated with flood control are handled separately from those associated with conservation. Institutional arrangements are based on separating flood control and conservation purposes. Although there is typically somewhat more interaction between water supply and the other conservation purposes, such as hydroelectric power and recreation, these interactions also tend to be minimized in the planning and construction of new reservoir projects. The planning emphasis is on formulating and evaluating a comprehensive array of alternatives for fulfilling each individual purpose or need, while taking advantage of opportunities afforded by multiple purpose development.

In sizing storage capacities and establishing operating procedures for proposed multiple purpose reservoir projects, the flood control and conservation pools are typically handled almost independently of each other. Although site characteristics may somewhat limit total storage capacity, the amount of storage capacity provided for water supply usually does not significantly constrain the amount of storage capacity provided for flood control and vice versa. The various conservation purposes are also separated as much as possible. This greatly simplifies modeling and analysis. Different modeling and analysis approaches are associated with different project purposes. Tradeoffs between purposes are typically not evaluated to any degree of detail. Thus, the levels of service provided for different purposes do not have to be measured in commensurate units.

Increasing water supply capabilities of completed projects often involves allocating limited fixed total available storage capacity between project purposes. A reallocation study may involve: (1) evaluation of the comparative worth of storage capacity used for alternative purposes, (2) identification and quantification of benefits lost by project beneficiaries due to an operational modification, and/or (3) formulation of operational strategies for increasing water supply while minimizing adverse impacts on other purposes. Evaluating tradeoffs between purposes may be the primary focus of modeling and analysis efforts. The need to develop a detailed understanding of the interactions and tradeoffs between project purposes makes modeling and analysis more complex.

In many areas of engineering, modeling uncertainties are commonly handled by being conservative. For example, in sizing storage capacity for a proposed new reservoir, necessary assumptions and judgments can be based on tending toward conservatively large conservation and flood control storage capacities. However, in optimizing the operation of existing fixed storage capacity, involving tradeoffs between purposes, it may not be appropriate to be conservative on one side or the other.

Refinements and Incremental Differences

Modeling and analysis of operational modifications to completed projects will focus on refinements and incremental differences. The sensitivity of reservoir effectiveness to relatively small changes in operations will typically be of concern. Modeling approximations and simplifications become more important when relatively small incremental changes in storage capacity or refinements in reservoir release procedures are being evaluated. Greater precision is required. This makes modeling and analysis more difficult. For example, estimating average annual flood damages necessarily involves significant approximations and simplifications. Average annual damages with

and without a proposed project can be meaningfully estimated and compared to quantify the reduction in flood damages to be derived from construction of the project. However, estimates of the change in average annual flood damages to result from permanent reallocation of a relatively small amount of storage capacity between purposes, adoption of a seasonal rule curve, or change in target release rates are much less meaningful because the change in average annual damages is too small relative to the inaccuracies caused by modeling approximations and simplifications.

Level of Detail of Water Supply Modeling and Analysis

Modeling and analysis of water supply and use systems will be a major focus of studies of plans for increasing water supply capabilities of existing reservoirs. Innovative plans for system operation or coordination of supply augmentation and demand management may be under consideration. The complex institutional interactions of numerous state and local agencies and private entities involved in water supply and use may be important. A greater level of detail for water supply studies may be required, in certain cases, when evaluating modifications to completed projects than in the past when evaluating inclusion of water supply storage capacity in proposed new multiple purpose reservoir projects. For example, water supply capabilities of a proposed reservoir site are commonly evaluated in terms of a firm yield versus storage capacity relationship. A firm yield versus storage capacity relationship is also a fundamental component of a study of storage reallocation or other operational modifications at existing reservoirs. However, a more detailed and meaningful estimation of the risks of shortages occurring and associated consequences may also be needed. In an economic evaluation of a proposed multiple purpose reservoir project, water supply benefits are estimated based on a least-costly-alternative analysis. However, a more detailed economic evaluation approach is necessary to meaningfully compare tradeoffs between water supply and other project purposes.

Expanded Data Availability

Studies of modifications to completed projects will typically have the advantage of a much better data base than was available when the project was originally planned and designed. For example, installation of stream gaging stations have often been motivated by the initiation of planning studies, and the gages are maintained continuously thereafter. Thus, there is typically significantly more years of streamflow data available now than during the time of project planning. More reservoir evaporation and precipitation data are also available. An existing project has a history of actual releases and storage levels. In addition to greater data availability, experiences and lessons learned from years of actual operations can be reflected in studies of modifications to completed projects.

Advances in Computer Technology

Advancements in computer technology in recent years have resulted in greatly expanded modeling capabilities. Computers run quicker and more economically now than in the past. Data handling and graphics capabilities as well as computational speed have been greatly improved. Personal computers as well as more powerful mainframe computers are now routinely used. The types of modeling studies conducted in the past can now be done much more efficiently and conveniently. More importantly, advances in computer technology also provide opportunities for developing new and better modeling and analysis methods. Thus, expanded computational and data handling capabilities are available now, as compared to several years ago, to support studies of either

proposed new projects or modifications to completed projects.

Modeling and Analysis Costs

Water resources planning studies are expensive. Obtaining adequate funding to support modeling and analysis efforts for studies of operational modifications of existing projects may be more difficult than for obtaining funds for comparable studies for proposed construction projects. Study costs tend to be viewed in terms of proportionality to investment costs. For traditional planning studies, study costs are high from some perspectives but yet are a very small percentage of the investment cost of potential construction projects. On the other hand, operational modifications of completed projects typically involve much smaller implementation costs. Also, many of the engineering design and environmental impact studies associated with new construction projects will not be required in studies of modifications to existing projects. Consequently, modeling and analysis of reservoir operations will typically represent a greater portion of the total study cost for reservoir modification studies than for planning studies involving proposed construction projects.

Summary

Modeling and analysis of plans for reallocating storage capacity or otherwise modifying reservoir operations may be more complex than the more traditional studies of proposed new projects. This is due to requirements to better understand interactions and tradeoffs between project purposes, to focus on refinements and incremental differences, and to evaluate water supply potentialities and complexities in greater detail. Modeling and analysis methods should take advantage of expanded data availability and advances in computer technology. The methods should be efficient from the perspective of effectively supporting the decision making process while keeping study costs to a minimum.

Review of Modeling and Analysis Approaches

The present review of USACE practices and the published literature addresses modeling and analysis of reservoir operations in general but from the perspective of focusing on methods most pertinent to increasing water supply capabilities of completed projects. The analysis methods used in past studies of operational modifications at completed projects are essentially the same general methods used in the more traditional planning studies involving sizing storage capacities and establishing release policies for proposed new reservoir projects. As discussed above, from certain perspectives, investigations of operational modifications of existing fixed storage capacity could be enhanced by different and expanded analysis capabilities. However, future development of expanded modeling and analysis capabilities should build upon and extend methods presently used by the USACE. The review of state-of-the-art modeling and analysis methods in general in this section is followed in the next section by a discussion of research and development needs related specifically to operational modifications to enhance water supply.

For purposes of the following review, modeling and analysis methods are divided into the following overlapping and interrelated categories:

- (1) reservoir system simulation models,
- (2) water supply yield analysis,
- (3) flood control storage frequency analysis,

- (4) economic analysis, and
- (5) optimization techniques.

Reservoir system simulation models serve as the central basic tool for hydrologic and economic evaluation of reservoir operations. Reservoir system simulation models are used for a variety of purposes including performing yield analyses, storage or discharge frequency analyses, and economic analyses. Economic analyses, yield analyses, and various other types of analyses can also be incorporated in optimization models. Optimization, or mathematical programming, techniques represent an alternative approach that can be adopted either in lieu of or in combination with simulation models. Optimization models dominate the published research literature related to reservoir operation. Simulation models dominate actual practice. Economic evaluation and hydrologic frequency analysis are fundamental to essentially all aspects of water resources planning and management.

Reservoir System Simulation Models

Models for simulating reservoir operations are basic analysis tools regardless of whether the application involves sizing storage capacities and establishing operating policies for proposed new reservoir projects, supporting real-time operating decisions, or analyzing proposed modifications to the operation of existing reservoirs. A reservoir system simulation model reproduces the hydrologic and, in some cases, economic performance of a reservoir system for given inflows and operating procedures. The model typically computes reservoir storage levels and releases and discharges at pertinent stream locations for specified sequences of hydrologic inputs (streamflow and reservoir evaporation rates), demands for releases or withdrawals for beneficial purposes, and operating rules. Constraints such as storage capacities, outlet and conveyance capacities, and requirements for maintaining minimum streamflows, are also reflected in the models. Flood routing techniques are included to simulate the attenuation effects of a flood wave moving through a stream/reservoir system. Models for simulating reservoir operations may also include economic evaluation capabilities such as computing expected annual flood damages or hydroelectric power benefits.

Modeling flood control operations is significantly different than modeling reservoir operations for conservation purposes such as municipal, industrial, and agricultural water supply, hydroelectric power, navigation, recreation, and maintenance of low flows for water quality. Although optional capabilities for analyzing flood control and conservation operations are combined in some models, other models are limited to one or the other type of operation. Hydrologic analysis of floods is probabilistic event oriented. Major flood events have durations of several hours to several weeks, with discharges changing greatly over periods of hours or days. Flood analyses are typically performed using daily or hourly streamflow data. Modeling flood wave attenuation effects is important. Hydrologic analysis of droughts is stochastic time series oriented. Reservoirs are planned and managed to supply water during extreme droughts with durations of several years. Evaporation is important. Although conservation analysis are sometimes based on daily streamflow and evaporation data, weekly or monthly data is more typical for planning studies.

Various strategies can be adopted for applying simulation models. Series of runs are typically made to compare system performance for alternative reservoir configurations, storage allocations, operating procedures, demand

levels, or hydrologic inflow sequences. System performance may be evaluated by simply observing the computed time sequences of storage levels, discharges, hydroelectric power generated, water supply diversions, and diversion shortages. Yield reliability analyses, flood control storage frequency analyses, and economic analyses are also performed either with or using output from reservoir simulation models; are particularly pertinent to studies of operational modifications of completed projects; and are further discussed later in this section.

USACE Reservoir System Simulation Models. Simulation modeling of major river basins began in the United States in 1953 with a study by the USACE of the operation of six reservoirs on the Missouri River. The objective was to maximize hydroelectric power generation subject to constraints imposed by specified requirements for navigation, flood control, and irrigation. Various versions of the Streamflow Synthesis and Reservoir Regulation (SSARR) Model, developed by the USACE North Pacific Division, date back to 1956. Since the 1950's, the various offices of the USACE have developed and applied a number of computer models to simulate reservoir operations.

The HEC-5 Simulation of Flood Control and Conservation Systems computer program is versatile in the sense of being applicable to a wide range of reservoir operation problems. It is also generalized for application to any reservoir system as opposed to other models which were developed for a specific river basin. HEC-5 is well documented and has been used in a relatively large number of studies, including studies of storage reallocations and other operational modifications at existing reservoirs. An initial version released in 1973 has subsequently been significantly expanded. Microcomputer versions of the model are available. Several utility programs exist to aid in developing input data files and analyzing output. Alternative versions of the model are available which exclude and include water quality analysis capabilities. The latest version of the user's manual dated April 1982 (main manual) and January 1989 (input description) provides detailed instructions for using the generalized computer program. Feldman (1981) describes HEC-5 and several other water resources system simulation models available from the Hydrologic Engineering Center. Various publications regarding the use of HEC-5 are available from the Hydrologic Engineering Center.

The HEC-3 Reservoir System Analysis for Conservation computer program simulates the operation of a reservoir system for conservation purposes such as water supply, low-flow augmentation, and hydroelectric power. HEC-3 and HEC-5 have similar capabilities for simulating conservation operations. However, HEC-3 does not have the comprehensive flood control capabilities of HEC-5. HEC-3 is documented by a user's manual (USACE, HEC 1981) and other publications available from the Hydrologic Engineering Center. A modified version of HEC-3 incorporating water rights considerations was developed by the USACE Southwestern Division for use in reallocation studies performed in conjunction with the previously discussed Kansas MOU. Various nonfederal entities have also adopted and modified HEC-3 for different applications involving operation of conservation storage systems.

A generalized reservoir system simulation model, called SUPER, was developed by the USACE Southwestern Division (SWD) and is described by Hula (1981). The SWD model simulates the daily sequential regulation of a multipurpose reservoir system. The model performs the same types of

hydrologic and economic simulation computations as HEC-5. The SWD model uses a one-day computation interval, whereas HEC-5 uses a variable time interval. Details of handling input data and various computational capabilities differ somewhat between HEC-5 and the SWD model. The division and district offices in the Southwestern Division have applied the model in a number of studies, including several of the previously cited reallocation studies. The Reservoir Modeling Center in the Tulsa District office is using the SWD model to simulate the various major USACE reservoir systems located in the division. The Reservoir Modeling Center was established in Tulsa several years ago to provide a center of expertise in reservoir system modeling to support reservoir operations throughout the SWD.

Non-USACE Reservoir System Simulation Models.

Other federal agencies, state agencies, consulting firms, and universities have also developed a number of computer simulation models for sizing reservoir storage capacities and establishing operating policies during project planning, supporting release decisions during real-time operations, and analyzing the operations of existing systems. Several examples of such models are cited below. Whereas USACE modeling efforts have tended to emphasize flood control, non-USACE entities have been concerned primarily with conservation purposes.

The Potomac River Interactive Simulation Model (PRISM) was originally developed by a research team at John Hopkins University (Palmer, Wright, Smith, Cohen, and Revelle 1980). A number of water management agencies in the Potomac River Basin participated in drought simulation exercises using PRISM during development and implementation of the previously discussed regional water supply plan for the Washington Metropolitan Area. The USACE modified PRISM for use in certain drought simulation studies (USACE, Baltimore District 1983). PRISM simulates the operation of the four reservoirs and allocation of water within the Washington Metropolitan Area. Input data include: (1) weekly streamflow into each reservoir and weekly flow of the Potomac River, (2) weekly water use demand coefficients for each of three water supply agencies, (3) an allocation formula for distribution of water to jurisdictions, and (4) rules and constraints for operating the reservoirs in the system. The model determines on a weekly basis the supply of water available to each of the three jurisdictions resulting from previous decisions made in response to information on the state of the system. A modified version of the model uses a daily rather than weekly time interval. PRISM is designed for use in a batch mode, where decision strategies are specified by the user prior to model execution, or in an interactive mode. When operating in the batch mode, PRISM performs the functions of the regional water supply manager in strict accordance with rules provided by the model user. The interactive mode allows participants to engage in a dialogue with the model as it is being executed, thereby changing model parameters and overriding prespecified decision rules. The interactive model represents an attempt to include, in a formal analytical modeling exercise, the process by which water supply management decisions are made.

The Texas Water Development Board began development of a series of surface water simulation models in the late 1960's in conjunction with formulation of the Texas Water Plan. The present Reservoir Operating and Quality Routing Program (RESOP-II), Simulation Model (SIMYLD-II), Surface Water Resources Allocation Model (AL-V), and Multireservoir Simulation and Optimization Model (SIM-V) evolved from earlier versions. The Texas Water

Development Board generalized models provide a broad range of capabilities for analyzing conservation operations but include essentially no capabilities for simulating flood control operations.

Sigvaldason (1976) describes a simulation model developed to assess alternative operation policies for the 48-reservoir multipurpose water supply, hydropower, and flood control system in the Trent River Basin in Ontario, Canada. Strzepek and Lenton (1978) describe the Massachusetts Institute of Technology (MIT) Simulation Model and its application to the Vardar/Azios Basin in Yugoslavia and Greece. Gilbert and Shane (1982) describe the HYDROSIM model used by the Tennessee Valley Authority. Barnes and Chung (1986) extensively modified HEC-3 for application to combined operation of the Central Valley Project and State Water Project in California. Ford (1987) developed a generalized user-friendly model for simulating a single reservoir which is also based largely on routines taken from HEC-3.

Yield Analysis

Yield estimates are a key element in practically all studies and decisions involving water supply, including investigations of storage reallocations and other modifications to reservoir operations. Yield is a measure of the amount of water which can be supplied by a stream/reservoir system under specified conditions. The stochastic nature of streamflow and other pertinent variables must be incorporated in yield analysis methods. Yield may be expressed in terms of a firm or dependable yield, percent of time specified quantities of water are available, reliability of meeting various demand levels, risk of shortages, likelihood of various reservoir storage levels occurring, or a tabulation of the amount of water available during each period of a simulation based on specified conditions or assumptions. Rippl presented his well-known mass diagram technique for determining reservoir firm yield over a century ago. Since that time, a variety of mathematical models have been developed to evaluate the amount of water which can be supplied by an unregulated stream, reservoir, or multiple reservoir system.

Most reservoir yield studies performed by the water management community in general and the USACE in particular are based on using a reservoir simulation model with sequential historical period-of-record or critical period hydrology (streamflow and reservoir evaporation rate input data). This is also the basic approach used in studies of operational modifications at completed projects. As previously discussed, reservoir system simulation models, such as HEC-3 or HEC-5, can be used for a variety of purposes including performing yield analyses. Water availability can be quantified in various ways using a reservoir simulation model. For example, for a given demand level or targeted diversion amount, the actual diversion and diversion shortage computed during each month of the simulation may be tabulated. Reservoir storage levels for each time period may be tabulated or plotted from simulation results for specified conditions. However, yield is most typically viewed in terms of a yield versus reliability relationship, and particularly firm yield, developed for a given storage capacity. Essentially all planning studies involving either proposed new reservoirs or storage reallocations in completed projects will include development of a storage capacity versus firm yield relationship.

Firm Yield and Reliability. Firm yield (or safe or dependable yield) is the estimated maximum release or withdrawal rate which can be maintained continuously during a hypothetical repetition of the hydrologic period-of-

record, based on specified assumptions regarding various complexities such as interactions between multiple reservoirs and multiple users. Firm yield is the yield which will just empty the reservoir or multiple reservoir system during a hydrologic period-of-record simulation. Yield is typically expressed in terms of a mean annual rate with monthly distribution factors being incorporated in the model to reflect the within-year seasonal variation in water use. Standard textbooks outline the traditional Rippl diagram and sequent peak algorithm approaches for estimating firm yield, which are amenable to manual computations. With the advent of computers, firm yield is now computed using a reservoir system simulation model. For a given reservoir storage capacity and inflow sequence, the system is simulated with alternative trial demand levels, in an iterative search for the demand level which just empties the reservoir. The iterative procedure for computing firm yield is automated within HEC-3, HEC-5 and certain other simulation models. Firm yield computational procedures are outlined by the Hydrologic Engineering Center (USACE, HEC 1975).

Reservoir reliability is an expression of the probability that a specified demand will be met in a given future time period. Reliability (R) is the complement ($R = 1 - F$) of the risk of failure (F) or probability that the demand will not be met. Reliability estimates are developed from the results of a reservoir system simulation. Various definitions of reliability can be formulated for alternative time periods. Computational procedures are dependent upon the manner in which reliability is defined. For example, reliability may be defined as the percentage of months during a simulation for which demand is met. Thus, the reliability would represent the likelihood of demand being met in a randomly selected month in the future. Alternatively, reliability could be defined as the likelihood that demand can be met continuously during a 50-year simulation period. These two approaches for defining reliability are discussed below.

Reliability estimates also can be formulated based on either a period or volumetric basis. HEC-3 or HEC-5 can be used to compute either period or volumetric reliability. Period reliability is defined as the proportion of time that the reservoir/stream system is able to meet demands. Reliability (R) is computed from the results of a simulation as ($R = n/N$) where n denotes the number of time periods (typically months) during the simulation for which demands could be met and N is the total number of time periods in the simulation. Volumetric reliability is the ratio of the volume of water supplied to the volume demanded. The shortages occurring in each period of a simulation are totalled and the total volume of the demands minus shortages divided by the total volume of the demands over the simulation period. By definition, firm yield and smaller yields have a period and volume reliability of 100%. Yields greater than firm yield have a reliability of less than 100%.

Reliability estimates can also be formulated in terms of the likelihood that demand can be met continuously during a long multi-year period. This type of reliability analysis typically requires streamflow sequences many times longer than the period-of-record. Consequently, synthetic streamflow generation techniques, discussed later, have been developed to provide sufficient data for reservoir reliability studies. Synthetic streamflow generation involves synthesis of equally likely streamflow sequences with a length equal to the time period over which the reservoir is being analyzed. With a large number of equally likely alternative inflow sequences routed through a reservoir using a simulation model, the number of times that demands

are met, without incurring a shortage due to an empty reservoir, can be counted. The reliability is estimated as the percentage of the inflow sequences for which demands are met without incurring a shortage. For example, a large number (say 100) of monthly streamflow sequences of a specified length (say 50 years) can be synthesized using a model such as HEC-4. Firm yields could then be computed for each of the 100 streamflow sequences and the number of times the computed firm yield equalled or exceeded various levels counted. The reliability associated with a given yield value would be the number of streamflow sequences for which the yield value was equalled or exceeded divided by 100.

Yields may reflect a diversion requirement met by an individual reservoir or a diversion requirement met by releases from multiple reservoirs combined with unregulated flows entering the river below the dams. System yields are typically represented in a simulation model by multiple reservoirs releasing for a common diversion or instream flow requirement at a common downstream location.

Firm yield and reliability are discussed above from the perspective of supplying water for various beneficial uses. The concepts are equally applicable to hydroelectric power. Firm power is the maximum rate of energy production which can be maintained continuously assuming the period-of-record historical inflows are repeated in the future. Firm power and reliability associated with various levels of power production are computed with a simulation model similarly to firm yield and reliability for water supply.

Stochastic Streamflow Models. Stochastic streamflow models are used to statistically characterize streamflow. These models have useful application in estimating probable future reservoir levels when performing yield studies.

Commonly, water resource engineers are familiar with applying stochastic models to infer the statistical characteristics of peak annual streamflows when performing flood flow frequency analyses. However, these engineers are much less familiar with the stochastic models used to statistically characterize stream volumes that are important in water supply studies. The lack of familiarity probably results from the greater mathematical complexity of the stochastic models needed to characterize streamflow volumes as compared to that needed to model peak annual flows. The increased complexity is needed because streamflow volumes are generally considered to be best modelled as a dependent random variable; whereas, peak annual flows are considered to be independent random variables. Selection of the stochastic model that best represents dependence and the inference of the magnitude of this dependence from observed streamflow depends on the statistical techniques developed for time series analysis (for a discussion of the application of time series analysis see e.g., Kottegoda, 1980, or Salas et al., 1980).

Application of stochastic models to streamflow volume characterization is also more complex than in the case of peak annual flows. For example, if the peak flows are assumed to be distributed lognormally, then the probability that flow will exceed a given level can be rather easily calculated from published tables once the mean and standard deviations of the flows are calculated from the observed data. However, tables or analytic methods do not generally exist to estimate probabilities when dependence is a key parameter in the stochastic model. Rather, a numerical integration technique known as Monte Carlo simulation is used to calculate the probabilities of interest in

water supply studies.

The Monte Carlo simulation method is used to produce synthetic sequences of streamflow once the parameters of the stochastic model are known. A standard frequency analysis is then performed on the synthetic sequences of flow to determine probable future streamflow volumes. Note that these synthetic sequences have been referred to in the literature as "generated" streamflows. This terminology is at best unfortunate and at worst incorrect. The synthetic sequences do not represent new streamflow data nor do these sequences effectively lengthen the streamflow record. Rather the longer the sequence the better the numerical estimate of the probabilities obtained from analyzing the synthetic sequence.

The synthetic sequences typically would be used in reservoir yield studies. The methodology used in this instance would be to simulate the sequences with a reservoir operation model to obtain a synthetic sequence of reservoir levels. A standard frequency analysis of the synthetic levels then can be performed to estimate probable future levels, and in turn probable future water supplies, given reservoir characteristics and operating policy.

Stochastic models currently available in public domain engineering software are HEC-4 (USACE, HEC, 1971) and LAST (Lane and Frevert, 1985). HEC-4 focuses on inferring the monthly characteristics of streamflows at a number of different locations, estimating flows for missing records and performing Monte Carlo simulation to produce synthetic streamflows. LAST is an improvement over HEC-4 in that the streamflow statistics for different user define periods (e.g., yearly and monthly) can be interrelated, as well as providing Monte Carlo simulation capabilities.

The need for more sophistication than is available in the above software is debatable (see Klemes, 1981). The debate stems from the relatively high degree of uncertainty involved in using stochastic models to predict the probability of having severe supply conditions (e.g., drought). The uncertainty stems from both the difficulty in postulating the correct stochastic model and the short record lengths available for inferring streamflow volume characteristics. Consequently, great care should be exercised in evaluating stochastic model predictions of extreme supply conditions.

Impacts of Basinwide Water Management on Yield. A reservoir/stream system simulation model combines historical hydrology with some form of representation of water use. A homogeneous set of streamflow and reservoir evaporation rate data are needed covering the period-of-analysis at all pertinent locations in the basin. In representing a specified water use scenario, the impacts of other water users and water management activities should be reflected in the model as well as water control and use associated with the reservoir or multiple reservoir system being investigated. Much of the overall effort entailed in a yield study involves the two tasks of (1) developing homogeneous sets of hydrologic data and (2) representing a specified scenario of basin water control and use. These tasks are typically performed on an ad hoc study-by-study basis rather than using specific well-established generalized computer software and data compilation procedures. These are complex areas which tend to be overly simplified in planning studies.

Streamflow characteristics change with time as a result of man's

activities in the basin. Land use changes, water use diversions and return flows, groundwater pumping, river regulation by major reservoirs, capture of runoff by numerous small reservoirs scattered throughout a watershed, and other activities affect streamflow. The objective of streamflow naturalization is to develop a homogeneous set of streamflow data representing conditions existing prior to man's activities changing the basin or conditions existing at some other specified past, present, or future point in time. Naturalized streamflows are provided as input to reservoir system simulation models for performing various types of yield studies. Evaluation of the impacts of man's activities in a basin on reservoir inflows and streamflows at other locations is a major area of needed additional research. Improved capabilities are needed for developing sets of homogeneous streamflow data, in a cost effective manner, which adequately represent specified conditions for modeling purposes.

The various approaches for representing a specified water use scenario are based on (1) recorded past or projected future water use data, (2) water rights, or (3) a hypothetical potential yield such as the firm yield or a yield associated with a specified reliability level. Firm yields and yields associated with alternative levels of reliability are hypothetical potential withdrawals or releases used to quantify the amount of water a system can provide. However, the impacts of other water users and water management activities should be reflected in the estimated yields and reliabilities of the reservoir or multireservoir system being investigated. Expanded modeling and analysis capabilities are needed for evaluating the impacts of basinwide water management activities on the yield provided by a particular reservoir system.

Wurbs, Bergman, Carriere, and Walls (1988) and Wurbs and Walls (1989) outline an approach for developing yield versus reliability relationships and firm yields for a reservoir system which reflects the impacts of senior water rights in the basin. The analysis is based on the assumption that all water users in the basin utilize the full amount, or some specified portion of the full amount, of water to which they are legally entitled. Return flow factors are based on historical records. A water rights analysis model, called TAMUWRAP, is used to adjust naturalized streamflows to reflect other reservoirs and senior water rights. The adjusted streamflows are then provided as input data to HEC-3 or HEC-5 to perform a yield analysis for the reservoir system of interest which reflects constraints imposed by senior water rights in the basin.

Storage Probability Theory and Related Methods. Another approach to yield analysis, which has been addressed extensively in the research literature, is based primarily on the theory presented by Moran (1959) and expanded by Gould (1961). Much of the published research related to storage probability methods represents modifications or extensions of the basic Moran and Gould models. Klemes (1981) and McMahon and Mein (1986) provide concise overviews and cite many references regarding storage probability theory and related methods. The objective of stochastic storage analysis methods is to determine the probability distribution of reservoir storage. The mathematics is complex, necessitating significant assumptions and simplifications. Many of the more sophisticated techniques are severely limited from a practical applications perspective. In terms of practical usefulness, the most important methods in this group are described as probability matrix methods.

This general type of analysis methods could be pertinent to implementation of operational modifications at existing reservoirs during a drought as significant drawdowns occur if the following type of computation is of concern. For a specified release rate and present storage level, the probabilities of the reservoir being at various storage levels at future times during the next several months (or timeframe of interest) are to be estimated.

Flood Control Storage Frequency Analysis

Reservoir flood control capacity is often measured in terms of the recurrence interval, exceedance probability, or exceedance frequency of the flood which will deplete the flood control storage capacity. Frequency analyses, using a plotting position formula or probability distribution function, are typically performed based on the storage levels computed by a reservoir system simulation model. The peak annual storage level for each year of the simulation may serve as the data set for the frequency analysis. Alternatively, the peak storage data set may be limited to selected extreme flood events.

The simulation approach discussed above for developing reservoir storage data for a frequency analysis, requires a long sequence of naturalized streamflow data. An alternative approach involves use of hypothetical rainfall events developed for specified exceedance probabilities. Watershed (rainfall-runoff) modeling techniques are applied to compute streamflows for the statistical rain storms. Storms for alternative exceedance probabilities are routed through the reservoir/stream system to determine the corresponding storage levels to which the flood control pool is filled.

Reservoir storage frequency analyses are complex, and necessarily approximate, because storage levels depend upon: the volume, duration, and timing of streamflow hydrographs as well as peak discharge; streamflow hydrographs for multiple locations at reservoirs and downstream control points throughout the stream/reservoir system; reservoir storage levels at the beginning of the flood; and flood control operating policies which are necessarily based on the judgment of the operator as well as specified operation criteria. Flood control operations are concerned with extreme flood events. Frequency analysis for extreme events requires longer data series and are more approximate than analysis of more frequent events.

Economic Evaluation

Economic evaluation consists of estimating and comparing the benefits and costs, expressed in dollars, which would result from alternative plans of action. The Flood Control Act of 1936 and subsequent statements of policy have required a benefit/cost justification for federal projects. Over the past several decades, detailed procedures have been developed by the USACE and other federal water agencies for estimating national economic development benefits associated with the various project purposes. The Institute for Water Resources is developing a series of procedures manuals for economic evaluation associated with alternative project purposes. Procedures manuals have been completed for recreation (Vincent, Moser, and Hansen 1986), agricultural flood damage (Hansen 1987), and urban flood damage (Davis (editor) 1988).

Traditional design philosophy and analysis methods for sizing storage capacities and establishing operating policies are different for the various project purposes. The procedures are based on evaluating alternatives, sizing

storage capacity, and determining economic feasibility for each individual project purpose. M&I water supply cannot really be meaningfully compared with other purposes using traditional economic evaluation procedures. For example, M&I water supply versus flood control is discussed below.

Flood control, or flood damage reduction, is associated with the concept of risks and economic consequences. The USACE has developed detailed methods for quantifying the economic benefits associated with reducing the risk of flooding. Flood control storage capacity must be economically justified as measured by estimated benefits exceeding costs when discounted to a common time base using a specified discount rate. Maximizing net economic benefits is a key consideration in sizing flood control storage capacity. Flood storage capacity has also been traditionally evaluated in terms of the return interval of a design flood that can be contained without releases contributing to downstream damages. The objective in sizing storage capacity has often been to maximize net benefits subject to the constraint of providing a specified minimum level of protection (such as 50-year or 100-year). The economic efficiency criterion of benefits exceeding costs has also been strictly applied.

Estimation of expected annual damages is a central component of economic evaluation methodology. Expected or average annual damage is a frequency weighted sum of damage for the full range of damaging flood events and can be viewed as what might be expected to occur on the average in any year. The expected value of annual damages is computed as the integral of the exceedance frequency versus damage relationship representing a flood plain reach. Exceedance frequency versus peak discharge, stage versus discharge, and stage versus damage relationships are combined to develop the exceedance frequency versus damage relationship. Average annual damage computational capabilities are included in the HEC-5 and Southwestern Division reservoir system simulation models.

The M&I water supply planning and management philosophy traditionally has been that firm yield should exceed water needs by some reasonable margin of safety. The major policy emphasis in recent years on demand management and achieving more efficient water use has resulted in reservoir planning studies now including projections of water needs alternatively assuming reasonable demand management strategies are, and are not, adopted. Water supply studies typically include two key components: (1) projecting needs and (2) developing a firm yield versus storage capacity relationship. The project is sized such that firm yield exceeds projected water needs throughout the analysis period. In benefit-cost evaluation of federal multiple purpose reservoir projects, M&I water supply benefits are estimated as the cost of the least costly alternative means of providing the same quantity and quality of water assuming the proposed project is not implemented. Separable costs must be less than benefits for inclusion of M&I water supply storage to be economically justified. Estimating M&I water supply benefits based on a least-costly-alternative analysis does not provide the precision and sensitivity needed to evaluate storage reallocation tradeoffs between M&I water supply and other project purposes.

Flood control economic evaluation procedures have been used primarily in preconstruction planning and design. Expected annual damage estimates with and without a proposed new reservoir project are much more accurate and meaningful than the incremental changes in expected annual damages associated

with a storage reallocation or other operational modification in an existing reservoir. Frequency versus discharge relationships can be most accurately estimated for the more frequent flood events. However, storage reallocations affect the releases only for the extreme, less frequent events, for which data is most uncertain. Storage reallocations also affect flow duration as much as peak discharge. The traditional expected annual damage estimation procedures treat damages as a function of peak discharge only. Development of the basic data required to perform a flood control economic evaluation is costly. Unless data previously developed during preconstruction planning can be updated, the scope and available funds for a study of modifications at completed projects may preclude performing an economic evaluation.

Wurbs and Cabezas (1987) present an economic evaluation procedure for analyzing proposed reallocations of reservoir storage capacity between flood control and M&I water supply, which was developed as a university research effort. The central thrust of the procedure is the estimation of average annual economic losses associated with alternative allocations of storage capacity between purposes. Average annual flood losses are computed using the traditional damage-frequency method described above. Unlike traditional practices, water supply is treated analogously with flood control with economic consequences of water shortages being quantified. Average annual water supply losses, in dollars, are estimated by developing a water shortage versus economic loss function which is then applied to water shortages computed by a hydrologic simulation. The water shortage versus loss function reflects emergency demand management and supply augmentation measures. Average annual water supply losses are estimated for a given demand level. Long-term demand management strategies are reflected in the water demand projections. The economic evaluation procedure allows the impacts of a storage reallocation on flood control versus water supply to be compared in commensurate units of dollars, thus providing a better understanding of the tradeoffs.

Wurbs and Cabezas (1987) applied the economic evaluation procedure to the previously discussed proposed storage capacity reallocation in Waco Reservoir. The results of the economic evaluation for this particular case study support the concept of reallocating storage capacity to maintain a firm yield somewhat in excess of water demand. If water demand levels exceed firm yield, the average annual economic losses associated with water shortages exceed the increased average annual flood losses which would result from reallocating flood control capacity to water supply to prevent shortages. The investigators concluded that water supply losses could be estimated as meaningfully as flood losses if a comparable level of effort were to be devoted to development and application of economic evaluation methods for water supply. Realizing of course, both water supply and flood control analyses involve significant estimations and engineering judgments and are necessarily approximate.

Optimization Techniques

During World War II, the Allies organized interdisciplinary teams to solve complex scheduling and allocation problems involved in military operations. Mathematical programming or optimization models were found to be very useful in this work. After the war, the evolving discipline of operations research or management science continued to rely heavily upon optimization models for solving a broad range of problems in private industry. The same mathematical programming techniques also became important tools in

the various systems engineering disciplines, including water resources systems engineering. Reservoir operations have been viewed as an area of water resources planning and management having particularly high potential for beneficial application of optimization models.

The literature related to optimization models in general and application to reservoir operation in particular is extensive. The various optimization techniques are treated in depth by numerous mathematics, operating research, and systems engineering textbooks. Application of optimization techniques to reservoir operation problems has been a major focus of water resources planning and management research during the past two decades. The textbook by Loucks, Stedinger, and Haith (1981) explains the fundamentals of applying optimization techniques in the analysis of water resources systems. Yeh (1982) reviews the state-of-the-art of optimization models applied to operation of reservoir systems. Wurbs, Tibbets, Cabezas, and Roy (1985) provide a state-of-the-art review and annotated bibliography of systems analysis techniques applied to reservoir operations, which is directed toward optimization, simulation, and stochastic analysis methods. A majority of the over 700 references cited in the bibliography focus on optimization techniques.

Most of the applications of optimization techniques in reservoir systems analysis involve linear programming, dynamic programming, or combining a simulation model with a search algorithm. Combined use of simulation and optimization models has been found to be an effective analysis strategy for certain reservoir operation problems.

There is no generalized model for optimizing reservoir operation. Rather, optimization models have been formulated for a variety of specific types of reservoir operation problems. The models have usually been developed for a specific reservoir system. University research projects involving case studies account for most of the applications of optimization techniques to reservoir operations to date. Major reservoir systems for which optimization models have been used to support actual operations decisions include the California Central Valley Project and Tennessee Valley Authority System (Yeh 1982). USACE use of optimization techniques has been limited. Ford, Garland, and Sullivan (1981) describe application of a simulation model combined with a nonlinear optimization algorithm to optimize the use of the conservation pool of Sam Rayburn Reservoir, an existing USACE project in Texas, for hydroelectric power, water supply, recreation, and water quality maintenance purposes. The widely-used HEC-1 Flood Hydrograph Package incorporates an univariant gradient search optimization algorithm in the parameter calibration and flood control system optimization options.

Optimization models are formulated in terms of determining values for a set of decision variables which will maximize or minimize an objective function subject to constraints. An objective function and constraints are represented by mathematical expressions as a function of the decision variables. For a reservoir operation problem, the decision variables might be release rates or end-of-period storage volumes. The objective function to be maximized could be a quantitative measure of economic benefits for various project purposes, hydroelectric energy produced, firm yield, a water quality index, or the length of the navigation season. Likewise, an objective function to be minimized could be expressed as deviations from target discharges, a shortage index such as the squared sum of deviations between

target and actual discharges, volume of water released to meet minimum flow requirements, economic costs due to water shortages, expected annual flood damages, or any number of other indices of system performance. Constraints typically include storage capacities, mass balances, and minimum diversion or low flow requirements for various purposes. If the problem can be formulated in the proper mathematical format, linear programming, dynamic programming, and other nonlinear programming algorithms provide readily available solution techniques.

Research and Development Needs

Several areas of research and development needs are cited below. Although the modeling and analysis methods associated with the identified research needs have broader applicability, the focus of the research needs assessment is on developing expanded capabilities for hydrologic and economic analysis of reservoir operations to support formulation, evaluation, and implementation of plans for modifying operations of completed projects to enhance water supply capabilities. The following areas of research and development needs are briefly discussed:

- (1) reservoir system simulation models,
- (2) water supply yield analysis,
- (3) flood control storage frequency analysis,
- (4) economic analysis,
- (5) technological advances in real-time reservoir operation,
- (6) drought contingency planning, and
- (7) design of operating rules for joint use storage.

Reservoir System Simulation Models

Flood control operations have been emphasized in USACE development and application of generalized reservoir system simulation models. The present discussion focuses specifically on simulation of water supply operations. One broad research and development need area involves: (1) better defining the water supply simulation modeling and analysis capabilities needed to support studies of storage reallocation and other modifications in operation of completed projects and to support other types of water supply related studies; (2) evaluating and testing water supply analysis capabilities provided by existing USACE and non-USACE generalized reservoir system simulation models; and (3) expanding and refining existing models or developing new models as needed.

A key area for improving capabilities for modeling and analysis of conservation pool operations involves better representation of basinwide water control and use and other related basinwide activities in the modeling process. This need is pertinent to three interrelated aspects of reservoir system simulation: (1) developing homogeneous sequences of naturalized streamflow input data, (2) modeling operations of the reservoir system being investigated, and (3) reflecting the impacts of other reservoirs and water users in the basin on the reservoir system being investigated. These three modeling tasks are discussed below.

Streamflow naturalization computations are required to develop a homogeneous set of input data representing basin conditions at a specified past, present, or future point in time. Developing a homogeneous set of streamflow data, adjusted to remove nonhomogeneities caused by man's

activities in the basin, typically represents a large portion of the effort involved in a simulation study. A need exists for computer software and procedures for more efficiently developing the basic adjusted streamflow input data sets.

The importance of system operation has been emphasized in recent years. System operation may involve coordination of releases from multiple reservoirs, diversions from unregulated flows, and implementation of emergency demand management or supply augmentation measures. Approaches are needed to more precisely and meaningfully represent operation of multiple reservoir systems to meet the demands of multiple users which vary with hydrologic and other conditions. From the perspective of analyzing innovation improvements in reservoir system operations, models need to better represent the complexities of a reservoir/stream/user system.

Expanded modeling capabilities are also needed to represent the impacts of other reservoirs and users in the basin on the reservoir system being investigated. A reservoir system simulation can be based on a specified basinwide water use scenario which might represent present or projected future conditions of development and water use. Alternatively, the simulation may represent water allocations specified by a water rights system. Constraints imposed by senior water rights or other basin water users and activities should be reflected in the yield versus reliability relationships, firm yields, or other information computed for the reservoir system being investigated.

The three modeling tasks discussed above can be combined in a single computer program or alternatively can be viewed as a package of three computer programs and associated data compilation and analysis procedures. A streamflow naturalization computer program computes a set of homogeneous streamflow data representative of some specified point in time based on inputted historical streamflows, diversions, return flows, and reservoir data which varies historically over time as reservoir projects are constructed and the basin is developed. A second computer program, such as the TAMUWRAP model presented by Wurbs and Walls (1989), then adjusts the naturalized streamflow data to reflect a specified water use scenario such as present or projected future water use conditions or a water rights system. The adjusted streamflow data then becomes input to a third reservoir system simulation models such as HEC-3, which is used for detailed modeling of the reservoir system actually being investigated. For example, in the case study described by Wurbs and Walls (1989), streamflow data adjusted by the TAMUWRAP model to reflect 1,300 water rights and 600 reservoirs in the basin were provided as input to HEC-3 to perform a detailed analysis of a 12-reservoir system.

This particular research and development need area involves: (1) evaluating existing modeling capabilities, (2) developing or refining a comprehensive easy-to-use generalized package of computer programs, and (3) developing guidance on procedures for compiling the voluminous input data required for a detailed water supply simulation study.

Water Supply Yield Analysis

Yield analysis is fundamental to essentially all types of water supply studies including investigations of storage reallocation and other modifications in operation of existing reservoirs. Traditional yield analysis involves using a reservoir simulation model, such as HEC-3 or HEC-5, to

compute yield versus reliability relationships and firm yields based on historical period-of-record or critical period hydrology. This general approach will continue to be a key element in studies of operational modifications at completed projects. The above discussion of research and development needs related to reservoir system simulation models in general is, of course, pertinent to yield analysis in particular.

Another research area involves development of approaches for developing yield versus reliability relationships based on synthetically generated streamflow sequences. Investigating modifications in the operation of existing reservoirs could provide opportunities to beneficially utilize synthetic streamflow generation techniques. Simulation based on historical hydrology demonstrates the impacts of a operational modification on one sequence of streamflows. A modification in reservoir operations might have a certain incremental effect on yield estimates based on a traditional period-of-record analysis but significantly different effects based on alternative synthetically rearranged streamflow sequences. Simulation of reservoir operations based on numerous alternative sequences of synthesized streamflows could provide a better understanding of the impacts of operational changes.

In addition to the traditional firm yield and various types of yield versus reliability relationships, investigations to increase water supply capabilities of existing reservoir systems could motivate development and adoption of other innovative approaches to quantifying water availability. Modeling and analysis approaches could be developed which more meaningfully quantify, in a probabilistic or reliability sense, estimated future water availability for a complex water supply and use system.

Flood Control Storage Frequency Analysis

The probability of a flood event exceeding the storage capacity of a flood control pool provides a logical index for evaluating the impacts of alternative storage reallocations and other operational modifications involving flood control. For example, the analyst would like to be able to accurately state, with a known level of confidence, that the proposed reallocation plan reduces the design flood which can be contained from an estimated 120-year to 105-year recurrence interval. Impacts of an operational modification on the storage versus frequency relationship for a range of storages below and above capacity also provides useful information.

Development of storage versus frequency relationships is necessarily complex and approximate due to the various factors involved. Another research area consists of (1) comparing and evaluating methods of developing storage versus frequency relationships from the perspective of their application in studies of operational modifications and (2) developing improved methods for evaluating the impacts of operational modifications on the probability of exceeding the flood control storage capacity.

Economic Analysis

Interactions and tradeoffs between project purposes may be a major focus of modeling and analysis efforts involving storage reallocations and other changes in operating procedures. Economic evaluation provides a mechanism for comparing the impacts of alternative operating plans on the various project purposes in commensurate units of dollars. Research needs in this area include assessing the adequacy of traditional economic evaluation methods associated with the various project purposes from the perspective of their use

in evaluating operational modifications to completed projects. As previously discussed, the traditional least-cost-alternative approach for assigning M&I water supply benefits is particularly poorly suited for evaluating operational modifications. However, methods for economic evaluation of M&I water supply potentially could be developed so that tradeoffs between M&I water supply and other purposes such as flood control and hydroelectric power could be directly compared in commensurate units.

Drought Contingency Planning

Development of drought contingency plans has become a significant aspect of reservoir management. Developing improved methodologies for drought contingency planning represents a broad general research area. With regard to reservoir operation, expanded capabilities are needed for formulating and evaluating reservoir operation strategies which involve curtailment of selected withdrawals and implementation of demand management and/or supply augmentation measures whenever prespecified conditions occur. Research needs include investigation of potentialities of various types of operating strategies that can be implemented as well as developing expanded analysis capabilities. Yield analysis methods are needed to estimate probabilities of shortages being incurred by various categories of water users under alternative management scenarios from the perspectives of both planning studies and real-time drought management decisions.

Technological Advances in Real-Time Reservoir Operation

Automated hydrologic data acquisition systems have been implemented in many locations throughout the nation in recent years, which provide reservoir operators with access to real-time precipitation and streamflow measurements. Computer simulation modeling capabilities have been developed to use this data for real-time streamflow forecasting and reservoir system simulation. The focus of improvements in real-time reservoir operation technology in the USACE has been on flood control operations. Another related general research area involves: (1) assessment of the potential for operational modifications facilitated by recent technological advances in real-time data acquisition, computer modeling, and forecasting capabilities; (2) development of reservoir operating strategies which utilize these technological advances, and (3) assessing needs for further technological advances in data acquisition, computer modeling, and forecasting from the perspective of increasing water supply capabilities of completed projects.

Design of Rule Curves for Joint-Use Storage

Rule curve operation of joint-use storage provides a mechanism for simultaneously enhancing multiple purposes or enhancing one purpose while minimizing adverse impacts on another. Rule curves are typically based on season of the year but may also reflect other parameters such as watershed moisture conditions, water demands, or floodplain activities. A seasonally varying designated top of conservation pool elevation delineates a joint-use pool operated for both flood control and conservation purposes. Rule curves can also be used to coordinate use of a conservation pool for water supply, hydropower, and/or other multiple conservation purposes.

There is no well-defined traditional approach for designing rule curves for joint-use storage. Rule curves have been established in the past using various reservoir simulation modeling and frequency analysis approaches combined with engineering judgment. Seasonal flood control/conservation rule curves have been adopted primarily in regions with very distinct flood

seasons. However, such rule curves can also be beneficial in regions with less distinct flood seasons, but the design and analysis are even more complex.

Adoption of joint-use storage rule curve operation is an important general strategy for increasing water supply at completed projects while minimizing adverse impacts on, or even enhancing, other project purposes. Another research area involves (1) assessment of the applicability and adequacy of present modeling and analysis methods in regard to developing operating rules for joint-use storage capacity and (2) developing improved methods for designing operating rules for joint-use storage.

SUMMARY AND CONCLUSIONS

The U.S. Army Corps of Engineers (USACE) manages numerous major multipurpose reservoir systems located throughout the nation. Reevaluation of operations of completed projects and, when found to be warranted, implementation of storage reallocations or other operational modifications are becoming an increasingly important component of the overall USACE civil works mission. Public needs and objectives and numerous factors affecting reservoir operation change over time. Population and economic growth, depleting groundwater reserves, and difficulties in developing new construction projects are resulting in intensifying demands to increase the water supply capabilities of completed USACE reservoir projects.

Significant issues need to be resolved, and additional issues will likely continue to surface as policies and practices evolve. However, the basic general authority and policy framework is well established for the USACE to modify operations of existing reservoirs to increase water supply capabilities. Past studies and experiences in implementing modifications indicate a broad range of potential approaches to increasing water supply capabilities of existing reservoirs. Modeling and analysis methods developed in the past primarily from the perspective of sizing storage capacities and establishing operating rules for proposed new construction projects are also applicable to analyzing operational modifications of completed projects. However, several general research and development areas associated with analyzing modifications have been identified.

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The U.S. Army Corps of Engineers owns and operates about 600 reservoirs located throughout the nation. Reallocation of storage capacity between purposes and other modifications in the operation of existing reservoirs is an ongoing consideration to meet future water supply needs. Conversion of storage capacity from water quality, hydroelectric power, or flood control to municipal and industrial water supply is of particular interest. Recent drought conditions experienced over large sections of the nation have focused attention on optimizing the effectiveness of single reservoirs and reservoir systems for meeting project purposes.					
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