PART 1

HYDROLOGIC ENGINEERING CONCEPTS FOR RESERVOIRS

Chapter 2
Reservoir Purposes

2-1. Congressional Authorizations

a. Authorization of purposes. The United States Congress authorizes the purposes served by U.S. Army Corps of Engineers reservoirs at the time the authorizing legislation is passed. Congress commonly authorizes a project "substantially in accordance with the recommendations of the Chief of Engineers," as detailed in a separate congressional document. Later, additional purposes are sometimes added, deleted, or original purposes modified, by subsequent congressional action. When the original purposes are not seriously affected, or structural or operational changes are not major, modifications may be made by the Chief of Engineers (Water Supply Act 1958).

b. General legislation. Congress also passes general legislation that applies to many projects. The 1944 Flood Control Act, for example, authorizes recreational facilities at water resource development projects. This authority has made recreation a significant purpose at many Corps reservoirs. Similar general legislation has been passed to enhance and promote fish and wildlife (1958) and wetlands (1976). The Water Resource Development Act of 1976 authorizes the Chief of Engineers, under certain conditions, to plan and establish wetland areas as part of an authorized water resource development project. A chronology of the congressional legislation authorizing various purposes and programs is shown in Figure 2-1 (USACE 1989).

c. Additional authorization. Figure 2-1 illustrates how additional authorizations have increased the number of purposes for which the Corps is responsible both in planning and managing water resource development projects. The first authorizations were principally for navigation, hydroelectric power, and flood control. Later authorizations covered a variety of conservation purposes and programs. During drought when there is a water shortage, all purposes compete for available water and are affected by the shortage. The more purposes and programs

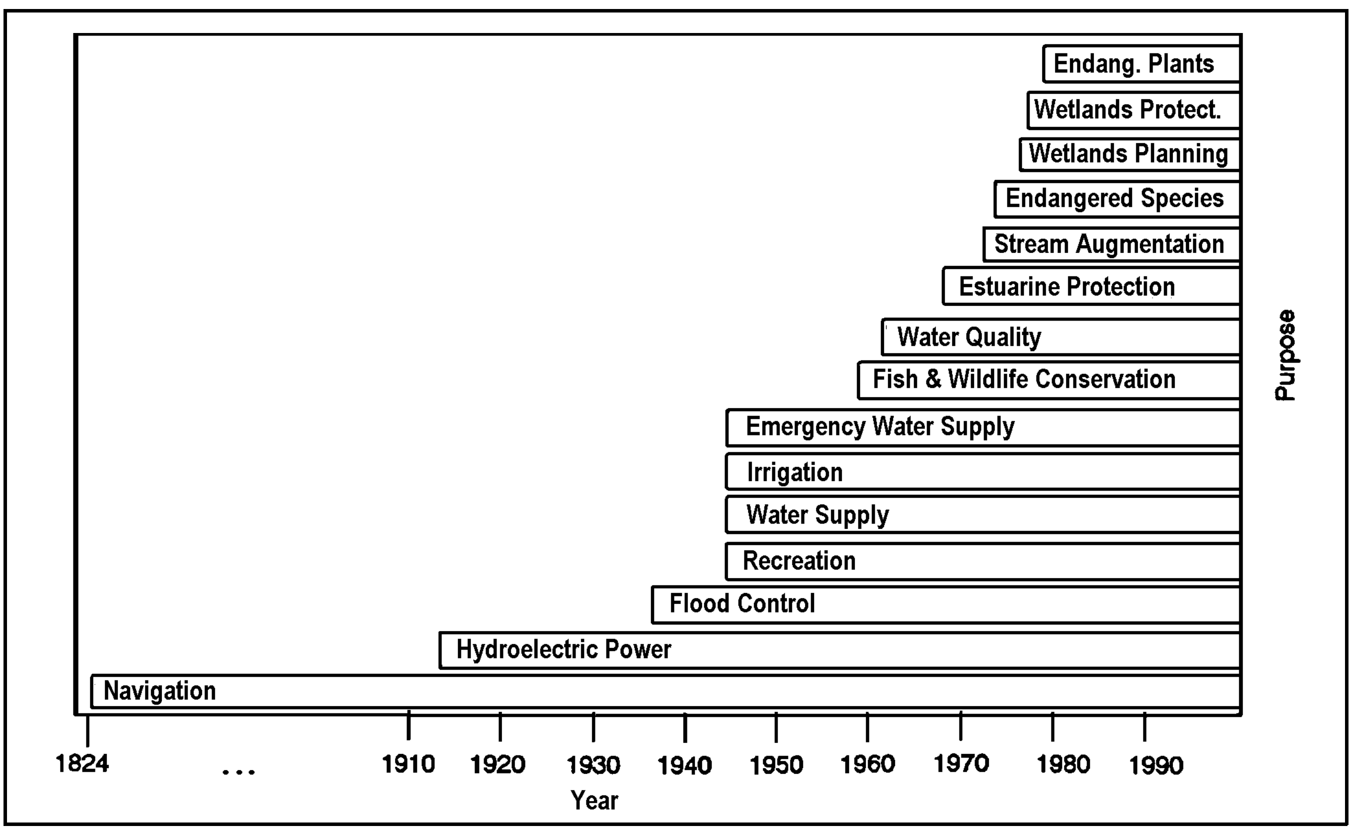

Figure 2-1. Purposes and programs authorized by Congress

there are to serve, the greater the potential for conflict, and the more complex the task of managing existing supplies. "Authorized and Operating Purposes of Corps of Engineers' Reservoirs" (USACE 1992) lists the purposes for which Corps operated reservoirs were authorized and are operated.

2-2. Reservoir Purposes

a. Storage capacity. A cross section of a typical reservoir is shown in Figure 2-2. The storage capacity is divided into three zones: exclusive, multiple-purpose, and inactive. While each Corps reservoir is unique both in its allocation of storage space and in its operation, the division of storage illustrated by Figure 2-2 is common.

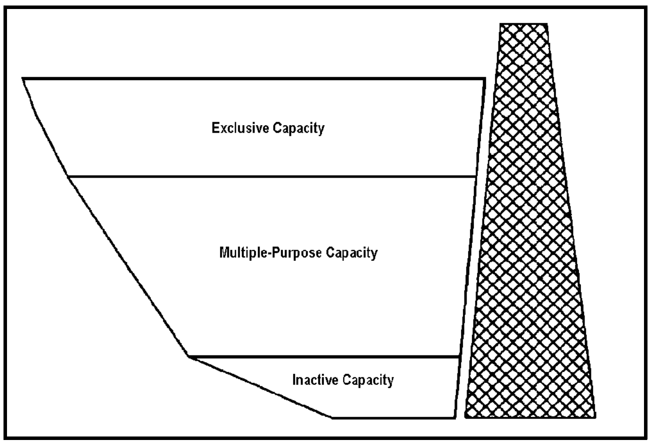

Figure 2-2. Typical storage allocation in reservoirs

b. Exclusive capacity. The exclusive space is reserved for use by a single purpose. Usually this is flood control, although navigation and hydroelectric power have exclusive space in some reservoirs. The exclusive capacity reserved for flood control is normally empty. Some reservoirs with exclusive flood control space have no multiple-purpose pool but have a nominal inactive pool that attracts recreational use. Recreational use is also common on pools originally established exclusively for navigation.

c. Multiple-purpose capacity. Multiple-purpose storage serves a variety of purposes. These purposes include both seasonal flood control storage, often in addition to exclusive storage, and conservation. Conservation purposes include: navigation, hydroelectric power, water supply, irrigation, fish and wildlife, recreation, and water quality. Other conservation purposes such as wetlands, groundwater supply and endangered species, while not included in this manual, are nonetheless important in water control management.

d. Inactive capacity. The inactive space is commonly used to maintain a minimum pool and for sediment storage. Sediment storage may affect all levels of the reservoir storage. Also, the inactive capacity may sometimes be used during drought when it can provide limited but important storage for water supply, irrigation, recreation, fish and wildlife, and water quality.

e. Storage space allocation. Reservoir storage space may not be allocated to specific conservation purposes. Rather, reservoir releases can serve several purposes. However, the amount of water needed to serve each purpose varies. During drought, with limited multiple-purpose storage available, the purposes requiring greater releases begin to compete with purposes requiring less. For example, if the greater releases are not made, the storage would last longer for the purposes served by the lesser releases.

f. General information. A brief description of project purposes is presented below. Additional detail and a discussion of reservoir operating procedures may be found in EM 1110-2-3600, from which the following sections are excerpts.

2-3. Flood Control

a. Utilizing storage space. Reservoirs are designed to minimize downstream flooding by storing a portion or sometimes the entire runoff from minor or moderate flood events. Each reservoir's water control plan defines the goals of regulation. Usually, a compromise is achieved to best utilize the storage space to reduce flooding from both major and minor flood events. In special circumstances where reservoir inflows can be forecast several days or weeks in advance (for example, when the runoff occurs from snowmelt), for the best utilization of storage space, the degree of control for a particular flood event may be determined on the basis of forecasts. When runoff is seasonal, the amount of designated flood control storage space may be varied seasonally to better utilize the reservoirs for multiple-purpose regulation.

b. Releases. Flood control releases are based upon the overall objectives to limit the discharges at the downstream control points to predetermined damage levels. The regulation must consider the travel times caused by storage effects in the river system and the local inflows between the reservoir and downstream control points.

c. Intervening tributary and downstream damage areas. A multiple-reservoir system is generally regulated for flood control to provide flood protection both in intervening tributary areas and at downstream main stem damage areas. The extent of reservoir regulation required for protecting these areas depends on local conditions of flood damage, uncontrolled tributary drainage, reservoir storage capacity, and the volume and time distribution of reservoir inflows. Either the upstream or downstream requirements may govern the reservoir regulation, and usually the optimum regulation is based on the combination of the two.

d. Coordinated reservoir regulation. Water control with a system of reservoirs can incorporate the concept of a balanced reservoir regulation, with regard to filling the reservoirs in proportion to each reservoir's flood control capability, while also considering expected inflows and downstream channel capacities. Evacuation of flood water stored in a reservoir system must also be accomplished on a coordinated basis. Each reservoir in the system is drawn down as quickly as possible, considering conditions at control points, to provide space for controlling future floods. The objectives for withdrawal of water in the various zones of reservoir storage are determined to minimize the risk of encroaching into the flood control storage and to meet other project requirements. Sometimes the lower portion of the flood control pool must be evacuated slower to transition to a lower flow to minimize bank caving and allow channel recovery.

2-4. Navigation

a. Navigational requirements. Problems related to the management of water for navigation use vary widely among river basins and types of developments. Control structures at dams, or other facilities where navigation is one of the project purposes, must be regulated to provide required water flows and/or to maintain project navigation depths. Navigational requirements must be integrated with other water uses in multiple-purpose water resource systems. In the regulation of dams and reservoirs, the navigational requirements involve controlling water levels in the reservoirs and at downstream locations, and providing the quantity of water necessary for the operation of locks. There also may be navigational constraints in the regulation of dams and reservoirs with regard to rates of change of water surface elevations and outflows. There are numerous special navigational considerations that may involve water control, such as ice, undesirable currents and water flow patterns, emergency precautions, boating events, and launchings.

b. Waterflow requirements. Navigation locks located at dams on major rivers generally have sufficient water from instream flows to supply lockage water flow requirements. Navigation requirements for downstream use in open river channels may require larger quantities of water over a long period of time (from several months to a year), to maintain water levels for boat or barge transportation. Usually, water released from reservoirs for navigation is also used for other purposes, such as hydroelectric power, low-flow augmentation, water quality, enhancement of fish and wildlife, and recreation. Seasonal or annual water management plans are prepared which define the use of water for navigation. The amount of stored water to be released depends on the conditions of water storage in the reservoir system and downstream requirements or goals for low-flow augmentation, as well as factors related to all uses of the water in storage.

c. Using water for lockage. Navigational constraints are also important for short-term regulation of projects to meet all requirements. In some rivers, supply of water for lockage is a significant problem, particularly during periods of low flow or droughts. The use of water for lockage is generally given priority over hydropower or irrigation usages. However, this is dependent on the storage allocated to each purpose. In critical low-water periods, a curtailment of water use for lockage may be instituted by restricting the number of locks used, thereby conserving the utilization of water through a more efficient use of the navigation system. Water requirements for navigation canals are sometimes based on lockage and instream flows as necessary to preserve water quality in the canal.

2-5. Hydroelectric Power

a. Reservoir project categories. Reservoir projects which incorporate hydropower generally fall into two distinct categories: storage reservoirs which have sufficient capacity to regulate streamflow on a seasonal basis and run-of-river projects where storage capacity is minor relative to the volume of flow. Most storage projects are multiple-purpose. Normally, the upstream reservoirs include provisions for power production at the site, as well as for release of water for downstream control. Run-of-river hydropower plants are usually developed in connection with navigation projects.

b. Integration and control of a power system. Integration and control of a major power system involving hydropower resources is generally accomplished by a centralized power dispatching facility. This facility contains the equipment to monitor the entire power system operation, including individual plant generation, substation operation, transmission line operation, power loads and requirements by individual utilities and other bulk power users, and all factors related to the electrical system control for real-time operation. The dispatching center is manned on a continuous basis, and operations monitor and control the flow of power through the system, rectify outages, and perform all the necessary steps to ensure the continuity of power system operation in meeting system loads.

c. Regulation of a hydropower system. Regulation of hydropower systems involves two levels of control: scheduling and dispatching. The scheduling function is performed by schedulers who analyze daily requirements for meeting power loads and resources and all other project requirements. Schedules are prepared and thoroughly coordinated to meet water and power requirements of the system as a whole. Projections of system regulation, which indicate the expected physical operation of individual plants and the system as a whole, are prepared for one to five days in advance. These projections are updated on a daily or more frequent basis to reflect the continuously changing power and water requirements.

2-6. Irrigation

a. Irrigation diversion requirements. Irrigation water diverted from reservoirs, diversion dams, or natural river channels is controlled to meet the water duty requirements. The requirements vary seasonally, and in most irrigated areas in the western United States, the agricultural growing season begins in the spring months. The diversion requirements gradually increase as the summer progresses, reaching their maximum amounts in July or August. They then recede to relatively low amounts by late summer. By the end of the growing season, irrigation diversions are terminated, except for minor amounts of water that may be necessary for domestic use, stock water, or other purposes.

b. Irrigation as project purpose. Corps of Engineers' reservoir projects have been authorized and operated primarily for flood control, navigation, and hydroelectric power. However, several major Corps of Engineers multiple-purpose reservoir projects include irrigation as a project purpose. Usually, water for irrigation is supplied from reservoir storage to augment the natural streamflow as required to meet irrigation demands in downstream areas. In some cases, water is diverted from the reservoir by gravity through outlet facilities at the dam which feed directly into irrigation canals. At some of the run-of-river power or navigation projects, water is pumped directly from the reservoir for irrigation purposes.

c. Meeting irrigation demands. The general mode for regulation of reservoirs to meet irrigation demands is to capture all runoff in excess of minimum flow demands and water rights during the spring and early summer. This usually results in refilling the reservoirs prior to the irrigation demand season. The water is held in storage until the natural flow recedes to the point where it is no longer of sufficient quantity to meet all demands for downstream irrigation. At that time, the release of stored water from reservoirs is begun and continued on a demand basis until the end of the growing season (usually September or October). During the winter, projects release water as required for instream flows, stock water, or other project purposes.

2-7. Municipal and Industrial Water Supply

a. Municipal and industrial use. Regulation of reservoirs for municipal and industrial (M&I) water supply is performed in accordance with contractual arrangements. Storage rights of the user are defined in terms of acre-feet of stored water and/or the use of storage space between fixed limits of reservoir levels. The amount of storage space is adjusted to account for change in the total reservoir capacity that is caused by sediment deposits. The user has the right to withdraw water from the lake or to order releases to be made through the outlet works. This is subject to Federal restrictions with regard to overall regulation of the project and to the extent of available storage space.

b. Temporary withdrawal. In times of drought, special considerations may guide the regulation of projects with regard to water supply. Adequate authority to permit temporary withdrawal of water from Corps projects is contained in 31 U.S.C. 483a (HEC 1990e). Such withdrawal requires a fee that is sufficient to recapture lost project revenues, and a proportionate share of operation, maintenance, and major replacement expenses.

2-8. Water Quality

a. Goal and objective. Water quality encompasses the physical, chemical, and biological characteristics of water and the abiotic and biotic interrelationships. The quality of the water and the aquatic environment is significantly affected by management practices employed by the water control manager. Water quality control is an authorized purpose at many Corps of Engineers reservoirs. However, even if not an authorized project purpose, water quality is an integral consideration during all phases of a project's life, from planning through operation. The minimum goal is to meet State and Federal water quality standards in effect for the lakes and tailwaters. The operating objective is to maximize beneficial uses of the resources through enhancement and nondegradation of water quality.

b. Release requirements. Water quality releases for downstream control have both qualitative and quantitative requirements. The quality aspects relate to Corps' policy and objectives to meet state water quality standards, maintain present water quality where standards are exceeded, and maintain an acceptable tailwater habitat for aquatic life. The Corps has responsibility for the quality of water discharged from its projects. One of the most important measures of quality is quantity. At many projects authorized for water quality control, a minimum flow at some downstream control point is the primary water quality objective. Other common objectives include temperature, dissolved oxygen, and turbidity targets at downstream locations.

c. Coordinated regulation. Coordinated regulation of multiple reservoirs in a river basin is required to maximize benefits beyond those achievable with individual project regulation. System regulation for quantitative aspects, such as flood control and hydropower generation, is a widely accepted and established practice, and the same principle applies to water quality concerns. Water quality maintenance and enhancements may be possible through coordinated system regulation. This applies to all facets of quality from the readily visible quantity aspect to traditional concerns such as water temperature and dissolved oxygen content.

d. System regulation. System regulation for water quality is of most value during low-flow periods when available water must be used with greatest efficiency to avoid degrading lake or river quality. Seasonal water control plans are formulated based on current and forecasted basin hydrologic, meteorologic and quality conditions, reservoir status, quality objectives and knowledge of water quality characteristics of component parts of the system. Required flows and qualities are then apportioned to the individual projects, resulting in a quantitatively and qualitatively balanced system. Computer programs capable of simulating reservoir system regulation for water quality provide useful tools for deriving and evaluating water control alternatives.

2-9. Fish and Wildlife

Project regulation can influence fisheries both in the reservoir pool and downstream. One of the most readily observable influences of reservoir regulation is reservoir pool fluctuation. Periodic fluctuations in reservoir water levels present both problems and opportunities to the water control manager with regard to fishery management. The seasonal fluctuation that occurs at many flood control reservoirs, and the daily fluctuations that occur with hydropower operation often result in the elimination of shoreline vegetation and subsequent shoreline erosion, water quality degradation and loss of habitat. Adverse impacts of water level fluctuations also include loss of shoreline shelter and physical disruption of spawning and nests.

2-10. Recreation

a. Reservoir level. Recreational use of the reservoirs may extend throughout the entire year. Under most circumstances, the optimum recreational use of reservoirs would require that the reservoir levels be at or near full conservation pool during the recreation season. The degree to which this objective can be met varies widely, depending upon the regional characteristics of water supply, runoff, and the basic objectives of water regulation for the various project purposes. Facilities constructed to enhance the recreational use of reservoirs may be designed to be operable under the planned reservoir regulation guide curves on water control diagrams, which reflect the ranges of reservoir levels that are to be expected during the recreational season.

b. Downstream river levels. In addition to the seasonal regulation of reservoir levels for recreation, regulation of project outflows may encompass requirements for specific regulation criteria to enhance the use of the rivers downstream from the projects, as well as to ensure the safety of the general public. The Corps has the responsibility to regulate projects in a manner to maintain or enhance the recreational use of the rivers below projects to the extent possible (i.e., without significantly affecting the project function for authorized purposes). During the peak recreation season, streamflows are regulated to ensure the safety of the public who may be engaged in water related activities, including boating, swimming, fishing, rafting, and river drifting. Also, the aesthetics of the rivers may be enhanced by augmenting streamflows during the low-water period. Water requirements for maintaining or enhancing the recreational use of rivers are usually much smaller than other major project functional uses. Nevertheless, it is desirable to include specific goals to enhance recreation in downstream rivers in the water control plan. The goals may be minimum project outflows or augmented streamflows at times of special need for boating or fishing. Of special importance is minimizing any danger that might result from changing conditions of outflows which would cause unexpected rise or fall in river levels. Also, river drifting is becoming an important recreational use of rivers, and in some cases it may be possible to enhance the conditions of stream flow for relatively short periods of time for this purpose.

2-11. Water Management Goals and Objectives

a. Water management. ER 1110-2-240 paragraph 6, defines the goals and objectives for water regulation by the Corps. Basically, the objective is to conform with specific provisions of the project authorizing legislation and water management criteria defined in Corps of Engineers reports prepared in the planning and design of the project or system. Beyond this, the goals for water management will include the provisions, as set forth in any applicable authorities, established project construction, and all applicable Congressional Acts and Executive Orders relating to operations of Federal facilities.

b. Water control systems management. EM 1110-2-3600 provides guidance on water control plans and project management. A general prime requirement in project regulation is the safety of users of the facilities and the general public, both at the project and at downstream locations. The development of water control plans and the scheduling of reservoir releases must be coordinated with appropriate agencies, or entities, as necessary to meet commitments made during the planning and design of the project. Additionally, water control plans must be reviewed and adjusted, when possible, to meet changing local conditions.

c. Regional management. Regional water management should consider the interaction of surface-groundwater resources. HEC Research Document 32 provides examples for several regions in the United States (HEC 1991c).

Chapter 3
Multiple-Purpose Reservoirs

3-1. Hydrologic Studies for Multipurpose Projects

a. Conception. Multipurpose reservoirs were originally conceived as projects that served more than one purpose independently and would effect savings through the construction of a single large project instead of two or more smaller projects. As the concept developed, the joint use of water and reservoir space were added as multipurpose concepts. Even such competitive uses as flood control and water supply could use the same reservoir space at different times during the year.

b. Feasibility. The feasibility of multiple-purpose development is almost wholly dependent upon the demonstrated ability of a proposed project to serve several purposes simultaneously without creating conditions that would be undesirable or intolerable for the other purposes. In order to demonstrate that multipurpose operation is feasible, detailed analyses of the effects of various combinations of streamflows, storage levels, and water requirements are required. Detailed analyses of these factors may be overlooked during the planning phase because the analyses are complex and simplifying methods or assumptions may not consider some details that may be important. However, ignoring the details of multipurpose operation in the planning phase is risky because the operation criteria are critical in determining the feasibility of serving several purposes simultaneously.

c. Defining the multipurpose project. One of the factors that make detailed sequential analyses of multipurpose operation difficult during planning studies is that sufficient data on various water demands are either not available or not of comparable quality for all purposes. To adequately define the multipurpose operation, the analyses must include information on the magnitude and seasonal variations of each demand, long-term changes in demands, relative priority of each use, and shortage tolerances. Information on magnitude and seasonal variation in demands and on long-term variations in demands is usually more readily available than information on relative priorities among uses and on shortage tolerances. If information on priorities and shortages is not available from the various users, one can make several assumptions concerning the priorities and perform sequential routing studies for each set of assumptions. The results of these studies can determine the consequences of various priorities to potential water users. It may be possible for the potential users to adopt a priority arrangement based on the value of the water for the various demands.

d. Success of multipurpose projects. The success of multipurpose operation also depends on the formulation of operational rules that ensure that water in the proper quantities and qualities is available for each of the purposes at the proper time and place. Techniques for formulating operational rules are not fixed, but the logical approach involves determining the seasonal variation of the flood-control space requirement, and the seasonal variation of conservation requirements, formulation of general operational rules that satisfy these requirements, and detailed testing of the operational rules to ascertain the adequacy of the plan for each specific purpose.

e. Multipurpose project rules. The judgment of an experienced hydrologic engineer is invaluable in the initial formulation and subsequent development and testing of operational rules. Although the necessary rules cannot be completely developed until most of the physical dimensions of the project are known, any tendency to discount the importance of operational rules as a planning variable should be resisted because of the important role they often assume in the feasibility of multipurpose projects. As a minimum, the operational rules used in a planning study should be sufficiently refined to assist the engineer in evaluating the suitability of alternative projects to satisfy water demands for specified purposes.

3-2. Relative Priorities of Project Functions

a. Developing project rules. As indicated above, the use of operational rules based on the relative priorities among the project purposes appears to offer the best approach to multipurpose operational problems. The degree of success that can be realized depends on a realistic priority system that accurately reflects the relative value of water from the project for a given purpose at a given time. Unless a realistic priority system is used to develop the operational rules, it will not be possible to follow the rules during the project life because the true priorities may control the operational decisions and prevent the project from supplying the services it was designed to provide.

b. Typical system priorities. Priorities among the various water resource purposes vary with locale, water rights, the need for various types of water use, the legal and political considerations, and with social, cultural, and environmental conditions. Although these variations make it impossible to specify a general priority system, it is useful to identify a set of priorities that would be typical under average conditions. In such a situation, operation for the safety of the structure has the highest priority unless the consequences of failure of the structure are minor (which is seldom the case). Of the functional purposes, flood control must have a high priority, particularly where downstream levees, bridges, or other vital structures are threatened. It is not unusual for conservation operations to cease entirely during periods of flood activity if a significant reduction in flooding can be realized thereby. Among the conservation purposes, municipal and industrial water supply and hydroelectric power generation are often given a high priority, particularly where alternative supplies are not readily available. After those purposes, other project purposes usually have a somewhat lower priority because temporary shortages are usually not disastrous. It should be emphasized again that there can be marked exceptions to these relative priorities. There are regional differences in relative needs and, legal and institutional factors may greatly affect priorities.

c. Complex system priorities. In complex reservoir systems, with competing demands and several alternative projects to meet the demand, the relative priority among projects and purposes may not be obvious. The operation rules, which can be evaluated with detailed simulation, may not be known or may be subject to criticism. In these situations, it may be useful to apply a system analysis based on consistent values for the various project purposes. The results of the analysis could suggest an operational strategy which can be tested with more detailed analysis. Chapter 4 presents information and approaches for system analysis.

3-3. Managing Competitive and Complementary Functions

a. Identifying interactions between purposes. Before operation rules can be formulated, the adverse (competitive) and the beneficial (complementary) interactions between purposes must be identified. The time of occurrence of the interactions is often as important as the degree of interaction, particularly if one or more of the water uses has significant variations in water demand. In supplying water from a single reservoir for several purposes with seasonally varying demands, it is possible for normally complementary purposes to become competitive at times due to differences in their seasonal requirements.

b. Allocating storage space. When several purposes are to be served from a single reservoir, it is possible to allocate space within certain regions of the reservoir storage for each of the purposes. This practice evolved from projects that served only flood control and one conservation purpose because it was necessary to reserve a portion of the reservoir storage for storing floodwater. It is still necessary to have a specific allocation of flood-control storage space (although the storage reservation can vary seasonally) because of the basic conflict between reserving empty storage space for regulating potential floods and filling that space to meet future water supply requirements. However, applying specific storage allocations or reservations for competing conservation purposes should be kept to a minimum because it reduces operational flexibility.

c. Operational conflicts. Allocation of specific storage space to several purposes within the conservation pool can result in operational conflicts that might make it impossible or very costly to provide water for the various purposes in the quantities and at the time they are needed. The concept of commingled or joint-use conservation storage for all conservation purposes with operational criteria to maximize the complementary effects and minimize the competitive effects is far easier to manage and, if carefully designed, will provide better service for all purposes. Where the concept of joint-use storage is used, the operational criteria should be studied in the planning process in such a way that the relative priorities of the various purposes are taken into account. This allows careful evaluation of a number of priority systems and operational plans. The operational decisions that result from such disputes are frequently not studied in enough detail (from the engineering point of view), and as a result, the ability of the project to serve some purposes may be seriously affected.

3-4. Operating Concepts

a. Operating goals. Reservoir operating goals vary with the storage in the reservoir. The highest zone in the reservoir is that space reserved at any particular time for the control of floods. This zone includes the operational flood-control space and the surcharge space required for the passage of spillway flows. Whenever water is in this zone it must be released in accordance with flood-control requirements. The remaining space can be designated as conservation space. The top zone of conservation space may include storage that is not required to satisfy the firm conservation demands, including recreational use of the reservoir. Water in this space can be released as surplus to serve needs or uses that exceed basic requirements. The middle zone of conservation space is that needed to store water to supply firm water needs. The bottom zone of conservation space can be termed buffer space, and when operation is in this zone the firm services are curtailed in order to prevent a more severe shortage later. The bottom zone of space in the reservoir is designated as the minimum pool reserved for recreation, fish, minimum power head, sediment reserve, and other storage functions.

b. Storage zone boundaries. The boundaries between storage zones may be fixed at a constant level or they may vary seasonally. In general, the seasonally varying boundaries offer the potential for a more flexible operating plan that can result in higher yields for all purposes. However, the proper location of the seasonal boundaries requires more study than the location of a constant boundary. This is discussed in more detail in Chapter 11. Furthermore, an additional element of chance is introduced when the boundaries are allowed to vary, because the joint use of storage might endanger firm supplies for one or more specific purposes. The location of the seasonally varying boundaries is determined by a process of formulating a set of boundaries and attendant operational rules, testing the scheme by a detailed sequential routing study, evaluating the outcome of the study, changing the rules or boundaries if necessary, and repeating the procedure until a satisfactory operation results.

c. Demand schedules. Expressing demand schedules as a function of the relative availability of water is another means of incorporating flexibility and relative priority in operational rules. For example, the balance between hydro and thermal power generation might well be a continuous function of available storage. As another example, it might be possible to have two or more levels of navigation service or lengths of navigation season with the actual level of service or length of season being dependent upon the availability of water in the reservoir. By regulating the level of supply to the available water in the reservoir, users can plan emergency measures that will enable them to withstand partial reductions in service and thereby avoid complete cessation of service, which might be disastrous. Terms such as desired flow and minimum required flow for navigation can be used to describe two levels of service.

d. Levels of service. There can be as many levels of service as a user desires, but each level requires criteria for determining when the level is to be initiated and when it is to be terminated. The testing and development of the criteria for operating a multipurpose project with several purposes and several levels of service are accomplished by detailed sequential routing studies. Because the development and testing of these criteria are relatively difficult, the number of levels of service should be limited to the minimum number needed to achieve a satisfactory plan of operation.

e. Buffer storage. Buffer storage or buffer zones are regions within the conservation storage where operational rules effect a temporary reduction in firm services. The two primary reasons for temporarily reducing services are to ensure service for a high-priority purpose while eliminating or curtailing services for lower-priority purposes, and to change from one level of service for a given purpose to a lower level of service for that same purpose when storage levels are too low to ensure the continuation of firm supplies for all purposes. As with the other techniques for implementing a multipurpose operation, the amount of buffer storage and the location of the boundaries cannot be determined accurately except by successive approximations and testing by sequential routing studies.

3-5. Construction and Physical Operation

a. General. In addition to hydrologic determinations discussed above, a number of important hydrologic determinations are required during project construction and during project operation for ensuring the integrity of the project and its operation.

b. Cofferdams. From a hydrologic standpoint, during construction the provisions for streamflow diversion are a primary concern. If a cofferdam used for dewatering the work area is overtopped, serious delays and additional construction costs can result. In the case of high cofferdams where substantial poundage occurs, it is possible that failure could cause major damage in downstream areas. Cofferdams should be designed on the same principles as are permanent dams, generally on the basis of balancing incremental costs against incremental benefits of all types. This will require flood frequency and hypothetical flood studies, as described in Chapters 6 and 7 of this manual. Where major damage might result from cofferdam failure, a standard project flood (SPF) or even a probable maximum flood (PMF) may be used as a primary basis for design.

c. Overtopping. Where a major dam embankment may be subject to overtopping during construction, the diversion conduit capacity must be sufficient to regulate floods that might occur with substantial probability during the critical construction period. It is not necessary that the regulated releases be nondamaging downstream, but it is vital that the structure remain intact. An explicit evaluation of risk of embankment failure and downstream impacts during construction should be presented in the design document.

d. Conduits, spillways, and gates. Conduits, spillways, and all regulating gates must be functionally adequate to accomplish project objectives. Their sizes, dependability, and speed of operation should be tested using recorded and hypothetical hydrographs and anticipated hydraulic heads to ensure that they will perform properly. The nature of stilling facilities might be dictated by hydrologic considerations if frequency and duration of high outflows substantially influence their design. The necessity for multilevel intakes to control the quality of reservoir releases can be assessed by detailed reservoir stratification studies under all combinations of hydrologic and reservoir conditions. Techniques for conducting reservoir stratification studies are discussed in EM 1110-2-1201.

e. Design. The design of power facilities can be greatly influenced by hydrologic considerations, as discussed in Chapter 11 of this manual and EM 1110-2-1701. General considerations in the hydrologic design of spillways are discussed in Chapter 10 and more detailed information is presented in Chapter 14 herein.

f. Extreme floods. Regardless of the reservoir purposes, it is imperative that spillway facilities provided will ensure the integrity of the project in the event of extreme floods. Whenever the operation rules of a reservoir are substantially changed, spillway facilities should be reviewed to ensure that the change in project operation does not adversely alter the capability to pass extreme floods without endangering the structure. The capability of a spillway to pass extreme floods can be adversely affected by changes in operation rules that actually affect the flood operation itself or by changes that result in higher pool stages during periods of high flood potential.

g. Special operating rules. A number of situations might require special operating rules. For example, operating rules are needed for the period during which a reservoir is initially filling, for emergency dewatering of a reservoir, for interim operation of one or more components in a system during the period while other components are under construction, and for unanticipated conditions that seem to require deviation from established operating rules. The need for operation rules during the filling period is especially important because many decisions must be based on the filling plan. Among the important factors that are dependent upon the filling schedule are the on-line date for power generating units, the in-service dates for various purposes such as water supply and navigation, and the effective date for legal obligations such as recreation concessions.

h. Specification of monitoring facilities. One of the more important considerations in the hydrologic analysis of any reservoir is the specification of monitoring facilities, including streamflow, rainfall, reservoir stage, and other hydrologic measurements. These facilities serve two basic purposes: to record all operations and to provide information for operation decisions. The former purpose satisfies legal requirements and provides data for future studies. The latter purpose may greatly increase the project effectiveness by enabling the operating agency, through reliable forecasts of hydrologic conditions, to increase operation efficiency. Hydrologic aspects of monitoring facilities and forecasts will be presented in a new EM on hydrologic forecasting.

i. Stream gauges. Because gauged data are most important during flood events, special care should be taken in locating the gauge. Stream gauges should not be located on bridges or other structures that are subject to being washed out. To the extent possible, the gauges should be capable of working up through extreme flood events, and stage-discharge relationships should be developed up to that level. The gauge should have reasonable access for checking and repair during the flood. Reservoir spilling, local flooding, and backwater effects from downstream tributaries should all be considered when finding a suitable location. More detailed information on stream gauges can be found in many USGS publications, such as Carter and Davidian (1968), Buchanan and Somers (1968 and 1969), or Smoot and Novak (1969).

3-6. General Study Procedure

As indicated earlier, there is no fixed procedure for developing reservoir operational plans for multipurpose projects; however, the general approach that should be common to all cases would include the following steps:

a. Survey the potential water uses to be served by the project in order to determine the magnitude of each demand and the seasonal and long-term variations in the demand schedule.

b. Develop a relative priority for each purpose and determine the levels of service and required priority that will be necessary to serve each purpose. If necessary, make sequential studies illustrating the consequences of various alternative priority systems.

c. Establish the seasonal variation of flood-control space required, using procedures discussed in Chapter 10.

d. Establish the total power, water supply, and low-flow regulation requirements for competitive purposes during each season of the year.

e. Establish preliminary feasibility of the project based on physical constraints.

f. Establish the seasonal variation of the storage requirement to satisfy these needs, using procedures described in Chapter 11.

g. Determine the amount of storage needed as a minimum pool for power head, recreation, sedimentation reserve, and other purposes.

h. Using the above information, estimate the size of reservoir and seasonal distribution of space for the various purposes that would satisfy the needs. Determine the reservoir characteristics, including flowage, spillway, power plant, and outlet requirements.

i. Test and evaluate the operation of the project through the use of recorded hydrologic data in a sequential routing study to determine the adequacy of the storage estimates and proposed rules with respect to the operational objectives for each purpose. If the record is short, supplement it with synthetic floods to evaluate flood storage reserves. If necessary, make necessary changes and repeat testing, evaluating, and changing until satisfactory operation is obtained.

j. Test proposed rules of operation by using sequential routing studies with stochastic hydrologic data to evaluate the possibility of historical bias in the proposed rules.

k. Determine the needs for operating and monitoring equipment required to ensure proper functional operation of the project.

l. As detailed construction plans progress, evaluate cofferdam needs and protective measures needed for the integrity of project construction, particularly diversion capacity as a function of dam construction stage and flood threat for each season.

Chapter 4
Reservoir Systems

4-1. Introduction

Water resource systems should be designed and operated for the most effective and efficient accomplishment of overall objectives. The system usually consists of reservoirs, power plants, diversions, and canals that are each constructed for specific objectives and operated based on existing agreements and customs. Nevertheless, there is considerable latitude in developing an operational plan for any water resource system, but the problem is greatly complicated by the legal and social restrictions that ordinarily exist.

a. Mathematical modeling. Water resource system operation is usually modeled mathematically, rather than with physical models. The mathematical representation of a water resource system can be extremely complex. Operations research techniques such as linear programming and dynamic programming can be applied to a water resource system; however, they usually are not capable of incorporating all the details that affect system outputs. It is usually necessary to simulate the detailed sequential operation of a system, representing the manner in which each element in the system will function under realistic conditions of inputs and requirements on the system. The simulation can be based on the results from the optimization of system outputs or repeated simulations. Successively refining the physical characteristics and operational rules can be applied to find the optimum output.

b. Inputs and requirements. A factor that greatly complicates the simulation and evaluation of reservoir system outputs is the stochastic nature of the inputs and of the requirements on the system. In the past, it has been customary to evaluate system accomplishments on the assumption that a repetition of historical inputs and requirements (adjusted to future conditions) would adequately represent system values. However, this assumption has been demonstrated to be somewhat deficient. It is desirable to test any proposed system operation under a great many sequences of inputs and requirements. This requires a mathematical model that will define the frequency and correlation characteristics of inputs and requirements and that is capable of generating a number of long sequences of these quantities. Concepts for accomplishing this are discussed in paragraph 5-5.

4-2. System Description

a. Simulating system operation. Water resource systems consist of reservoirs, power plants, diversion structures, channels, and conveyance facilities. In order to simulate system operation, the system must be completely described in terms of the location and functional characteristics of each facility. The system should include all components that affect the project operation and provide the required outputs for analysis.

(1) Reservoirs. For reservoirs, the relation of surface area and release capacity to storage content must be described. Characteristics of the control gates on the outlets and spillway must be known in order to determine constraints on operation. The top-of-dam elevation must be specified and the ability of the structure to withstand overtopping must be assessed.

(2) Downstream channels. The downstream channels must be defined. Maximum and minimum flow targets are required. For short-interval simulation, the translation of flow through the channel system is modeled by routing criteria. The travel time for flood flow is important in determining reservoir releases and potential limits for flood control operation to distant downstream locations.

(3) Power plants. For power plants at storage reservoirs, the relation of turbine and generation capacity to head must be determined. To compute the head on the plant, the relation of tailwater elevation to outflow must be known. Also, the relation of overall power plant efficiency to head is required. Other characteristics such as turbine leakage and operating efficiency under partial load are also important.

(4) Diversion structures. For diversion structures, maximum diversion and delivery capacity must be established. The demand schedule is required, and the consumptive use and potential return flow to the system may be important for the simulation.

b. Preparing data. While reservoir system data must be defined in sufficient detail to simulate the essence of the physical system, preparing the required hydrologic data may require far more time and effort. The essential flow data are required for the period of record, for major flood events, and in a consistent physical state of the system. Flow records are usually incomplete, new reservoirs in the system change the flow distribution, and water usage in the watershed alters the basin yield over time. Developing a consistent hydrologic data series, making maximum use of the available information, is discussed in Chapter 5.

4-3. Operating Objectives and Criteria

a. User services. Usually, there is a fixed objective for each function in a water resource system. Projects are constructed and operated to provide services that are counted on by the users. In the case of power generation and water supply, the services are usually contracted, and it is essential to provide contracted amounts insofar as possible. Services above the contracted amounts are ordinarily of significantly less value. Some services, such as flood control and recreation, are not ordinarily covered by contracts. For these, service areas are developed to provide the degree of service for which the project was constructed.

b. Rules for services. Shortages in many of the services can be very costly, whereas surpluses are usually of minor value. Accordingly, the objectives of water resource system operational are usually fixed for any particular plan of development. These are expressed in terms of operational rules that specify quantities of water to be released and diverted, quantities of power to be generated, reservoir storage to be maintained, and flood releases to be made. These quantities will normally vary seasonally and with the amount of storage water in the system. Rule curves for the operation of the system for each function are developed by successive approximations on the basis of performance during a repetition of historical streamflows, adjusted to future conditions, or on the basis of synthetic stream flows that would represent future runoff potential.

4-4. System Simulation

The evaluation of system operation under specified operation rules and a set of input quantities is complex and requires detailed simulation of the operation for long periods of time. This is accomplished by assuming that steady-state conditions prevail for successive intervals of time. The time interval must be short enough to capture the details that affect system outputs. For example, average monthly flows may be used for most conservation purposes; however, for small reservoirs, the flow variation within a month may be important. For hydropower reservoirs, the average monthly pool level or tailwater elevation may not give an accurate estimate of energy production.

To simulate the operation during each interval, the simulation solves the continuity equation with the reservoir release as the decision variable. The system is analyzed in an upstream-to-downstream direction. At each pertinent location, requirements for each service are noted, and the reservoirs at and above that location are operated in such a way as to serve those requirements, subject to system constraints such as outlet capacity, and channel capacity, and reservoir storage capacity. As the computation procedure progresses to downstream locations, the tentative release decisions made for upstream locations become increasingly constraining. It often becomes necessary to assign priorities among services that conflict. Where power generation causes flows downstream to exceed channel capacity, for example, a determination must be made as to whether to curtail power generation. If there is inadequate water at a diversion to serve both the canal and river requirements, a decision must be made.

4-5. Flood-Control Simulation

Flood discharge can change rapidly with time. Therefore, steady-state conditions cannot be assumed to prevail for long periods of time (such as one month). Also, physical constraints such as outlet capacity and the ability to change gate settings are more important. The time translation for flow and channel storage effects cannot ordinarily be ignored. Consequently, the problem of simulating the flood-control operation of a system can be more complex than for conservation.

a. Computational interval. The computation interval necessary for satisfactory simulation of flood operations is usually on the order of a few hours to one day at the most. Sometimes intervals as short as 15 or 30 min are necessary. It is usually not feasible to simulate for long periods of time, such as the entire period of record, using such a short computation interval. However, period-of-record may be unnecessary because most of the flows are of no consequence from a flood-control standpoint. Accordingly, simulation of flood-control operation is usually made only for important flood periods.

b. Starting conditions. The starting conditions for simulating the flood-control operation for an historic flood period would depend on the operation of the system for conservation purposes prior to that time. Accordingly, the conservation operation could be simulated first to establish the state of the system at the beginning of the month during which the flood occurred as the initial conditions for the flood simulation. However, the starting storage for flood operation should be based on a realistic assessment of likely future conditions. If it is likely that the conservation pool is full when a flood occurs, then that would be a better starting condition to test the flood-pool capacity. It may be possible that the starting pool would be higher if there were several storms in sequence, or if the flood operation does not start the instant excessive inflows raise the pool level into flood-control space.

c. Historic sequences. While simulating historic sequences are important, future floods will be different and occur in different sequences. Therefore, the analysis of flood operations should utilize both historic and synthetic floods. The possibility of multiple storms, changes in the upstream catchment, and realistic flood operation should be included in the analysis. Chapter 7 presents flood-runoff analysis and Chapter 10 presents flood-control storage requirements.

d. Upstream-to-downstream solution. If the operation of each reservoir in a system can be based on conditions at or above that reservoir, an upstream-to-downstream solution approach can establish reservoir releases, and these releases can be routed through channel reaches as necessary in order to obtain a realistic simulation. Under such conditions, a simple simulation model is capable of simulating the system operation with a high degree of accuracy. However, as the number of reservoirs and downstream damage centers increase, the solution becomes far more complex. A priority criteria must be established among the reservoirs to establish which should release water, when there is a choice among them.

e. Combination releases. The HEC-5 *Simulation of Flood Control and Conservation Systems* (HEC 1982c) computer program can solve for the combination of releases at upstream reservoirs that will satisfy channel capacity constraints at a downstream control point, taking into account the time translation and channel storage effects, and that will provide continuity in successive time intervals. The time translation effects can be modeled with a choice of hydrologic routing methods. Reservoir releases are determined for all designated downstream locations, subject to operation constraints. The simulation is usually performed with a limited foresight of inflows and a contingency factor to reflect uncertainty in future flow values. The concept of pool levels is used to establish priorities among projects in multiple-reservoir systems. Standard output includes an indicator for the basis of reservoir release determination, along with standard simulation output of reservoir storage, releases, and downstream flows.

f. Period-of-record flows. Alternatively, a single time interval, such as daily, can be used to simulate period-of-record flows for all project purposes. This approach is routinely used in the Southwestern Division with the computer program "Super" (USACE 1972), and in the North Pacific Division with the SSARR program (USACE 1991). The SSARR program is capable of simulation on variable time intervals.

4-6. Conservation Simulation

While the flood-control operation of a reservoir system is sensitive to short time variations in system input, the operation of a system for most conservation purposes is usually sensitive only to long-period streamflow variations. Historically, simulation of the conservation operation of a water resource system has been based on a relatively long computation interval such as a month. With the ease of computer simulation and available data, shorter computational intervals (e.g., daily) can provide a more accurate accounting of flow and storage. Some aspects of the conservation operation, such as diurnal variations in power generation in a peaking project, might require even shorter computational intervals for selected typical or critical periods to define important short-term variations.

a. Hydropower simulation. Hydropower simulation requires a realistic estimate of power head, which depends on reservoir pool level, tailwater elevation, and hydraulic energy losses. Depending on the size and type of reservoir, there can be considerable variation in these variables. Generally, the shorter time intervals will provide a more accurate estimate of power capacity and energy productions.

b. Evaporation and channel losses. In simulating the operation of a reservoir system for conservation, the time of travel of water between points in the system is usually ignored, because it is small in relation to the typical computation interval (e.g., monthly or weekly). On the other hand, evaporation and channel losses might be quite important; and it is sometimes necessary to account for such losses in natural river channels and diversion canals.

c. Rule curves. Rule curves for the operation of a reservoir system for conservation usually consist of standard power generation and water supply requirements that will be served under normal conditions, a set of storage levels that will provide a target for balancing storage among the various system reservoirs, and maximum and minimum permissible pool levels for each season based on flood control, recreation, and other project requirements. Often some criteria for decreasing services when the system reservoir storage is critically low will be desirable.

4-7. System Power Simulation

Where a number of power plants in the water resource system serve the same system load, there is usually considerable flexibility in the selection of plants for power generation at any particular time. In order to simulate the operation of the system for power generation, it is necessary to specify the overall system requirement and the minimum amount of energy that must be generated at each plant during each month or other interval of time. Because the entire system power requirement might possibly be supplied by incidental generation due to releases made for other purposes, it is first necessary to search the entire system to determine generation that would occur with only minimum power requirements at each plant and with all requirements throughout the system for other purposes. If insufficient power is generated to meet the entire system load in this manner, a search will be made for those power reservoirs where storage is at a higher level, in relation to the rule curves, than at other power reservoirs. The additional power load requirement will then be assigned to those reservoirs in such a manner as to maintain the reservoir storage as nearly as possible in conformance with the rule curves that balance storage among the reservoirs in the most desirable way. This must be done without assigning more power to any plant than it can generate at overload capacity and at the system load factor for that interval. EM 1110-2-1701 paragraph 5-14, describes hydropower system analysis.

4-8. Determination of Firm Yield

If the yield is defined as the supply that can be maintained throughout the simulation period without shortages, then the process of computing the maximum yield can be expedited. This is done by maintaining a record of the minimum reserve storage (if no shortage has yet occurred) or of the amount of shortage (if one does occur) in relation to the total requirement since the last time that all reservoirs were full. The surplus or shortage that existed at the end of any computation interval would be expressed as a ratio of the supply since the reservoirs were last full, and the minimum surplus ratio (if no shortage occurs) or maximum shortage ratio (if a shortage does occur) that occurs during the entire simulation period would be used to adjust the target yield for the next iteration. This basic procedure for computing firm yield is included in the HEC-5 computer program. Additionally, the program has a routine to make an initial estimate of the critical period and expected yield. After the yield is determined using the critical period, the program will evaluate the yield by performing a simulation with the entire input flow record. Chapter 12 describes storage-yield procedures.

4-9. Derivation of Operating Criteria

A plan of development for a water resource system consists not only of the physical structures and their functional characteristics but also of the criteria by which the system will be operated. In order to compare alternative plans of development, it is necessary that each plan be operated optimally. The derivation of optimal operation criteria for a water resource system is probably more difficult than the derivation of optimum configuration and unit sizes because any small change in operation rules can affect many functions in the system for long periods of time and in very subtle ways.

a. Simulation. Operation criteria generally consist of release schedules at reservoirs, diversion schedules at control points, and minimum flows in the river at control points, in conjunction with reservoir balancing levels that define the target storage contribution among the various reservoirs in the system. All of these can vary seasonally, and target flows can vary stochastically. Once the unit sizes and target flows are established for a particular plan of development, a system of balancing levels must be developed. The system response to a change in these balancing levels is a complicated function of many system, input, and requirement characteristics. For this reason, the development of a set of balancing levels is an iteration process, and a complete system simulation must be done for each iteration.

(1) When first establishing balancing levels in the reservoir system, it usually is best to simulate system operation only for the most critical periods of historical streamflows. The final solution should be checked by simulation for long periods of time. The balancing levels defining the flood-control space are first tentatively established on the basis of minimum requirements for flood control storage that will provide the desired degree of protection. Preliminary estimates of other levels can be established on the basis of reserving the most storage in the smaller reservoirs, in those reservoirs with the least amount of runoff, and in those reservoirs that supply operation services not producible by other reservoirs.

(2) After a preliminary set of balancing levels is established, they should be defined approximately in terms of a minimum number of variables. The general shape and spacing of levels at a typical reservoir might be defined by the use of four or five variables, along with rules for computing the levels from those variables. Variations in levels among reservoirs should be defined by one or two variables, if possible, in order to reduce the amount of work required for optimization to an acceptable quantity.

(3) Optimization of a set of balancing levels for operational rule curves can be accomplished by successive approximations using a complete system simulation computation for critical drought periods. However, the procedures are limited to the input specifications of demands and storage allocation. While one can compare simulation results and conclude one is better than another based on

performance criteria, there is no way of knowing that an optimum solution has been achieved.

b. Optimization. While water resource agencies have generally focused on simulation models for system analysis, the academic community and research literature have emphasized optimization and stochastic analysis techniques. Research performed at HEC (HEC 1991b) has found a proliferation of papers on optimization of reservoir system operations written during the past 25 years, primarily by university researchers. There still remains a considerable gap between the innovative applications reported in the literature and the practices followed by the agencies responsible for water resource development. One basic problem is that many of the reported applications are uniquely formulated to solve a specific problem for a given system. There is a general view that the models performance, or the methods assumptions, would not sufficiently evaluate a different problem and system.

c. Prescriptive reservoir model. HEC has developed a system analysis tool based on a network flow model (HEC 1991a). The Prescriptive Reservoir Model (HEC-PRM) will identify the water allocation that minimizes poor performance for all defined system purposes. Performance is measured with analyst-provided functions of flow or storage or both. The physical system is represented as a network, and the allocation problem is formulated as a minimum-cost network flow problem. The objective functions for this network problem are convex, piecewise-linear approximations of the summed penalty functions for each project purpose (HEC 1991d).

(1) Systems have been analyzed in studies on the Missouri River (HEC 1991d) and the Columbia River (HEC 1991f). A preliminary analysis of the Phase I Missouri River study has developed initial methodologies for developing operation plans based on PRM results (HEC 1992b). Continued application experience is required to define generalized procedures for these analyses.

(2) The primary advantages for the HEC-PRM approach are the open state of the system and the required penalty functions for each system purpose. There are no rule curves or details of storage allocation, only basic physical constraints are defined. The reservoir system information defines maximum and minimum storage in the reservoirs and the linking of the system through the network of channels and diversions. The other primary reservoir data is traditional period-of-record monthly flows for the system.

(3) The development of the penalty functions requires an economic evaluation of the values to be placed on flow and storage in the system. The process is difficult and there are disagreements on the values, due to the difficulty of defining values for some purposes. However, the process does provide a method for defining and reviewing the purposes and their relative values.

(4) The primary disadvantage of the HEC-PRM is that the monthly flow data and lack of channel routing limit its application for short interval simulation, such as flood control and peaking hydropower. Additionally, the optimized solution is provided in terms of period-of-record flows and storage; however, the basis for the system operation are not explicitly defined. The post-processing of the results requires interpretation of the results in order to develop an operation plan that could be used in basic simulation and applied operation. More experience with this analysis of results is still required to define these procedures.

4-10. System Formulation Strategies

a. Determining the best system. A system is best for the national income criteria if it results in a value for system net benefits that exceeds that of any other feasible system. Except where noted, the following discussion was developed in a paper presented at the International Commissions on Large Dams Congress (Eichert and Davis 1976). For a few components, analysis of the number of alternative systems that are feasible is generally manageable, and exhaustive evaluation provides the strategy for determining the best system. When the number of components is more than just a few, then the exhaustive evaluation of all feasible alternative systems cannot practically be accomplished. In this instance, a strategy is needed that reduces the number of system alternatives to be evaluated to a manageable number while providing a good chance of identifying the best system. System analysis does not permit (maximum net benefit system) for reasonably complex systems even with all hydrologic-economic data known. An acceptable strategy need not make the absolute guarantee of economic optimum because seldom will the optimum economic system be selected as best.

b. Incremental test. The incremental test of the value of an individual system component is definitive for the economic efficiency criteria and provides the basis for several alternative formulation strategies. If existing reservoir components are present in the system, then they define the base conditions. If no reservoirs exist, the base condition would be for natural conditions. The strategies described below are extensions of currently used techniques and are based upon the concept of examining in detail the performance of a selected few alternative systems. The performance is assumed to be evaluated generally by traditional simulation methods, like the use of HEC-5.

c. Reasoned thought strategy. This strategy is predicated upon the idea that it is possible to reason out using judgment and other criteria, reasonable alternative systems. The strategy consists of devising through rational thought, sampling, public opinion, literature search, and brainstorming, a manageable number of system alternatives that will be evaluated. No more than 15 to 20 alternative systems could be evaluated by detailed simulation in a practical sense.

(1) The total performance of each system in terms of economic (net benefit) and performance criteria is evaluated by a system simulation. A system (or systems if more than one have very similar performance) is selected that maximizes the contribution towards the formulation objectives (those that exhibit the highest value of net benefits while satisfying the minimum performance criteria). To confirm the incremental justification of each component, the contribution of each system component in the last added position is evaluated. The last added value is the difference between the value (net benefits) of the system with all components in operation and the value (net benefits) of the system with the last added component removed. If each component is incrementally justified, as indicated by the test, the system is economically justified, and formulation is complete. If any components are not incrementally justified, they should be dropped and the last added analysis repeated.

(2) The system selected by this strategy will be a feasible system that is economically justified. Assuming the method of devising the alternative systems is rational, the chances are good that the major worthwhile projects will have been identified. On the other hand, the chances that this system provides the absolute maximum net benefits is relatively small. This strategy would require between 30 and 60 system evaluations for a moderately complex (15 component) system.

d. First added strategy. This strategy is designed such that its successive application will yield the formulated system. The performance of the systems, including the base components (if any), are evaluated with each potential addition to the system in the "first added" position. The component that contributes the greatest value (net benefit) to the system is selected and added to the base system.

(1) The analysis is then repeated for the next stage by computing the first added value of each component to the system again, the base now including the first component added. The strategy is continued to completion by successive application of the first added analysis until no more component additions to the system are justified.

(2) The strategy does have a great deal of practical appeal and probably would accomplish the important task of identifying the components that are clearly good additions to the system and that should be implemented at an early stage. The strategy, however, ignores any system value that could be generated by the addition of more than one component to the system at a time, and this could omit potentially useful additions to the system. For example, the situation sometimes exists where reservoirs on, say, two tributaries above a damage center are justified, but either one analyzed separately is not, i.e., the system effect is great enough to justify both. The number of system analyses required to formulate a system based on this strategy could range upwards to 120 for a moderately complex (15 component) system, which is probably close to being an unmanageably large number of evaluations.

e. Last added strategy. This strategy, similar to first added strategy, is designed such that successive application yields the formulated system. Beginning with all proposed components to the system, the value of each component in the last added position is computed. The project whose deletion causes the value (net benefit) of the system to increase the most is dropped out. The net benefits would increase if the component is not incrementally justified. The strategy is continued through successive staged applications until the deletion of a component causes the total system value (net benefits) to decrease.

(1) The last added strategy will also yield a system in which all components are incrementally justified and in which the total system will be justified. This strategy would probably identify the obviously desirable projects, as would the others. However, its weakness is that it is slightly possible, though not too likely, that groups of projects that would not be justified are carried along because of their complex linkage with the total system. For example, the situation sometimes exists where reservoirs on two tributaries above a damage center are not justified together, but deletion of each from a system that includes both results in such a great loss in system value that individual analysis indicates neither should be dropped individually.

(2) The number of systems analyses required for this strategy would be similar to the first added strategy

requiring perhaps 10-20 percent more evaluations. Twenty-two last added analyses were made in the four stages required to select four new projects out of seven alternatives. This strategy is more efficient than the first added if the majority of the potential system additions are good ones.

f. Branch-and-bound enumeration. "Branch-and-bound enumeration is a general-purpose technique for identifying the optimal solution to an optimization problem without explicitly enumerating all solutions," (HEC 1985a). The technique provides a framework to evaluate independent alternatives by dividing the entire set into subsets for evaluation. The method has been applied in resource planning to problems of sizing, selecting, sequencing, and scheduling projects. HEC has developed a training document illustrating the application to flood-damage-mitigation plan selection (HEC 1985). Additionally, HEC Research Document No. 35 (Bowen 1987) illustrates an application for reservoir flood control plan selection using computer program HEC-5 for reservoir simulation. The procedure can use any criteria for evaluation and supports detailed simulation in the analysis process.

4-11. General Study Procedure

There is no single approach to developing an optimum plan of improvement for a complex reservoir system. Ordinarily many services are fixed and act as constraints on system operation for other services. In many cases, all but one service is fixed, and the system is planned to optimize the output for one remaining service, such as power generation. It should also be recognized that most systems have been developed over a long period of time and that many services are in fact fixed, as are many system features. Nevertheless, an idealized general study procedure is presented below:

a. Prepare regional and river-system topographic maps showing locations of hydrologic stations, existing and contemplated projects, service and damage areas, and pertinent drainage boundaries. Obtain all precipitation, evaporation, snowpack, hydrograph timing and runoff data pertinent to the project studies. Obtain physical and operational data on existing projects. Construct a normal seasonal isohyetal map for the river basin concerned.

b. For each location where flood protection is to be provided, estimate approximately the nondamaging flow capacity that exists or could be ensured with minor channel and levee improvements. Estimate also the amount of storage (in addition to existing storage) that would be needed to provide a reasonable degree of protection, using procedures described in Chapter 10. Distribute this storage in a reasonable way among contemplated reservoirs in order to obtain a first approximation of a plan for flood control. Include approximate rule curves for releasing some or all of this storage for other uses during the nonflood season where appropriate.

c. Determine approximately for each tributary, where appropriate, the total water needed each month for all conservation purposes and attendant losses, and, using procedures described in Chapter 11, estimate the storage needed on each principle tributary for conservation services. Formulate a basic plan of development including detailed specification of all reservoir, canal, channel, and powerplant features and operation rules; all flow requirements; benefit functions for all conservation services; and stage-damage functions for all flood damage index locations. Although this part of plan formulation is not entirely a hydrologic engineering function, a satisfactory first approximation requires good knowledge of runoff characteristics, hydraulic structure characteristics and limitations, overall hydroelectric power characteristics, engineering feasibility, and costs of various types of structures, and relocations.

d. Using the general procedures outlined in Part 2, develop flood frequencies, hypothetical flood hydrographs, and stage-discharge relations for unregulated conditions and for the preliminary plan of development for flood control. It may be desirable to do this for various seasons of the year in order to evaluate seasonal variation of flood-control space. Evaluate the flood-control adequacy of the plan of development, using procedures described in paragraph 4-5 and Chapter 10, modify the plan, as necessary, to improve the overall net benefits for flood control while preserving basic protection where essential. Each modification must be followed by a new evaluation of net benefits for flood control. Each iteration is costly and time-consuming; consequently, only a few iterations are feasible, and considerable thought must be given to each plan modification.

e. For system analysis to determine the best allocation of flow and storage for conservation purposes, consider optimization using a tool HEC-PRM (paragraph 4-9*c*). The program outputs would then be analyzed to infer an operation policy that could be defined for simulation and more detailed analysis. The alternative is to repeatedly simulate with critical low-flow periods to develop a policy to meet system goals and then perform a period-of-record simulation to evaluate total system performance.

f. Consider generating synthetic sequences of flow to evaluate the system's performance with different flow sequences (see paragraph 5-5). Future system flows replicate the period-of-record. Also, projected changes in the basin should be factored into the analysis. Typically, future conditions are estimated at several stages into the future. The system analysis should be performed for each stage. While these analyses will take additional time and effort, they will also provide some indication of how responsive the system results are to changing conditions.