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Optimization of Multiple-Purpose Reservoir System Operations: A Review of Modeling and Analysis Approaches

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This report is a literature-review-based assessment of the state-of-the-art of modeling and analysis approaches for evaluating multiple-purpose reservoir system operations. Fundamentals of reservoir operation are reviewed from the perspective of categorizing and defining typical decision problems and associated decision variables and performance criteria. A broad range of modeling and analysis methods are covered, including traditional approaches used by the water resources development agencies and other techniques emphasized in the literature.

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OPTIMIZATION OF MULTIPLE-PURPOSE RESERVOIR SYSTEM OPERATIONS: A REVIEW OF MODELING AND ANALYSIS APPROACHES

Contents

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INTRODUCTION

Optimizing Reservoir System Operations

Numerous major multiple-purpose reservoir systems have been constructed throughout the nation during the past several decades. Public needs and objectives and many factors affecting operation of these reservoirs change over time. Reservoir system operations are complex and often offer substantial increases in benefits for relatively small improvements in operating efficiency. Consequently, evaluation of refinements and modifications to the operations of existing reservoir systems is becoming an increasingly important activity.

A broad array of computer modeling and analysis techniques are available for developing quantitative information for use in evaluating reservoir operations. Development and application of decision-support tools within the major reservoir development and management agencies, such as the U.S. Army Corps of Engineers (USACE), Bureau of Reclamation (USBR), and Tennessee Valley Authority (TVA), have focused on simulation models. The academic community and research literature have emphasized optimization (mathematical programming) and stochastic analysis techniques. Determining optimum reservoir operating policies has been viewed as an ideal application for systems analysis methods. During the past 25 years, a proliferation of papers on optimization of reservoir system operations, written primarily but not exclusively by university researchers, has appeared in the published literature. A large gap exists between research studies and innovative applications reported in the literature and the more traditional proven practices followed by the agencies responsible for the actual planning, construction, and operation of reservoir projects.

There is no single type of reservoir operation problem but rather a multitude of decision problems and situations. Decision-making situations and decision-support tools can be categorized in a number of ways. For example, decisions regarding reservoir operating policies may be made during:

- preconstruction planning involving proposed new reservoir projects
- postconstruction planning involving reevaluation of operations of completed projects
- real-time operations

Reservoir purposes include:

- flood control
- navigation
- hydroelectric power
- municipal and industrial water supply
- irrigation
- water quality management
- recreation
- fish and wildlife enhancement
- erosion and sedimentation control
- combinations of the above

System analysis models used in studies to optimize reservoir system operations may be categorized as follows:

- descriptive simulation models
- prescriptive optimization models
- hybrid simulation and optimization models

This report addresses the broad area of optimizing reservoir system operations in general, but with a particular emphasis on methods which are applicable to reevaluation studies of existing multiple-purpose reservoir systems. A state-of-the-art review is presented which covers a comprehensive array of reservoir system simulation and optimization models.

Formulating the Modeling and Analysis Approach

Simulation and optimization modeling exercises provide quantitative information for use in a typically complex decision making process. Formulating an approach for modeling and analyzing a problem requires a good understanding of the real-world problem and the overall decision making process. The following questions must be answered in formulating the modeling and analysis approach for studying proposed modifications to the operation of a particular reservoir system.

- What is to be determined or what variables are to be "optimized"?
- What criteria should be used to measure the optimality of alternative decisions?
- What constraints must be considered?
- Which models and analysis techniques should be used?

Each reservoir system and each study are unique. In past studies, a variety of decision variables, decision criteria, and constraints have been incorporated into various simulation and optimization modeling approaches. This report reviews modeling and analysis capabilities from the perspective of the four basic questions cited above.

Report Purpose and Scope

This report is a literature-review-based assessment of the state-of-the-art of modeling and analysis approaches for evaluating multiple-purpose reservoir system operations. Fundamentals of reservoir operation are reviewed from the perspective of categorizing and defining typical decision problems and associated decision variables and performance criteria. A broad range of modeling and analysis methods are covered, including traditional approaches used by the water resources development agencies and other techniques emphasized in the literature.

The objectives of the report are:

- to inventory and outline the types of decisions made in situations in which modifications to reservoir release policies are being considered,
- to inventory and outline the types of information computed in modeling and analysis studies of reservoir operations,
- to inventory and outline state-of-the-art modeling and analysis methods, and
- to evaluate modeling and analysis capabilities from the perspective of meaningfully and effectively supporting the types of actual decisions which are being made in conjunction with optimizing the operation of reservoir systems.

Reservoir System Analysis Literature

A large number of publications on applying systems analysis techniques to reservoir operation problems have appeared in the literature during the past 25 years. This general topic area has been greatly emphasized in water resources planning and management related journals and conferences. There has been a particularly large number of journal and conference papers reporting academic research studies on applying mathematical programming and stochastic analysis techniques to problems of reservoir operation. Many university research reports sponsored by the various water resources research institutes have addressed the subject. The federal water resources development agencies have been very active in reservoir system analysis. Numerous federal agency reports and publications document work on various aspects of reservoir operations. Several state water agencies, such as the California Department of Water Resources and Texas Water Development Board, have also been active in this area. The subject is a major focus of the several books on water resources systems engineering and stochastic hydrology.

A number of major conferences, including the several cited here, have dealt specifically with reservoir operations. Seminars conducted by the USACE Hydrologic Engineering Center in November 1969 on Reservoir System Analysis and in November 1975 on Real-Time Water Control Management outlined practices followed, and key issues of concern, in operating USACE reservoir systems. The American Society of Civil Engineers (ASCE) sponsored National Workshop on Reservoir Systems Operations in August 1979 compiled the views and experiences of a large number of reservoir operation practitioners, with a particular focus on case studies of the following major reservoir systems: California Central Valley Project, Arkansas River System, Tennessee Valley Authority System, Columbia River System, Lower Colorado River System, and Duke Power Company System. The ASCE also sponsored the Symposia on Surface Water Impoundments in June 1980 and Accomplishments of Reservoirs in October 1983 and Water Resources Operations Management Workshops in 1977, 1981, and 1988. International conferences have included: the Workshop on Operation of Multiple Reservoir Systems conducted by the International Institute for Applied Systems Analysis in May - June 1979; International Symposium on Real-Time Operations of Hydrosystems at the University of Waterloo in June 1981; and the North Atlantic Treaty Organization (NATO) Advanced Study Institute on Operation of Complex Water Systems in May - June 1981. The proceedings documenting each of these conferences are included in the reference list of this report.

Yeh (1982 and 1985) presents state-of-the-art reviews of reservoir management and operations models, which include extensive lists of references. Wurbs et al. (1985) provides a state-of-the-art review and annotated bibliography of systems analysis techniques applied to reservoir operation, which cites over 700 references. The present report and most of the references cited in the present report view reservoir operation primarily from the perspective of practices followed and work accomplished in the United States. Votruba and Broza (1989) provide a European perspective and cite numerous references from outside the United States.

RESERVOIR OPERATION PRACTICES AND PROCEDURES

Institutional Framework

Institutional considerations are fundamental in establishing and modifying reservoir operating plans. Reservoir development and management is accomplished within a complex system of organizations, laws, and traditions. In addition to the agency which owns and operates a reservoir system, numerous other public agencies, officials, project beneficiaries, industries, interest groups, and concerned citizens play significant roles in determining operating policies.

The responsibilities of the various organizations involved in operating reservoir systems are based upon project purposes. The U.S. Army Corps of Engineers (USACE) has played a clearly dominant role nationwide in constructing and operating major reservoir systems for navigation and flood control. The U.S. Bureau of Reclamation (USBR) water resources development program in the West was founded upon irrigation and hydroelectric power. The Tennessee Valley Authority (TVA) reservoir system is operated in accordance with operating priorities mandated by the 1933 Congressional act which created the TVA. This act specified that the TVA system be used to regulate streamflow primarily for the purposes of promoting navigation and controlling floods and, so far as may be consistent with such purposes, for generation of electric energy. The activities of the federal water resources development agencies have evolved over time to emphasize comprehensive multiple-purpose water resources management. Municipal and industrial water supply has been primarily a nonfederal responsibility though significant municipal and industrial storage capacity has been included in federal reservoirs for the use of nonfederal project sponsors. Private companies as well as governmental entities play key roles in hydroelectric power and industrial water supply. A majority, though certainly not all, of the very large reservoir systems in the United States are operated by the federal water agencies. Most reservoirs in the nation were constructed and are operated by nonfederal entities. The much more numerous nonfederal conservation reservoirs tend to be smaller in size than the multipurpose federal projects.

The USACE is the largest reservoir management agency in the nation. Flood control and navigation play a much greater role in USACE reservoir systems than in most other reservoir systems in the nation. Project purposes and storage capacities in USACE reservoirs are included in a data base described by USACE, HEC (1990). Storage capacities by purpose for the 516 reservoirs included in this data base are summarized in Table 1. The 516 reservoirs have a total controlled storage capacity of 220,615,000 acre-feet. About 94,950,000 acre-feet, or 43.0%, of this capacity is designated for use exclusively for flood control. An additional 1.1% and 0.2% of the total capacity is used exclusively for navigation and hydroelectric power, respectively. The remaining 122,926,000 acre-feet, or 55.7%, of the storage capacity provides multiple-purpose use, which may include flood control, navigation, and/or hydroelectric power as well as the other purposes cited in Table 1. The multiple use storage capacity in each reservoir serves two or more purposes. The number and corresponding total multiple-purpose storage capacity of reservoirs which include specified purposes in the multipurpose capacity are also tabulated in Table 1. For example, there are 117 reservoirs, with multiple use storage capacities totalling 82,976,000 acre-feet, which include municipal & industrial water supply as one of the purposes served by the multiple use storage capacity.

Table 1

USACE RESERVOIR STORAGE CAPACITY

Storage Allocation	Number of Reservoirs	Storage Capacity (acre-feet)
Exclusive Flood Control	330	94,950,000
Exclusive Navigation	135	2,354,000
Exclusive Hydropower	5	385,000
* Multiple-purpose Use[1]	385	122,926,000
Total (516 reservoirs)		220,615,000
* Multiple-purpose capacity in reservoirs which include:		
Flood Control	207	99,961,000
Navigation	49	66,058,000
Municipal & Industrial Water Supply	117	82,976,000
Irrigation	33	59,168,000
Hydroelectric Power	84	99,351,000
Recreation	361	117,974,000
Fish & Wildlife Enhancement	118	71,223,000
Low Flow Augmentation	92	65,154,000

[1] The table provides data for 516 USACE reservoirs with storage capacities totalling 220,615,000 acre-feet. The indicated multiple-purpose capacity represents storage capacity not designated for use exclusively for a single purpose. For example, the table indicates that 207 reservoirs, with multiple-purpose storage capacities totalling 99,961,000 acre-feet, include flood control as one purpose for which the multiple-purpose storage capacity is used. The 99,961,000 acre-feet is the total multiple-purpose storage capacity in the 207 reservoirs, not the flood control capacity. The table also indicates that 330 reservoirs have a total storage capacity of 94,950,000 acre-feet used exclusively for flood control. Many reservoirs have both storage capacity designated exclusively for flood control and additional multiple-purpose capacity of which a portion is sometimes used for flood control.

A typical USACE reservoir system will include several or all of the purposes cited in Table 1. Contractual arrangements and other institutional aspects of system operations vary greatly between purposes. For example, flood control operations for a USACE reservoir are simpler institutionally (through not necessarily simpler otherwise) than water supply and hydroelectric power operations due to the USACE being directly responsible for flood control operations. The USACE is responsible for flood control operations at reservoir projects constructed by the USBR as well as its own projects.

Nonfederal sponsors contract with the USACE and USBR for municipal and industrial water supply storage capacity. Costs allocated to municipal and industrial water supply are reimbursed by nonfederal sponsors in accordance with the Water Supply Act of 1958, as amended. Nonfederal sponsors are often regional water authorities who sell water to numerous municipalities, industries, and other water users, under various contractual arrangements. Water allocation and use is regulated by state water rights systems and other permit programs. Thus, water supply operations are controlled by agency responsibilities, contractual commitments, and legal systems for allocating and administering water rights.

Hydroelectric power generated at USACE and USBR reservoirs is marketed to electric utilities by the five regional power marketing administrations of the Department of Energy. The power administrations are required by law to market energy in such a manner as to encourage the most widespread use at the lowest possible rates to customers consistent with sound business principles. The power administrations operate through contracts and agreements with the electric cooperatives, municipalities, and utility companies which buy and distribute the power. Reservoirs are operated in accordance with the agreements. The TVA is directly responsible for marketing, dispatching, and transmission of power generated at its plants.

The purposes to be served by a federal reservoir project are established with Congressional authorization of project construction. Later, additional purposes are sometimes added or the original purposes modified by subsequent congressional action. When the original purposes are not seriously affected and structural or operational changes are not major, modifications in operating policies can be made at the discretion of the agency. USACE (1990) review legislative authorities and USACE policies regarding modifying operations at completed reservoir projects and also survey USACE projects for which storage reallocations and operational modifications have been proposed or implemented.

Many of the major reservoir systems in the United States are on interstate rivers, and several major reservoir systems are on rivers shared with either Mexico or Canada. Operations of some reservoir systems are strictly controlled by agreements between states and even nations which were negotiated over many years. A classic example is the "Law of the River" which guides operation of the system of reservoirs operated by the USBR in the Colorado River Basin. The "Law of the River" is a series of river basin compacts, laws, treaties, and other agreements between the several states and two countries developed over a period of several decades. As another example, the International Boundary and Water Commission operates a reservoir system on the Rio Grande River in accordance with treaties and agreements between Mexico and the United States. Operation of several major reservoir systems are significantly constrained by river basin compacts and other agreements between states.

Regulation Procedures

This report addresses the topic of "optimizing reservoir operations" which essentially means designing operating rules which best fulfill specified objectives and making real-time release decisions within the framework of the operating rules. In this report, the terms operating (or regulation or release) procedures, rules, schedule, policy, or plan are used interchangeably. A regulation procedure or release policy is a set of rules for determining the quantities of water to be stored released, or withdrawn from a reservoir or system of several reservoirs under various conditions. Operating decisions involve allocation of storage capacity and water releases between reservoirs, between uses, and between time periods. Regulation procedures are needed to provide guidance to reservoir operation personnel. In modeling and analysis of a reservoir system, a set of operating decision rules must be incorporated into the model. The present discussion focuses on outlining the various basic formats in which quantitative operating rules are expressed.

The wide variety of regulation policies presently in use range from operating rules which specify ideal pool levels but provide no guidance on what to do when deviations from these pool levels become necessary to operating rules that define very precisely how much water to release for a full range of conditions. Typically, a regulation plan involves a framework of quantitative rules within which significant flexibility exists for qualitative judgement. Day-to-day operating decisions may be influenced by a complex array of factors and often are based largely on judgement and experience. Regulation procedures may change over time with experience and changing conditions.

Reservoir Pools

Reservoir operating policies are based on dividing the total storage capacity into designated pools or vertical zones. A typical reservoir consists of one or more of the 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 facilitate withdrawals from outlet structures which are significantly higher than the invert of the lowest outlet structure at the project. The inactive zone is sometimes called dead storage. It may provide a portion of the sediment reserve, head for hydroelectric power, and water for recreation and fish habitat.

Conservation purposes, such as municipal and industrial water supply, irrigation, navigation, hydroelectric power, and instream flow maintenance, involve storing water during periods of high streamflow and/or low demand for later beneficial use as needed. Conservation storage also provides opportunities for recreation. The reservoir water surface is maintained at or as near the designated top of conservation pool elevation as streamflows and water demands allow. Drawdowns are made as required to meet the various needs for water.

The flood control zone remains empty except during and immediately following a flood event. The top of flood control pool elevation is often set by the crest of an uncontrolled emergency spillway, with releases being made through other outlet structures.

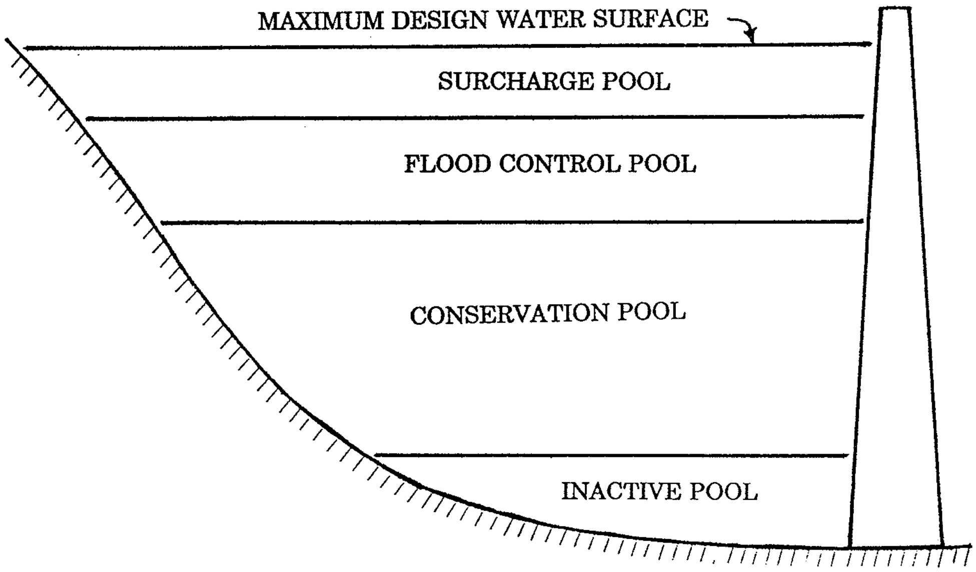


Figure 1. Reservoir Pools

Gated spillways allow the flood control pool to exceed the spillway crest elevation.

The surcharge zone is essentially uncontrolled storage capacity above the flood control pool (or conservation pool if there is no designated flood control storage capacity) and below the maximum design water surface. Major flood events exceeding the capacity of the flood control pool encroach into surcharge storage. Encroachments into the surcharge zone are accompanied by flows being passed through the spillway.

The maximum design water surface is an elevation established during project design from the perspective of dam safety. The top of dam elevation is set by adding a freeboard to the maximum design water surface. For major reservoir projects, the maximum design water surface is typically determined by routing the probable maximum flood through the reservoir, assuming a conservatively high initial storage level. Hydrologic design procedures and data have been developed for computing probable maximum precipitation and the associated probable maximum flood. Reservoir design and operation is based on assuring that the actual reservoir water surface level will never exceed the designated maximum design water surface elevation.

The term "rule curve" is used to refer to elevations which define ideal (desirable or target) storage volumes and provide a mechanism for release rules to be specified as a function of storage content. Rule curves are typically expressed as water surface elevation or storage capacity versus time of the year. Although the term "rule curve" denotes various other types of storage volume designations as well, the top of conservation pool is a common form of rule curve.

The top of conservation pool is varied seasonally at many reservoirs, particularly in regions with distinct flood seasons. The seasonal rule curve illustrated by Figure 2 reflects a location in which the summer months are characterized by high water demands, low streamflows, and a low probability of floods. The top of conservation pool could conceivably also be varied as a function of watershed conditions, forecasted inflows, floodplain activities, storage in other system reservoirs, or other parameters as well as season of the year. A seasonally or otherwise varying top of conservation pool elevation defines a joint use pool which is treated as part of the flood control pool at certain times and part of the conservation pool at other times. Also, as discussed below, either the flood control pool or conservation pool can be subdivided into any number of vertical zones to facilitate specifying reservoir releases as a function of amount of water in storage.

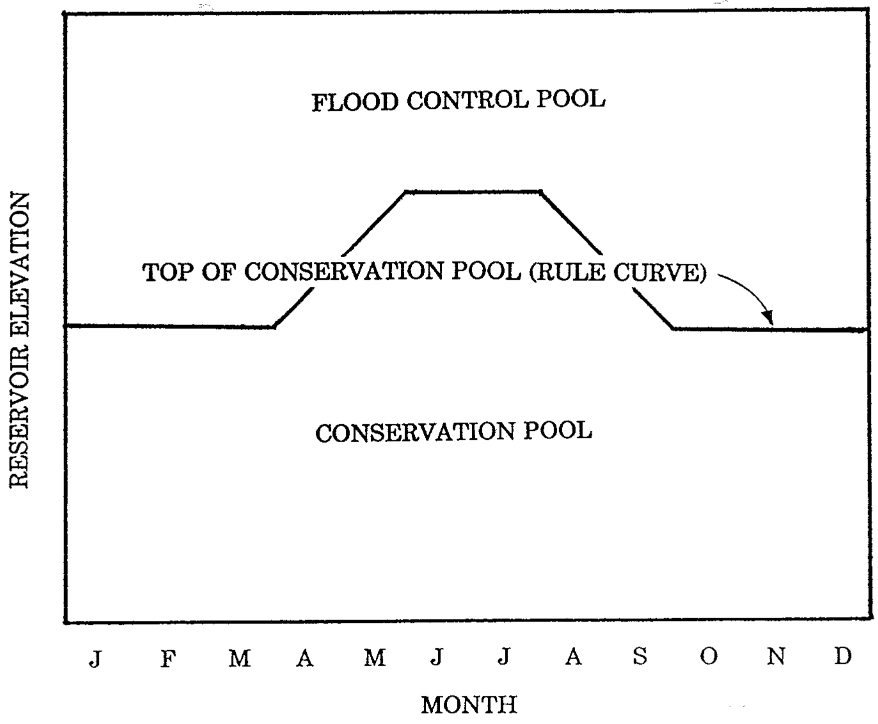


Figure 2. Seasonal Top of Conservation Pool

Regulation Rules for Flood Control Storage Capacity

The USACE is responsible for operating a majority of the major flood control reservoir systems in the nation. USACE procedures are representative of flood control operations in general. Flood control regulation plans are developed to address the particular conditions associated with each individual reservoir and multiple-reservoir system. Peculiarities and exceptions to standard operating procedures occur at various projects. However, the regulation rules for most reservoirs follow the same general strategy, as outlined in the USACE Engineering Manual on Management of Water Control Systems (USACE, 1987).

Release decisions depend upon whether or not the flood control storage capacity is exceeded. A specified set of rules, based on downstream flow rates, are followed as long as sufficient storage capacity is available to handle the flood without having to deal with the water surface rising above the top of flood control pool. Operation is switched over to an alternative approach, based on reservoir inflows and storage levels, during extreme flood conditions when the anticipated inflows are expected to deplete the controlled storage capacity remaining in the reservoir. The reservoir release rates necessitated by the flood control storage capacity being exceeded will, in most cases, contribute to downstream flooding. The objective is to assure that reservoir releases do not contribute to downstream discharges rising above allowable levels as long as the storage capacity is not exceeded. However, for extreme flood events which would exceed the storage capacity, moderately high release rates beginning before the flood control pool is full may be preferable to waiting until a full flood control pool necessitates even higher release rates.

Regulation Based on Downstream Flow Rates

Assuming the flood control storage capacity is not exceeded, flood control operations are based on target allowable flow rates and stages at selected index locations or control points. The allowable flow rates are typically related to bankful stream capacities, stages at which significant damages occur, environmental considerations, and/or constraints such as inundation of road crossings or other facilities. Stream gaging stations are located at the control points. Releases are made to empty the flood control pool as quickly as possible without exceeding the allowable flow rates at each downstream control point.

When a flood occurs, the spillway and outlet works gates are closed. The gates remain closed until a determination is made that the flood has crested and flows are below the target levels specified for each of the control points. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the control points.

Normally, no flood control releases are made if the reservoir level is at or below the top of conservation pool. However, in some cases, if flood forecasts indicate that the inflow volume will exceed the available conservation storage, flood control releases from the conservation storage may be made if downstream conditions permit. The idea is to release some water before the stream rises downstream, if practical, for a forecasted flood.

For many reservoirs, the allowable flow rate associated with a given control point is constant regardless of the reservoir surface elevation. At other projects, the flood control pool is subdivided into two or more zones with the allowable flow rates at one or more of the control points varying depending upon the level of the reservoir surface with respect to the discrete alternative zones. This allows stringently low flow levels to be maintained at certain locations as long as only a relatively small portion of the flood control pool is occupied, with the flows increased to a higher level, at which minor damages could occur, as the reservoir fills. The variation in allowable flow rates at a control point may also be related to whether the reservoir level is rising or falling.

Most reservoirs are operated based on maintaining flow rates at several control points located various distances below the dam. The most downstream control points may be several hundred miles below the dam. Lateral inflows from uncontrolled watershed areas below the dam increase with distance downstream. Thus, the impact of the reservoir on flood flows decreases with distance downstream. Operating to downstream control points requires streamflow forecasts. Flood attenuation and travel time from the dam to the control point and inflows from watershed areas below the dam must be estimated as an integral part of the reservoir operating procedure.

Most flood control reservoirs are components of basinwide multiple-reservoir systems. Two or more reservoirs located in the same river basin may have common control points. A reservoir may have one or more control points which are influenced only by that reservoir and several other control points which are influenced by other reservoirs as well. Multiple-reservoir release decisions may be based on simply maintaining approximately the same percentage of flood-control storage utilized in each reservoir, or more complex balancing criteria may be used. Releases from all reservoirs, as well as runoff from uncontrolled watershed areas, must be considered in forecasting flows at control points.

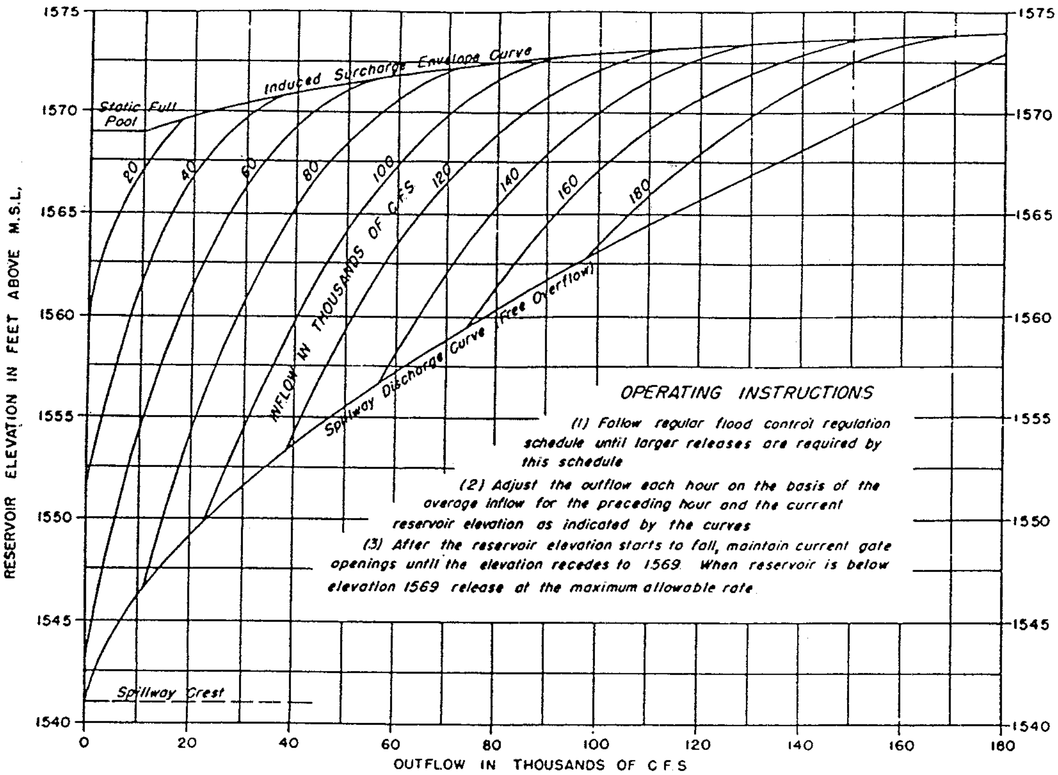
Maximum allowable rate of change of reservoir release rates are also specified. Abrupt gate openings causing a flood wave with rapid changes in stage may be dangerous and contribute to streambank erosion.

Regulation Based on Reservoir Inflows and Storage Levels

For an extreme flood event, limiting reservoir releases based on allowable downstream flow rates, as discussed above, could result in the storage capacity of the flood control pool being exceeded. If the releases are based on downstream target flows until the flood control pool fills, later uncontrolled spills at high flow rates could result. The higher peak release rate necessitated by this hypothetical release policy would typically be more damaging than a lower peak release rate with a longer duration beginning before the flood control pool is full. On the other hand, an operator would not want to make releases exceeding the allowable downstream flow rates early in a storm if the flood control pool remained partially empty during the storm. Although streamflows that will occur several hours or days in the future are often forecast during real-time operations, future flows are still highly uncertain.

Consequently, the overall strategy for operating the outlet works and spillway gates of a flood control reservoir typically consists of two component types of regulation procedures. The type of procedure requiring the largest release rate controls for given flooding and storage conditions. The regulation approach discussed above, based on downstream allowable flow rates, is followed until such time, during a flood, that the release rate indicated by the schedule outlined below is higher than that indicated by the downstream allowable flow rates. The regulation procedure outlined below is based on reservoir inflows and storage levels.

An example regulation schedule is presented in Figure 3 (USACE 1987). This type of schedule controls releases during an extreme flood which would otherwise exceed the capacity of the flood control pool. Downstream flooding conditions are not reflected in the family of curves illustrated in Figure 3. The reservoir release rate is read directly from the graphs, as a function of current water surface elevation and inflow rate. An alternative version of the schedule provides release rates as a function of the current water surface elevation and rate of rise of water surface. The two forms of the schedule are intended to result in the same release rate. Release rates are typically determined at a reservoir control center which has access to real-time streamflow measurements and can base release rates on inflow rates. If communications between the control center and operator at the project are interrupted during a flood emergency, the operator can determine gate releases based on rate of rise of the water surface without needing measurements of inflow rates.



OPERATING INSTRUCTIONS

(1) Follow regular flood control regulation schedule until larger releases are required by this schedule

(2) Adjust the outflow each hour on the basis of the average inflow for the preceding hour and the current reservoir elevation as indicated by the curves

(3) After the reservoir elevation starts to fall, maintain current gate openings until the elevation recedes to 1569. When reservoir is below elevation 1569 release at the maximum allowable rate

Source: USACE EM 1110-2-3600

Figure 3. Flood Control Regulation Schedule

The regulation schedule curves are developed based on estimating the minimum volume of inflow that can be expected in a flood, given the current inflow rate and reservoir elevation. Having estimated the minimum inflow volume to be expected during the remainder of the flood, the outflow required to limit storage to the available capacity is determined by mass balance computations. For a given current inflow rate, the minimum inflow volume for the remainder of the storm is obtained by assuming the inflow hydrograph has just crested and computing the volume under the recession side of the hydrograph. For conservatively low inflow volume estimates, the assumed recessive curve is made somewhat steeper than the average observed recession. The complete regulation schedule which allows the outflow to be adjusted on the basis of the current inflow and empty storage space remaining in the reservoir is developed by making a series of computations with various assumed values of inflows and amounts of remaining storage available.

The family of curves of Figure 3 also illustrate the concept of incorporating induced surcharge storage in the regulation plan. The release rates are set to allow specified encroachments into surcharge storage, above the static full flood control pool. The example regulation schedule of Figure 3 is for a gated spillway. However, the same general approach is applicable for reservoirs with uncontrolled spillways combined with outlet works with ample release capacity.

Regulation Rules for Conservation Storage Capacity

In general, conservation operations can be categorized as being primarily influenced by either seasonal fluctuations in streamflow and/or water use or long-term threat of drought. In some parts of the nation and world, a reservoir will be filled during a distinct season of high rainfall or snow melt and emptied during a dry season with high water demands. Thus, the reservoir level fluctuates greatly each year in a predictable seasonal cycle. In other cases, surface water management is predominately influenced by a long-term threat of drought. Water must be stored through many wet years, or decades, to be available during extended low-flow periods. Although reservoir storage may be significantly depleted within several months, severe drought conditions are characterized as a series of several dry years rather than the dry season of a single year. Reservoir operation during infrequent drought periods is significantly different than during normal or wet conditions. Although the relative importance of seasonal fluctuations versus long-term threat of drought varies between reservoir systems, both aspects of reservoir operations will typically be of some concern in any system.

Multiple-Purpose Considerations

Reservoir operation depends on purposes. Reservoir operation for municipal and industrial water supply is based on meeting demands subject to institutional constraints related to project ownership, contractual agreements, and water rights. Municipal and industrial water supply operations are typically based on assuring a high degree of reliability in meeting demands during anticipated infrequent but severe droughts. Supplying water for irrigation often involves a willingness to accept greater risks of shortages than municipal and industrial water supply and is based more on maximizing economic benefits. Irrigation reservoirs involve consumptive withdrawals and significant fluctuations in reservoir storage levels. Conversely, in steam-electric power plant cooling water reservoirs, most of the water withdrawn may be returned to the reservoir and water surface levels fluctuate very little. Hydroelectric power plants are typically components of complex energy systems which include thermal-electric as well as hydroelectric generation. Reservoir operations are based on both maintaining a high reliability of meeting hydroelectric power and energy commitments and minimizing total costs including both thermal and hydro generation. Reservoir storage for navigation purposes involves assuring sufficient water depths in downstream navigation channels and sufficient water supply for lockages. Instream flow needs include maintenance of streamflow for water quality, fish and wildlife habitat, livestock water, river recreation, and aesthetics. Reservoir operating policies may include specified minimum flow rates to meet instream needs. Reservoir recreation typically means maintenance of desirable storage levels and minimizing fluctuations in storage levels. Multiple purpose reservoir operation involves various interactions and trade-offs between purposes, which are sometimes complimentary but often competitive or conflicting.

Reservoir operations also address requirements other than the primary project purposes. For example, releases may be required to pass inflows through the reservoir to other water users and management entities located downstream. Such requirements may be specified in terms of maintaining minimum release rates or discharges at specified downstream locations, subject to the stipulation that reservoir releases in excess of inflows are not required. Another consideration involves restricting the rate of change in release rates to prevent downstream erosion. Storage level fluctuations are sometimes made to help control vectors such as mosquitos. Water quality storage has been included in reservoirs, as a primary project purpose, to provide releases for dilution of downstream pollution. Water quality is often an important incidental consideration in operations for other purposes. The quality of downstream flows and water supply diversions is sometimes controlled by selection of the vertical storage levels from which to make the releases.

Regulation Rules

A multitude of factors and considerations may be important in the operation of specific reservoir systems. Each reservoir and multiple-reservoir system has unique aspects and a variety of mechanisms are used to define operating rules. There is no standard format for specifying operating rules which is applicable to all situations. However, several basic concepts pertinent to a wide range of operating policies are discussed below.

Buffer Zones. Conservation operations may include designation of one or more buffer pools, or rule curves, as illustrated by Figure 4. Full demands are met as long as the reservoir water surface is above the top of buffer pool, with certain demands being curtailed whenever the water in storage falls below this level. The top of buffer zone elevation may be constant or may be specified as a function of time of the year or other parameters. Buffer zones provide a means to allow water supply or hydroelectric energy levels with different levels of reliability to be provided by the same reservoir. Certain water users require a high degree of reliability. For other water users, obtaining a relatively large quantity of water with some risk of shortage may be of more value than a supply of greater reliability but smaller quantity. Also, implementation of drought contingency plans may be triggered by the storage level falling below a specified buffer level. Buffer pools may also provide a mechanism for reflecting relative priorities or tradeoffs between purposes. specified buffer level.

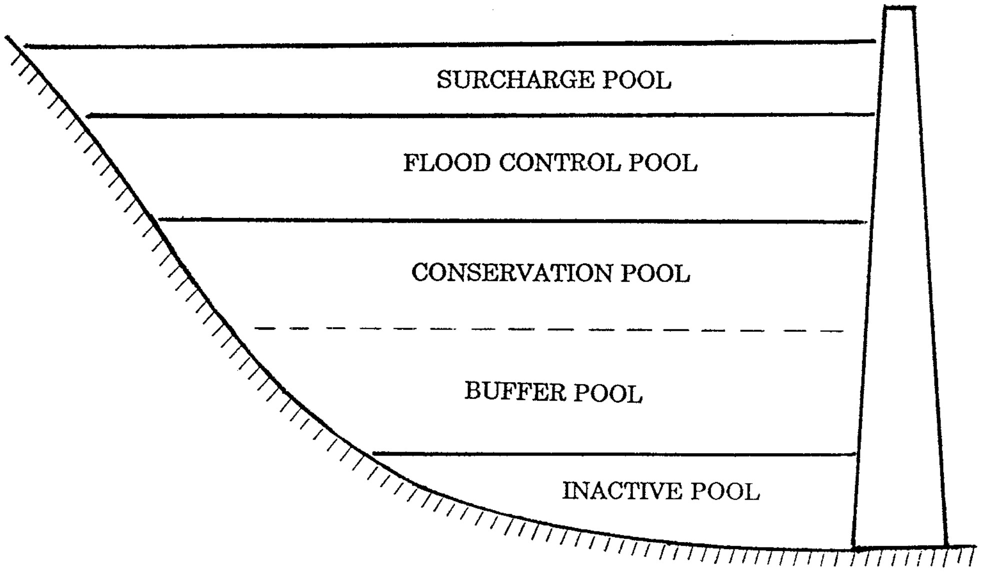


Figure 4. Conservation Pool Subdivided to Include a Buffer Pool

Multiple-Reservoir Operations. Multiple-reservoir release decisions occur in situations in which water needs alternatively can be met by releases from two or more reservoirs. In Figure 5, diversions 1 and 3 are based specifically on releases from reservoirs 1 and 3, respecitvely, but diversion 4 can be met by releases from any of the three reservoirs. One criterion for deciding from which reservoir to release is to minimize spills from downstream reservoirs, since such spills represent water loss from the system. Spills from upstream reservoirs may still be stored in downstream reservoirs and thus are not loss to the system. The term "spill" refers to discharges through an uncontrolled spillway or controlled releases made simply to prevent the reservoir surface from rising above the designated top of conservation pool elevation.

For reservoirs in series, such as reservoirs 1 and 2 in Figure 5, the downstream reservoir would be depleted before using upstream reservoir water to meet downstream demands. In addition to minimizing spills from the downstream reservoir, this procedure maximizes the amount of water in storage above, and thus accessible to, each diversion location. For example, water stored in reservoir 1 can be used to meet diversions 1, 2, and 4, but water stored in reservoir 2 can be used to meet only diversions 2 and 4.

For reservoirs in parallel, such as reservoirs 2 and 3 in Figure 5, minimizing spills involves balancing storage depletions in the different reservoirs. The simplest approach might be to release from the reservoir with the largest ratio of conservation pool storage content to storage capacity. Thus, release decisions would be based on balancing the percent depletion of the conservation pools. Other more precise and more complex

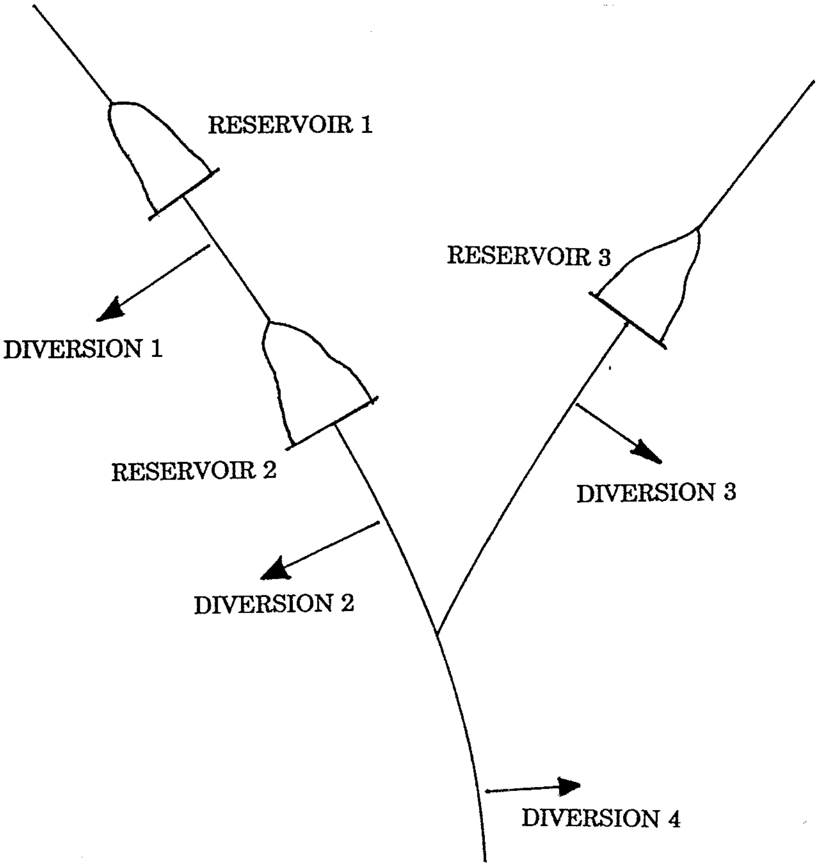


Figure 5. Multiple-Reservoir System

approaches can be adopted to select the reservoir with the highest likelihood of incurring future spills.

Numerous other considerations may be reflected in multiple-reservoir release decisions. If the reservoirs have significantly different evaporation potential, minimization of evaporation may be an objective. The criteria of minimizing spills or evaporation are pertinent to either single-purpose or multiple-purpose systems. Multiple-purpose multiple-reservoir release decisions can involve a wide variety of interactions and tradeoffs. For example, releases to meet downstream municipal, industrial, or irrigation water supply demands may be passed through hydroelectric power turbines. Thus, multiple-reservoir water supply release decisions may be based on optimizing power generation. Likewise, recreational aspects of the system could motivate release decisions which minimize storage level fluctuations in certain reservoirs.

As illustrated by Figure 6, conservation pools can be subdivided into any number of zones to facilitate formulation of multiple-reservoir release rules. The multiple-zoning mechanism can be reflected in the operating criteria actually followed by water control managers. Also, even in cases where operating rules are not actually precisely defined by designation of multiple zones, the multiple-zone mechanism can be used in computer models to approximate the somewhat judgmental decision process of actual operators. The zones provide a general mechanism or format for expressing operating rules. Multiple-reservoir release rules are defined based on balancing the storage content such that the reservoirs are each in the same zone at a given time to the extent possible. For example, water is not released from zone 2 of one reservoir until zone 3 has been depleted in all the reservoirs.

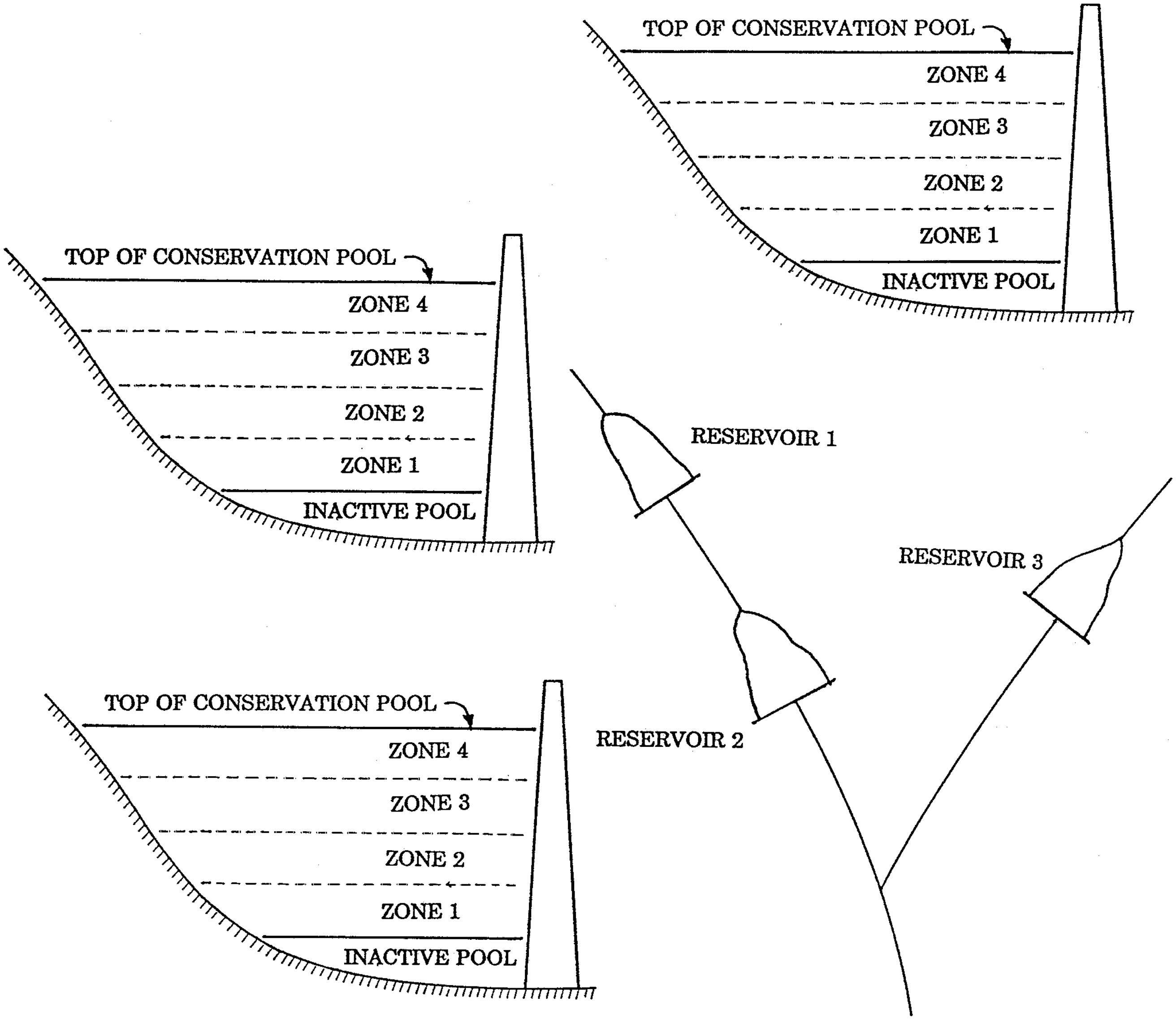


Figure 6. Conservation Pool Zones for Multiple-Reservoir Operations

QUANTITATIVE MEASURES OF SYSTEM PERFORMANCE

Defining quantitative measures of system performance is a key element of formulating a modeling and analysis approach. The reservoir system analysis model must be able to compute values of the performance measures as a function of operating policies. The performance measures provide a mechanism for evaluating and comparing alternative reservoir operating plans.

Hierarchy of Goals and Objectives

Reservoir systems are constructed and operated to meet a broad spectrum of goals and objectives. Quantitative performance measures are formulated within a hierarchial framework of goals and objectives, which range from general expressions of societal goals to the specific quantitative performance measures to be used in a particular modeling and analysis exercise. Although the concept of a hierarchy of goals and objectives has been expressed in various ways, the following nomenclature is used here to outline the hierarchy.

- societal goals and objectives for water resources development and management
- project purposes
- planning objectives
- performance measures

Societal Goals and Objectives for Water Resources Development and Management

Hall and Dracup (1970) suggest that the broad spectrum of societal goals for water resources systems can be approximated by the following fundamental objectives:

- To control or otherwise manage the freshwater resources of the cognizant geographic or political subdivision so as to provide protection against injurious consequences of excesses or deficiencies in quantity or quality.

- To provide or maintain water in such places and times and in adequate quantity and quality for human or animal consumption, wildlife (including native plants), food production and processing, industrial production (including energy), commerce, and for the recreational, aesthetics and conservation purposes considered desirable by the body politic.

- Accomplish all of the above with a minimum expenditure of the physical, economic, and human resources available.

Broad goals and objectives related to enhancing the welfare of society are established at the policy level. Planning of federal projects follows the Water Resources Council (1983) Principles and Guidelines (P&G) which state:

> "The Federal objective of water and related land resources project planning is to contribute to national economic development consistent with protecting the Nation's environment, pursuant to national environmental statutes, applicable executive orders, and other planning requirements."

The P&G outline four accounts to facilitate evaluation and display of effects of alternative plans.

- The national economic development (NED) account displays changes in the economic value of the national output of goods and services.

- The environmental quality (EQ) account displays nonmonetary effects on ecological, cultural, and aesthetic resources.

- The regional economic development (RED) account registers changes in regional economic activity.

- The other social effects (OSE) account registers plan effects from perspectives that are relevant to the planning process, but are not reflected in the other three accounts.

Federal projects involve partnership arrangements with state and local entities to address regional and local problems and needs. State and local objectives are also incorporated into the planning process for federal studies and projects. Many of the major reservoir systems in the United States are on interstate rivers, and several major reservoir systems are on rivers shared with either Mexico or Canada. Thus, different objectives articulated by several states and even neighboring countries may be important in establishing operating policies for a particular reservoir system.

Project Purposes

A reservoir typically serves one or more of the following purposes: flood control, navigation, hydroelectric power, municipal and industrial water supply, irrigation, recreation, fish and wildlife enhancement, erosion and sedimentation control, and water quality management. Operating policies are established within the framework of reservoir purposes. Congressional authorization of federal projects includes specification of the purposes to be served. Nonfederal projects are also constructed for particular purposes. Institutional considerations, such as agency responsibilities and cost-sharing, are based on project purposes. Modeling and analysis methods vary significantly depending on the purposes being considered.

Planning Objectives

Defining problems, needs, and opportunities is a major initial step in the planning process for feasibility studies in which either construction projects or operational modifications at existing facilities are being considered. An analysis of problems, needs, and opportunities typically results in a set of planning objectives for guiding plan formulation and evaluation. Planning objectives are formulated within the framework of the general societal goals discussed above and are typically associated with particular project purposes. Planning objectives are specific to the problems, needs, and opportunities being addressed by a particular study. The effectiveness of alternative plans in meeting the planning objectives should be quantified as much as possible but may be evaluated qualitatively as well as quantitatively.

A broad range of objectives may be pertinent depending on the circumstances of the particular reservoir system being studied. Examples of planning objectives might include the following:

- Reduce the risk and consequences of flooding of residential and commercial properties along a certain reach of a river through a particular urbanizing area for a full range of flood frequencies.

- Increase the firm yield to that required to meet projected year 2010 municipal and industrial water needs of a particular city.
- Minimize the cost of meeting electrical energy demands in a particular region.
- Reduce the risk and consequences of irrigation water supply shortages for existing farming activities in a region as well as for a projected increase in irrigated acreage.
- Maximize opportunities for specific reservoir recreation activities consistent with present and projected future needs for recreation in a certain region.

Performance Measures

Quantitative measures of system performance to be used in modeling and analysis exercises are formulated within the framework of the hierarchy of goals and objectives discussed above. The purpose of performance measures is to have a mechanism to quantitatively compare, for alternative operating plans, the effectiveness of the reservoir system in meeting specified objectives. Consequently, the performance measures must be a function of the storage and release parameters which define an operating policy. The performance measure could be a well-defined objective function incorporated in an optimization model. However, performance measures typically include a wide range of information computed by simulation and/or optimization models in addition to values for single-valued well-defined objective functions. The remainder of this chapter provides an overview of the various performance measures which are used in reservoir system analysis studies.

Economic Evaluation

Economic decision criteria are often applied in establishing reservoir operating policies. Economic evaluation provides important capabilities for comparing beneficial and adverse consequences of alternative operating plans, but is limited by complexities and difficulties in developing benefit and cost estimates which are meaningfully sensitive to the changes in operating plans. Basic economic evaluation concepts are briefly outlined below. Specific economic-related performance measures used in reservoir system analysis are addressed in later sections.

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 federal water agencies for estimating national economic development benefits associated with the various project purposes. The Principles and Guidelines (Water Resources Council 1983) outline the basic concepts of economic evaluation presently followed by the federal water agencies. The USACE 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 et al. 1988). The Hydropower Engineering Manual

(USACE, OCE 1985) outlines economic evaluation procedures for hydroelectric power. Past federal work in developing and applying economic evaluation methods has been accomplished primarily from the perspective of planning studies involving proposed construction projects, rather than reevaluation of completed projects. However, the economic efficiency objective is also applied to reevaluation of operations of existing reservoir systems.

Economic evaluation consists of estimating and comparing the benefits and/or costs, in dollars discounted to a common time base, which would result from implementation of alternative plans of action. The economic objective function may be to either maximize net benefits, minimize costs, or maximize benefits. Net benefits are total benefits minus total costs. If a fixed level of service is provided by all the alternative plans being considered, the economic objective function may be expressed as minimizing costs, without needing estimates of benefits. Likewise, in operations of an existing facility, the costs may be fixed, and alternative plans are compared based only on benefits. If most of the benefits and costs are fixed for all alternative plans, the evaluation may be based on a specific component of either the benefits or costs.

Benefit estimates are based on the standard of willingness-to-pay, which is defined as the amount a rational and fully informed buyer should be willing to pay for one more unit of a service or commodity. If a competitive unregulated market exists for a commodity, then the market price would be the willingness-to-pay. However, market prices typically do not reflect the true marginal cost or economic benefit of the output of water projects. In evaluating proposed construction projects, benefit estimates, representing willingness-to-pay, are estimated using approaches such as the alternate cost, cost savings, and travel cost approaches cited below.

In the alternate cost approach, benefits are estimated as the cost of the least costly alternative method for providing the service. It is assumed that the service must be provided even if the proposed plan is not implemented. For example, benefits for including municipal and industrial water supply capacity in a multiple-purpose reservoir project are typically 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. Benefits for constructing hydroelectric power projects are typically estimated as either (1) the cost of constructing and operating an alternative thermal plant or an increment thereof or (2) the value of generation (primarily fuel costs) from existing thermal plants that would be displaced by the output of the proposed hydroelectric plant. The alternate cost approach has also been used to estimate water quality management benefits.

Benefits can also be estimated as a cost savings. For example, navigation benefit estimates are based on comparing the cost of shipping pertinent goods by barge with the cost of transporting the same goods by the least-costly available alternative method. Flood control benefits are estimated as the reduction in expected annual flood damages to result from implementation of a proposed plan of improvement.

Recreation benefits are sometimes estimated using the travel cost method which relates the marginal willingness to pay to the rate at which the percentage of population visiting the reservoir falls off as a function of distance from the reservoir.

Cost estimates are usually more straight-forward than benefit estimates.

Conventional engineering estimates of construction, major replacement, operation & maintenance, and fuel costs are common to many applications. The concept of shadow price is an example of another less conventional approach which has been used to estimate the relative utility of alternative plans for modifying reservoir operations. Shadow price is the dollar amount associated with one objective given up in order to gain an extra unit on a second objective with the performance of all other objectives remaining the same. For example, levels of service of other purposes in a multiple-purpose reservoir may be shadow priced to hydroelectric power revenue. The cost of modifying the operating policy to enhance water supply, recreation, or other purposes is related to the corresponding reduction in hydroelectric power revenue.

Economic evaluation of operations of existing reservoir systems differ significantly from evaluating proposed construction projects. The economic feasibility criterion, which requires that benefits exceed costs for a construction project to be justified, has been a major consideration in developing traditional economic evaluation procedures. Economic evaluation of proposed construction projects incorporate a comprehensive array of benefits and costs, but the evaluation procedures are not necessarily sensitive to refinements and relatively small changes in operating policies. In evaluating modifications to reservoir operating rules, most of the project benefits and costs are fixed and only selected pertinent benefit and/or cost components are reflected in the analysis. Quantitative dollar-related measures of system performance are often adopted in reservoir system analysis studies which do not necessarily reflect the willingness-to-pay benefit standard. For example, the objective function of optimization models are sometimes based on revenues from selling water or hydroelectric energy. Although in some situations such revenues may accurately reflect willingness to pay, water supply and hydroelectric power revenues typically do not represent marginal cost or the actual price consumers are willing to pay. However, water supply or hydroelectric revenues may still provide a meaningful index or performance measure for comparing alternative operating plans even though the willingness to pay standard is not accurately represented. For purposes of comparing alternative operating plans, a high degree of accuracy in estimating economic parameters may not necessarily be required as long as the sensitivity relative to differences between alternative plans is properly reflected.

Yield Versus Reliability Relationships

Yield is a measure of the amount of water which can be supplied by a stream/reservoir system under specified conditions. Yield may be expressed in terms of a firm or dependable yield, reliability of meeting various demand levels, percent of time specified quantities of water are available, risk of shortages, probability of various storage levels occurring, or a tabulation of the amount of water available during each time interval of a simulation, based on specified conditions or assumptions. The stochastic nature of streamflow and other pertinent variables must be reflected in estimates of yield. Yield estimates are based on specified scenarios regarding reservoir operating policies and the impacts of other water users and activities in the river basin.

Firm yield (or safe or dependable yield) is the estimated maximum release or diversion rate which can be maintained continuously during a hypothetical repetition of the hydrologic period-of-record, based on specified assumptions regarding operating policies, diversion locations, impacts of other water users and activities in the basin, and other complexities. Firm yield is the draft which will just empty the reservoir or multiple reservoir system during a hydrologic period-of-record simulation. Firm yield is typically expressed in terms of a mean annual rate with monthly, or other time interval, distribution factors being incorporated in the model to reflect the within-year seasonal variation in water use. Essentially all feasibility studies of proposed new reservoir projects include development of firm yield versus storage capacity relationships. Firm yield estimates are also fundamental to reevaluation studies of existing water supply reservoir systems.

Reservoir reliability is an expression of the likelihood or probability of meeting a given demand or, equivalently, the percent of time the given demand can be met. Reliability (R) is the complement ($R = 1 - F$) of the risk of failure (F) or probability that the demand will not be met or, equivalently, the percent of time that the demand will not be met.

Various definitions of reliability can be formulated to serve the purposes of the particular study. Computational procedures are dependent upon the manner in which reliability is defined. For example, reliability estimates can be computed on either a period or volumetric basis. Period reliability can be defined as the proportion of time that the reservoir/stream system is able to meet demands. This reliability is computed from the results of a historical hydrologic period-of-record simulation as ($R = n/N$) where n denotes the number of time periods (such as 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. With these definitions, 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%.

Various definitions of reliability can be formulated for alternative time periods. Reliability estimates may be formulated as the percentage of either days, weeks, months, or years, during a historical hydrologic period-of-record simulation, for which demands are met. The reliability would represent the likelihood or probability of demand being met in a randomly selected time period, of appropriate length (day, week, month, year), in the future. Alternatively, reliability can be defined in terms of the likelihood that demands can be met during a long multiple-year period-of-analysis as discussed below. Reliabilities, as defined above based on historical hydrologic period-of-record analyses are incorporated quite often in studies performed by the water resources management agencies. Reliability analysis approaches, as illustrated below, based on synthetically generated streamflows, have been addressed quite extensively in the research literature but have been used relatively little in actual studies conducted by the water agencies.

Analyses of the reliability of meeting demands continuously during long multiple-year periods are typically based on synthetically generated streamflow sequences. Streamflow synthesis models, discussed later, generate streamflow sequences of any desired length based on preserving specified statistical characteristics of the historical data. Equally likely streamflow sequences with a length equal to the time period over which the reservoir is being analyzed are synthesized. 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 200) of monthly streamflow sequences of a specified length (say 50 years) can be synthesized using an appropriate model, such as those cited later in this report. Firm yields could then be computed for each of the 200 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 200.

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.

Starting reservoir storage is a significant factor in defining yield versus reliability relationships. Yield studies are typically based on assuming that reservoir storage capacity is full at the beginning and end of a critical drawdown period contained within the historical hydrologic period-of-record. However, analyses can also be performed to estimate reliabilities of meeting demands during specified future time periods given present storage levels which are not necessarily full reservoirs.

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 similarly to firm yield and reliability for water supply.

Simulation Results

Simulation and optimization models are discussed in some detail later in this report. Optimization models also "simulate" as well as "optimize." Therefore, the present discussion on "simulation results" is generally pertinent to either type of model. Modeling and analysis studies typically involve numerous executions, of sometimes several models, with each execution generating voluminous output data. For a given reservoir system operating plan and specified set of conditions, an extensive amount of data can be developed. The model output data can be used in a variety of ways, based on the ingenuity and preferences of the analyst, to develop a better understanding of the operation of the reservoir system. Quantitative measures of system performance typically involve an array of information. There is seldom, if ever, a simple single-number answer to a reservoir operation problem.

A wide variety of modeling and analysis approaches are possible. However, a somewhat typical study would involve simulating a reservoir system operating plan based on streamflows from an assumed repetition of the entire historical hydrologic period-of-record, or some portion thereof, with storages, discharges, and other pertinent quantities being computed at some appropriate time interval such as a day or month. A primary output of reservoir operation studies has often been simply plots of storage content versus time for the period-of-analysis. Discharge hydrographs at pertinent locations are typically key output. Tabulations of hydroelectric power or water supply shortages may be of particular concern. Frequency analyses are often applied to the results of a simulation to develop reservoir storage versus exceedence frequency or duration relationships and, similarly, streamflow discharge versus duration relationships. Economic performance measures may be the principal output of concern. Likewise, yield versus reliability relationships may be important.

Optimization Objective Functions

Mathematical programming (optimization) methods involve determining values for a set of decision variables which will minimize or maximize an objective function subject to a set of constraints. Application of mathematical programming techniques requires development of an objective function consisting of a single mathematical equation expressing the objective as a function of the decision variables. Although much stricter requirements are placed on the mathematical form of an objective function incorporated in mathematical programming models, precisely defined objective functions are also useful for optimization strategies involving multiple comparative runs of a simulation model with alternative operating plans.

The simulation results discussed above include an array of functional relationships and sets of numbers descriptive of the performance of a reservoir system for a specified operating plan, as well as some performance criteria that may be represented by a single computed value. The objective functions discussed here provide a single value of a performance measure for a specified operating plan. The objective function is a single-valued criterion for guiding the determination of an optimal plan, which can be expressed in a format suitable for a mathematical programming model.

Examples of Decision Criteria

A variety of objective functions have been incorporated in the different optimization (mathematical programming) models for analyzing reservoir operations which have been reported in the literature. The objective functions may be similar and are sometimes identical in various optimization models. However, in general, individual objective functions have been formulated for each specific model and reservoir system operation study. A number of specific reservoir optimization models are cited in the later section on state-of-the-art models. The objective functions incorporated in the models are a main emphasis of the discussion of the models. The objectives listed in Table 2 have all been reflected in objective functions incorporated in one or more of the optimization models addressed later in this report.

Multiple Decision Criteria

Several different objectives will typically be of concern in a particular reservoir system analysis study. An optimization model can incorporate only one objective function. If the various objectives can all be expressed in commensurate units, they can each be a component of the same objective function. For example, economic benefits and costs, in discounted dollars, for flood control, hydroelectric power, and water supply may be included in the same objective function. However, typically, the objectives are not in commensurate units. Two alternative approaches are typically adopted to analyze tradeoffs between alternative objectives.

The first approach is to execute the optimization model with one selected objective reflected in the objective function and the other objectives treated as constraints at fixed

Table 2

EXAMPLES OF OBJECTIVES WHICH HAVE BEEN REFLECTED IN THE OBJECTIVE FUNCTIONS OF OPTIMIZATION MODELS

- Economic Benefits and Costs
  - minimize the sum of damages at pertinent locations associated with a specified flood event
  - maximize hydroelectric power revenues
  - minimize the cost of meeting total power commitments from a combined hydro/thermal system.
  - maximize water supply revenues
  - minimize economic losses due to water shortages
  - minimize the electrical cost of pumping water in a distribution system
  - maximize net benefits of multiple purpose operations
- Water Availability and Reliability
  - maximize firm yield
  - maximize yields for specified reliabilities
  - maximize reliabilites for specified demands
  - minimize shortage frequencies and/or volumes
  - minimize shortage indices, such as the sum of the squared deviations, where the deviations are the target minus actual diversion in each time interval
  - minimize the weighted sum of shortage indices
  - maximize the reliability of maintaining minimum streamflows required for nagivation or other instream uses
  - maximize the minimum streamflow
  - maximize reservoir storage content at the end of the optimization horizon
  - minimize evaporation losses
  - minimize spills
  - minimize average monthly storage fluctuations
  - maximize the length of the navigation season
  - minimize the total volume of water released for minimum navigation needs
- Hydroelectric Power Generation
  - maximize firm power
  - maximize average annual energy
  - minimize energy shortages
  - minimize energy shortage indices, such as the sum of squared deviations
  - maximize the potential energy of water stored in the system

user-specified levels or values. For example, the model might maximize average annual energy, subject to the constraints that a user-specified water supply firm yield level and firm energy level be maintained. Alternative runs of the model could be made to show how the average annual energy is affected by changes in the user-specified water supply firm yield and firm energy.

An alternative approach for analyzing tradeoffs between noncommensurate objectives involves treating each objective as a weighted component of the objective function. The objective function is the sum of each component multiplied by a weighting factor reflecting the relative importance of that objective. The weighting factors are arbitrary and have no physical significance other than to reflect relative weights assigned to the alternative objectives included in the objective function. The model can be executed iteratively with different sets of weighting factor values to analyze the tradeoffs between the objectives with alternative operating plans.

Role of Objective Functions

The objective function is the heart of the optimization models discussed later in this report. Two equally valid but somewhat contrasting perspectives on the role of objective functions, and the models into which they are incorporated, in the overall process of evaluating alternative operating plans are presented in the following two paragraphs. Reconciling and balancing these two perspectives is a key consideration in formulating a modeling and analysis approach for a particular reservoir system operation study. This is also a basic philosophical issue in assessing the practical utility of optimization models in general. The question is how completely and accurately does the objective function incorporated in a model have to reflect actual societal objectives to provide meaningful information for use in the decision making process.

The usefulness of a model depends on how meaningfully the complex real world can be represented by a set of mathematical equations. A key consideration with optimization models is how well the objectives of the decision makers can be represented by a single-equation objective function. Public needs and objectives are complicated and typically ill-defined. The physical and institutional characteristics of multiple-purpose water control and management systems, electric utility systems, and water allocation and use systems are complex. Likewise, hydrologic and environmental characteristics of a river basin are complex. The risks and consequences of water shortages and flooding and the benefits of water management are difficult to quantify. Functional relationships between the complex characteristic of floods and droughts and the objectives to be served by a reservoir system can be only approximated. Quantitative measures of system performance must meaningfully capture the complexities of the real world. Necessary simplifications and approximations severely limit the utility of models.

On the other hand, objective functions are simply quantitative measures of system performance which can be meaningfully utilized to obtain a better understanding of the system. Even if planning objectives can be precisely articulated, which is typically not the case, it will likely not be possible to incorporate an objective function into an optimization model which captures the total essence of the planning objectives. However, models still provide valuable analysis tools. A model can significantly contribute to the evaluation process even though it can never tell the whole story. The objective function can be a simple index of the relative utility of alternative operating plans, which provides significant information regarding which alternative plan best meets the planning objectives. Modeling exercises with alternative decision criteria help address different aspects of the overall story.

DEFINING THE RESERVOIR SYSTEM OPERATION OPTIMIZATION PROBLEM

Reservoir system operations involve a multitude of decision problems and situations. This section attempts to outline, in general, what is typically being "optimized" in reservoir system analysis studies. The variety of decision problems are categorized. Decision variables, tradeoffs, and system performance criteria associated with different types of reservoir system operation optimization problems are discussed.

Sizing storage capacities during the planning and design of proposed new reservoir projects has been a major reservoir operation problem addressed in the past. Developing at least a tentative operating plan is required to size storage capacity. In recent years, modifications and refinements to the operations of completed projects have become a major concern. The present discussion focuses on the operation of existing reservoir systems.

Categories of Operating Decisions

Reservoir operating rules and the actual day-to-day operating decisions made within the framework of these rules can be categorized as follows:

- operations during hydrologic extremes
    - operations during flood events
    - operations during low flow or drought conditions

- operations during relatively normal hydrologic conditions from the perspective of maintaining capabilities for responding to infrequent hydrologic extremes expected to occur at unknown times in the future
    - maintaining empty flood control storage capacity
    - maintaining reliable supplies of water for various conservation purposes
- operations during relatively normal hydrologic conditions from the perspective of optimizing the present day-to-day, seasonal, or within-year beneficial use of the reservoir system.

Conservation storage operations can be further categorized by the different project purposes. The following discussion of operating decisions and system performance criteria is organized by project purpose with the categorization outlined above also being considered.

Flood Control Operations

The Optimization Problem

Flood control pool operations are based primarily on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint of assuring absolutely that the maximum design water surface is never exceeded. Flood control pools must be emptied as quickly as downstream flooding conditions allow to reduce the risk of future highly damaging releases being necessitated by filling of the available storage capacity. Minimizing the risks and consequences of storage backwater effects contributing to flooding upstream of the dam is also an important tradeoff consideration at some reservoir projects.

One type of reservoir system operation optimization problem consists of developing an operating plan. Another closely related but distinctly different reservoir system operation optimization problem involves making release decisions during real-time flood control operations, within the framework of the operating plan. The operation plan provides guidance for real-time release decisions but typically still leaves a degree of flexibility during real-time operations. During normal nonflooding conditions, real-time flood control operations consist simply of passing inflows to maintain empty storage capacity.

Decision variables during real-time operations consist of release rates as a function of time at each reservoir in the system. Real-time operating decisions are guided by the predetermined operating rules. Decision variables in establishing or modifying operating rules include the storage capacity allocated to flood control and the allowable discharge rates established for downstream control points. The storage capacity allocated to flood control may be a function of time of the year or other parameters. The allowable discharges at downstream control points may be a function of time of the year, current reservoir storage content, or other parameters. Regulation curves expressing releases as a function of reservoir inflow and storage, as previously discussed and illustrated in Figure 3, are also an important component of a flood control regulation plan. Balancing the emptying of the flood control pools of the different reservoirs of a multiple reservoir system is also a key consideration in developing operating rules and in making real-time release decisions.

Interactions between flood control and conservation purposes in a multiple purpose reservoir involve allocation of storage capacity as represented by the designated top of conservation pool elevation, which is a form of a rule curve. Modifications to the operations of completed projects may involve either permanent long-term reallocations of storage capacity or establishing or refining seasonally varying rule curves for joint use storage. Studies of long-term storage reallocations and designing seasonal rule curves are two important types of reservoir system operation optimization problems.

Interactions between flood control and conservation purposes may also involve flood control pool release rates. For example, in some cases, flood control pool releases may be passed through hydroelectric power plants and limited to the maximum discharge that can be used to generate power. Also releases from conservation storage may be made to partially draw the pool down in anticipation of forecasted flood inflows. Releases from the conservation pool in anticipation of forecasted flood inflows are particularly important for reservoirs with little or no designated flood control storage capacity. These types of considerations may also be important in formulating the reservoir operation problem.

System Performance Measures

The effects of alternative operating strategies on various characteristics of specified historical or hypothetical design flood streamflow hydrographs may be of concern. Such characteristics include peak stage, peak discharge, duration, volume, velocity, rate of rise or warning time, and sediment transport rates. Discharge and/or stage versus exceedence frequency relationships are typically computed for pertinent streamflow locations. Variations in reservoir storage hydrographs and/or storage versus exceedence frequency relationships, with alternative operating plans, also provide meaningful comparisons which are often used.

Flood control storage capacity has traditionally been evaluated in terms of the recurrence interval, or exceedence probability, of a flood that can be contained without releases contributing to downstream flooding. For example, a typical USACE reservoir may be sized to contain either a standard project flood, 1%, or 2% exceedence frequency design flood. A flood of the specified magnitude just fills the flood control pool. Frequency analyses, using a plotting position formula or probability distribution function, are often performed based on a series of peak annual storage levels computed using a reservoir system simulation model with period-of-record historical streamflow data. Alternatively, hypothetical design floods computed using a rainfall-runoff model are routed through the reservoir to determine peak storage levels associated with specified recurrence intervals.

The USACE and other federal agencies have developed detailed methods for quantifying the economic benefits associated with reducing the risk of flooding. 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. Expected annual damage computational capabilities are included in the HEC-5 and Southwestern Division reservoir system simulation models, discussed later in this report.

Economic feasibility, as measured by estimated benefits exceeding costs when discounted to a common time base using a specified discount rate, is a strict requirement for justification of a federal flood control project. Maximizing net economic benefits is a key consideration in sizing flood control storage capacity. The objective in sizing storage capacity has often been to maximize net benefits subject to the constraint of providing at least a specified minimum level of protection, such as containing a 2% or 1% exceedence frequency flood without releases contributing to downstream flooding.

Flood control economic evaluation procedures have been used primarily in preconstruction planning and design, but have also been used in reevaluation studies of operational modifications at existing projects. 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 at an existing reservoir. Frequency versus discharge relationships can be most accurately estimated for the more frequent flood events. However, storage reallocations and certain other types of modifications in reservoir operations affect the release only for the extreme, less frequent events, for which data is most uncertain. Storage reallocations and other modifications 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.

Thus, the economic efficiency objective provides an important measure of system performance, but like all performance measures, has its limitations.

Water Supply Operations

The Optimization Problem

Maintaining a high reliability for meeting water needs during infrequent drought or low flow conditions expected to occur at unknown times in the future is a key consideration in water supply management. During normal hydrologic conditions, municipal and industrial (M&I) and irrigation water supply operations involve meeting water demands in accordance with contractual arrangements and agreements. Operating plans may also include maintenance of minimum instream flows for fish & wildlife, freshwater inflows to bays and estuaries, or wetlands. During low flow or drought conditions, operations may involve allocating limited water resources to competing uses and users within the institutional framework of project ownership and agency responsibilities, contractual agreements, legal systems for allocating and administering water rights, and political negotiations.

M&I water supply typically requires a very high level of reliability. Project planning and design, contractual agreements, and water rights are typically based on assuring that firm, or high reliability, yields exceed water needs. In recent years, implementation of appropriate demand management strategies has been considered in estimating water supply needs.

Supplying water for irrigation often involves acceptance of greater risks of shortages than M&I water supply and is based more on maximizing net economic benefits. Obtaining a relatively large quantity of water with some significant risk of shortage may be of more value than a supply of greater reliability but smaller quantity. A operating plan may involve allocating water to the various users at the beginning of each water year or irrigation season based upon current reservoir storage levels and present and forecasted future hydrologic conditions.

Developing contractual arrangements, allocating water rights, developing reservoir operating plans, and making operating decisions involve various types of reservoir system operation problems. The optimization problems can be categorized as follows.

- determination of the amount of water to release from each reservoir of a multiple reservoir system

- allocation of a limited amount of water over each time interval of the period of analysis (for example, distributing available water over the irrigation season)

- determination of the tradeoff between the amount of water to use during the current water year or irrigation season and the amount of water to be carried over in storage into the next year

- allocation of a limited amount of water between competing users

- coordination of water supply operations with other project purposes

- coordination of water supply operations with other sources of supply, such as groundwater, and demand management strategies

- preservation of existing water rights and various combinations of the above

Multireservoir system operation involves coordinated releases from two or more reservoirs to supply common diversions or instream flow needs at downstream locations. Manmade conveyance and pumping facilities also allow diversion locations which are not necessarily at or downstream of the reservoirs making the releases. Multiple-reservoir system firm yields, or yields associated with specified reliabilities, may be significantly higher than the sum of the corresponding individual reservoir firm yields. Coordinated releases from two or more reservoirs increase yields by sharing the risks associated with the individual reservoirs not being able to meet their individual demands. Operated individually, one reservoir may be completely empty and unable to supply its users while significant storage remains in the other reservoirs. At other times, the other reservoirs may be empty. System operation balances storage depletions. Multireservoir system operation can also serve to minimize reservoir spills and evaporation and channel losses due to seepage and evaporation. In some systems, water treatment costs and electrical pumping costs for water conveyance and distribution may vary significantly depending on which demands are met by releases or withdrawals from which reservoirs.

Utilization of unregulated flows entering the river below the most downstream dams, and thus not flowing into any reservoir, is another key aspect of system operation. Unregulated river flows may be highly variable, with significant magnitude some of the time, and zero or very low at other times. Unregulated flows typically have firm yields of zero or very little. However, when combined with reservoir releases during low-flow periods, the unregulated streamflows may significantly contribute to the overall stream/reservoir system firm yield (or yield associated with some other specified reliability).

Developing operating plans for multiple purpose operations typically involves rule curves. Allocation or reallocation of storage capacity between flood control and water supply purposes consists of determining a designated top of conservation pool elevation, which may be constant or vary seasonally over the year. Likewise, water supply and hydroelectric power operations may be coordinated by a designated rule curve. Multiple purpose operations may also involve multireservoir water supply release decisions. Water supply releases may be made from the reservoir which best facilitates hydroelectric power generation. Multireservoir water supply release decisions may be based on minimizing storage fluctuations in certain reservoirs used heavily for recreation.

System Performance Measures

As previously discussed, water supply system performance measures includes various forms of yield versus reliability relationships. The various types of water availability and reliability objectives illustrated in Table 2 have been incorporated into modeling and analysis exercises. The economic performance measures cited in Table 2 have also been used.

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 include projections of future water needs alternatively assuming reasonable demand management strategies are, and are not, adopted. Water supply studies typically include two key elements: (1) projections of water needs and (2) estimation of firm yields, or yield versus reliability relationships, for alternative water supply augmentation plans. New water supplies are developed and/or operations of existing facilities modified to assure that firm yields are maintained in excess of needs. Thus, water needs can continue to be met during future extreme drought conditions.

In economic evaluations of proposed new federal multipurpose 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 modifications in reservoir operating plans. Young, Taylor, and Hanks (1972), Dziegielewski and Crews (1986), and Wurbs and Cabezas (1987) suggest economic evaluation procedures, in which average annual losses due to water shortages are computed, which may be more pertinent for evaluating alternative reservoir operating policies.

Hydroelectric Power Operations

Hydroelectric plants are generally used to complement the other components of an overall electric utility system. Because the demand for power varies seasonally, at different times during the week, and during the day, the terms base load and peak load are commonly used to refer to the constant minimum power demand and the additional variable portion of the demand, respectively. Hydroelectric power is typically used for peak load while thermal plants supply the base load. Hydroelectric power plants can assume load rapidly and are very efficient for meeting peak demand power needs. In some regions, hydroelectric power is a primary source of electricity, supplying much or most of the base load as well as peak load. Availability of water is generally a limiting factor in hydroelectric energy generation.

Hydroelectric plants may be classified as storage, run-of-river, or pumped storage. A storage-type plant has a reservoir with sufficient capacity to permit carry-over storage from the wet season to the dry season or from wet years through a drought. A run-of-river plant has essentially no active storage, except possibly some pondage to permit storing water during off-peak hours for use during peak hours of the same day or week, but may have a significant amount of inactive storage which provides head. Flows through the turbines of run-of-river plants are limited to unregulated streamflows and releases from upstream reservoirs. A pumped-storage plant generates energy for peak load, but during off-peak periods, water is pumped from the tailwater pool to the headwater pool for future use. The pumps are powered with secondary energy from some other plant in the system.

At many projects, reservoir releases are made specifically and only to generate hydroelectric power. At other projects, power generation is limited to releases which are being made anyway for other purposes, such as municipal, industrial, or agriculture water supply. An upstream reservoir may be operated strictly for hydropower, with the releases being reregulated by a downstream reservoir for water supply purposes.

The objective of a electric utility is to meet system demand for energy, capacity (power), and reserve capacity (for unexpected surges in demand or loss of a generating unit) at minimum cost. Power is the rate at which energy is produced. Capacity is the maximum rate of energy production available from the system. The value of hydroelectric energy and power is a function of the reliability at which they can be provided.

Three classes of energy are of interest in hydroelectric power operations: average, firm, and secondary. Average energy is the mean annual amount of energy that could be generated assuming a repetition of historical hydrology. Firm energy, also called primary energy, is estimated as the maximum constant annual energy that could be generated continuously during a repetition of historical hydrology. From a marketing perspective, firm energy is electrical energy that is available on an assured basis to meet a specified increment of load. Secondary energy is energy generated in excess of firm energy. Secondary energy, expressed on an average annual basis, is the difference between average annual energy and firm energy.

The Optimization Problem

Reservoir operating rules for hydroelectric power generation assume many different forms depending on the characteristics of the electric utility system and reservoir system, hydrologic characteristics of the river basin, and institutional constraints. However, designation of a power pool and power rule curve, as illustrated by Figure 7, is a key aspect of hydroelectric operations. The power pool is reserved for storage of water to be released through the turbines. Inactive or active storage below the power pool provides additional head. If the reservoir water surface is at the top of power pool, net inflows (inflows minus

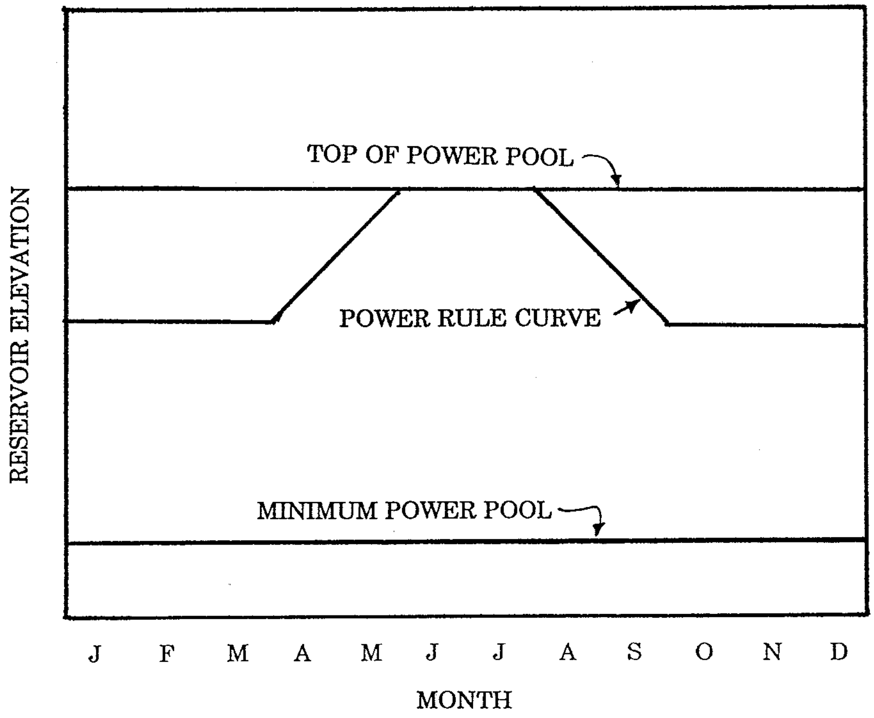


Figure 7. Rule-Curve for Hydroelectric Power Operations

evaporation minus withdrawals) are passed through the reservoir. Flows up to the maximum generating capacity of the plant may be used to generate energy, and the remainder of the flow is spilled. If the reservoir contains flood control storage, water will be stored in the flood control pool above the top of power pool during flood events. Power generation is curtailed any time the water surface elevation drops below the designated minimum power pool elevation.

Hydroelectric power operations are typically based on two objectives: (1) to assure firm energy in accordance with contractual agreements or other commitments and (2) to meet total system energy and power demands at minimum cost. The rule curve is designed to assure firm energy. Operation is based on meeting firm energy commitments continuously as long as the power pool contains water. Additional secondary energy is generated only if the reservoir storage content is above the rule curve. The seasonal variation of the rule curve over the year is tailored to the hydrologic and power demands of the particular area. For example, the rule curve shown in Figure 7 reflects the following considerations. Power storage must be a maximum during the middle of the calendar year in anticipation of high summer power demands coincident with low inflows. Droughts usually begin during the early summer in this area. A low pool elevation is acceptable in the fall and winter season because demands are lower and inflows higher.

The USACE Hydropower Engineer Manual (USACE, OCE 1985) outlines methods for developing power rule curves. The power rule curve is typically based on the historical hydrologic period-of-record streamflows. Droughts more severe than the critical drought of record can result in depleting the power pool and interrupting firm energy generation. Although power rule curves are discussed here from the perspective of a single reservoir, rule curves can also be developed for a multiple reservoir system on the basis of total system storage or potential energy.

Determining day-to-day and hour-to-hour releases when the storage is above the power rule curve represents a basic real-time decision problem. Only firm energy can be generated if the storage is at or below the rule curve. However, secondary energy can be generated with storage above the rule curve. A variety of approaches can be adopted for utilizing this water. Although, in some systems, detailed guidelines have been developed to guide secondary energy generation decisions, typically considerable flexibility exists for operator judgement on a day-to-day basis. If opportunities exist for displacing very expensive thermal generation, secondary hydroelectric energy can be very worthwhile. The optimization problem consists of timing secondary energy generation to minimize thermal generation costs or to maximize hydroelectric revenues. However, drawing the storage down to near the rule curve increases the risk of not meeting firm energy requirements if a future inflow sequence is more adverse than the critical period of historical inflows upon which rule curve development was based. Thus, a tradeoff also exists between minimizing thermal generation fuel costs or hydroelectric power revenues and maintaining a high reliability of firm energy commitments being met in the future. The impacts of secondary energy generation decisions on average annual energy also involves tradeoffs between maintaining a high head and minimizing the probability of spills. In multiple reservoir systems, the decision problem involves balancing storage and releases between reservoirs as well as timing of releases.

Developing, modifying, and refining reservoir operating policies often involves interactions between hydroelectric power and other project purposes. If the reservoir includes flood control, the top of power pool coincides with the bottom of the flood control pool. The top of power pool may be a seasonally varying rule curve defining a joint-use pool used sometimes for flood control and sometimes for power. Design of the rule curve must reflect both hydroelectric power and flood control objectives. Rule curves can also be established to optimize hydroelectric power operations subject to the constraint of maintaining highly reliable supplies for municipal, industrial, agricultural, and/or low flow augmentation purposes. Likewise, water supply release decisions may be based on optimizing hydroelectric power operations while meeting water supply demands. Hydropower operations may be constrained by minimum streamflow requirements for fish and wildlife or other instream flow needs. Minimizing the adverse impacts of storage level fluctuations on recreation may be an important consideration. The rate of change of release rates is often limited to reduce adverse impacts on streambank erosion.

System Performance Measures

Measures of system performance include firm energy, average annual energy, energy and power reliability, risk of shortages, shortage indices, total cost of meeting power and energy demands, savings in thermal power fuel costs, and hydroelectric power revenues.

Navigation Operations

Reservoirs provide slack pools for navigation and releases which supplement natural flows in maintaining minimum flow depths in downstream channels. Use of reservoir releases to maintain streamflows for navigation is limited due to the large quantities of water required. Slack water waterways, such as the Tennessee Valley System, provide required depths by maintaining reservoir storage levels and dredging. Open river waterways like the Missouri and Mississippi rely on channel constriction, dredging, and flow augmented by reservoirs to maintain the minimum depth for navigation. When available water is limited, navigation is concerned with depth, width, and channel alignment and length of navigation season at authorized depth. During floods, navigation is affected by flow velocities, cross currents, bridge clearances, docking and locking difficulties, and shoaling.

Reservoir operations for navigation involves optimizing the use of available water for maintaining storage levels to provide slack pools, releases to augment flows in downstream channels, and providing water for locking operations. Reservoir operations also involve minimizing the adverse impacts of floods on navigation. Quantitative measures of system performance include:

- maximizing the length of the navigation season
- maximizing the reliability of the dependable minimum depth
- minimizing fuel and other operating costs
- minimizing dredging costs
- minimizing the volume of water released from storage to meet minimum navigation requirements

Recreation Operations

Recreation aspects of reservoir operations involve maintaining lake levels and minimizing fluctuations in lake levels. Reservoir water surface area, depths, length of shoreline, area and quality of beaches, and usability of facilities such as marinas, docks, and boat ramps are related to lake level.

Water quality affects body contact activities such as swimming and water skiing. Temperature, fecal coliform count, dissolved oxygen, and turbidity are important water quality parameters for recreation. Water quality is also a consideration in maintaining a recreational fishery in the lake.

In streams below reservoirs, recreation is impacted by flow rates, variations in flow rates, and water quality. Both high flows and low flows can reduce the recreation potential. Reservoir releases can also cause safety hazards for downstream recreationists.

STATE-OF-THE-ART RESERVOIR SYSTEM ANALYSIS MODELS

Decision Support Activities

Numerous mathematical models have been developed for sizing reservoir storage capacities and establishing operating policies during project planning, for reevaluating the operating policies of existing projects, and for supporting release decisions during real-time operations. Reservoir system analysis models provide quantitative information to help support a typically complex decision-making process.

Reservoir system analysis models may be used for various purposes in a variety of settings. Models are used in planning studies to aid in the formulation and evaluation of alternative plans for responding to water related problems and needs. Feasibility studies may involve proposed reservoir construction projects and/or reallocations of storage capacity or other operational modifications at completed projects, along with other plans not involving reservoirs. Another modeling application involves studies made specifically to reevaluate operating policies for existing reservoir systems. Periodic reevaluations may be made routinely to assure system responsiveness to current conditions and objectives. However, more typically, reevaluation studies are made in response to a particular perceived problem or need. Development of drought contingency plans is another activity which is receiving increasing attention. Execution of models during actual reservoir operations in support of real-time release decisions represents another major area of application.

Computerized decision support systems have been increasingly emphasized during the past ten years, for use both in planning-type reevaluation studies and real-time operations. A decision support system consists of integrated computer hardware and software packages readily usable by managers as an aid for making implementation and operations decisions (Johnson 1986). The three main components of a computerized decision support system are: (1) a data acquisition, management, and processing subsystem, (2) models for analysis, prediction, and decision guidance, and (3) a dialog management interfacing for interactive man-machine coordination. Development of such systems has emphasized use of technological advancements in microprocessor-based data collection platforms, management of large data bases, personal computers, computer networks, user-friendly interfaces and software, and graphics capabilities.

Hydrologic Input Data

Various types of input data are required for reservoir system analysis models. Essentially all models require, for each reservoir, a relationship between elevation, storage volume, and water surface area. The storage versus area relationship is required for evaporation computations. The elevation versus storage relationship is required for determining head in hydropower computations. The elevation/storage/area data are developed for specified past, present or future conditions of reservoir sedimentation. Rule curves, storage targets, diversion requirements, instream flow targets and limits, and other data are required for defining reservoir operating rules. The mechanism for defining operating rules is a key model component which varies significantly between models. Depending on the purposes and capabilities of the model, hydroelectric power plant characteristics, streamflow routing parameters, water quality data, and economic evaluation data may be input. The brief comments below are limited to hydrologic data, which consists primarily of streamflows and reservoir evaporation rates.

Homogeneous streamflow data is required for essentially all reservoir system modeling and analysis approaches. Since future streamflows are unknown, planning studies must be based on historical data. Modeling studies typically use historical measured streamflow data, adjusted to represent flow conditions at pertinent locations for a specified condition of river basin development. The gaged streamflow data are typically nonhomogeneous due to reservoir construction and other activities of man in the river basin. The historical streamflow measurements must be adjusted to reflect conditions of river basin development at a specified past, present, or future point in time. These adjustments are typically performed on an ad hoc study-by-study basis rather than using specific well-established generalized computer software and data compilation procedures. The data must also be transposed from the location of the stream gages to other pertinent locations required by the study, using simple drainage area ratios or more complex approaches.

Gaged streamflow records also typically contain periods of missing data, or various pertinent gages have different periods-of-record. Missing data are typically reconstituted by a regression analysis based on flows during preceding months at the location and flows during the current and preceding periods at nearby locations. The HEC-4 Monthly Streamflow Simulation computer program (USACE, HEC 1971) is an example of a model which provides streamflow synthesis capabilities. The MOSS-IV Monthly Streamflow Simulation program is an improved version of HEC-4 (Beard 1973). HEC-4, or MOSS-IV, fills in missing monthly streamflow data based on streamflows at other nearby gage stations using a multiple linear regression algorithm with a random component.

Limited historical data may be extended by synthetic streamflow generation methods to provide the lengthy sequences required by certain types of reservoir system analysis exercises. For example, hundreds or thousands of years of monthly streamflows may be synthesized based on statistical parameters determined from a reasonably long period-of-record of several decades. Streamflow sequences of any specified length are synthesized based on preserving specified statistical parameters of the input data, in the sense that the parameter values for an infinitely long sequence of synthetically generated data would be the same as for the original input data. Markov models, such as HEC-4, MOSS-IV, and LAST (Lane and Frevert 1985), preserve the mean, standard deviation, and lag-1 autocorrelation coefficient. Loucks et al. (1981) include a concise overview of synthetic streamflow generation. Bras and Rodriquez-Iturbe (1985) provide an indepth theoretical treatment of stochastic hydrology. Goldman (1985) provides a presentation of synthetic streamflow generation from the perspective of practical application of HEC-4.

As an alternative to using gaged streamflow data, watershed (rainfall-runoff) models can be used to synthesize streamflow. The HEC-1 Flood Hydrograph Package is an example of an event-type rainfall-runoff model which is used to develop flood hydrographs associated within specified rainfall events. The HYDROCOMP Model and its predecessor the Stanford Watershed Model are examples of continuous watershed models which generate sequences of streamflows over a long period of time which may include many rainfall events and dry periods.

Streamflow characteristics are typically represented in a reservoir system analysis model as an inputed sequence of streamflows at each pertinent location for each time interval (hour, day, week, month) of the period-of-analysis. Inputed streamflow sequences could consist of either of the following:

- adjusted historical period-of-record streamflows,
- adjusted historical streamflows during a critical period or other selected subperiod of the period-of-record,
- synthetically generated streamflow sequences which preserve selected statistical characteristics of the adjusted historical data,
- flood hydrographs for a hypothetical storm event generated using a rainfall-runoff model, or
- long-term streamflow sequences generated using a continuous rainfall-runoff model

Alternatively, some reservoir system modeling and analysis approaches are based on representing the streamflow inflows as probability distributions or stochastic processes in various formats which capture the probabilistic characteristics of the adjusted historical data. For example, the reservoir inflows in an explicit stochastic model may be represented by a transition probability matrix which describes the discrete probability of a certain inflow conditioned on the previous period inflow. Other deterministic models require that streamflow inflows be simplified to one average or otherwise characteristic flow for each season or subperiod of a representative year.

Reservoir system analysis studies conducted by the federal water agencies, involving conservation operations, are typically based on adjusted historical period-of-record or critical period streamflows. Studies involving flood control operations typically include flood hydrographs computed using watershed (rainfall-runoff) models as well as adjusted historical period-of-record streamflows. The other approaches for developing streamflow input data cited above have all been used in various studies reported in the literature, most typically in university research projects.

Reservoir net evaporation rates are also key input data for modeling conservation operations. Net evaporation rates consist of gross evaporation rates adjusted for precipitation. Since net evaporation rates during drought years are typically significantly greater than during more normal or wet years, evaporation rate data should preferably be provided for each time interval of the analysis period. However, net evaporation rates are often provided for each month or time interval within the year but assumed to remain constant from year to year.

Reservoir evaporation is computed in a model by multiplying the average water surface area during a computational time interval by a net evaporation rate. Reservoir storage versus area relationships are provided as input data. Average water surface area for a computational time interval is dependent on both beginning-of-period and end-of-period storage. Since end-of-period storage is a variable being computed, evaporation computations require an iterative routine in simulation models. The nonlinear storage versus area relationship must be approximated in linear programming models.

Categorization of Reservoir System Analysis Models

Reservoir system modeling and analysis approaches can be characterized or classified in various ways. For example, models can be categorized by the measures of system performance computed, such as yield analysis models, economic analysis models, or other types of analyses. As discussed above, modeling approaches can be categorized by the method of handling the stochastic nature of streamflow inflows to the system. Models may have the capability to analyze multiple reservoir systems or be limited to a single reservoir. Models may be developed for a specific reservoir system or generalized for application to essentially any system. Models may be developed for mainframe computers and/or microcomputers and be coded for batch and/or interactive executive. A model may be either stand-alone or an integrated component of a complex computerized decision support system. Models may be developed for a specific project purpose, such as hydroelectric power or flood control, or may be developed for analyzing multiple purposes but have particularly extensive capabilities associated with a particular purpose. As noted below, the distinction between flood control and conservation purposes is particularly significant.

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 instream flows for fish & wildlife or water quality purposes. 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 dry seasons with durations of several months and during extreme droughts with durations of several years. Evaporation is important. Although conservation analyses are sometimes based on daily streamflow and evaporation data, monthly data are more typical for planning studies. Models developed by the USACE address both flood control and conservation purposes but tend to emphasize flood control. The TVA is equally concerned with both flood control and conservation operations. Modeling studies, other than USACE and TVA studies, in the United States have tended to be concerned primarily with conservation purposes, with flood control being a secondary consideration.

Systems analysis models are commonly categorized as being either descriptive or prescriptive. Descriptive models demonstrate what will happen if specified decisions are made. Prescriptive models determine what decisions should be made to achieve a specified objective. Simulation models are descriptive. Optimization techniques, such as linear programming, dynamic programming, and other nonlinear programming methods, are generally viewed as being prescriptive. However, a descriptive reservoir system simulation model may incorporate an optimization algorithm, such as linear programming, to perform key computations. Likewise, a simulation model may be embedded within a prescriptive optimization model. Thus, although models can be categorized as being either simulation (descriptive) or optimization (prescriptive), the alternative approaches are closely related and overlapping. The most effective strategy for analyzing certain reservoir operation problems may involve various combinations of optimization and simulation models.

Simulation models have been routinely applied for many years by the USACE and other water agencies and entities responsible for planning, design, and operation of reservoir projects. A number of well-documented, extensively-tested generalized reservoir system simulation computer programs are readily available for practical application. Optimization strategies often consist of numerous systematic trial-and-error runs of a simulation model with alternative decision policies.

The academic research community in particular, and many practitioners as well, have been extremely enthusiastic about optimization, in the sense of mathematical programming techniques, applied to reservoir operation problems. The characteristics of certain reservoir operation problems are ideally suited for applying linear and dynamic programming and various other nonlinear programming algorithms. Research results, case studies, and limited experience in application of optimization models in actual planning and real-time operation decisions appear to indicate a high potential for improving reservoir operations through their use. However, optimization techniques have played a relatively minor role compared to simulation models in regard to influencing decisions made in the planning and operation of actual projects.

Optimum sizing of storage capacities, establishing release policies, and real-time operations are complex tasks involving numerous hydrologic, economic, environmental, institutional, and political considerations. Defining system objectives, developing criteria for quantitatively measuring system performance in fulfilling the objectives, and handling interactions and conflicts between objectives are major areas of complexity. Mathematical programming techniques require that the real system be represented in the proper mathematical format. Representing complex project objectives and performance criteria in the required format, without unrealistic simplifications, is a particularly difficult aspect of the modeling process which limits the application of optimization techniques.

Developing relationships between storage capacity, yield, and reliability is an important aspect of reservoir system analysis. Such relationships are typically developed using conventional simulation models with inputed streamflow sequences. Mathematical programming techniques can also be used. Another simulation approach for analyzing storage/yield/reliability relationships involves the use of storage probability theory and related methods. Storage probability theory models are extensively addressed in the research literature but have not been widely adopted in actual practice. This type of analysis will also be briefly covered in the following discussion.

For purposes of this state-of-the-art review, reservoir system analysis models are categorized as indicated in Table 3. Table 3 provides an outline for the following discussion.

This report focuses on reservoir system analysis models which deal specifically and primarily with sizing storage capacities and determining optimal operating policies. However, it is noted that other categories of hydrologic and hydraulic simulation models, though not addressed by the present report, also play important roles in evaluating reservoir operations. These models include watershed (rainfall-rainfall), synthetic streamflow generation, frequency analysis, river hydraulics, outlet structure hydraulics, sediment transport, and water quality models.

Table 3
CLASSIFICATION OF RESERVOIR SYSTEM ANALYSIS MODELS

- Descriptive Simulation Models
  - conventional simulation models
  - simulation models which use network flow programming algorithms
  - stochastic storage theory models

- Prescriptive Optimization Models
  - linear programming
  - dynamic programming
  - nonlinear programming

- Various Other Combinations of Optimization and Simulation Models

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Simulation Models

A simulation model is a representation of a system used to predict the behavior of the system under a given set of conditions. Simulation is the process of experimenting with a simulation model to analyze the performance of the system under varying conditions. 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. A simulation model is based on a mass-balance accounting procedure for tracking the movement of water through a reservoir-stream system. 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. In models having capabilities for detailed simulation of flood control operations, 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 benefits for various project purposes. (Benefit evaluation requires functional relationships relating benefits to storage contents and/or releases.) Water quality simulation capabilities are included in some models.

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, and/or water quality parameter values. Various types of storage frequency or discharge frequency analyses may be performed. Simulation models may also provide the capability to analyze reservoir system operations using hydrologic and economic performance measures such as firm yield, yield versus reliability relationships, hydroelectric revenues, flood damages, and economic benefits associated with various purposes.

As indicated in Table 3, reservoir system simulation models are divided into three categories: (1) conventional simulation models, (2) simulation models which use network flow programming algorithms, and (3) stochastic storage theory models. The first two categories of simulation models involve similar input and output, but the internal computations are different. The second category involves incorporation of a particular type of mathematical programming algorithm into the model. The third category, which utilizes concepts from probability theory, represents a special area of modeling which is significantly different from the first two categories.

Conventional Reservoir System Simulation Models

For lack of better terminology, the term "conventional" is adopted here to distinguish the first category of simulation models from the other two. Conventional simulation models are based on a traditional mass balance accounting approach in which inputed sequential streamflow inflows are routed through the system control point by control point starting at upstream locations on the main river and each tributary.

Early 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 (Manzer and Barnett 1966). The objective was to maximize power generation subject to constraints imposed by specified requirements for navigation, flood control, and irrigation. The International Boundary and Water Commission simulated a two-reservoir system on the Rio Grande River in 1954. A simulation study for the Nile River Basin in Egypt in 1955 considered alternative plans with as many as 17 reservoirs or hydropower sites. The objective was to determine the particular combination of reservoirs and operating procedures which would maximize the volume of useful irrigation water (Manzer and Barnett 1966). Hufschmidt and Fiering (1966) discuss the pioneering simulation modeling work of the Harvard Water Program and application to multipurpose planning in the Lehigh River Basin.

State-of-the-Art Simulation Models

Development and application of a number of reservoir system simulation models has been reported in the literature. Several models considered to be representative of the state-of-the-art are listed in Table 4 and briefly described below.

HEC-5. The HEC-5 Simulation of Flood Control and Conservation Systems computer program is probably the most versatile of the available models in the sense of being applicable to a wide range of reservoir operation problems. It is also totally 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 as well as feasibility studies for proposed new projects. The program is also used for real-time operation. An initial version released

Table 4

"CONVENTIONAL" RESERVOIR SYSTEM SIMULATION MODELS

Simulation Model	Developer	Primary Purpose
Simulation of Flood Control and Conservation Systems (HEC-5)	USACE Hydrologic Engineering Center	Flood Control, Conservation, and Water Quality
Reservoir System Analysis for Conservation (HEC-3)	USACE Hydrologic Engineering Center	Conservation
Southwestern Division Reservoir System Simulation Model (SUPER)	USACE Southwestern Division	Flood Control and Conservation
Streamflow Synthesis and Reservoir Regulation (SSARR)	USACE North Pacific Division	Flood Control
NPD Hydropower Models (HYSSR, HLDPA, and HYSYS)	USACE North Pacific Division	Hydropower
Basin Runoff and Streamflow Simulation (BRASS)	USACE Savannah District	Flood Control
Colorado River Simulation System (CRSS)	Bureau of Reclamation	Conservation and Water Quality
Department of Water Resources Simulation Model (DWRSIM)	California Department of Water Resources	Conservation
Potomac River Interactive Simulation Model (PRISM)	John Hopkins University and Potomac River Basin Commission	Conservation
MIT Simulation Model (MITSIM)	Massachusetts Institute of Technology	Conservation
Single Reservoir Operation Simulation (RESQ)	Private Consulting Engineer	Conservation
Interactive River System Simulation Model (IRIS)	Cornell University and International Institute for Applied Systems Analysis	Conservation
Reservoir Operating and Quality Routing Program (RESOP-II)	Texas Water Development Board	Conservation and Water Quality

in 1973 has subsequently been significantly expanded. Microcomputer versions of the model have been recently released. Several utility programs are available 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 users manual (USACE, HEC 1982, 1986 & 1989) provides detailed instructions for using the generalize computer program. Feldman (1981) describes HEC-5 as well as the 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 and include training documents covering various features of the model and reports and papers documenting specific applications of the model in actual reservoir system analysis studies.

HEC-3. 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 users manual (USACE, HEC 1981) and other publications available from the Hydrologic Engineering Center. Various USACE offices and other federal and nonfederal entities have modified HEC-3 for different applications involving operation of conservation storage systems.

SUPER. 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 SUPER 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 SUPER model. The division and district offices in the Southwestern Division have applied the model in a number of studies. The Reservoir Modeling Center in the Tulsa District office has been using the SUPER model to simulate the various major USACE reservoir systems located throughout the Southwestern Division.

SSARR. The Streamflow Synthesis and Reservoir Regulation (SSARR) model was developed by the USACE, North Pacific Division (NPD) primarily for streamflow and flood forecasting and reservoir design and operation studies. Various versions of the model date back to 1956. A program description and user manual (USACE, NPD 1975) documents the present version of the computer program. Numerous reservoir systems, including the Columbia River Basin in the United States and Mekong River Basin in Southeast Asia, have been modeled with the generalized computer program by various agencies, universities, and other organizations. The SSARR computer program simulates the hydrology of a river system. The model is comprised of three basic components: (1) a watershed model for synthesizing runoff from rainfall and snowmelt, (2) a streamflow routing model, and (3) a reservoir regulation model for analyzing reservoir storage and outflow.

NPD Hydropower Models. The Hydro System Seasonal Regulation (HYSSR), Hourly Load Distribution and Pondage Analysis Program (HLDPA), and Hydropower System Regulation Analysis (HYSYS) models were also developed by the USACE, NPD.

User's manuals are available from NPD. The models are also described in the USACE Hydropower Engineer Manual (USACE, OCE 1985). HYSSR is a monthly sequential routing model designed to analyze the operation of a large reservoir system for hydroelectric power and snowmelt flood control. It has been used to analyze proposed new reservoirs and operations of existing systems in the Columbia River Basin and a number of other river basins. HLDPA is a hourly time-interval planning tool designed to address such problems as optimum installed capacity, adequacy of pondage for peaking operation, and impact of hourly operation on non-power river uses. HYSYS is a generalized model designed to support real-time operations.

BRASS. The Basin Runoff and Streamflow Simulation (BRASS) model was developed by the USACE Savannah District to provide flood management decision support for operation of a reservoir system in the Savannah River Basin. The model is described by McMahon, Fitzgerald, and McCarthy (1984) and Colon and McMahon (1987). Model documentation also includes a user's manual available from the Advent Group, Brentwood, TN. Documentation is not available from the Savannah District. BRASS is an interactive hydrologic/hydraulic simulation model which includes rainfall-runoff modeling, storage routing through gated reservoirs, and dynamic streamflow routing capabilities. BRASS incorporates the NWS DWOPER program for streamflow routing. The National Weather Service (NWS) Operational Dynamic Wave Model (DWOPER) computes discharges and water surface elevations based upon a numerical solution of the St. Venant equations.

CRSS. The Colorado River Simulation System (CRSS), originally developed by the USBR during the 1970's and subsequently revised and updated, simulates operations of the major reservoirs in the Colorado River Basin for water supply, low flow augmentation, hydroelectric power, and flood control (Schuster 1987). The CRSS is a set of computer programs, data files, and data bases used in long range planning. The monthly time-interval historical hydrologic period-of-record model reflects operation of the system in accordance with a series of river basin compacts, laws, and agreements collectively called the "law of the river." In addition to simulating the water quantity aspects of reservoir operations, salt concentrations are also computed.

DWRSIM. The California Department of Water Resources developed the DWRSIM model to simulate operation of the Central Valley Project and State Water Project storage and conveyance systems (Barnes and Chung 1986). DWRSIM is a monthly time-interval planning model for analyzing system operations for water supply, recreation, instream flow augmentation, and hydroelectric power. DWRSIM was developed by modifying HEC-3 to provide expanded capabilities needed for the particular reservoir/conveyance systems of concern. As discussed in the next section, a new version of DWRSIM was recently developed which utilizes a network flow programming algorithm.

PRISM. The Potomac River Interactive Simulation Model (PRISM) was originally developed by a research team at John Hopkins University (Palmer, Wright, Smith, Cohon, 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 a 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 formulation 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.

MITSIM. Strzepek and Lenton (1978) describe the Massachusetts Institute of Technology (MIT) River Basin Simulation Model and its application to the Vardar/Axios Basin in Yugoslavia and Greece. A users manual is provided by Strzepek et al. (1979). The generalized computer program provides the capability to evaluate the hydrologic and economic performance of a river basin development system. Existing and proposed reservoirs, hydroelectric power plants, thermal power stations, irrigation areas, and diversions and withdrawals for municipal, industrial, and other uses are represented in the model as a system of arcs and nodes. The model computes the monthly flows at all nodes in the basin, given the streamflows at the start nodes. System reliability in meeting water demands is assessed. Irrigation, hydroelectric power, and municipal and industrial water supply benefits are computed and compared with project costs. Benefits are divided into long-term benefits and short-term losses.

RESQ. The RESQ model is a interactive menu-driven microcomputer single-reservoir simulation model (Ford 1990). RESQ performs the same basic computations as HEC-3 but is limited to a system consisting of a single reservoir and one downstream control point. RESQ provides expanded capabilities in the areas of user interface and output analysis.

IRIS. The Interactive River System Simulation Program (IRIS) was developed with support from the Ford Foundation, United Nations Environment Program, International Institute for Applied Systems Analysis, and Cornell University (Loucks et al. 1989 and 1990). IRIS simulates a water supply storage and conveyance system of essentially any normal configuration. Limited hydroelectric power simulation features are also included in the model. The program operates in a menu-driven microcomputer or workstation environment with extensive use of computer graphics for information transfer between machine and user.

Model Comparison

As indicated by Table 4, the conventional reservoir system simulation models can be categorized by the reservoir purposes that the model was primarily designed to analyze. HEC-5, SUPER, SSARR, and BRASS have capabilities for detailed simulation of flood control operations. Although numerous differences exist in the details of these models, simulation of flood control operations with any of the models involves the same basic types of computational algorithms, input data requirements, and output. SSARR and BRASS have watershed (precipitation-runoff) modeling capabilities whereas HEC-5 and SUPER do not. However, other precipitation-runoff models are readily available to develop flood inflow hydrograph input for HEC-5 and SUPER, whenever adjusted (unregulated) gaged streamflow data is not being used. The dynamic streamflow routing capability of BRASS is not included in HEC-5, SUPER, and SSARR which use hydrologic streamflow routing methods such as modified Puls and Muskingum. HEC-5 and SUPER provide economic evaluation capabilities for computing average annual flood damages.

The HYSSR, HLDPA, and HYSYS models were developed specifically for simulating hydroelectric power operations. HEC-3, HEC-5, SUPER, CRSS, DWRSIM, MITSIM, and IRIS also have hydropower capacities. Although the basic power and energy computations are the same, a variety of differences exist in the capabilities of the alternative models. For example, the computational time interval varies. HEC-3, HYSSR, CRSS, DWRSIM, MITSIM, and IRIS are monthly time interval models. SUPER is a daily model. HEC-5 has a variable computational time interval. HYDPA has special capabilities and uses a hour time interval. The degree of flexibility in handling various hydroelectric system configurations and operating rules varies significantly between the models.

HEC-5, HEC-3, SUPER, CRSS, DWRSIM, PRISM, MITSIM, RESQ, IRIS, and RESOP-II all have conservation storage simulation capabilities for water supply diversions and instream flow requirements. Several of the models have optional capabilities for developing yield versus reliability relationships and/or computing firm yield.

HEC-5, CRSS, and RESOP-II have water quality modeling capabilities. The water quality version of HEC-5 includes a module which computes the vertical distribution of temperature and other constituents in the reservoirs and water quality in the downstream reaches. This version of HEC-5 provides a water quality evaluation associated with a specified operation of the reservoir system or the water quality associated with the "best" system operation for water quantity. The gate operation for these flows will be optimized using a non-linear algorithm on a water quality index objective function. An additional option for HEC-5 includes the capability to modify the flows decided by the previous operation using a linear optimization algorithm to improve the water quality condition at the control points. Temperature and selected conservative and non-conservative constituents, including dissolved oxygen, can be simulated. CRSS performs salt mass balances, with inputed salt loads, to compute monthly salt concentrations at pertinent locations. RESOP-II, discussed in the next section, has the capability of routing conservative constituents through a single reservoir.

Simulation Models Which Use Network Flow Programming Algorithms

The reservoir system simulation models cited above are conventional simulation models in the sense that no formal mathematical programming methods are used. Linear programming, dynamic programming, and other nonlinear programming methods are covered later in this report. However, the distinction between simulation and optimization (mathematical programming) is somewhat obscured by models which combine the two approaches. The present discussion focuses on a specific approach in which a network flow programming algorithm is incorporated in a simulation model. A more general discussion of strategies for combining optimization and simulation models is found later in this report.

Simulation models which use network flow programming algorithms are still descriptive simulation models in the sense that the reservoir is simulated for a user specified set of operating rules. Multiple runs of the model with alternative user-specified operating policies are required to compare system performance. However, a linear programming algorithm computes the releases, and resulting storage changes, required to satisfy the user-specified operating policy.

Network Flow Programming

Jensen and Barnes (1980) and Kennington and Helgason (1980) provide a thorough coverage of network flow programming. Network flow programming techniques can be applied to any problem which can be formulated in the required format, which involves representing the system as a network of nodes and arcs having certain characteristics. There are various recognized standard forms or classes of network flow problems and corresponding solution algorithms. Mathematical programming algorithms are available for solving problems which have been formulated in the specified network format. Network flow models have broad applicability in operations research and management science. Water resources engineers have found that water storage and distribution systems also can be represented in the required network format for solution with available mathematical programming algorithms. Most reservoir systems analysis applications of network flow models are formulated in a particular format, referred to as a minimum cost network flow problem, which can be solved using the out-of-kilter algorithm. The out-of-kilter algorithm is a special form of linear programming which is applicable to this particular problem formulation.

In formulating a network flow model to be solved by the out-of-kilter linear programming algorithm, the system is represented as a collection of nodes and arcs. For a reservoir/stream system, the nodes represent reservoirs, diversion and/or return flow locations, tributary stream confluences, and other pertinent system features. The nodes are connected by arcs representing the way "flow" can be conveyed. For a reservoir/stream system, flow represents either a discharge rate or change in reservoir storage per unit of time.

For the network flow programming models cited below, the general form of the linear programming problem, for a given computational time period, is as follows.

$$\text{minimize} \quad \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}\, q_{ij}$$

$$\text{subject to} \quad \sum_{i=1}^{n} q_{ij} - \sum_{i=1}^{n} q_{ji} = 0 \qquad \text{for } j = 1,2,\ldots,n$$

$$\text{and} \quad l_{ij} \le q_{ij} \le u_{ij} \qquad \text{for } i = 1,2,\ldots,n$$

where
q_{ij} = integer value flow rate in the arc connecting node i to node j
c_{ij} = penalty or weighting factor for flow q_{ij}
l_{ij} = lower bound on q_{ij}
u_{ij} = upper bound on q_i
n = number of arcs

Thus, the network flow programming algorithm computes the values of the flows (q_{ij}) in each of n arcs (node i to node j) which minimizes an objective function consisting of the sum of the flows multiplied by corresponding weighting factors, subject to constraints which include maintaining a mass balance at each node and not violating user-specified upper and lower bounds on the flows. Each arc has three parameters: (1) a weighting, penalty, or unit cost factor (c_{ij}) associated with q_{ij}, (2) lower bound (l_{ij}) on q_{ij}, and (3) upper bound (u_{ij}) on q_{ij}. The requirement for lower and upper bounds results in the term "capacitated" flow networks. The weighting factor (c_{ij}) could be a unit cost in dollars but is more typically a penalty or utility term which is a devised mechanism for expressing relative priorities for use in defining operating rules. A penalty weighting factor is the same as a negative utility weighting factor. Reservoir operating rules are defined by user specified values of c_{ij}, l_{ij}, and u_{ij}. The user of the model provides lower and upper bounds on diversions, instream flows, and reservoir storage levels and assigns relative priorities for meeting each diversion and instream flow requirement and for maintaining target reservoir storage levels. The out-of-kilter algorithm computes the releases and storage changes (q_{ij}), in each time interval of the overall simulation period, required to satisfy the user-specified operating rules.

Reservoir System Analysis Models

A number of simulation models which incorporate network flow programming have been reported in the literature. Several such models considered to be representative of the state-of-the-art are listed in Table 5 and briefly described below.

TWDB Models. The Texas Water Development Board (TWDB) began development of a series of surface water simulation models in the late 1960's in conjunction with formulation of the Texas Water Plan (TWDB 1974). RESOP-II, SIMYLD-II, AL-V, SIM-V and a number of other models been developed and modified through various versions. SIMYLD-II, AL-V, and SIM-V incorporate a capacitated network flow formulation solved with the out-of-kilter linear programming algorithm. RESOP-II is also included in the present discussion because it can be used in combination with SIMYLD-II.

The Reservoir Operating and Quality Routing Program (RESOP-II) is a conventional simulation model designed for performing a detailed analysis of the firm yield of a single reservoir. A quality routing option adds the capability to route up to three nondegradable constituents through a reservoir and to print a frequency distribution table and a concentration duration plot for the calculated end-of-month quality of the reservoir (Browder 1978).

SIMYLD-II provides the capability for analyzing water storage and transfer within a multireservoir or multibasin system (TWDB 1972). The model simulates storage and transfer of water within a system of reservoirs, rivers, and conduits on a monthly basis with the object of meeting a set of specified demands in a given order of priority. If a shortage occurs such that not all demands can be met for a particular time period, the shortage is located at the lowest priority demand node. SIMYLD-II also provides the capability to determine the firm yield of a single reservoir within a multireservoir water resources system. An iterative procedure is used to adjust the demands at each reservoir of a multi-reservoir system in order to converge on its maximum firm yield at a given storage capacity assuming total system operation. While SIMYLD-II is capable of analyzing multi-reservoir systems, it is not capable of analyzing a single reservoir as accurately as RESOP-

Table 5

RESERVOIR SYSTEM SIMULATION MODELS WHICH USE NETWORK FLOW PROGRAMMING ALGORITHMS

Simulation Model	Developer	Primary Purpose
River Basin Simulation Model (SIMYLD-II)	Texas Water Development Board	Water supply
Surface Water Resources Allocation Model (AL-V)	Texas Water Development Board	Conservation
Multireservoir Simulation and Optimization Model (SIM-V)	Texas Water Development Board	Conservation
Trent River Basin Model	Acres Consulting Services, Ltd.	Flood control and Conservation
MODSIM2	Colorado State University	Hydropower and water supply
MODSIM3	Colorado State University	Water supply
Central Resource Allocation Model (CRAM)	City of Boulder	Water supply
Water Assignment Simulation Package (WASP)	City of Melbourne	Water supply
Department of Water Resources Simulation Model (DWRSIM)	California Department of Water Resources	Conservation

II. Consequently, SIMYLD-II and RESOP-II are both used in an interactive manner to analyze complex systems.

The Surface Water Resources Allocation Model (AL-V) and Multireservoir Simulation and Optimization Model (SIM-V) simulate and optimize the operation of an interconnected system of reservoirs, hydroelectric power plants, pump canals, pipelines, and river reaches (Martin 1981, 1982, 1983). SIM-V is used to analyze short-term reservoir operations. AL-V is for long-term operations. A system is represented as a network flow problem solved using the out-of-kilter linear programming algorithm. Hydroelectric benefits, which are complicated by nonlinearity, are incorporated by solving successive minimum-cost network flow problems, where flow bounds and unit costs are modified between successive iterations to reflect first-order changes in hydroelectric power generation with flow release rates and reservoir storage.

Acres Model. Sigvaldason (1976) describes a simulation model developed by Acres Consulting Services 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. The model was originally developed for planning but has also been used for real-time operation. In the model, each reservoir was subdivided into five storage zones. Time based rule curves were prescribed to represent ideal reservoir operation. The combined rule curve and storage zone representation is similar to HEC-5. Ranges were prescribed for channel flows, which were dependent on water-based needs. Penalty coefficients were assigned to those variables which represented deviations from ideal conditions. Different operational policies were simulated by altering relative values of these coefficients. The development and use of the model were simplified by representing the entire reservoir system in capacitated network form and deriving optimum-solutions for individual time periods with the out-of-kilter algorithm. This optimization submodel for achieving optimal responses during individual time intervals is similar to the approach used in the Texas Water Development Board models except for differences in the objective functions.

Bridgeman et al. (1988) describes recent applications of a new version network flow model designed to forecast inflows, simulate operations, and postprocess results. Acres International Limited has applied the model to the complex multiple-reservoir Trent River Basin system in both a planning mode and real-time operations mode.

MODSIM. MODSIM was developed at Colorado State University based on modifying and updating the Texas Water Development Board SIMYLD-II model. Various versions of MODSIM are described by Shafer (1979), Labadie and Shafer (1979), Labadie (1983), and Labadie, Pineda, and Bode (1984). The first version of MODSIM was essentially a water supply model. Version 2 is primarily for hydroelectric power studies. The third version, MODSIM3, is a water supply model which provides significant improvements over version 1 in regard to water right considerations, reservoir operating rules, computer core memory requirements, and model output design. The models have been applied in a number of studies, including a MODSIM2 application reported by Faux, Labadie, and Lazaro (1985) and a MODSIM3 application recently reported by Frick, Bode, and Salas (1990). The model operates in an interactive menu-driven microcomputer environment.

For a user-specified operating policy, for each computational time interval during the total simulation period, MODSIM3 computes: diversions and diversion shortages;

streamflows; return flows; water exchanges between basins; and reservoir releases, evaporation, and storage contents. The computational time interval is typically a month but could be a week. Operating policies are defined by a scheme in which user-specified priorities are assigned to target diversions, streamflows, and reservoir storage levels. The system is represented as a capacitated network problem which is solved by the out-of-kilter algorithm.

MODSIM2 is based on the same network flow modeling concepts as MODSIM3. MODSIM3 has expanded water supply modeling capabilities not included in MODSIM2. However, MODSIM2 allows the operating rules to include specification of a hydroelectric power generation requirements. MODSIM2 is designed to analyze the amount of energy that can be generated while allocating water supply demands according to user specified priorities.

CRAM. Brendecke, DeOreo, Payton, and Rozakis (1989) describe the Central Resource Allocation Model (CRAM) developed by WBLA, Inc. for use in preparing a water supply master plan for the city of Boulder, Colorado. The model was used to compute yields which could be achieved with various system operation plans. CRAM also uses the out-of-kilter algorithm solution of a capacitated network formulation. Development of CRAM was built upon MODSIM and added various improvements pertinent to the particular application.

WASP. The Water Assignment Simulation Package (WASP) is described by Kuczera and Diment (1988). WASP was developed to analyze the water supply system of the city of Melbourne, Australia, which includes nine reservoirs and a complex conveyance and distribution system, but is generalized for application to other water supply systems as well. The interactive menu-driven software package is supported by extensive diagnostics and graphics. WASP allocates water according to the following criteria in order of decreasing priority: (1) satisfy all demands, (2) satisfy instream requirements, (3) minimize spills from reservoirs and gravity diversions, (4) ensure that water assignments are consistent with user-defined operating rules, and (5) minimize operating cost. The network programming solution is based on minimizing a weighted penalty function, with a hierarchy of penalties based on the above priorities.

DWRSIM. The DWRSIM model (Barnes and Chung 1986) is discussed earlier in this report. DWRSIM was developed by the California Department of Water Resources to simulate the combined operation of the California State Water Project and the Federal Central Valley Project. The previously discussed original model is strictly a conventional mass-balance type simulation model with no mathematical programming algorithm. Chung, Archer, and DeVries (1989) describe the recent revision of DWRSIM to incorporate the out-of-kilter network flow programming algorithm. The versions of DWRSIM with and without the network flow programming algorithm are used for the same types of analyses. The input and output data formats are essentially the same.

Model Comparison

The network flow models cited above do not include capabilities for a detailed analysis of flood control operations. Therefore, the present discussion addresses a comparison of (1) the general approach incorporated in HEC-3, the conservation options of HEC-5, the original DWRSIM, and other similar models and (2) the general approach reflected in the network flow models. In general, the two alternative approaches serve the same purposes and are quite similar from a model user perspective. The "pure" simulation approach might be a little easier to understand. The main advantage of network models appears to be an increase in flexibility in representing system operations in certain circumstances. The network modeling approach can also result in a significant savings in computer execution time.

As discussed below, reservoir operating rules are defined somewhat differently in the two approaches, in regard to assigning water demand deficits or shortages and also in specifying multiple-reservoir release criteria. Also, closed loops can be easily included in a network flow model but are more difficult, requiring development of special algorithms, to include in a conventional simulation model. Closed loop type system configurations might involve diverting water from a downstream location to be returned at an upstream location on the same stream or conveying water by pipeline or canal from one tributary to another.

In either modeling approach, the user specifies diversion and instream flow requirements at pertinent locations in the system. However, the computations in the two approaches assign shortages differently, in those time intervals in which not enough water is available to meet all diversion and instream flow requirements. In the conventional HEC-3 type model, computations start at the most upstream control point on the main stream or a tributary and proceed downstream. Thus, a diversion at a upstream control point automatically has first access to available water, with flow remaining after the diversion contributing to water available at the next downstream control point. With network flow models, the user specifies the relative priorities between users. Thus, a downstream water user can be given priority over a upstream user.

Multiple-reservoir release criteria are also formulated differently. With either approach, the user specifies which reservoirs should be considered in making releases for downstream diversion and instream flow requirements. In the HEC-3/HEC-5 type models, the releases are based on balancing the percent depletion of user specified zones in the conservation pools of each of the reservoirs. In network flow models, the user specifies relative priorities for maintaining target storage levels in the reservoirs.

Beard, Weiss, and Austin (1972) compared HEC-3 and SIMYLD by analyzing a case study water resources storage and conveyance system alternatively using both models. They concluded that both models appeared to simulate the operation of a complex water resource system as accurately as pertinent functions and features of the system can be described. Both models yielded similar results. SIMYLD had the flexibility not available in HEC-3 of simulating a closed loop. The computational speed of SIMYLD was found to be about twice as fast as HEC-3.

Chung, Archer, and DeVries (1989) state that the out-of-kilter network flow model was incorporated into DWRSIM to enhance capabilities for analyzing consequences of different operational scenarios. The most significant capabilities introduced by addition of the out-of-kilter algorithm are stated to be:

- The capability to provide a better balance among the reservoirs in the system.
- The capability to give different relative priorities to the different demand points.
- The capability to give different relative priorities to the different components that make up a demand point.
- The capability to allocate storage within a reservoir to specific demands.

Stochastic Storage Theory Models

Stochastic storage theory and related models have been addressed extensively in the research literature but applied very little by the agencies that actually construct and operate reservoir systems. This large group of analysis methods is based primarily upon the theory presented by Moran (1959) and expanded by Gould (1961). Klemes (1981) and McMahon and Mein (1986) provide in depth overviews and cite many significant references.

The objective of stochastic storage theory models is to determine the probability distribution of reservoir storage. For a specified water supply release policy and present storage level, the probabilities of the reservoir being at various storage levels at future times are computed. Storage probabilities may be computed at steady state or as a time dependent function of the starting conditions. Thus, for a given release policy and initial storage content, the probabilities of the reservoir being at various storage levels at future times during the next several months or several years may be estimated. As the analysis period becomes longer, a steady state condition is reached in which the storage probabilities at a future time are no longer dependent upon the starting storage contents.

A nonsteady state analysis could be useful in developing and implementing reservoir operating plans in which allocations of water to alternative users are made at the beginning of each water year, each irrigation season, or other time period of interest, based upon the likelihood of water being available to meet the allocations during the time period. The likelihood of meeting the allocations would be based upon the reservoir storage levels existing at the time the allocations are made. Under this type of operating plan, during drought conditions, as significant reservoir drawdowns occur, the allotment of water to the various users for the upcoming irrigation season or other specified time period would be reduced accordingly. Storage probability theory models could provide useful information regarding the probabilities of the reservoir being emptied by the end of the time period given the known present storage level and assuming different alternative withdrawal rates.

Steady state probabilities are not dependent upon initial storage levels. In this case, storage probability theory models represent an alternative to regular simulation models, using period-of-record or synthetically generated streamflow sequences, for developing yield versus reliability relationships.

In terms of practical usefulness, the most important storage probability theory models are described as probability matrix methods (McMahon and Mein 1986). Other methods are of theoretical interest. The mathematics of stochastic storage analysis is complex, necessitating significant assumptions and simplifications. Many of the more sophisticated techniques are severely limited from a practical applications perspective. Klemes (1982) has observed: "This theory has evolved into a highly esoteric branch of pure mathematics which, apart from some elements of the jargon, has very little relevance to the original physical problem. It often solves the wrong problems simply because they are mathematically tractable...and that, from the physical point of view, are trivial or irrelevant."

The stochastic storage theory models assess system performance based on describing inflows by a probability distribution or stochastic process. The methods are typically applied to a single reservoir, but multiple reservoir analysis procedures have also been developed. Modeling is performed in two stages. First, a probability distribution function, if the inflows are assumed independent, or stochastic process, such as a Markov chain, is fitted to the historical streamflow record. Then, simulation or probability techniques are used to develop the storage versus yield function and corresponding reliability estimators. Discrete probabilities are typically used to approximate the continuous distributions of the inflow process. The assumption of first order Markovian processes for representing the inflow process of a reservoir has generally been considered in the literature as adequate for most purposes. The development of models incorporating other approaches result in extremely complex transition probability matrices.

Moran (1959) presents various procedures for determining storage probabilities. Numerous other authors have presented solutions or extensions to the basic models formulated by Moran. McMahon and Mein (1986) outline the basic computational procedures and cite many of the key references. A group of Moran procedures are based on considering either time or both time and volume as continuous variables. Solutions are complex. Another group of procedures treat time and volume as discrete variables, and application is more practical. A reservoir is subdivided into a number of zones and a system of equations developed which approximate the possible states of the reservoir storage. Two main assumptions can be made regarding the inflows and outflows, which occur at discrete time intervals. In a mutually exclusive model, there is a wet period, with all inflows and no outflows, followed by a dry season, with all releases but no inflows. In the more general simultaneous model, inflows and outflows can occur simultaneously. The simultaneous approach is the most practical of the Moran models, but has a number of limitations. Inflows are assumed to be independent, which is not valid for a monthly time period. A constant release rate is typically assumed. A varying release rate can be accommodated if it is storage, not time, dependent. Thus, seasonality of inflows and releases is not considered. Estimates of the probability of the state of the reservoir can be computed either at steady state or as a time dependent function of starting conditions.

Gould (1961) modified the simultaneous Moran-type model to account for both seasonality and auto-correlation of monthly inflows by using a transition matrix with a yearly time period, but accounting for within-year flows by using a monthly behavior analysis. Thus, monthly auto-correlation and seasonal release variations can be included. The Gould method, like other probability matrix methods, computes the probability of reservoir storage levels for a given storage capacity and release rate. Storage probabilities can be computed either at steady state or as a time dependent function of the starting conditions.

Much of the work published in the literature represents modifications or extensions to the basic Moran and Gould models cited above.

Optimization Models

During World War II, the Allies organized interdisciplinary teams to solve complex scheduling and allocation problems involved in military operations. Mathematical 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 mathematical programming techniques are treated in depth by numerous mathematics, operations 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 25 years. The textbook by Loucks, Stedinger, and Haith (1981) explains the fundamentals of applying optimization techniques in the analysis of water resources systems. Yeh (1985) reviews the state-of-the-art of optimization models applied to operation of reservoir systems.

There is no generalized model for optimizing reservoir operations. 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.

The term "mathematical programming" refers to a specific type of mathematical problem in which variable values are computed such that an objective function is minimized or maximized subject to constraints. The broader term "optimization model" refers to tools for determining optimal decision policies in general, which could include mathematical programming, various simulation modeling strategies, and/or human judgement. However, in the present discussion, the term "optimization" is used in the sense of mathematical programming.

Optimization (mathematical programming) 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. The 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 and/or end-of-period storage volumes. The objective function to be maximized or minimized could be a quantitative measure of an objective such as those cited in Table 2 or a penalty or utility function such as the previously discussed network flow programming approach of defining operating rules based on relative priorities. Constraints typically include physical characteristics of the reservoir-stream system, minimum diversion or low flow requirements for various purposes, and mass balances.

Most of the applications of optimization techniques in reservoir system analysis involve various variations and extensions of linear programming and/or dynamic programming. Various other nonlinear programming methods, particularly search algorithms, have also been used.

Linear Programming (LP)

Of the many mathematical programming techniques, linear programming (LP) is the simplest and most widely used in many fields. Its popularity in water resources systems analysis, as well as in other operations research, management science, and systems engineering disciplines, is due largely to the following factors.

- The method is applicable to a wide variety of types of problems.
- Efficient solution algorithms are available.
- Generalized computer software packages are readily available for applying the solution algorithms.

Considerable ingenuity and significant approximations may be required to formulate a real-world problem in the required mathematical format. However, if the problem can be properly formulated, solving for the optimum values for the decision variables is straightforward. The simplex algorithm, used in most linear programming computer codes, is explained in detail in a number of textbooks, including Wagner (1975). Computationally efficient special algorithms are available for certain forms of LP problems, such as the previously cited out-of-kilter algorithm for solving minimum cost network flow problems. In some cases, nonlinear features of a problem may approximated by linearization techniques for incorporation into a LP model. Successive iterative solutions of a LP problem are sometimes used to handle nonlinearities.

Linear programming consists of minimizing or maximizing a linear objective function subject to a set of linear constraints, expressed as follows.

$$\text{maximize (or minimize)} \qquad Z = \sum_{j=1}^{n} c_j\, x_j$$

$$\text{subject to} \qquad \sum_{j=1}^{n} a_{ij} x_j \leq b_i \qquad \text{for } i = 1,2,\ldots,m$$

$$\text{and} \qquad x_j \geq 0 \qquad \text{for } j = 1,2,\ldots,n$$

where Z is the objective function, x_j are the decision variables, c_j, a_{ij}, and b_i are constants, n is the number of decision variables, and m is the number of constraints. The "less than or equal" sign in the constraint inequalities may be replaced by "greater than or equal" or "equal" signs to suit the particular problem being modeled.

Illustrative Problem Formulation Example

An example problem is used to introduce the concept of formulating a problem in the LP format. Consider the problem of developing a firm yield versus storage capacity relationship for a proposed single reservoir. Firm yield is the maximum constant release rate that can be maintained continuously assuming repetition of historical period-of-record monthly streamflows. The firm yield (Y) can be computed for a given storage capacity (C) with the following LP formulation, which ignores evaporation.

$$\text{maximize} \qquad Y$$

$$\text{subject to} \qquad s_{t+1} = s_t + i_t - Y - r_t \qquad \text{for } t = 1,2,\ldots,n$$

$$\text{and} \qquad s_t \leq C \qquad \text{for } t = 1,2,\ldots,n$$

and $s_t, Y, r_t \geq 0$ for t = 1,2,...,n

where:

Y = firm yield or constant continuous release rate

t = month

n = number of months in the period-of-analysis (historical hydrologic period-of-record)

s_t = storage content at the end of month t

i_t = streamflow inflow to the reservoir during month t

r_t = all spills and releases other than Y during month t

C = reservoir storage capacity

Thus, the constant release rate (Y) is maximized subject to constraints which include: the reservoir mass balance; not allowing storage content (s_t) to exceed storage capacity (C); and not allowing the variables to have negative values. The constraints are repeated for each month (t) of the period-of-analysis. The known reservoir storage capacity (C) and monthly reservoir inflows (i_t) are provided as input data. The model computes the value of the firm yield (Y) and also values of end-of-period storage (s_t) and other releases (r_t) for each month t. For example, for a 20-year period-of-analysis consisting of a sequence of 240 monthly inflows, the problem would have 481 decision variables (s_t and r_t for 240 months and Y), 240 mass balance constraints, and 240 capacity constraints. Generalized computer programs, using the standard simplex algorithm, are readily available to solve the LP problem.

With the above formulation, the firm yield (Y) is computed for a user specified reservoir storage capacity (C). An alternative formulation of almost the same problem consists of changing the objective function to:

minimize C

subject to the same constraints as before. With this formulation, a fixed firm yield (Y) is provided as input, and the model computes the required storage capacity (C), along with values of s_t and r_t for each month.

The above formulations are unrealistic because evaporation in not included is the reservoir mass balance. Reservoir evaporation is computed as a net evaporation rate multiplied by the mean water surface area during the month. Water surface area is a nonlinear function of storage. Thus, the area versus storage function must be approximated as a piece-wise linear function for incorporation into the linear programming formulation. Loucks et al. (1981) outlines linearization methods for handling evaporation and other nonlinearities. Hydroelectric power is a function of both head and discharge and represents another typical nonlinearity which complicates but can be addressed using LP models.

LP Formulations

A real-world problem is represented as a linear programming problem by formulating the objective function and constraints to fit the situation. For reservoir operation problems, the decision variables are typically releases and end-of-period storages for each time period (hour, day, week, or month) of the period-of-analysis. The objective function may represent a storage volume or release rate (as in the above illustrative example), net economic benefits, economic costs, hydroelectric power revenue, summation of deviations from discharge or storage targets, a penalty or weighting function, or other expressions, depending on the problem formulation. Constraints may include numerous problem-specific considerations as well as the reservoir mass balance and capacity constraints illustrated by the above simplified example. A variety of methodologies have been developed to represent various characteristics of reservoir operations problems in LP formulations.

A large number of papers in the research literature have focused on chance-constrained formulations and related linear decision rules. ReVelle, Joeres, and Kirby (1969) published one of the key early papers on these methods. Other authors, such as Loucks and Dorfman (1975) and Houck, Cohon, and ReVelle (1980), built upon and extended the basic concepts (Yeh 1985).

The linear decision rule provides a mechanism for reflecting reservoir operating rules in a LP model, which also simplifies solution of the model. The linear decision rule specifies the release during any time interval as the difference between the storage at the beginning of the period and a decision parameter for that period. The LP model computes values for the decision parameters which optimizes some specified objective function. For example, the optimum operating policy could be represented by computed values for 12 decision parameters, one for each month of the year, which relates the optimum release for a given month to the storage at the beginning of the month.

Chance-constrained LP formulations allow certain constraints to violated a specified percentage of the time. Chance-constrained formulations are typically applied to selected constraints which limit the permissible range of reservoir storage volumes or releases. Based on known or estimated probability distributions for reservoir inflows, constraints can be formulated which allow specified minimum or maximum storage or release limits to be exceeded a specified percentage of the time. For example, for a LP formulation with both linear decision rules and chance constraints, a set of values for a release parameter for each month (or other time period) of the year is computed which minimizes some specified objective function subject to certain discharge or storage limits being violated no more than a specified percentage of time.

Specific LP Models

A number of reservoir system analysis models based on linear programming have been reported in the literature. Several LP models representing a variety of applications and formulations are cited below. Other models combining both linear and dynamic programming are cited in the later discussion of dynamic programming. Yeh (1985) provides a more in depth literature review which cites a more comprehensive list of references.

Dorfman (1962) illustrated the use of linear programming with three versions of a model, each with increasing complexity, in which values of decision variables, consisting of reservoir storage capacities and release targets, were computed to maximize an economic objective function. Loucks (1968) developed a stochastic LP model for a single reservoir subject to random serially correlated net inflows. Release rates were determined which minimized an objective function consisting of the sum of the expected squared deviations from target reservoir volumes and discharges. Streamflow input data consisted of an inflow transition probability matrix. Windsor (1973) developed a LP model for analyzing multiple-reservoir flood control operations. Release schedules were determined which minimized the total damage cost at pertinent locations for a design storm. Palmer et al. (1982) used LP to determine firm yields for single reservoirs and a multiple reservoir system in the Potomac River Basin. Tradeoff analysis were performed to determine the impact of instream flow requirement constraints on system yields.

Palmer and Holmes (1988) describe the Seattle Water Department integrated drought management expert system (SID) model. A LP model is incorporated in this decision support system to determine optimal operating policies and system yield. The LP model is based on the two objectives of maximizing yield and minimizing the economic loss associated with deficits from a specified target.

Randall, Houck, and Wright (1990) developed a LP model to study the operation, during drought, of a metropolitan water system consisting of multiple reservoirs, groundwater, treatment plants, and distribution facilities. Four objectives were incorporated in the modeling study: (1) maximize net revenues, which were the difference between revenues for selling water and electrical pumping cost; (2) maximize reliability, expressed as the minimum of the ratios of consumption to demand for each water use district; (3) maximize reservoir storage at the end of the optimization horizon; and (4) maximize the minimum flow in the streams. Alternative versions of the model were formulated with one objective being optimized as the objective function, with the other objectives being incorporated as constraints at user-specified levels. Optimum operating plans were determined for the alternative formulations. Trade-off curves were developed to show the tradeoffs between the four alternative objectives.

Martin (1987) describes the MONITOR-I model developed by the Texas Water Development Board to analyze complex surface water storage and conveyance systems operated for hydroelectric power, water supply and low flow augmentation. A successive linear programming approach involving multiple solutions of a iteratively adjusted LP problem is incorporated in the model. The iterative algorithm is required to handle nonlinearities associated with hydroelectric power and other features of the model. The decision variables are daily reservoir releases, water diversions, and pipeline and canal flows. The objective function to be maximized is an expression of net economic benefits.

Brown and Shelton (1986) outline the Tennessee Valley Authority's use of computers in water resources management. Shane and Gilbert (1982) and Gilbert and Shane (1982) describe a particular model, called HYDROSIM, developed and used by the TVA to compute long-term week-to-week variations in water level, discharge, and electrical generation for the 42 reservoirs operated by the TVA. The HYDROSIM model uses linear programming to compute reservoir storages, releases, and hydroelectric power generation for each week of a 52-week period beginning at the present. Stream inflows forecasted based on current conditions are used for the first week. Since future inflows are unknown and forecasts of more than a week are considered to be highly uncertain, user-specified periods of historical streamflows are used for all weeks after the first. A data base has been developed which includes weekly streamflows at all pertinent locations for the entire period since 1903. At the completion of a model run, a complete system operation schedule is available for every year of historical hydrology specified by the user. The voluminous LP computed output is then interrogated interactively by output analysis programs.

Operating objectives and guidelines for resolving conflicts between competing objectives are provided by operating priorities mandated by Congress as part of the TVA act in 1933 which created the agency. Operating objectives follow the following order of priority.

flood prevention
navigation
water supply
power generation: energy and capacity assurance
water quality
drawdown rates
recreation
minimization of power production costs
balancing of reservoirs

The HYDROSIM model is based on these priorities. A series of operating constraints are formulated to represent the objectives listed above. The model sequentially minimizes the violation of these constraints in their order of priority. The violation of each constraint is minimized subject to the condition that the violation of no higher priority constraint is increased. (This general approach has been used elsewhere and called preemptive goal programming.) A LP algorithm is used to perform the computations. Finally, a nonlinear hydropower cost function in minimized subject to the condition that no constraint violation is increased. The cost function is in the form of current power cost plus expected future power cost. Cost for the current week is the total cost (thermal, purchase, and peak sharing) of meeting the load for the current week. The expected future cost is the expected cost of meeting the power load for the remainder of the planning horizon. The nonlinear hydropower cost function is minimized subject to the priority constraints by a search procedure which involves iteratively solving a sequence of linear programming problems.

The HYDROSIM model has been designed to be used by TVA reservoir management personnel in the following ways (Shane and Gilbert 1982):

- Evaluation of the impact of new operating requirements on established objectives.
- Continual checking of current reservoir system status to warn of possible future problems.
- Forecasting of reservoir system operation in terms of possible and likely pool level and discharge variations, constraint violations, and generation characteristic anticipated in the next 1 - 52 weeks of operation.
- Development of long-range operating guides.

Dynamic Programming (DP)

Dynamic programming (DP) is not a precise algorithm like linear programming, but rather a general approach to solving optimization problems. The dynamic programming approach involves decomposing a complex problem into a series of simpler subproblems which are solved sequentially, while transmitting essential information from one stage of the computations to the next using state concepts.

Dynamic programming models have the following characteristics.

- The problem is divided into stages with a decision required at each stage. The stages may represent different points in time (as in determining reservoir releases for each time interval), different points in space (for example, releases from different reservoirs), or different activities (such as releases for different project purposes or water users).
- Each stage of the problem must have a definite number of states associated with it. The states describe the possible conditions in which the system might be at that stage of the problem. The amount of water in storage is an example of a typical state variable.
- The effect of a decision of each stage of the problem is to transform the current state of the system into a state associated with the next stage. If the decision is how much water to release from the reservoir at the current time, this decision will transform the amount of water stored in the reservoir from the current amount to a new amount for the next stage.
- A return function indicating the utility or effectiveness of the transformation is associated with each potential state transformation. The return function allows the objective function to be represented by stages.
- The optimality of the decision required at the current stage is judged in terms of its impact on the return function for the current stage and all subsequent stages.

Bellman (1957) is credited with originating the dynamic programming (DP) approach. The fundamentals of DP are presented by Wagner (1975) and other operations research and systems engineering textbooks. Buras (1966) and Loucks, Stedinger, and Haith (1981) outline water resources systems analysis applications of DP. Labadie (1990) describes a generalized microcomputer DP package, called CSUDP, which has been used for a broad range of water resources planning and management applications. Yeh (1985) reviews the various types and variations of DP formulations of reservoir operation models, including incremental DP, discrete differential DP, incremental DP with successive approximations, stochastic DP, and the principal of progressive optimality.

DP is a general methodology for applying state concepts to the formulation and solution of problems which can be viewed as optimizing a multiple-stage decision process. In some cases, the same problem can be solved by alternative DP formulations or by either DP or LP. In general, LP has the advantage, over DP, of being a well-defined, easy-to-understand algorithm readily available in the form of generalized computer codes. DP is generally more difficult to learn and understand than LP. The degree of generalization and the availability of generalized computer codes is much more limited for DP than for LP. Many reservoir operation problems can be presented realistically by a linear objective function and set of linear constraints. Various linearization techniques have been used successfully to deal with nonlinearities. However, the strict linear form of the LP formulation does significantly limit its applicability. Nonlinear properties of a problem can be readily reflected in a DP formulation. However, various assumptions, including a separable objective function, limit the range of applicability and require ingenuity and understanding by the modeler in applying dynamic programming. The so-called "curse of dimensionality" is a major consideration in dynamic programming. Increasing the number of state variables greatly increases the computational burden. For example, since reservoir storage is typically a state variable, the number of reservoirs which can be considered in a DP model may be limited.

Specific DP Models

The annotated bibliography compiled by Wurbs et al. (1985) includes abstracts for over a hundred references dealing with applications of DP to problems of optimizing reservoir operations. Most of the references involve university research studies in which DP formulations were developed and applied to case study reservoir systems. A variety of different types of reservoir operation problems have been addressed. Flood control, hydroelectric power, water supply, and the other project purposes have each been addressed by a significant number of studies, but DP has probably been applied to hydroelectric power more than to any other project purpose. DP has often been applied in combination with other types of optimization techniques. Several references are cited below to illustrate some of the types of reservoir operation problems which have been analyzed using DP.

Hall et al. (1968) used DP to determine releases over time for a single reservoir which maximized revenues from the sale of water and energy. Liu and Tedrow (1973) combined dynamic programming and a multivariable pattern search technique to determine seasonal rule curves for flood control and conservation operation of a 5-reservoir system in the Oswego River Basin in New York. Collins (1977) developed a dynamic programming model to determine least cost withdrawal and release schedules for a 4-reservoir water supply system operated by the city of Dallas. The objective function consisted of electricity costs for operating pumps in the water distribution system and a water loss penalty function related to evaporation losses.

Giles and Wunderlich (1981) describe a model based on DP and simulation which was developed by the Tennessee Valley Authority for reservoir system planning studies and long range operational studies. The model determines weekly release schedules and end-of-week storage levels for 19 reservoirs, for an analysis period of up to 52 weeks. The objective function consists of five cost functions representing the major operating purposes of the system (flood control, navigation, hydroelectric power, recreation, and water quality). The cost functions can be multiplied by weights to reflect emphasis given to the operating purpose in addition to their economic value, or to include a safety factor that accounts for approximations in the cost evaluations. The streamflow input data consists of historical streamflows during user-selected years of the period-of-record.

Chung and Helweg (1985) combined dynamic programming with the HEC-3 simulation model in an analysis of operating policies for Lake Oroville and San Luis Reservoir, which are components of the California State Water Project. HEC-3 was used to determine the amount of excess water still available for export after all system commitments were met. A DP model was then used to determine how the reservoirs should be operated to maximize the net benefits of exporting the excess water. The DP decision variables were reservoir releases in each time period, and the objective function was an expression of revenues from selling the water. Since approximations were necessary in formulation of the DP model, HEC-3 was used to check and refine the release schedules determined with the DP model.

Allen and Bridgeman (1986) applied dynamic programming to three case studies involving hydroelectric power scheduling. The case studies included: (1) the optimal instantaneous scheduling of hydropower units with different generating characteristics to maximize overall plant efficiency; (2) the optimal hourly scheduling of hydropower generation between two hydrologically linked power plants to maximize overall daily/weekly system efficiency; and (3) the optimal monthly scheduling of hydropower generation to minimize the purchase cost of imported power supply subject to a time-of-day rate structure.

A real-time optimization procedure, involving combined use of DP and LP, was developed to determine multiple-reservoir release schedules for hydroelectric power generation in the operation of the California Central Valley Project (Yeh 1981; Becker and Yeh 1974; and Yeh, Becker, and Chu 1979). The overall procedure optimizes, in turn, a monthly model over a period of one year, a daily model over a period of up to one month, and an hourly model for 24 hours. Outputs from one model (monthly ending storages or daily releases) are used as inputs to the next echelon model. The monthly model is a combined LP-DP formulation which computes releases and storages based on the objective of minimizing the loss of stored potential energy. Given end-of-month storage levels, the daily month uses LP to determine the daily releases for each power plant which minimizes loss of stored potential energy in the system. The hourly model uses a combination of LP and DP to determine hourly releases for each plant which maximizes total daily system power output.

Martin (1987) incorporated a DP algorithm in a modeling procedure for determining an optimal capacity expansion plan for a water supply system. The optimization procedure determines the estimated least-costly sizing, sequencing, and operation of storage and conveyance facilities over a specified set of staging periods. A Texas Water Development Board DP-based model, called DPSIM-I, is combined with the previously cited TWDB models Al-V and SIM-V.

Nonlinear Programming (NLP)

Nonlinear functions are common in modeling reservoir operations. For example, reservoir water surface area versus storage relationships, required for evaporation computations, are nonlinear. Hydroelectric power is a function of storage or head as well as discharge. Objective functions often consist of benefits and costs expressed as a nonlinear function of storage and discharge.

Linearization techniques are used to approximate nonlinear functions in linear programming formulations. Various successive LP algorithms have been developed to handle nonlinearities, which involve iteratively executing a LP code with approximations of nonlinear features being improved in each iteration. Nonlinearities pose no significant difficulties in dynamic programming.

Nonlinear programming (NLP) algorithms, such as quadratic programming, geometric programming, and separable programming are covered in standard operations research and systems engineering textbooks. These NLP methods provide a more general mathematical formulation than LP but the mathematics involved is much more complicated. The NLP techniques have been applied relatively little to problems of optimizing reservoir system operations. The significant advancements in computer technology in recent years have removed computational constraints which could result in greater use of NLP in the future.

Next to LP and DP, search methods represent the optimization approach which has been most extensively used in optimizing reservoir operations. Search methods iteratively change the values of the decision variables in such a way as to move closer to the optimum value of the objective function. A broad range of nonlinear optimization algorithms are classified as search methods. Search techniques are typically combined with simulation models and are also often combined with LP and DP algorithms.

Diaz and Fontane (1989) present a quadratic programming approach for optimizing hydroelectric power releases from a multiple-reservoir system based on a objective of maximizing economic benefits.

Gagnon et al. (1974) optimized the operation of a large hydroelectric system using a method called elimination by affine transformation which incorporated the Fletcher-Reeves gradient search method. Chu and Yeh (1978) developed a gradient projection model for optimizing the hourly operation of a hydropower reservoir. Simonovic and Marino (1980) applied the gradient projection method with a two-dimensional Fibonacci search to solve a reliability programming problem for a single multipurpose reservoir. Rosenthal (1981) applied a reduced gradient method and integer programming to maximize the benefits in a hydroelectric power system.

Duren and Beard (1972) incorporated a univariate gradient search algorithm, with the Newton-Raphson convergence technique, into a Hydrologic Engineering Center reservoir simulation model to develop a method for determining the economically optimum flood control diagram for a single multipurpose reservoir. The model was applied to Folsom Reservoir in California. The general approach of incorporating the univariate gradient search algorithm into a simulation model was also adopted for the parameter calibration and flood damage reduction system optimization options of the HEC-1 Flood Hydrograph Package (USACE, HEC 1987).

Ford, Garland, and Sullivan (1981) combined a reservoir yield simulation model (USACE, HEC 1966) and the Box-Complex search algorithm (Box 1965 and Kuester and Mize 1973) to analyze the operation of the multipurpose conservation pool of Sam Rayburn Reservoir in Texas. The combined simulation-optimization approach for selecting an optimal operation policy was as follows. The simulation model was used to simulate a given operating policy, satisfying all demands when possible and allocating the available water according to specific priorities when conflicts occurred. The simulation model was linked to the search algorithm which automatically selected the optimal operation policy given data generated by the simulation model and a user-specified objective function. The operation policy identified by the optimization model was then smoothed using engineering judgement based on experience with operation of the system. The system response with the smoothed operating policy was then simulated with the simulation model, and adjustments in the operating policy made as necessary.

The optimization problem was formulated with the decision variables being the allocation of the fixed conservation storage capacity to four zones. The reservoir operating rules were based on specifying hydroelectric power requirements, water supply demands, and downstream releases to prevent saltwater intrusion, as functions of the zone within which the water surface elevation happened to be at a particular time. An objective function was formulated as the sum of ten weighted indices. The relative weights assigned to each index were user-specified and could be varied in alternative runs of the model to facilitate various trade-off analyses. The ten indices that comprised the objective function are as follows.

- energy shortage index computed as the sum of the squares of the annual shortage ratios multiplied by (100/number of years of analysis), where the shortage ratio is the annual shortage divided by the annual requirement
- downstream discharge shortage index computed similarly to the above energy shortage index
- number of times a downstream saltwater barrier is installed in the period of analysis
- number of times saltwater barrier fails in the period of analysis
- average annual energy shortage
- average annual downstream discharge shortage
- average monthly conservation pool elevation fluctuation
- average annual energy
- number of times conservation pool is emptied
- number of times downstream discharge shortage occurs

Comparison of Models

From the perspective of being widely accepted and applied by the agencies responsible for the actual planning, construction, and operation of reservoir systems, the "work-horse" of reservoir system analysis is simulation modeling with deterministic sequences of adjusted[1] historical streamflow data provided as input. The university research community in particular, and many practitioners as well, have been extremely enthusiastic about applying optimization (mathematical programming) and stochastic analysis techniques to problems of reservoir operation. Mathematical programming and stochastic analysis methods dominate the published literature. However, to date, these methods have played a relatively minor role compared to conventional deterministic simulation models in regard to influencing decisions made in the planning and operation of actual projects. In recent years, a major emphasis in all modeling sectors, regardless of the simulation or optimization computational algorithms being used, has been to use microcomputers as well as mainframe computers and to take advantage of technological advances in computer technology to expand capabilities in the areas of data management, output analysis, and user-friendly interactive man-machine interfacing.

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[1] Historical streamflow data are adjusted to provide complete sequences of homogeneous flows at pertinent locations representing unregulated or other specified conditions of basin development.

Models can be categorized by the reservoir purposes which can be represented. Differences between flood control and conservation purposes are particularly significant. Flood control has been a major focus of model development and application within the USACE. Essentially all the available generalized reservoir system analysis models, developed in the United States, with comprehensive capabilities for detailed representation of the complexities of flood control operations were developed within the USACE. The HEC-5, SSARR, SUPER, and BRASS models are examples of such flood control models. Flood control has also been a primary consideration in the notable model development work of the TVA, but the TVA models are more river basin specific rather than generalized. Modeling and analysis of conservation operations has a much broader patronage, including the USACE, TVA, USBR, other federal agencies, state water agencies, cities and other local entities, and private industry. University research efforts have also focused more on conservation operations than flood control.

Conventional Simulation Models

A comparison of the several reservoir system simulation models listed in Table 4 is presented earlier in this report. The present discussion focuses on HEC-3 and HEC-5, which are considered to be representative of the conventional simulation modeling approach.

A review of the literature indicates that HEC-3 and HEC-5 are probably the most widely recognized and often cited of the numerous simulation and optimization models developed to analyze reservoir operations. HEC-3 and HEC-5 have probably been applied to more reservoir systems in more studies than any other single computer program. 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. Extensive flood control features result in HEC-5 being an extremely large and complex model. HEC-3 has the advantage of being much smaller and simpler for conservation only studies. HEC-5 has the advantage of having all the flood control and conservation simulation capabilities combined in a single integrated model. A water quality version of HEC-5 provides additional simulation capabilities but makes the model even larger and more complex. HEC-5 is unique from the perspective of combining the following features: (1) being completely generalized for application to a broad range of reservoir system configurations, reservoir purposes, and operating rules; (2) providing a broad range of optional capabilities for various types of analyses; and (3) being well documented, tested, and supported.

HEC-5, as well as other USACE flood control simulation models, contain iterative search algorithms for making multiple-reservoir release decisions for each time interval during the simulation of a flood event. Flood control pools are emptied as quickly as possible without contributing to flows exceeding user specified allowable discharges at a number of downstream control points. Streamflow routing computations model the channel storage attenuation effects. At each control point, unregulated flows and releases from all upstream reservoirs are considered in determining the additional channel capacity still remaining without exceeding the allowable discharge. Multiple-reservoir release decisions are based on balancing the percent depletion of specified zones of the flood control pool in each reservoir. Both HEC-5 and SUPER also have optional economic analysis capabilities for computing expected annual flood damages for alternative system configurations or operating plans. Very few currently available models include these types of capabilities for detailed simulation of flood control operations.

HEC-3 and HEC-5 also have extensive capabilities for simulating reservoir operations involving hydroelectric power, water supply, and low flow augmentation. Multiple-reservoir and buffer zone operations can be simulated. Optional capabilities are provided for developing yield versus reliability relationships and/or computing firm yields. Many other simulation models contain conservation capabilities similar to HEC-3 and HEC-5 and/or other capabilities not included in HEC-3 and HEC-5. A broad spectrum of concerns are addressed in modeling and analysis of conservation operations. A number of simulation and optimization models have been developed which provide expanded capabilities for analyzing particular aspects of hydroelectric power, water supply, or multiple-purpose conservation operations.

Optimization Models

Whereas the federal water agencies have played a major role in development and application of conventional simulation models, the academic research community has provided the primary motivation for adopting mathematical programming methods to problems of reservoir system operations. The Tennessee Valley Authority is perhaps the most notable exception. The extensive ongoing model development efforts of the TVA have included successfully incorporating optimization techniques into the models used to support actual planning and real-time operations decisions.

Optimization (mathematical programming) algorithms systematically and automatically search through all feasible decision policies (sets of values for the decision variables) to find the decision policy which minimizes or maximizes a defined objective function. Mathematical programming methods provide useful capabilities for analyzing problems characterized by a need to consider an extremely large number of combinations of values for decision variables. As a simple example, consider the problem of temporally distributing limited available water over a year. The problem might be formulated in terms of determining daily water supply and hydroelectric power releases from each of ten reservoirs, for each of the 365 days in a year, which optimizes a specified objective function. Thus, the problem involves 7,300 decision variables (365 water supply releases and 365 hydroelectric power releases from 10 reservoirs), which can each take on a range of values. The extremely large number of decision variables, and infinite number of possible decision policies, illustrates the need for a mathematical programming algorithm.

Since simulation models are limited to predicting the system performance for a given decision policy, optimization models have a distinct advantage in being able to search through an infinite number of feasible decision policies to find the optimum policy. However, simulation models have certain advantages over optimization models from a practical applications perspective. Simulation models generally permit more detailed and realistic representation of the complex physical and hydrologic characteristics of a reservoir system. Mathematical programming requires that objectives and system characteristics be represented in the proper mathematical format. Representing the objectives, performance criteria, operating rules, and physical and hydrologic characteristics of the system in the required format, without unrealistic simplifications, is a particularly difficult aspect of the modeling process which limits the application of optimization techniques.

Linear programming (LP) has the advantage, over other mathematical programming methods, of being a well-defined, easy-to-understand, readily available algorithm. Numerous generalized computer codes are available for solving LP problems, including very efficient algorithms applicable to particular formulations such as network flow problems. Many reservoir operation problems can be represented realistically by a linear objective function and set of linear constraints. Various linearization techniques have been used successfully to deal with nonlinearities. However, the strict linear form of LP does definitely limit its applicability. Nonlinear programming techniques are more complex but can overcome certain limitations of LP.

Nonlinear properties of a problem can be readily reflected in a dynamic programming (DP) formulation. DP is applicable to problems which can be formulated as optimizing a multiple-stage decision process. Numerous variations and extensions to the general DP approach have been developed specifically for reservoir system analysis problems.

Search algorithms have the advantage of being readily combined with a complex simulation model. The simulation model captures the complexities of the real-world reservoir system operation problem. The search algorithm provides a mechanism to systematize and automate the series of iterative executions of the simulation model required to find a near optimum decision policy.

Combination of Optimization and Simulation Models

Optimization and simulation may be effectively used in combination. Jacoby and Loucks (1972) investigated several strategies for combining optimization techniques with simulation models. Preliminary screening with an optimization model may be used to develop a manageable range of alternative decision policies for further detailed analysis with a simulation model. The Potomac River Study (Palmer et al. 1980) is an example of this general approach. Another strategy, illustrated by the Tennessee Valley Authority HYDROSIM model (Gilbert and Shane 1982), is for an optimization model to be embedded as a component of a complex simulation model. Likewise, an optimization model may search for an optimum decision policy while activating a simulation model to compute the objective function value for any given set of decision variable values. Ford, Garland, and Sullivan (1981) provide an example of combining a reservoir operation simulation model with a nonlinear optimization algorithm. Many of the other references cited in this report present modeling approaches which involve combining optimization and simulation models and also combining two or more optimization techniques.

In actuality, the distinction between simulation and optimization is obscured by the fact that most models, to various degrees, contain elements of both approaches. All optimization models also simulate system performance for alternative decision policies. The objective function and constraint equations incorporated in optimization models are a representation and, thus a simulation model, of the real system. Optimization strategies often consist of iterative trial-and-error runs of a simulation model. Many complex simulation models also contain optimization algorithms to perform certain functions. For example, as discussed above, HEC-5 contains an iterative search algorithm to determine flood control releases for each time interval during the simulation, following user specified operating rules. HEC-3 and HEC-5 contain firm yield optimization options which automate the iterative search for the diversion or instream flow requirement which just empties the storage capacity of a single reservoir or multiple reservoir system.

Reservoir system simulation models based on network flow programming using the out-of-kilter linear programming algorithm provide another example of the general approach of a simulation model which automatically makes release decisions, using an optimization algorithm, for each time interval during the simulation, in accordance with user specified operating rules. Previous discussions have addressed the differences between the formats in which the user specifies operating rules in network flow models as compared to conventional simulation models.

Stochastic Analysis Methods

As previously discussed, modeling and analysis approaches can also be categorized by the manner in which the random or stochastic nature of streamflow and other variables are handled. Deterministic models are most often used in actual practice. Adjusted historical gaged streamflows covering the entire period-of-record or some subperiod thereof (such as the critical drought period or most severe flood of record) are typically provided as input data for simulation and optimization models.

In flood control studies, rainfall data are commonly used, in addition to streamflow data, to capture the probabilistic characteristics of flood events. Hypothetical design rainfall events, developed for specified exceedence probabilities, combined with a watershed (rainfall-runoff) model provide flood inflow hydrographs, with associated estimated exceedence frequencies, for use as input to reservoir system analysis models.

Two general areas of stochastic analysis which have been addressed extensively in the reservoir systems analysis literature, but adopted relatively infrequently in actual practice, are: (1) stochastic reservoir storage theory models and (2) a variety of methods incorporated in LP, DP, and NLP models to represent the stochastic characteristics of streamflow either in lieu of or in addition to inputed deterministic adjusted historical streamflow sequences. For example, reservoir inflow characteristics are often represented by a inputed transition probability matrix which specifies the discrete probability of a certain streamflow conditioned on the previous period streamflow.

Synthetic streamflow generation is another stochastic analysis tool which has been addressed extensively in the research literature, during the past 25 years, but applied relatively little by water resources development and management agencies. Streamflow synthesis models appear to have a particularly significant potential for greater practical application in analyzing reservoir operations for conservation operations. The adjusted historical hydrologic period-of-record is representative of flow characteristics but will not be repeated in the future. The period-of-record streamflows provide only one sequence of streamflows. Streamflow synthesis, while preserving selected statistical parameters of the adjusted historical data, provides any number of alternative sequences of streamflows which can be input to reservoir system analysis models to provide a more thorough testing of alternative operating policies. Disadvantages of synthetic streamflow generation include: (1) questions regarding the validity of statistical methods in representing the likelihood of extreme droughts, (2) difficulties in explaining stochastic hydrology to decision makers and the public, (3) the effort involved in conducting the modeling and analysis exercises. Also, in many typical studies, the adjusted historical streamflow data adequately serves the purpose of the study, and no need exists to extend the record with synthesized data. However, streamflow synthesis models can be worthwhile from a practical applications perspective in certain types of reservoir systems analysis studies.

SUMMARY

Optimization of multiple-purpose reservoir operations is a very complex and important area of water resources planning and management. Development and application of reservoir system analysis methods has been a major concern for both the water agencies and the research community. This report reviews modeling and analysis approaches which have been emphasized in either the research literature, actual practice, or both. Very definite differences are evident between the methods developed and the general emphasis of the research literature and the approaches developed and adopted by the agencies which actually operate reservoir systems. A broad range of computer modeling capabilities have been developed during the past 25 years which can serve a variety of roles in optimizing reservoir system operations. Hopefully, this report can contribute to ongoing efforts throughout the profession in sorting through the numerous modeling and analysis approaches and better understanding which techniques might be most useful in addressing various types of reservoir system optimization problems.

Optimization of reservoir system operations is addressed from the perspective of formulating the modeling and analysis approach. The wide variety of types of reservoir operation optimization problems are categorized and defined with a focus on the decisions to be made and quantitative measures of system performance to be used to evaluate the optimality of the decisions. The report also outlines fundamentals of reservoir operation practices and procedures. Reservoir operations vary significantly between regions of the country, between water management agencies, and even between individual reservoirs operated by the same agency in the same river basin. However, a commonality of fundamental concepts exists which is pertinent to reservoir operations in general.

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