Comparative Evaluation of Generalized River/Reservoir System Models

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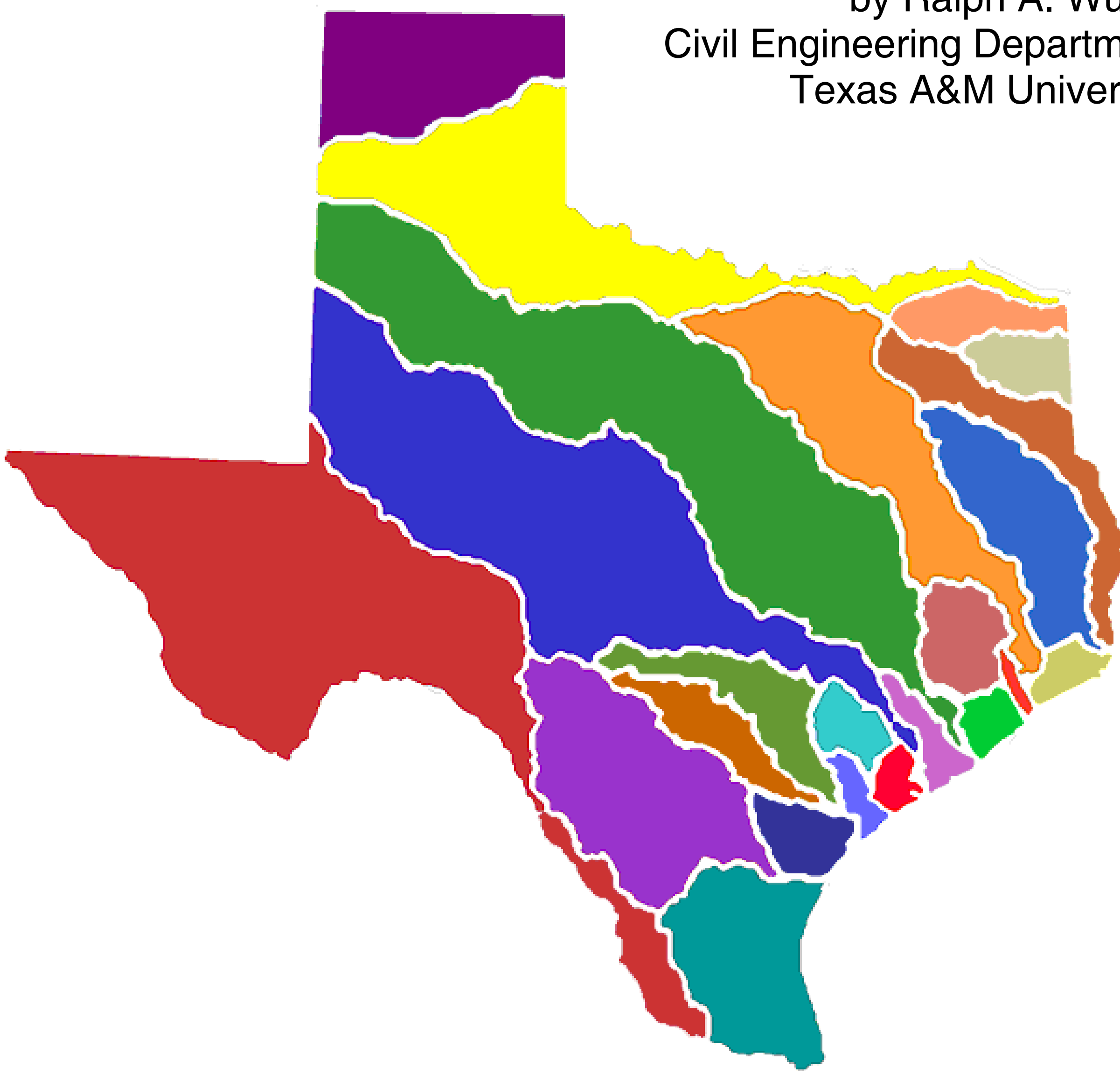

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make every drop count

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for the

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U.S. Army Corps of Engineers

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Chapter 1 Introduction

Reservoir/River System Models

This report reviews user-oriented generalized reservoir/river system models. The terms *reservoir/river system*, *reservoir system*, *reservoir operation*, or *river basin management "model"* or "*modeling system"* are used synonymously to refer to computer modeling systems that simulate the storage, flow, and diversion of water in a system of reservoirs and river reaches. *Generalized* means that a computer modeling system is designed for application to a range of concerns dealing with river basin systems of various configurations and locations, rather than being site-specific customized to a particular system. *User-oriented* implies the modeling system is designed for use by professional practitioners (model-users) other than the original model developers and is thoroughly tested and well documented. User-oriented generalized modeling systems should be convenient to obtain, understand, and use and should work correctly, completely, and efficiently.

Modeling applications often involve a system of several simulation models, utility software products, and databases used in combination. A reservoir/river system model is itself a modeling system, which often serves as a component of a larger modeling system that may include watershed hydrology and river hydraulics models, water quality models, databases and various software tools for managing time series, spatial, and other types of data.

Reservoir/river system models are based on volume-balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. The model computes reservoir storage contents, evaporation, water supply withdrawals, hydroelectric energy generation, and river flows for specified system operating rules and input sequences of stream inflows and net evaporation rates. The hydrologic period-of-analysis and computational time step may vary greatly depending on the application. Storage and flow hydrograph ordinates for a flood event occurring over a few days may be determined at intervals of an hour or less. Water supply capabilities may be modeled with a monthly time step and several decade long period-of-analysis capturing the full range of fluctuating wet and dry periods including extended drought. Stream inflows are usually generated outside of the reservoir/river system model and provided as input to the model. However, reservoir/river system models may also include capabilities for modeling watershed precipitation-runoff processes to generate inflows to the river/reservoir system. Some reservoir/river system models simulate water quality constituents along with water quantities. Some models include features for economic evaluation of system performance based on cost and benefit functions expressed as a function of flow and storage.

Modeling Applications

Reservoir system management practices and associated modeling support involve:

- minimizing flood damages
- minimizing the risks and consequences of water shortages
- allocating storage capacity and streamflow between multiple users and types of use
- optimizing the beneficial use of water, energy, and land resources
- managing environmental resources

Modeling systems provide quantitative information for use in evaluating storage and flow allocations and regulation policies in support of:

- pre-construction planning and design of new projects
- reevaluation of storage allocations and operating plans of existing multiple-purpose reservoir systems
- administration of water allocation systems that may include international treaties, interstate compacts, water right permit systems, and agreements between reservoir owners, water suppliers, and water users
- operational planning for developing management strategies for the next year or season
- real-time operations during floods, droughts, and more normal hydrologic conditions

Models are used for various purposes in a variety of settings. They 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 construction projects or reallocations of storage capacity or other operational modifications at existing projects. Periodic reevaluation of operating policies for existing systems may be made routinely to assure responsiveness to current conditions and objectives. Reevaluation studies may also be made in response to a particular perceived problem or need. Studies may be motivated by drought conditions, a major flood event, water quality problems, or environmental losses such as fish kills. Models may also be used in annual operational planning studies to develop operating plans for the next year or next season. Models support the administration of water right permits and other types of water allocation systems. Real-time modeling applications may involve decision-support for water management and use curtailment actions during droughts. Likewise, use of modeling systems during flood control operations in support of real-time release decisions represents another major area of application.

Scope of the Comparative Evaluation

The primary purpose of this state-of-the-art review is to assist practitioners in selecting and applying models in various types of situations. The review is also designed to support research and development efforts in continuing to improve and expand modeling capabilities. The objectives of the comparative evaluation presented by this report are to:

1. outline water management decision-support settings in which the models are applied and the reservoir/river system operating practices that are modeled
2. explore simulation and optimization strategies and methods, model development software, data management, and other key aspects of constructing modeling systems
3. review the state-of-the-art of reservoir/river system modeling capabilities focusing on compiling an inventory of user-oriented generalized modeling systems
4. highlight key considerations in developing and implementing modeling systems for various types of reservoir/river system management applications

This report on user-oriented generalized modeling systems begins by describing in Chapter 2 the river basin management setting within which modeling systems are implemented. Alternative approaches for constructing models to support reservoir/river system management decision-making processes and the simulation and optimization methods incorporated in the models are outlined in Chapters 3 and 4. Software environments in which models are constructed are described in Chapter 5. Models reported in the literature and applied by the water management agencies are reviewed in Chapter 6. The review describes state-of-the-art reservoir/river system modeling capabilities in general. The focus then narrows in Chapter 7 to five generalized reservoir/river system models. The five modeling systems are described in Chapter 7 and compared in Chapter 8. The comparative assessment of modeling capabilities presented in Chapter 8 focuses on the five selected models but also addresses modeling capabilities in general. The final Chapter 9 summarizes the comparative evaluation of alternative reservoir/river system management models. A list of references cited and a glossary defining pertinent terms are found at the end of the report.

This report is written with a bias toward river basin planning and management activities accomplished by federal, state, and regional agencies in Texas and their consultants. However, reservoir/river system management practices and associated modeling applications in Texas are representative of water resources planning and management throughout the nation and world.

Selected Generalized Reservoir/River System Models

Chapters 2 through 6 provide a broad treatment of key aspects of developing and applying reservoir/river system models. Many models are cited in Chapter 6. Chapters 7 and 8 focus on five models that are viewed as being representative of reservoir/river system modeling capabilities in general and particularly pertinent to water resources planning and management by the U.S. Army Corps of Engineers (USACE) and other agencies in Texas. The following five modeling systems discussed in Chapters 7 and 8 provide a focus for the comparative evaluation.

SUPER developed by the USACE Southwestern Division

HEC-ResSim developed by the USACE Hydrologic Engineering Center

RiverWare developed by the Bureau of Reclamation, Tennessee Valley Authority, and Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado

MODSIM developed at Colorado State University with support from the Bureau of Reclamation and other agencies

WRAP developed at Texas A&M University sponsored by the Texas Water Resources Institute, Texas Commission on Environmental Quality, USACE Fort Worth District, and other agencies in Texas

The *SUPER* model was originally developed during the 1970's at the Southwestern Division office in Dallas. *SUPER* has been applied to Corps of Engineers reservoir systems in the Fort Worth, Tulsa, and Little Rock Districts for many years.

HEC-ResSim is the *NexGen* successor to the *HEC-5 Simulation of Flood Control and Conservation Systems* model. *ResSim* serves as the reservoir simulation component of the new Corps Water Management System (CWMS) being implemented at the field offices throughout the Corps of Engineers.

RiverWare is the product of a long pioneering endeavor in object-oriented programming. *RiverWare* was developed originally for application to Bureau of Reclamation and Tennessee Valley Authority reservoir systems but is now also being applied to other reservoir/river systems.

MODSIM developed at Colorado State University is also based on object-oriented programming and has been applied in studies sponsored by the Bureau of Reclamation and various other entities. *MODSIM* is representative of a group of water allocation models based on network flow programming that includes early Texas Water Development Board models as well as several other major models.

The *Water Rights Analysis Package (WRAP)* is applied in conjunction with the Texas Water Availability Modeling (WAM) System by the Texas Commission on Environmental Quality, Texas Water Development Board, river authorities, other agencies, and consulting firms in regional and statewide planning studies and in the preparation and evaluation of water right permit applications.

Chapter 2
Reservoir/River System Management

Dams and appurtenant structures are required to control highly fluctuating river flows to reduce flooding and develop reliable water supplies. Management of the water and related land and environmental resources of a river basin integrates natural and man-made systems. Institutional arrangements for allocating and managing water resources are integrally connected to systems of constructed facilities. Reservoir/river system analysis models have evolved in recent years to encompass a broad array of hydrologic, physical infrastructure, and institutional aspects of river basin management.

River Basin Development and Management

River basin management involves the development, conservation, control, regulation, protection, allocation, and beneficial use of water in streams, rivers, lakes, and reservoirs. Reservoir storage is necessary to use the extremely variable water resources of a river basin for beneficial purposes such as municipal and industrial water supply, irrigation, hydroelectric power generation, and navigation. Dams and appurtenant structures also regulate rivers to reduce damages caused by floods. Public recreation, water quality, erosion and sedimentation, and protection and enhancement of fish, wildlife, and other environmental resources are important considerations in managing reservoir/river systems.

The hydrograph of Figure 2.1 illustrates the great natural variability of river flows throughout the United States and the world that is fundamental to river basin development and management. Reservoirs are essential for regulating flow fluctuations to develop dependable water supplies and mitigate floods. The monthly naturalized flows at the U.S. Geological Survey gage on the Brazos River near Hempstead in central Texas plotted in Figure 2.1 were developed by adjusting gaged flows to remove the historical effects of upstream reservoirs and water supply diversions and return flows. Flow conditions vary from a dry stream to major floods. Both seasonal within-year variations and multiple-year droughts are important in reservoir/river system operations. The mean monthly flows plotted in the figure do not show daily and instantaneous variations that may also be important. The 1951 to 1957 most hydrologically severe drought on record for much of Texas and the major flood in April 1957 that ended the record drought are reflected in Figure 2.1.

Spatial variations in geography, economic development, and climate are also key considerations in water resources development and management. Water resources and water needs often do not coincide geographically. The California Central Valley and State Water Projects reflect the fact that the majority of the precipitation in California occurs in the northern third of the state, but most of the water use occurs in the southern half of the state. Farmers and municipalities in eastern Colorado are supplied water diverted through the Big Thompson Project from the Colorado River on the opposite side of the continental divide through the Rocky Mountains. Mean annual precipitation in Texas varies dramatically from 8 inches at El Paso on the Rio Grande to 56 inches in the lower Sabine River Basin in southeast Texas.

Water resources development and management is accomplished within an institutional framework of organizations, traditions, programs, policies, and political processes. Funding and financial arrangements are key considerations in constructing reservoir projects and establishing operating strategies. Water is a publicly-owned resource, and its allocation and use is governed by state water rights systems. Treaties and interstate compacts allocate river flows between neighboring countries and states. River basin management must be consistent with federal and state environmental laws and policies.

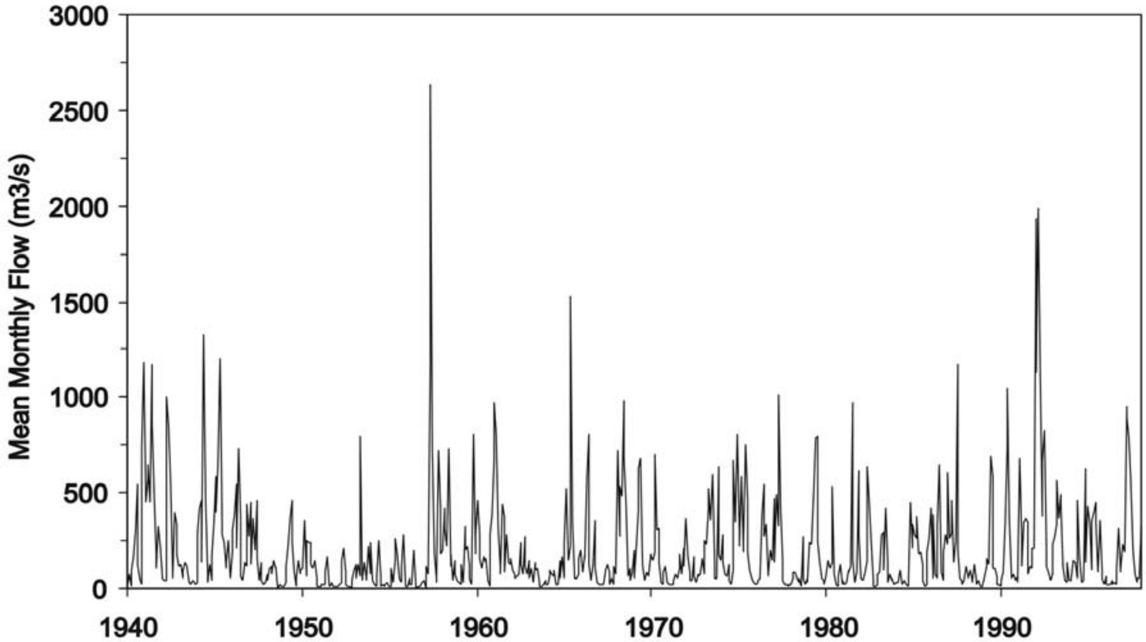

Figure 2.1 Monthly Naturalized Flows at the Hempstead Gage on the Brazos River

Evolution of Development/Management Focus

Numerous major reservoir projects, located throughout the United States, are operated by the Corps of Engineers, Bureau of Reclamation, International Boundary and Water Commission, Tennessee Valley Authority, other federal agencies, river authorities, water districts, cities, and private industry. Most of these projects were constructed during the period from the 1920's through the 1970's, which has been called the construction era of water resources development. Texas has 211 reservoirs with storage capacities of 5,000 acre-feet or greater (TWDB 2002). Most of the major reservoirs in Texas were constructed during the period from the 1940's through 1970's. Although additional new reservoir projects are needed and continue to be developed, most of the major reservoir systems required to manage our rivers are in place. Economic, environmental, and institutional considerations constrain construction of water resources development projects. Since the 1970's, water resources management policy and practice have shifted to a greater reliance on managing floodplain land use, improving water use efficiency, and optimizing the operation of existing facilities.

Public needs and objectives and numerous factors affecting reservoir management change over time. Population and economic growth in various regions of the nation are accompanied by increased needs for flood control, water supply, energy, recreation, and the other services provided by water resources development. Depleting groundwater reserves are resulting in an increased reliance on surface water in many areas. With increasing demands on limited water resources, water rights and systems for allocating water resources among numerous water users have grown in importance. Concerns continue to grow regarding maintenance of instream flows for preservation of riverine habitat and species, wetlands, and freshwater inflows to bays and estuaries. Environmental restoration has become a major concern. With an aging inventory of numerous dams and reservoirs being operated in an environment of change and intensifying demands on limited resources, operational improvements are being considered increasingly more frequently. These general observations are valid both for Texas and the nation in general.

Comprehensive river basin planning and management integrates the myriad of considerations involved in solving water-related problems and meeting needs associated with population growth, economic development, and environmental protection. The concept emphasizes comprehensive integration of:

- multiple purposes (water supply, hydropower, flood mitigation, etc.)
- economic development, social welfare, and environmental protection
- water supply augmentation and demand management
- structural and nonstructural flood damage reduction strategies
- human and ecosystem needs for water
- water quantity and quality considerations
- conjunctive management of surface and ground water resources
- management of water, land, energy, and biological resources

The fundamental importance of comprehensive water resources planning and management has been recognized for decades. Varying degrees of success have been achieved in actually incorporating the holistic systems concept in planning studies and implementation of management strategies.

Environmental Policy

Environmental legislation greatly affects river basin management. Several examples of the numerous federal environmental policies and programs that guide river basin management are cited as follows. The Fish and Wildlife Conservation Act of 1958 (PL 85-624) established the policy that fish and wildlife conservation be coordinated with other project purposes and receive equal consideration. The National Environmental Policy Act of 1970 (PL 91-190) articulated the policy of protecting the environment and established requirements for evaluating the environmental impacts of federal actions.

Section 404 of the Water Pollution Control Act Amendments of 1972 (PL 92-500), as further amended by the Clean Water Act of 1977 (PL 95-217), established the dredge and fill permit program administered by the USACE. Construction, land development, and other activities involving placing of dredge or fill materials into streams, rivers, lakes, or wetlands requires USACE approval of a permit application. The objective is to assure that every reasonable effort is made to minimize adverse impacts of development activities on the environment. The Corps of Engineers seeks public input and collaborates with the Environmental Protection Agency and Fish and Wildlife Service in determining whether the permit application should be approved and, if so, what modifications to a proposed project that may be required.

Protection of wetlands is an important part of the Section 404 regulatory program. The term *wetland* includes swamps, marshes, bogs, bottomlands, sloughs, and wet meadows. Wetland ecosystems represent the transition between aquatic and terrestrial ecosystems. Prior to the 1970's, drainage of wetlands for agricultural and urban development was accepted practice. Wetlands disappeared at alarming rates. The importance of preserving wetland ecosystems became widely recognized. Restoration of the Florida Everglades during the 1990's-2000's is a particularly notable example of efforts to protect and preserve wetlands.

Requirements for conservation of endangered species, pursuant to the 1973 Endangered Species Act (PL 93-205) as amended by the Endangered Species Act Amendments of 1978 and 1979 (PL 95-632 and PL 96-159) and other legislation, are administered by the Fish and Wildlife Service in coordination with other agencies. Many species of fish, wildlife, and plants have been rendered extinct as a consequence of economic development. The objective of the Endangered Species Act is to prevent loss of additional species. Endangered species are officially identified, and they and their habitat are protected from actions that could cause their destruction.

Endangered species have significantly impacted river basin management nationwide including operations of several major reservoir systems. For example, although salmon migration had been for decades an important consideration in reservoir system management in the Columbia River Basin, the 1992 listing of certain types of salmon as endangered resulted in intensified fish protection efforts. Programs have been implemented in the Susquehanna River to restore populations of American chad. Reservoir operations on the Missouri River have been modified to prevent inundation of sandbars that serve as nesting habitat for the least tern and piping plover, which are endangered birds.

Water Rights and Water Allocation Systems

Streamflow and reservoir storage capacity in major river basins are typically shared by many water users who use the water for a variety of purposes. Water rights systems provide a basis to (1) allocate resources among users, (2) protect existing users from having their supplies diminished by new users, and (3) govern the sharing of limited streamflow and water in storage during droughts when supplies are inadequate to meet all needs. The institutional framework for river basin management involves a hierarchy of water allocation systems. The water resources of international river basins may be allocated between nations by treaties and other agreements. In the U.S., water is allocated among states through river basin compacts and other means. Within individual states, water is shared by river authorities, municipal water districts, cities, irrigation districts, individual farmers, industries, and private citizens through water rights systems. A water district or river authority distributes water to its customers in accordance with contractual commitments. Water allocation at all of these levels is a governing concern in water management in Texas.

States in the western and eastern halves of the U.S. have generally adopted different approaches to water rights due largely to the western states having much drier climates. Wurbs (2003) describes water allocation systems in Texas, which have characteristics of both the western and eastern states. Water allocation and accounting systems tend to be more rigorous in regions where demands approach or exceed supplies. Each state has developed its own set of rules and practices governing water rights. These water allocation systems have evolved historically and continue to change. State water rights systems generally have the following components or features.

- State negotiated compacts approved by the federal government allocate waters of interstate river basins between states. Some states are also affected by federal agreements with Canada or Mexico for sharing international waters or by rights reserved for Indian reservations, military installations, and other federal lands.

- A legally established priority system based generally on variations of the riparian and/or prior appropriation concepts guides the allocation of the waters within a state among numerous water management entities and water users.

- An administrative system is needed to grant, limit, and modify water rights and to enforce the allocation of water resources, particularly during droughts and times of insufficient supply. These systems may or may not include formal issuance of written permits to water right holders.

- Increasingly more states, including Texas, are implementing reservoir/river system modeling systems to support administration of their water allocation systems and associated water resources planning and management activities.

Organizational Framework

The water management community consists of water users, concerned citizens, public officials, professional engineers and scientists, special interest groups, businesses, utilities, cities, and local, state, regional, federal, and international agencies. In addition to the entities that own and operate a reservoir system, numerous other public agencies, project beneficiaries, and interest groups play significant roles in determining operating policies. Within this complex institutional framework, a number of organizations are directly responsible for developing and managing reservoir projects. Most reservoirs in the United States are owned and operated by private electrical and water utilities, cities, water districts, and other local entities. However, the majority of the storage capacity is contained in federal reservoirs. Most, though certainly not all, of the very large reservoir systems in the United States are operated by the federal water agencies. The much more numerous nonfederal reservoirs tend to be much smaller in size than the federal projects.

The U.S Army Corps of Engineers (USACE) is the largest reservoir management agency in the nation, with over 500 reservoirs in operation. The Corps of Engineers is unique in having nationwide responsibilities for construction and operation of large-scale multiple-purpose reservoir projects. The U.S. Bureau of Reclamation (USBR) operates about 130 reservoirs in the 17 western states and has constructed numerous other projects which have been turned over to local interests for operation. The Tennessee Valley Authority (TVA) operates a system of about 50 reservoirs in the seven-state Tennessee River Basin. The Natural Resource Conservation Service, Forest Service, and National Park Service are among the various other federal agencies responsible for reservoirs.

The responsibilities of the various organizations involved in operating reservoir systems are based upon project purposes. The Corps of Engineers has played a clearly dominant role nationwide in constructing and operating major reservoir systems for navigation and flood control. The Bureau of Reclamation water resources development program was founded upon facilitating development of the arid West by constructing irrigation projects. The Tennessee Valley Authority reservoir system is operated in accordance with operating priorities mandated by the 1933 Congressional act that 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. Hydroelectric power, recreation, and fish and wildlife are major purposes of USACE, USBR, and TVA projects. 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. Numerous cities, municipal water districts, and other local agencies operate their own reservoir projects. Private companies as well as governmental entities play key roles in hydroelectric power generation, thermal-electric cooling water projects, and industrial water supply.

Contractual arrangements and other institutional aspects of reservoir operations vary greatly between purposes. For example, flood control operations for a Corps of Engineers reservoir are simpler institutionally 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 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. All costs, including construction and maintenance, allocated to municipal and industrial water supply are reimbursed by nonfederal sponsors in accordance with the Water Supply Act of 1958, as amended by the Water Resources Development Act of 1986 and other legislation. Construction costs are reimbursed, with interest, through annual payments over a period not to exceed 50 years. Nonfederal sponsors for federal projects are often regional water authorities who sell water to municipalities, industries, and other water users, under various contractual arrangements. Of the 117 USACE reservoirs nationwide that contain municipal and industrial water supply, about 75 percent of the water supply storage is in reservoirs in the Southwestern Division, mainly in Oklahoma and Texas (Institute for Water Resources 2003). Wurbs (1994) and the Institute for Water Resources (2003) review policies and practices regarding municipal and industrial water supply in federal reservoirs.

The Reclamation Acts of 1902 and 1939 and other legislation dictate the policy that costs allocated to irrigation in federal projects be reimbursed by the project beneficiaries. The details of repayment requirements for irrigation projects have varied over the years with changes in reclamation law. Congressional acts authorizing specific Bureau of Reclamation projects have often included repayment provisions tailored to the circumstances of the individual project. Thus, local sponsor repayment contracts for water supply for irrigation vary between projects.

Water supply operations are controlled by agency responsibilities, contractual commitments, and legal systems for allocating and administering water rights. Water allocation and use is regulated by state water rights systems and permit programs. Many of the major reservoir systems in the United States are on interstate rivers, and several are on rivers shared with either Mexico or Canada. Operations of some reservoir systems are strictly controlled by agreements between states and/or nations which were negotiated over many years.

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 that 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. Many private and public electrical power companies operate their own reservoirs and hydropower plants. Several large hydroelectric power systems are composed of multiple storage and generating components owned and operated by federal, state or local, and private entities. Hydroelectric power facilities are typically components of systems which rely primarily on thermal plants for the base load, with hydropower supplying peak loads.

Storage Reallocations

Most of the major reservoirs in the United States have been in operation for over thirty years, many have been in operation for over 50 years, and a few much longer. Population and economic growth and many factors affecting reservoir operation change over time. Storage reallocations and other operational modifications are a key strategy for responding to changing water management needs and objectives. Reallocations at USACE reservoirs may involve transfer of storage capacity between flood control and conservation pools. Operational modifications for non-federal or federal reservoir systems may involve reallocation of conservation storage between users and types of use, conjunctive surface/ground water management, schemes to operate water supply reservoirs to better deal with floods, and various other refinements in operating practices.

The purposes to be served by a federal reservoir project are established with Congressional authorization of project construction. Later, additional purposes may be 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 without congressional action.

Various references explore issues to be addressed in reallocating storage capacity and/or otherwise modifying operations of federal reservoir projects. Wurbs (1990) and Johnson *et al.* (1990) reviewed legislative authorities and policies and surveyed federal projects for which storage reallocations and operational modifications had been proposed or implemented. The Institute for Water Resources (2003) provide a more recent review of policies and practices. McMahon and Farmer (2004) investigate the various considerations involved in reallocating storage capacity and changing operating policies for federal multiple-purpose reservoirs.

Reservoir System Operations

An operating plan or release policy is a set of guidelines for determining the quantities of water to be stored and to release or withdraw from a reservoir or system of several reservoirs under various conditions. The terms operating (or release or regulation or water control) procedures, rules, schedule, policy, or plan are used here interchangeably. Operating decisions involve allocation of storage capacity and water releases between multiple reservoirs, between project purposes, between water users, and between time periods. Typically, a regulation plan includes a set of quantitative criteria within which significant flexibility exists for qualitative judgment. Operating plans provide guidance to reservoir management personnel. In modeling and analysis of a reservoir system, some mechanism for representing operating rules and/or decision criteria must be incorporated in the model. Reservoir system analysis models contain various mechanisms for making period-by-period release decisions within the framework of user-specified operating rules and/or criteria functions.

Reservoir system operations can be categorized as:

- operations during normal hydrologic conditions from the perspective of optimizing the present day-to-day, seasonal, or year-to-year use of the reservoir system
- operations during 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
- operations during hydrologic extremes
    - operations during flood events
    - operations during low flow or drought conditions

A wide variety of operating policies are presently in use at reservoir projects throughout Texas, the United States, and the world. For many water supply reservoirs, operations are based simply on making withdrawals or releases as necessary to meet water demands. Flood flows pass through uncontrolled spillways, and no pre-developed plans are in place for responding to supply depletion during infrequent severe droughts. On the other hand, complex regulation plans guide operations of many reservoirs including major federal multiple-purpose, multiple-reservoir systems. Typically, a operating plan involves a framework of quantitative rules within which significant flexibility exists for operator judgement. Day-to-day operating decisions may be influenced by a complex array of factors and often are based largely on judgement and experience. Operating procedures may change over time with experience and changing conditions.

Outlet Structures

Reservoir projects include dams and appurtenant outlet structures, pumping plants, pipelines, canals, channel improvements, hydroelectric power plants and transmission facilities, navigation locks, fish ladders, recreation facilities, and various other structures. The extensive literature on design, maintenance, operation, and rehabilitation of dams, spillways, outlet works, gates, energy dissipators, and related hydraulic structures includes books by the Bureau of Reclamation (1976, 1977, 1987), Jansen (1988), Kollgaard and Chadwick (1988), Senturk (1994), Singh and Varshney (1995), Kutzner (1997), Vischer and Hager (1998), and Herzog (1999).

Reservoir releases to the river below a dam are made through spillways and outlet works. Spillways provide the capability to release high flow rates during major floods without damage to the dam and appurtenant structures. Spillways are required to allow flood inflows to safely flow over or through the dam, regardless of whether the reservoir contains flood control storage capacity. Spillways may be gated or uncontrolled. A controlled spillway is provided with crest gates or other facilities that allow the outflow rate to be adjusted. For an uncontrolled spillway, the outflow rate is a function of the head or height of the water surface above the spillway crest. Since spillway flows involve extremely high velocities, stilling basins or other types of energy dissipation structures are required to prevent catastrophic erosion damage to the downstream river channel and dam. For many reservoir projects, a full range of outflow rates are discharged through a single spillway. Some reservoirs have more than one spillway. A service spillway conveys smaller, more frequently occurring release rates, and an emergency spillway is used only rarely during extreme floods.

The major portion of the storage volume in most reservoirs is located below the spillway crest. Flows over the spillway can occur only when the storage level is above the spillway crest. Outlet works are used for releases from storage both below and above the spillway crest. Discharge capacities for outlet works are typically much smaller than for spillways.

Outlet works are used to release water for downstream water supply diversions, maintenance of instream flows, and other beneficial uses. Flood control releases may also be made through outlet works. An outlet works typically consists of an intake structure in the reservoir, one or more conduits or sluices through the dam, gates located either in the intake structure or conduits, and a stilling basin or other energy dissipation structure at the downstream end.

Water supply diversions may be either lakeside or downstream. Lakeside withdrawals are require intake structures, pumps, and pipeline or canal conveyance facilities. Downstream releases through an outlet works may be diverted from the river at locations that are great distances below the dam. Downstream releases may be made through hydroelectric power penstocks, navigation locks, or other structures, as well as outlet works and spillways.

Release requirements specified in operating plans are expressed in terms of flow rates or discharges. Rating curves are used by reservoir operators to relate release rates to storage levels and gate openings. The rating curves are developed by hydraulic analyses of the outlet structures, typically in conjunction with pre-construction design of the project.

Reservoir Pools

Reservoir operating policies typically involve dividing the total storage capacity into designated pools. A typical reservoir consists of one or more of the vertical zones, or pools, illustrated by Figure 2.2. The allocation of storage capacity between pools may be permanent or may vary with seasons of the year or other factors.

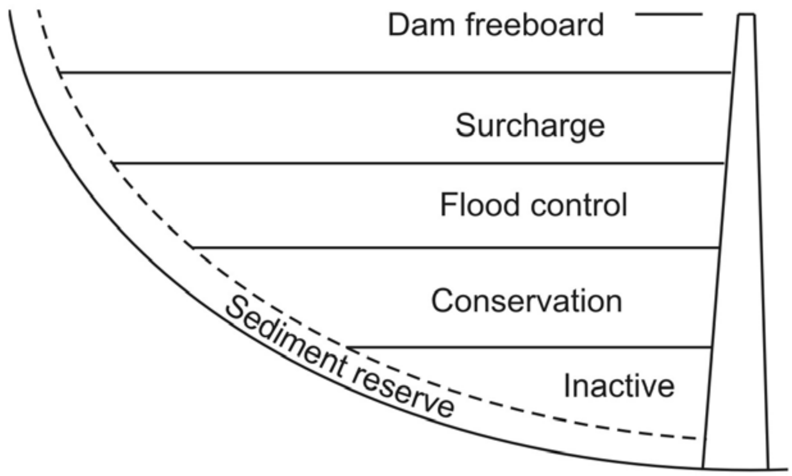

Figure 2.2 Reservoir Pools

Water is not withdrawn 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 also may 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 pool 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 storage 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 pool remains empty except during and immediately following a flood event. The top of flood control elevation is often set by the crest of an uncontrolled emergency spillway, with releases being made through other outlet structures. Gated spillways allow the top of flood control pool elevation to exceed the spillway crest elevation.

The surcharge pool 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. The maximum design water surface profile, or top of the surcharge storage, is established during project design from the perspective of dam safety. Reservoir design and operation is based on assuring that the reservoir water surface will never exceed the designated maximum design water surface elevation under any conditions. For most dams, particularly earthfill embankments, the top of dam elevation includes a freeboard allowance above the top of surcharge pool to account for wave action and provide an additional safety factor against overtopping.

Sediment Reserve

Reservoir storage capacity is lost over time due to sedimentation. The rate of sediment deposition various greatly between reservoir sites, depending on flow rates and sediment loads in the rivers flowing into the reservoirs and the trap efficiencies of the reservoirs. Since sediment transport increases greatly during flood events, reservoir sedimentation also varies greatly over time with the random occurrence of floods. As illustrated in Figure 2.2, sediment deposits occur throughout the reservoir in each of the designated pools. As streamflow velocities decrease in the upper reaches of a reservoir, sediments are deposited forming deltas. Smaller particles will move further into the reservoir before depositing. Reservoir sediment surveys are performed periodically to determine current bottom topography and resulting storage capacities. However, since the measurements are expensive, many reservoirs have existed for decades without sediment surveys ever having been performed. Thus, storage capacity estimates may be somewhat uncertain.

For many smaller reservoirs constructed by local entities, no special provisions are made to allow for sedimentation. Although it is recognized that the storage capacity of these reservoirs will significantly decrease over time, no attempt is made to estimate the volume and location of the sediment deposits at future points in time. However, for most federal projects and other large reservoirs, sediment reserve storage capacity is provided to accommodate sediment deposition expected to occur over a specified analysis period, typically 50 to 100 years. The volume and location of the sediment deposits and resulting changes in reservoir topography are predicted using methods outlined by the Bureau of Reclamation (1987) and U.S. Army Corps of Engineers (1989). Storage capacity reserved for future sediment accumulation is reflected in water supply contracts and other administrative actions.

Rule Curves and Water Control Diagrams

The terms *rule curve* or *guide curve* are typically used to denote operating rules which define ideal or target storage levels and provide a mechanism for release rules to be specified as a function of storage content. Rule curves may be expressed in various formats such as water surface elevation or storage volume 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 designation.

The top of conservation pool may be varied seasonally, particularly in regions with distinct flood seasons. The seasonal rule curve illustrated by Figure 2.3 reflects a location where summer months are characterized by high water demands, low streamflows, and a low probability of floods. The top of conservation pool could also be varied as a function of watershed moisture 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. Figure 2.4 illustrates such an operating plan where upper and lower zones are used exclusively for flood control and conservation purposes, respectively, and the storage capacity in between is used for either purpose depending on season or other factors. Also, either the flood control 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.

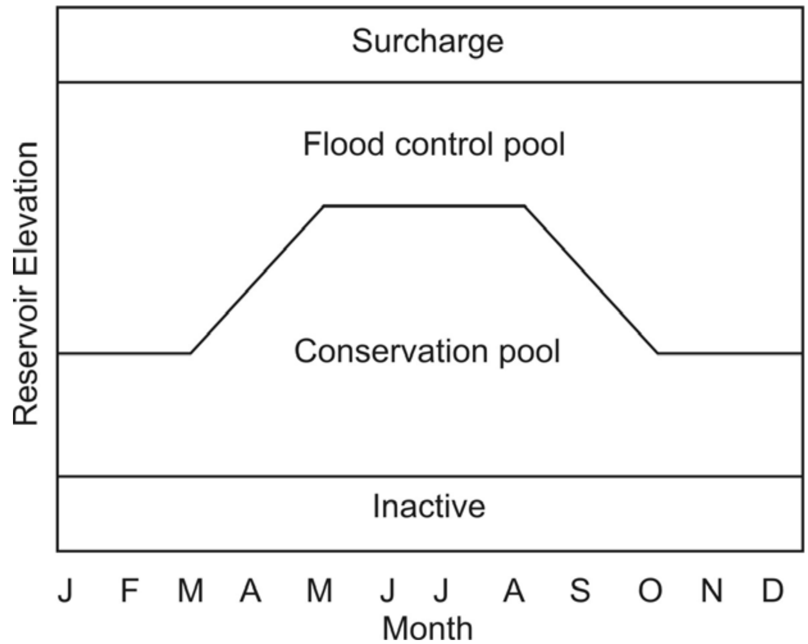

Figure 2.3 Seasonal Top of Conservation Pool

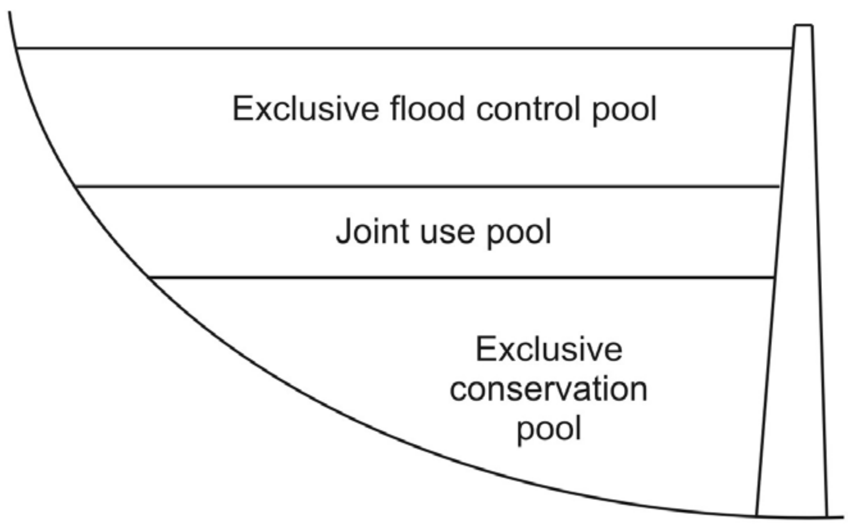

Figure 2.4 Exclusive and Joint Use Pools

Operating plans may be expressed in various formats. A water control diagram represents a compilation of regulating criteria, guidelines, rule curves, and specifications that govern the storage and release functions of a reservoir. A water control diagram or set of rule curves specify release rules as a function of storage levels, season of the year, and related factors. The format and types of rules reflected in water control diagrams vary greatly for different reservoir projects.

An example of a water control diagram for a particular reservoir is presented in Figure 2.5 (U.S. Army Corps of Engineers 1987). The Youghiogheny Reservoir on the Youghiogheny River, a tributary of the Monongahela River, in Pennsylvania is operated as a component of a multiple reservoir system in the Ohio River Basin. The Youghiogheny Reservoir is operated for flood control, hydroelectric power, and low flow augmentation for downstream navigation, water quality, and recreation (white water rafting). Releases from the conservation pool are specified in the water control diagram of Figure 2.5 as a function of uncontrolled streamflow at a gaging station located downstream, time of the year, and storage content. Reservoir storage levels are expressed alternatively as volume in acre-feet, volume equivalent in inches of runoff depth over the 434 square mile (1,120 km^2) watershed above the dam, and water surface elevation in feet above mean sea level. Storage capacities at the top of inactive pool and top of flood control pool are 5,200 acre-feet (6.4x10^6 m^3) and 254,000 acre-feet (3.13x10^8 m^3), respectively. The 248,800 ac-ft (3.07x10^8 m^3) of active storage capacity is allocated to flood control and conservation purposes by a designated top of conservation pool which varies from 103,500 ac-ft (1.28x10^8 m^3) during December through February to 154,500 ac-ft (1.91x10^8 m^3) from April to early November.

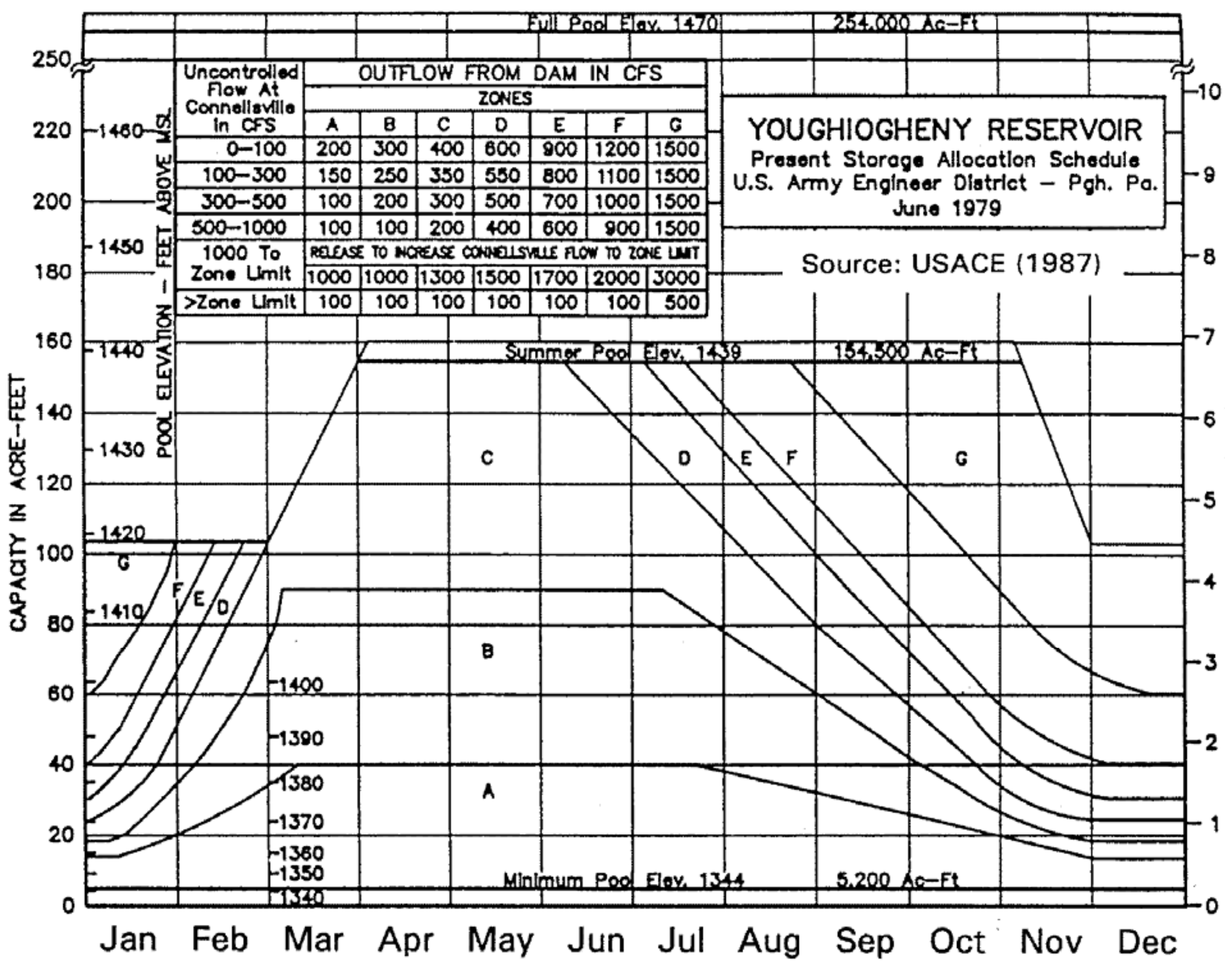

Figure 2.5 Example Water Control Diagram

Flood Control Operations

Flood control pool operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint of assuring 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 problem consists of developing an operating plan, often called a regulation schedule. Another related but distinctly different reservoir system operation problem involves making release decisions during real-time flood control operations, within the framework of the regulation schedule. The operation plan provides guidance for real-time release decisions but typically still leaves a significant degree of flexibility. Information regarding current storage levels and streamflows is used, in combination with the regulation schedule, to make release decisions. Real-time operations often involve collection of current precipitation and streamflow data and forecasting flows to be expected at pertinent locations during the next several hours or days, to enable more effective release decisions. During normal non-flooding conditions, flood control operations consist simply of passing inflows to maintain empty storage capacity.

The Corps of Engineers is responsible for operating a majority of the major flood control reservoir systems in the nation. 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, operating schedules for most reservoirs follow the same general strategy, which is outlined as follows.

Release decisions depend upon whether or not the flood control storage capacity is exceeded. Although reservoir storage capacities at many reservoirs are exceeded more frequently, federal reservoirs are typically sized to contain at least a 50-year recurrence interval (2% probability of exceedence in any year) flood and, for many projects, design floods greater than the 100-year flood (1% annual exceedence probability), perhaps much greater.

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 contribute to downstream flooding. The objective is to assure that reservoir releases do not contribute to downstream damages as long as the storage capacity is not exceeded. However, for extreme flood events which would exceed the reservoir storage capacity, moderately high damaging discharge rates beginning before the flood control pool is full are considered preferable to waiting until a full reservoir necessitates much higher release rates.

Regulation Based on Downstream Flow Rates

Flood control operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding. Maximum allowable flow rates and stages at downstream control points are set based on bank-full 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 contributing to streamflows exceeding specified maximum allowable flow levels at downstream gages.

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 gaged control points. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the downstream locations.

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, to maximize storage capacity available for regulating the forecasted flood. Pre-releases are particularly important in operating reservoirs with only limited amounts of flood control storage capacity.

For many reservoirs, the allowable flow rate associated with a given location is constant regardless of the volume of water in storage. At other projects, the allowable flow rates at one or more control points vary depending upon the volume of water currently stored in the flood control pool. 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.

Flood control reservoirs are typically operated based on maintaining flow rates at several gages located various distances below the dam. The most downstream control points may be several hundred kilometers 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 sites 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 will 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. For example, in Figure 2.6, streamflow gage 3 is used as a control point for both Reservoirs A and B; and gage 4 controls releases from all three reservoirs. Multiple-reservoir release decisions may be based on maintaining some specified relative balance between the percentages of flood-control storage capacity utilized in each reservoir. For example, if unregulated flows are below the maximum allowable flow rates at all the control points, the reservoir with the greatest amount of water in storage, expressed as a percentage of flood control storage capacity, might be selected to release water. Various balancing criteria may be adopted. Releases from all reservoirs, as well as runoff from uncontrolled watershed areas, must be considered in forecasting flows at control points.

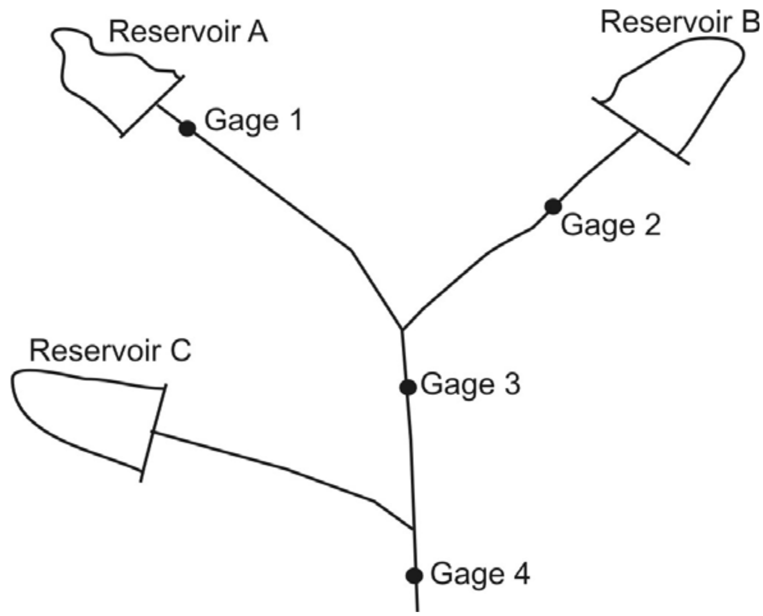

Figure 2.6 Multiple Reservoir Flood Control Operations

Maximum allowable rate of change of reservoir release rates are also specified. Abrupt gate openings causing a flood wave with rapid changes in stage are dangerous from the perspective of downstream hazards to public safety. Rapid variations in flow rates also 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 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 in excess of allowable downstream flow rates during a storm and then later learn that the flood control pool never filled and the releases unnecessarily contributed to downstream damages. 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 previously, based on downstream allowable flow rates, is followed until such time, during a flood, that the release rate indicated by the schedule outlined next is higher than that indicated by the downstream allowable flow rates. The regulation procedure outlined next is based on reservoir inflows and storage levels.

An example regulation schedule is presented in Figure 2.7 (U.S. Army Corps of Engineers 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 2.7. 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.

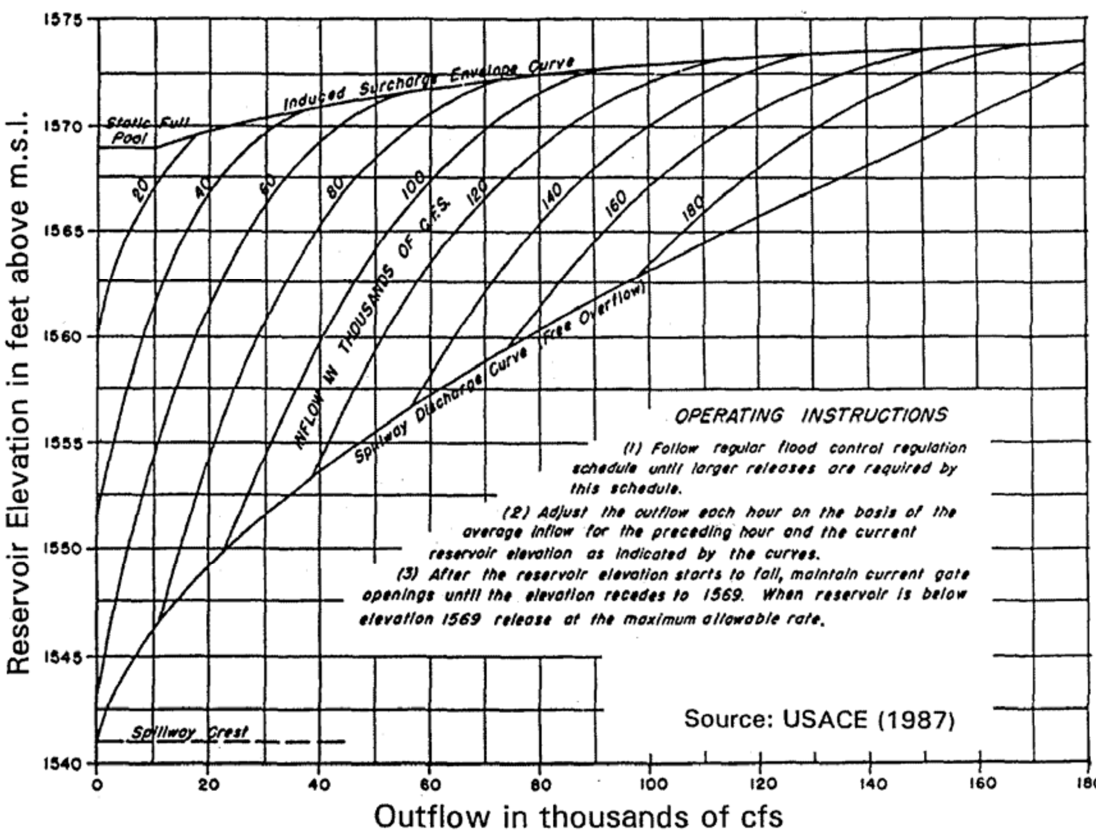

Figure 2.7 Example Flood Control Regulation Schedule

The operating plan is prepared during preconstruction planning of the project. 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 recession 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 2.7 also illustrates the concept of incorporating induced surcharge into the regulation plan. The release rates are set to allow specified encroachments into surcharge storage, above the static full flood control pool. For most of the range of conditions reflected in the regulation schedule, the gates are not fully open, and thus additional storage in the surcharge pool is induced over that which result from fully opening the gates sooner. The example regulation schedule of Figure 2.7 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.

Rivera (2004) and Rivera and Wurbs (2004) proposed a risk-based methodology for developing emergency operating curves based on historical inflow records. Stochastic generation methods are used to generate many thousands of years of daily inflows that preserve the statistical characteristics of the historical gaged inflows. Operating curves in the format of Figure 2.7 are developed based on a specified risk of storage exceeding a specified level. The research project included applying the methodology to the USACE Addicks and Barker Reservoir System in the Buffalo Bayou Watershed in Houston, Texas. The risk-based methodology is particularly pertinent for this reservoir system because urban development adjacent to the government owned flood control pool land upstream is subject to flooding as well as urban development along the downstream channel.

Conservation Storage Operations

A multitude of factors and considerations may be important in the operation of specific reservoir systems for water supply, hydropower, recreation, and other conservation purposes. 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 noted in the following paragraphs.

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 regions of the United States and the world, a reservoir will be filled during a distinct season of high rainfall or snowmelt 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 to be available during drought conditions. 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. The terms *"within-year storage"* and *"carry-over storage"* are sometimes used to differentiate between storage capacity required to handle seasonal variations in streamflows and water demands and the additional capacity required for variations between years.

Conservation storage capacity serves a variety of project purposes or types of water use. 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 acceptance of greater risks of shortages than municipal and industrial water supply and is based more on maximizing economic benefits. Irrigation involves consumptive withdrawals and significant fluctuations in reservoir storage levels. Conversely, in steam-electric power plant cooling water reservoirs, most of the water withdrawn is 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 maintaining a high reliability of meeting hydroelectric power and energy commitments while minimizing the total costs of 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. Environmental instream flow needs also include maintenance of streamflow for water quality, fish and wildlife habitat, livestock water, river recreation, and aesthetics. Reservoir operating policies may include specified flow rates to meet instream needs. Operating considerations for reservoir recreation typically involve maintenance of desirable storage levels and minimizing fluctuations in storage levels.

Reservoir operations also address requirements other than the primary project purposes. For example, due to water rights considerations, releases may be required to pass inflows through the reservoir to other more senior water users and management entities located downstream, which are not directly served by the reservoir. Such requirements may be specified in terms of maintaining minimum release rates 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 public safety hazards. Rapid increases in stage and velocity can be dangerous for people recreating in the river downstream of a reservoir. Rapid changes in release rates are also undesirable from the perspective of river bank 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 low flow augmentation. 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. Operation during floods is an important consideration for conservation-only projects without flood control storage capacity.

Multiple-Purpose and Multiple-User Operating Considerations

Multiple-purpose reservoir operation involves various interactions and trade-offs between purposes, which are sometimes complimentary but often competitive or conflicting. Reservoir operation may be based on the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space available for storing future flood waters to reduce downstream damages. Conservation pools are shared by various purposes that involve both consumptive withdrawals and in-reservoir and in-stream uses.

Common practice is to operate a reservoir for conservation only, flood control only, or a combination of flood control and conservation with separate pools designated for each. 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 modeling applications.

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.

Conservation pools typically serve multiple-purposes with at least some complimentary characteristics. Water stored for water supply and hydroelectric power provides opportunities for recreation and reservoir fisheries. Hydroelectric power releases contribute to other instream flow uses and can be diverted at downstream locations for water supply. On the other hand, sharing of reservoir storage capacity and limited water resources by multiple users involves conflicting demands.

Conservation operations may include design of a triggering mechanism by which certain demands are curtailed whenever storage falls below pre-specified levels. This allows water supply withdrawals, instream flows, and/or hydroelectric energy levels with different levels of reliability to be provided by the same reservoir. Specifying the release or withdrawal rate as a function of storage (or storage plus inflow) is sometimes called a *"hedging rule."* The storage designations, or rule curves, used as a triggering mechanism in allocating water between competing users and uses are sometimes called buffer zones. Full demands are met as long as the reservoir water surface is above the top of buffer pool, which certain demands being curtailed whenever the water in storage falls below this level. The top of buffer pool elevation may be constant or may be specified as a function of time of the year or other parameters. A range of different storage levels in one or more reservoirs may be designated as triggering mechanisms for various management decisions.

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. Storage triggering designations may also provide a mechanism for reflecting relative priorities or tradeoffs between purposes. For example, a reservoir operating plan may involve assuring a high degree of reliability for a municipality and lesser reliability for agricultural irrigators. All demands are met as long as storage is above a specified level, but the irrigation demands are curtailed whenever storage falls below the specified level. Release requirements for maintaining instream flows for fish and wildlife habitat and/or freshwater inflows to estuaries may be conditioned upon storage being above a specified buffer level. Implementation of drought contingency plans may be triggered by the storage level falling below a specified buffer level. More severe demand management options may be implemented as storage contents fall below various pre-specified levels. Conjunction management of ground water and surface water sources may involve shifting to greater use of groundwater whenever reservoir storage falls below designated levels.

Multiple-Reservoir System Operations

Multiple-reservoir release decisions occur in situations in which water needs can be met by releases from two or more reservoirs. In Figure 2.8, diversions 1 and 3 are from specific reservoirs, but diversion 4 can be met by releases from either of the three reservoirs. Instream flow, as well as diversion, requirements at diversion location 4 can be met by releases from the reservoirs.

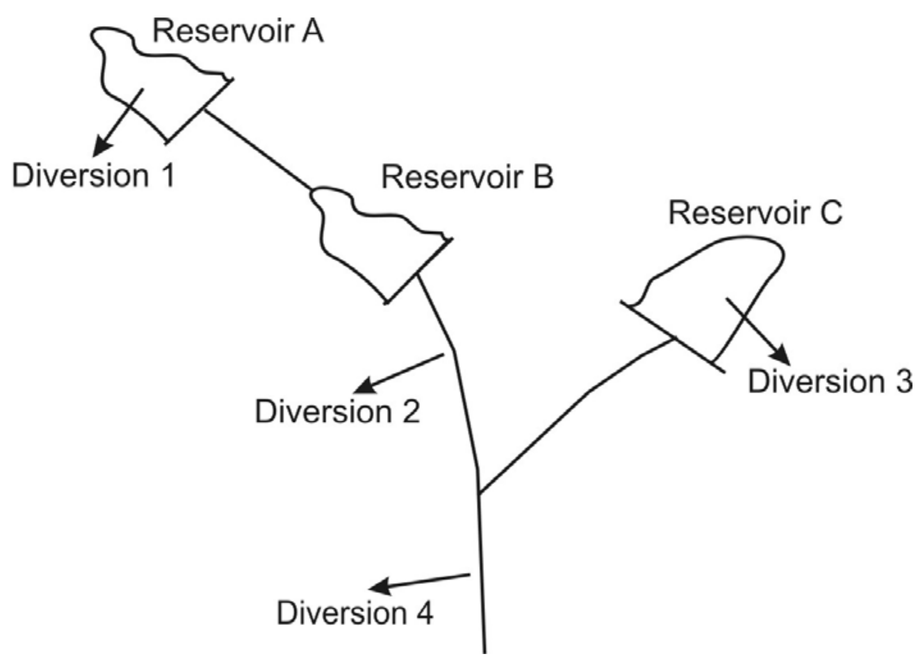

Figure 2.8 Multiple Reservoir Conservation Operations

One criterion for deciding from which reservoir to release is to minimize spills, since they represent water loss from the system. Spills from an upstream reservoir (such as reservoir A in Figure 2.8) may still be stored in a downstream reservoir (reservoir B) 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. For reservoirs in series, such as Reservoirs A and B in Figure 2.8, 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 by gravity flow to each diversion location. For example, water stored in Reservoir A can be used to meet diversions 1, 2, and 4, but water stored in Reservoir B can be used to meet only diversions 2 and 4.

For reservoirs in parallel, such as Reservoirs B and C in Figure 2.8, 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 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 in Figure 2.9, 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 rules actually followed by reservoir operators. 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, in meeting the downstream diversion (or instream flow) requirement of Figure 2.9, water is not released from zone 2 of one reservoir until zone 1 has been depleted in all the reservoirs. Since zone 1 in Reservoir A is assigned zero storage capacity, no releases are made from Reservoir A until zone 1 is empty in the other two reservoirs. With the storage content falling in the same zone of each reservoir, the release is made from the reservoir which is most full in terms of percentage of the storage capacity of the zone. For example, if the storage capacities of zone 2 of Reservoirs A, B, and C, respectively, are 55%, 60%, and 68% full, a release is made from Reservoir C to meet the downstream diversion requirement. Variations of this general type of multiple-reservoir release rule can be formulated.

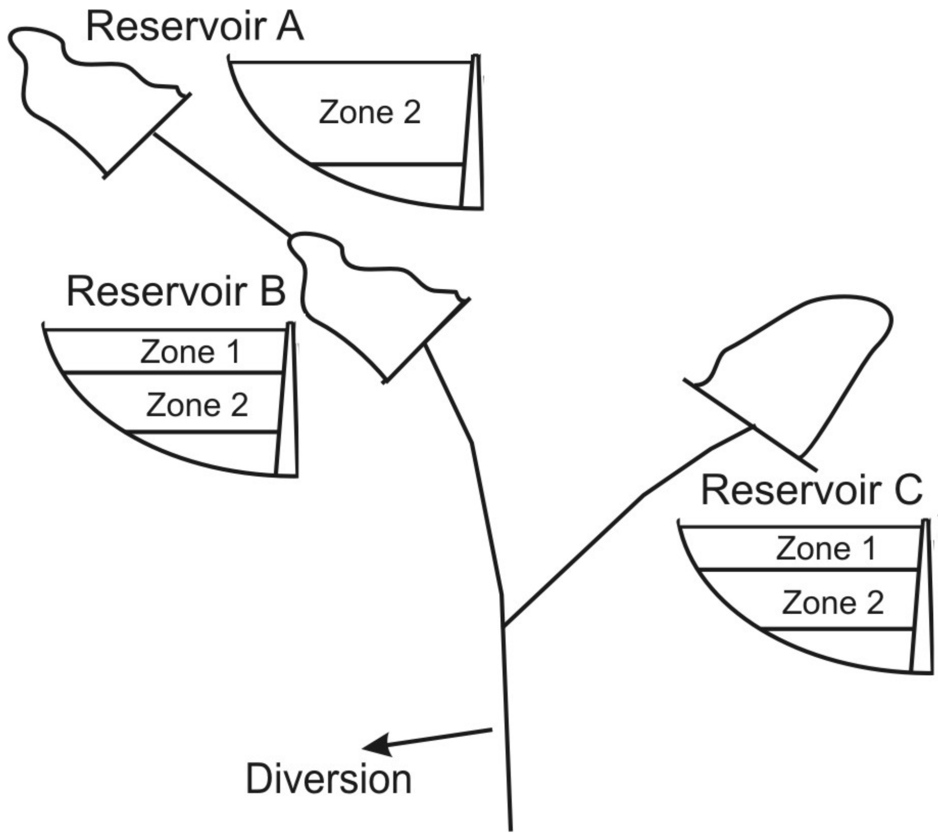

Figure 2.9 Storage Zones for Defining Release Rules

Water Supply

Water is diverted or withdrawn from rivers and reservoirs for municipal, industrial, agricultural, and other beneficial uses. During normal hydrologic conditions, real-time reservoir operations involve meeting water demands in accordance with the commitments and responsibilities of the water supply agencies. During low flow or drought conditions, operations may involve allocating limited water resources to competing users within the institutional framework of project ownership and agency responsibilities, contractual agreements, legal systems for allocating and administering water rights, and political negotiations.

Developing and administering water supply contracts and agreements, water rights allocation systems, and reservoir operating plans involve various types of reservoir system operation decision problems, which can be categorized as follows:

- allocation of a limited amount of water between competing uses and users
- within-year temporal allocation of a limited amount of water (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 and the amount of water to be carried over in storage into the next year

- coordination of water supply operations with demand management strategies and other sources of supply such as groundwater
- coordination of water supply operations with other project purposes
- coordination of the releases from each reservoir of a multiple reservoir system
- and various combinations of the above

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. Municipal and industrial water supply typically requires a particularly high level of reliability. Project planning and design, contractual agreements, and water rights are typically based on assuring a very dependable supply.

Supplying water for irrigation often involves acceptance of greater risks of shortages than municipal and industrial water supply. 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.

The amount of water required to meet the demands for growing crops for the entire season is called the water duty. This is equal to the amount of water supplied to the land by means of gravity diversions from rivers and reservoirs or pumped from rivers, reservoirs, or groundwater aquifers. Net duty is the amount of water delivered to individual farm units, considering losses in canals, laterals, and waste from the point of diversion to the point of application to the land. Irrigation water diverted from reservoirs, diversion dams, or natural river channels is controlled in a manner to supply water for the irrigation system as necessary to meet water duty requirements, which vary seasonally. In most irrigated areas of the western United States, the agricultural growing season begins in the spring months of April and May. The diversion requirements gradually increase as the summer progresses, reaching their maximum amounts in July or August. By the end of the growing season, irrigation requirements are terminated. The return flow of water from irrigated lands is collected in drainage channels and flows back into natural creeks and rivers. The return flows may vary from essentially zero to greater than half of the diversion amounts. Increases in salinity concentrations are often associated with irrigation return flows.

Shifting to a greater reliance on demand management has been a major emphasis in recent years in all sectors including municipal, industrial, and irrigation. Implementation of appropriate demand management strategies is an important consideration in determining water needs to be supplied by reservoirs. Implementation of short-term or emergency demand management measures are dependent on current reservoir storage levels and associated risks of future shortages in supply. Coordination of reservoir operations and demand management programs is important.

Multiple-reservoir system operation involves coordinated releases from two or more reservoirs to supply common diversions or instream flow needs at downstream locations. Under appropriate circumstances, multiple-reservoir system operations can significantly increase reliabilities, as compared to operating each individual reservoir independently of the others. Coordinated releases from two or more reservoirs increase reliabilities by sharing the risks associated with the individual reservoirs not being able to meet their individual demands. Operated independently, 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.

Another key aspect of system operation involves use of unregulated flows entering the river below the most downstream dams but above the location of water supply diversions. For example, the diversion in Figure 2.9 is partially supplied by surface runoff and baseflow from subsurface sources entering the river below Reservoirs B and C. This unregulated streamflow does not flow into any reservoir but flows past pumping plants where water is diverted from the river for beneficial use. Unregulated river flows are typically highly variable, of significant magnitude much of the time, but zero or very low some of the time. Thus, unregulated flows 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 water supply capabilities.

Hydroelectric Power

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, hydroelectric power generation is limited essentially 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 re-regulated 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.

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 2.10, 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 less evaporation and 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.

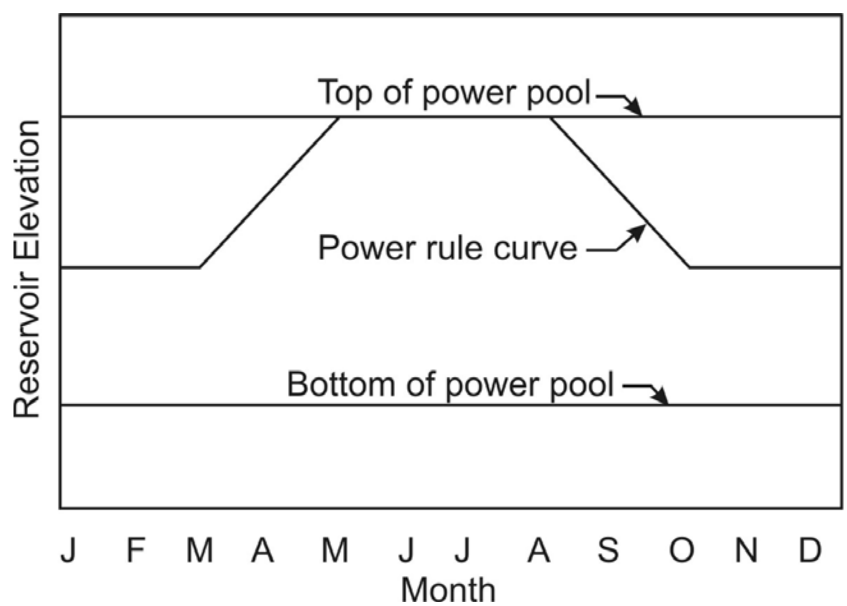

Figure 2.10 Hydroelectric Power Rule Curve

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 conditions and power demands of the particular area. For example, the rule curve shown in Figure 2.10 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 power rule curve is typically developed 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 streambank erosion.

Navigation

The Corps of Engineers is the primary agency in the United States responsible for navigation improvements. During the past century and a half, the Corps of Engineers has been involved in the improvement for navigation of some 35,000 kilometers of inland and coastal waterways. Navigational improvements include canals, locks, dams and reservoirs, maintained channels and estuaries, bank protection, and channel stabilization measures.

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 normal depth of flow 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 involve 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. Typical objectives considered in developing and evaluating reservoir operating plans for navigation 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

The general public uses reservoirs and rivers for boating, swimming, fishing, and other recreational activities. Reservoir operating plans include consideration of recreation in the reservoir, along the shore, in the river just below the dam, and at river locations further downstream.

Recreational aspects of reservoir operations involve maintaining storage levels and minimizing fluctuations in storage 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 storage level. Under most circumstances, the optimal recreation use of reservoirs would require that the water level be maintained at or near top of conservation pool during the recreation season. This is often infeasible due to other project purposes.

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. Operating plans often include specification of minimum streamflows and possibly augmented flows during short periods for special activities such as river rafting.

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.

The effects of reservoir regulation on the aesthetics of the riverine environment are closely related to public use. Aesthetic considerations in reservoir operating plans may involve maintaining minimum streamflows, releasing water for special aesthetic purposes, or minimizing the duration of exposure of mud flats or unsightly shoreline resulting from drawdowns.

Water Quality Management

Water quality encompasses the physical, chemical, and biological characteristics of water. Both natural water quality and man-induced changes in quality are important considerations in river basin management.

Water Quality Aspects of Reservoir System Operations

Water quality and the aquatic environment may be significantly impacted by reservoir management practices. Water quality requirements for reservoir releases may involve both flow rates and quality parameters. Low flow augmentation, or maintenance of minimum streamflow rates at downstream locations, is a primary water quality operating objective at many reservoir projects. The quality of the releases is controlled at many projects through multiple-level selective withdrawals.

Common reservoir water quality problems include turbidity, suspended solids, and associated impacts on fisheries, algae, and water quality. Pollution from watershed activities such as acid mine drainage, oil field operations, agricultural activities, and municipal and industrial wastewater effluents are problems in many areas. Problems are often related to eutrophication. Eutrophication is the process of excessive addition of organic matter, plant nutrients, and silt to reservoirs at rates sufficient to cause increased production of algae and rooted plants. Symptoms of eutrophication include algae blooms, weed-choked shallow areas, low dissolved oxygen, and accumulation of bottom sediments. Resulting problems include elimination of reservoir fisheries, adverse impacts on downstream ecosystems, degradation of water supplies, and reduced storage capacity.

Reservoir water quality problems may also be related to seasonal stratification. As illustrated by Figure 2.11, in a stratified lake, the well mixed surface layer, called the *epilimnion*, and the colder bottom layer, called the *hypolimnion*, are separated by a layer of sharp temperature gradient, called the *metalimnion*. Most impoundments exhibit some degree of temperature stratification. In general, deeper lakes are more likely to become highly stratified each summer and are not as likely to become mixed by wind or short-term temperature changes. When the surface of the lake begins to receive a greater amount of heat from the sun and air than is lost, it becomes warmer and less dense, while the colder, more dense water remains on the bottom. In the layer of colder water near the bottom, little if any oxygen is transferred from the air to replace that depleted by oxidation of organic substances, and, eventually anoxia may develop. Under this condition, a reducing environment is created, resulting in elevated levels of parameters such as iron, manganese, ammonia, and hydrogen sulfide. Changes such as these may result in water that is degraded and toxic to aquatic life.

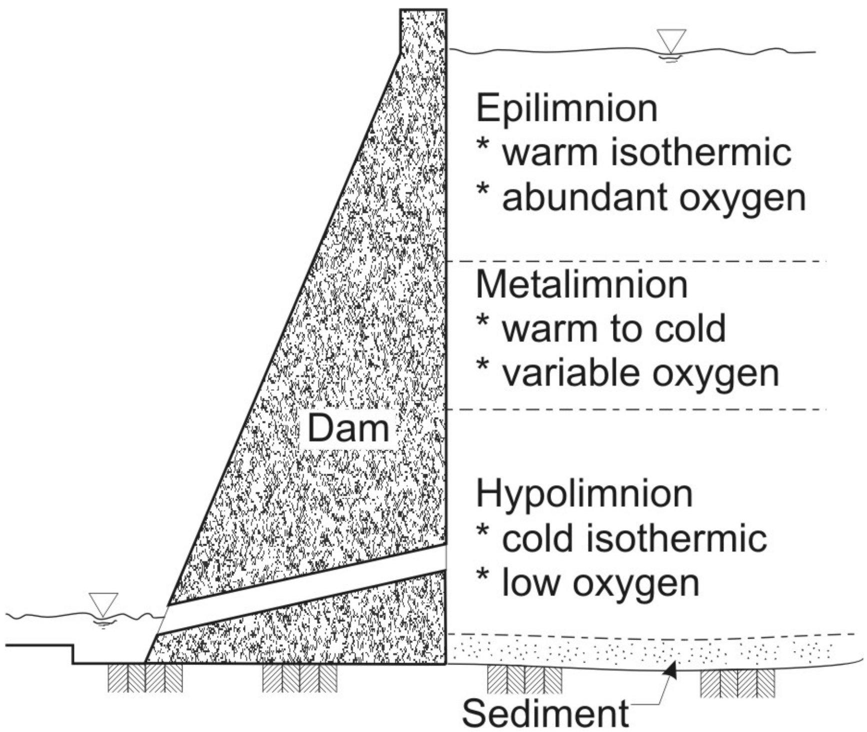

Figure 2.11 Thermally Stratified Reservoir

A primary means of managing the water quality of reservoir releases is to control the vertical levels at which water is withdrawn from the reservoir. Many reservoir projects include outlet works intake structures providing multilevel withdrawal capabilities. The reservoir operating decision problem involves establishing the desired temperature, dissolved oxygen, and other water quality criteria and selecting the elevations at which to make releases to meet the criteria. Water from different levels may have to be mixed to meet the different water quality criteria. Management of water quality in the reservoir pool may also be a consideration in selective withdrawals from multilevel intake structures. Good and poor quality water can be blended to meet the release criteria with a minimum of good and maximum of poor quality water. This type of release policy will help to prevent a deterioration of quality in the reservoir which could lead to an eventual inability to meet the release criteria.

Natural Salt Pollution Control

Dissolved solids or salts are the inorganic solutes that occur in all natural waters because of weathering of rocks and soils. Total dissolved solids (TDS) or salinity increases as waters move over the land surface and through soils and aquifers. Evaporation and transpiration increase concentrations. Human activities such as irrigated agriculture and construction of reservoirs increase evaporation and the salinity of land and water resources. Ground water pumping, oil field operations, and municipal use and wastewater disposal activities may also increase salinity. The ocean is a major source of salt in coastal areas. Salinity plays an important role in water resources development and management throughout the world, particularly in relatively arid regions. In the United States, salinity is a particularly important consideration in the states located west of the Rocky Mountains as well as in Texas and neighboring states.

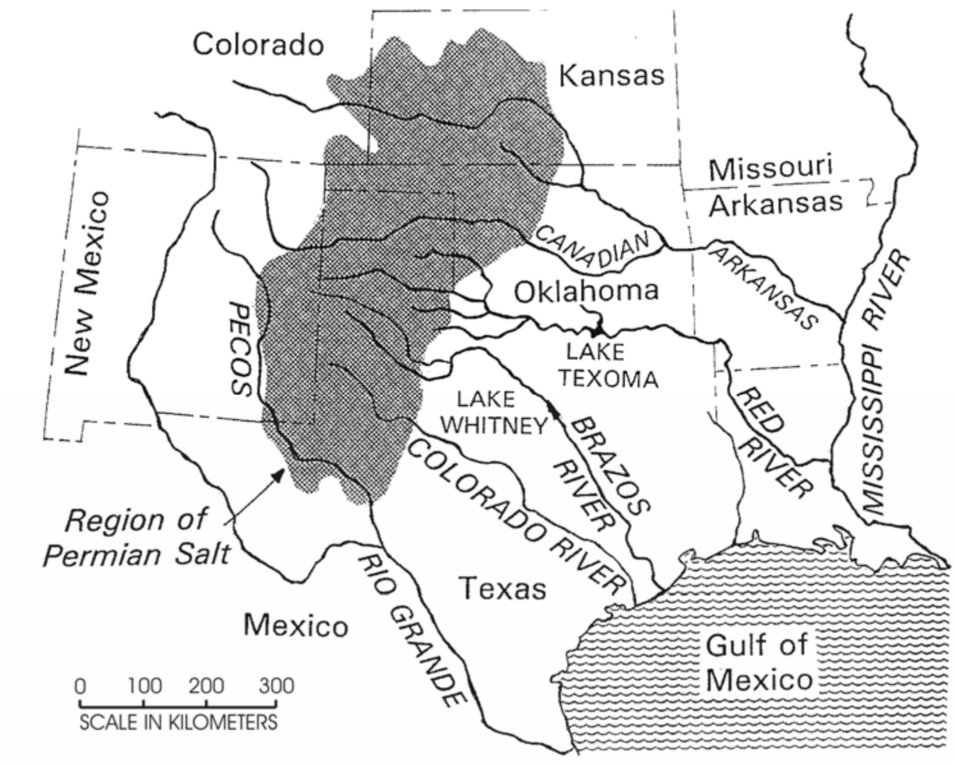

Figure 2.12 Natural Salt Pollution in the Southwest

In the Southwestern U.S., geologic formations underlying the upper watersheds of the Rio Grande, Pecos, Colorado, Brazos, Red, Canadian, and Arkansas Rivers in Texas, New Mexico, Oklahoma, Kansas, and Arkansas contribute large salt loads to these rivers. Most of the salt loads in the river/reservoir systems originate from formations at shallow depths within the Permian Basin geologic region delineated in Figure 2.12. During the Permian age about 230 million years ago, this region was covered by a large inland sea. Thick deposits of halite were formed as evaporating sea water precipitated salts. The semiarid region now consists of gypsum and salt-encrusted rolling plains containing numerous salt springs and seeps that contribute large salt loads to the rivers. The mineral pollutants consist largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids. The primary salt source subwatersheds of these major river basins have streams with extremely high total dissolved solids (TDS) concentrations that at some locations exceed TDS concentration of seawater. Salt concentrations in the downstream reaches of the rivers decrease with dilution from low-salinity tributary inflows.

Population and economic growth combined with depleting groundwater reserves have greatly increased demands on the water resources of these river basins. Salinity severely limits use of large amounts of streamflow and reservoir storage in areas where water demands are surpassing supplies. Many studies have been conducted to develop strategies for dealing with the salinity. Several of many proposed salt control plans have been implemented. Economic feasibility, institutional difficulties, environmental concerns, and lack of funding have prevented or delayed construction of most proposed projects. Measures for dealing with salinity that have been implemented or serious considered fall into three categories: (1) dilution of high-salinity water with better quality water, (2) desalination plants for treating municipal and industrial supplies, and (3) collection and disposal of brine in primary source areas. Brine collection facilities include both shallow well systems and surface impoundments. Disposal facilities include both deep-well injection and surface storage (Rought 1984; Wurbs 2002).

Environmental Management

Ecological systems are the interacting components of air, land, water, and living organisms including humans. From a water resources perspective, an ecosystem could be anything from a drop of water to the entire global hydrologic cycle. From the perspective of river basin management, the concept of ecosystem management emphasizes protection and restoration of natural resources including fish and wildlife, vegetation, and various aquatic and riparian ecosystems including streams, lakes, wetlands, estuaries, and coastal waters (Mac *et al*. 1998).

Environmental resources management opportunities and problems associated with reservoir operations vary widely between regions and between reservoirs. Reservoir operations influence fish, wildlife, and ecological systems both in the reservoir pool and in the river downstream.

Reservoir releases contribute to maintenance of instream flows necessary for the support of aquatic habitat and species, protection or enhancement of water quality, preservation of wetlands, and provision of freshwater inflows to bays and estuaries. Reservoir operating plans may include maintenance of specified minimum flow rates at downstream locations. Periodic flooding as well as low flow augmentation may be important for certain ecosystems. The required flow rates may be specified as a function of season, reservoir storage, reservoir inflows, and other factors.

Reservoir releases for downstream fishery management depends upon water quality characteristics and water control capabilities. Achieving optimal temperatures for either cold water or warm water fisheries through selective multilevel releases may be an operating objective. Maintenance of dissolved oxygen levels may be an operating objective. Releases can be beneficial for maintaining gravel beds for certain fish species. Dramatic changes in release rates, typically associated with hydropower and flood control operations can be detrimental to downstream fisheries.

Migration of anadronomous fish, such as salmon in the Pacific Northwest and striped bass in the Northeast, is a concern in some regions. Declines in anadronomous fish populations have been attributed to dams due to blockage of migration, alteration of normal streamflow patterns, habitat modification, blockage of access to spawning and rearing areas, and changes in water quality. Regulation for anadromous fish is particularly important during certain seasons of the year.

Project regulation can influence fisheries in the pool as well as downstream. Water surface level fluctuations is one of the most apparent influences of reservoir operation. Periodic fluctuations in water levels present both problems and opportunities in regard to reservoir fisheries. The seasonal fluctuations that occur at many flood control projects and daily fluctuations at hydropower projects often eliminate shoreline vegetation and cause subsequent shoreline erosion, water quality degradation, and loss of habitat. Adverse impacts of water level fluctuations also include loss of shoreline shelter and physical disruption of spawning and nests. Beneficial fisheries management techniques include: pool level management for weed control; forcing forage fish out of shallow cover areas, making them more susceptible to predation; and maintaining appropriate pool levels during spawning.

Erosion and Sedimentation

Natural stream erosion and deposition processes are significantly altered through the construction and operation of reservoir projects. The impacts of individual projects vary significantly, depending on the streamflow and sediment characteristics of the parent stream, and the specific operating rules of a given project. Interruption of the natural sediment processes of a stream generally results in deposition of sediment in the upstream reservoir area, and corresponding erosion and degradation of the streambed and banks immediately downstream from the project. The location of deposits in the reservoir is a function of the size of the reservoir, the amount and gradation of the sediments being transported, and the pool level at the time of significant inflow. The amount of bank and shoreline erosion is closely related to the rate and magnitude of the pool level fluctuations.

Large reservoir projects frequently trap and retain essentially all of the suspended sediment and bed material load within the upstream pool, thus releasing sediment free water. These releases are capable of eroding the bed and banks of the river downstream of the outlet structure. The extent of this erosion is related to the composition of the bed and bank material, the volume of water released on an annual or seasonal basis, release rates and flow velocities, and the manner in which the flow is released. Fluctuating releases often result in an initial loss of the banks. This loss is closely related to the magnitude of the stage fluctuation. The recession of banks due to fluctuating releases usually stabilizes in the first few years of operation, as the underwater slope reaches a quasi state of equilibrium. Once this equilibrium slope has been achieved, the bank erosion process behaves as in the natural channel. Periodic wetting and drying of the banks through fluctuating releases accelerates this process. Reservoir releases also result in lowering the streambed, with the maximum amount of lowering occurring immediately downstream from the outlet structures, and decreasing in the downstream direction. This degradation process continues until the slope is reduced to its equilibrium value and/or the bed becomes naturally armored by removal of the fines, which exposes the coarser, non-erodible bed materials. After the bed becomes naturally armored, future lowering of the streambed is usually insignificant.

Channels downstream from small and medium size reservoir projects often exhibit entirely different characteristics than described above for large reservoirs. Channel capacity below the smaller reservoirs tends to be lost over time. Reservoir projects that make only limited releases may result in extensive deposition and subsequent vegetative encroachment in the downstream channel. With construction of a reservoir, the pre-construction periodic flushing flows, that are capable of removing deposits near the mouth of tributaries, are often replaced by low non-erosive reservoir releases. This contributes to the loss of channel capacity and reservoir operating flexibility.

Reservoir shorelines are subject to a number of forces contributing to their instability, and frequently undergo major changes during the life of a project. Fluctuating pool levels saturate previously unsaturated material, resulting in massive slides when the pool is drawn down to lower levels. This material accumulates at the base of the slope, and often forms an underwater bench, leaving steep unstable slopes above the water line. Reservoir banks are also subject to attacks by both wind and waves, which tend to remove this material and undercut the banks.

Sediment deposits in the reservoir pool are an important consideration, since storage capacity and many reservoir management activities are adversely impacted. Sediment deposits occur throughout a reservoir but particularly in the upper reaches where inflow velocities are reduced by the impoundment. The impacts of sediment accumulations, over the life of the reservoir, should be recognized in project planning and operation.

Much of the erosion and deposition process is beyond the control of reservoir managers. However, the following precautions can significantly minimize problems (U.S. Army Corps of Engineers 1987).

- Minimize the rate of reservoir pool drawdown.
- Avoid sudden increases in reservoir releases and subsequent downstream stage fluctuations.
- Keep reservoir pool levels as low as possible during known periods of high sediment inflow, thus encouraging sediment to deposit in the lower zones of the reservoir.
- Periodically raise pool levels high enough to inundate existing sediment deposits, thus precluding the establishment of permanent vegetation and subsequent increased sediment deposits in the backwater reaches entering the pool.
- Schedule periodic releases through the outlet works to preclude sediment accumulations in and near the intake structure and in the downstream channel.
- Be aware of conditions that may impact on the erosion/deposition process, such as the potential for ice jams, tributary inflow, shifting channels, and local constraints, and adjust regulation criteria to minimize adverse impacts.

Chapter 3
Structure of Reservoir/River System Management Models

The general structure and organization of reservoir/river system modeling software and computational methods are outlined in Chapters 3, 4 and 5 prior to exploring specific models in Chapters 6 and 7. Model components and analysis methods are discussed in Chapter 3.

Computer Modeling Systems

Generalized modeling systems include the following software components:

- one or more computational engines that simulate the real-world system
- programs for acquiring, preparing, checking, manipulating, and storing input data
- programs for managing, analyzing, interpreting, summarizing, displaying, and communicating simulation results
- user interfaces to facilitate use of the software

A generalized reservoir/river system model is combined with input data that characterize the spatial configuration, hydrology, physical facilities, water management practices, and water use requirements for the river basin or region of concern.

Reservoir/river systems are modeled with sets of computational algorithms that process various data. A user interface allows the model-user to enter information and instructions, control the software and data files, and access modeling results. Data management programs facilitate the handling of input and output. Model development in recent years has been characterized by an emphasis on interactive user interfaces and data management systems oriented toward using advances in computer technology to make models more efficient to use. Graphical user interfaces are popular. A graphical user interface is particularly important for applications involving the production or processing of graphic images such as maps, diagrams, drawings, and charts. An array of data management programs has been used with reservoir system analysis models to store, manipulate, and analyze various types of data including time series, parametric, and spatial data.

Reservoir/river system analysis applications often involve integration of several different types of models. For example, a water quality model might be combined with an operations model dealing with water quantities. A watershed hydrology (precipitation-runoff) model may be used to develop runoff hydrographs and pollutant loadings for input to reservoir operation models, which in turn determine discharges and contaminant concentrations at pertinent locations in the river/reservoir system. Other models are used to establish diversion and instream flow requirements. The modeling system could also include a river hydraulics model to compute flow depths and velocities. A geographic information system, database program, spreadsheet, graphics package, and other data management programs are included in the modeling system to: (1) develop and manage voluminous input data, (2) perform statistical and graphical analyses of simulation output, and (3) display and communicate results.

The concept of decision support systems became popular during the 1980's in the water management community as well as in business, engineering, and other professional fields in general. A decision support system is a user-oriented computer system that supports decision-makers in addressing unstructured problems. The general concept emphasizes:

- solving unstructured problems which require combining the decision-makers' judgment with quantitative information
- capabilities to answer *"what if"* questions quickly and conveniently by making multiple runs of one or more models
- use of enhanced user interfaces and graphical displays

Decision support systems include a collection of software packages and hardware. For example, decision support systems are used for real-time flood control operations. Making release decisions during a flood event is a highly unstructured problem because reservoir operations are highly dependent on operator judgment as well as pre-specified operating rules and current and forecasted streamflows, reservoir storage levels, and other available data. The decision support system includes: user interface software; data management programs; watershed runoff, stream hydraulics, and reservoir/river system operation models; a computer with various peripheral hardware devices; and an automated real-time hydrologic data collection system.

The reservoir/river system analysis models cited in this report are often used as components of decision support systems. The models are also often applied in other planning, design, and resource management situations that do not exhibit all the characteristics attributed to decision support systems. For example, models are frequently used to develop firm yield versus storage capacity relationships for feasibility studies, within a setting that may not necessarily qualify as a decision support system. The relationships between decision-making processes and modeling systems vary depending on the particular water management application.

Generalized Versus Site Specific Models

A computer model may be developed for a specific reservoir/river system or may be generalized for application to essentially any reservoir/river system. With site-specific models, unique features of the particular reservoir system are built into the computer code. Numerous customized site-specific models have been applied in evaluating the operation of various systems throughout the nation and world. The concepts and methods adopted in these models and the lessons learned in their development and application are certainly pertinent to other river basins. However, the computer software is not designed to be applied to other reservoir systems. Modifications in operating polices and other changes may also be difficult to model for the reservoir/river system for which the site-specific modeling system was developed.

Fifteen generalized modeling systems are listed in Tables 6.1 and 6.2 of Chapter 6. Generalized models are designed for application to a range of problems dealing with systems of various configurations and locations, rather than being developed to analyze one specific reservoir system. With a generalized model, the unique features and information reflecting the particular reservoir system of concern are provided in the input data. Thus, the meaning of the generic term *model* varies with the context. For example, the HEC-ResSim *model* is a generalized package of computer software available from the USACE Hydrologic Engineering Center. A *model* of the

Buffalo Bayou flood control system in Houston consists of the HEC-ResSim software combined with an input data files developed for that particular reservoir/stream system.

The general trend in recent years has been to shift away from customized system-specific models to generalized models. Multiple applications of generalized software are usually the optimal use of available expertise, time, and funds. Formulating algorithms, devising data management schemes, writing and debugging code, and testing new programs are extremely time consuming and expensive and need not be repeated for every reservoir/river system that is modeled.

Models may also fall somewhere between the extremes of being customized for a specific system and being completely generalized. A computer program may be developed specifically for a particular reservoir system, with features included in the code to facilitate future adaptation to other reservoir systems. Generalized models may also provide various capabilities for customization.

Flood Control Versus Conservation Purposes

Reservoir purposes represent a key consideration in formulating a modeling and analysis approach. The distinction is particularly significant between flood control and conservation storage purposes such as municipal, industrial, and agricultural water supply, hydroelectric power, navigation, recreation, and maintenance of instream flows for fish and wildlife or water quality purposes. Reservoir operating rules are different for flood control and conservation purposes. Computational algorithms and data requirements are also different. Although capabilities for analyzing both flood control and conservation operations are combined in some models, other models focus on one or the other type of operation.

Hydrologic analyses of floods are probabilistic event oriented, and droughts are long-term stochastic time series 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 a computational time step in the range of one hour to one day. Modeling flood wave attenuation effects is important. Hydrologic routing or perhaps hydraulic routing is required.

Conservation storage reservoirs 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 often based on daily or weekly streamflow and evaporation rates, a monthly interval is more typical for planning studies. Conservation storage models also vary in their capabilities for analyzing the various conservation purposes. For example, a model may be categorized by whether or not capabilities are provided for analyzing hydroelectric power operations.

The Corps of Engineers has played a particularly notable role in developing models for analyzing flood control operations as well as operations of conservation storage. The Tennessee Valley Authority also has an extensive background in modeling both flood control and conservation operations. Modeling studies, other than Corps and TVA studies, in the United States have tended to most often be concerned primarily with conservation purposes, with flood control being a secondary consideration.

Reservoir Operation Models Versus Other Related Models

This report deals with reservoir/river system models constructed around algorithms that simulate storage, release, flow, and diversion of water in a system of reservoirs and associated river reaches. An array of other types of computer models and evaluation procedures also play important roles in analyzing reservoir/river systems, including:

- water requirements models for estimating present and future needs for ecosystem, agricultural, municipal, and industrial water uses
- watershed hydrology (precipitation-runoff) models for synthesizing streamflows from rainfall and snowfall data
- stochastic hydrology models for synthesizing streamflows which preserve statistical characteristics of the historical streamflows
- statistical analysis methods for analyzing model input and output and other data
- river hydraulics models for predicting flow rates, stages, and velocities
- methods for analyzing the hydraulics of water control structures
- erosion and sediment transport models
- water quality models for simulating the transport and transformation of water quality constituents and characteristics
- ground water models and methods for analyzing interactions between surface and ground water systems and conjunctive management
- comprehensive water budget models for accounting for water uses and surface and ground water supplies
- economic evaluation methods
- environmental impact analysis methods
- data management software for collecting, storing, manipulating, analyzing, displaying, and otherwise managing time series, spatial, and static data

Models and methods from several or all of the categories listed above may be applied together in evaluating the operations of a particular reservoir/river system. All of the modeling and analysis categories listed have been incorporated into reservoir operation models and/or applied in combination with reservoir operation models. These modeling and analysis methods are also applied in many other water resources planning and management situations that do not necessarily involve reservoir/river systems.

Water quality management aspects of reservoir operations involve both flow rates and quality parameters. Maintaining minimum instream flows is a primary water quality operating objective of many reservoir systems. At many reservoir projects, the quality of the releases may be controlled through multiple-level selective withdrawals, since thermal stratification can significantly affect water quality characteristics. Many reservoir system analysis models deal only with water quantities, but may still address instream flow quantity requirements for managing water quality. Other models incorporate temperature, dissolved oxygen, salinity, and other more complex physical, chemical, and biological parameters.

Components of Reservoir/River System Models

Reservoir/river system models are based on volume-balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. The model computes storage contents and flows for given sequences of hydrologic inputs (streamflows and reservoir evaporation rates) and operating rules. Some models simulate water quality constituents as well as water quantities. Some models include features for economic evaluation of system performance. Reservoir/river system models are often components of larger modeling systems that include watershed hydrology and river hydraulics models and spatial and time series databases and software for managing the simulation input and output data.

Reservoir/river system models typically include features for representing the:

- spatial configuration of the river basin system
- river basin hydrology
- physical characteristics of reservoirs, spillways and outlet works, hydroelectric power plants, and other water control facilities
- system operating rules
- water use requirements
- effects of basinwide water management on the reservoir/river/use system of concern and vice versa the effects of the system of concern on basinwide water management
- measures of system performance

Spatial Configuration

The spatial configuration of a river/reservoir/use system is typically represented by a set of index locations called nodes, stations, or control points. The location of reservoirs, diversions, return flows, instream flow requirements, streamflows, and other system features are specified by control point. For example the system shown in Figure 3.1 is modeled as a set of 12 control points.

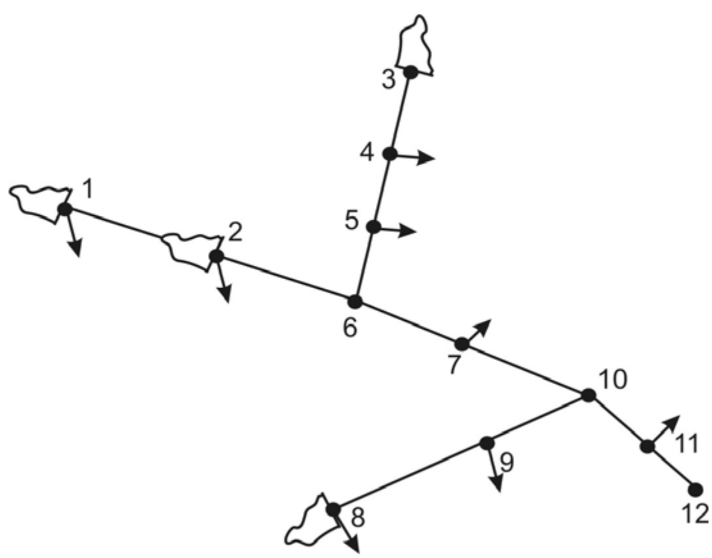

Figure 3.1 Reservoir/River System Schematic

River Basin Hydrology

Basin hydrology is represented by sequences of streamflows and reservoir evaporation rates, which are provided as input to the reservoir/river system operation model. Water quality parameters are also included in some models. Historical gaged streamflows may be adjusted to represent flow conditions at pertinent locations for a specified past, present, or future condition of river basin development. In some cases, particularly in flood control studies, watershed modeling is used to compute streamflows from precipitation data. In applying sequential reservoir operation models, the inputted streamflow sequences consist of either:

1. adjusted historical period-of-record streamflows
2. adjusted historical streamflows during a critical drought period, flood event, or other selected sub-period of the period-of-record
3. synthetically generated flows which preserve selected statistical characteristics of the adjusted historical streamflow record
4. flows computed with a watershed hydrology model from either gaged precipitation or synthetic storms

Reservoir/river system modeling analyses involving conservation operations are typically based on sequences of adjusted historical period-of-record or critical-period streamflows. Studies of flood-control operations include flood hydrographs computed using watershed precipitation-runoff models as well as adjusted historical gaged streamflows. Other stochastic hydrology approaches based on either synthetically generated streamflow sequences or transition-probability matrices have been used in studies reported in the literature, most typically in university research projects.

Developing a complete set of homogeneous streamflows covering the period of analysis at all pertinent locations typically represents a major portion of the total work required for a modeling study. Modeling studies are commonly based on historical gaged streamflow data adjusted to represent flow conditions at pertinent locations for a specified past, present, or future condition of river-basin development. The sequence of unregulated or naturalized monthly flows plotted in Figure 2.1 was developed by adjusting gaged flows to remove the historical effects of upstream reservoirs and water management and use. Gaging records are extended and missing data reconstituted through regression analyses with data from other gages. Various techniques are applied for transferring flows from gaged sites to pertinent ungaged sites.

Reservoir evaporation volumes are typically computed within a model by combining inputted evaporation rates with water surface areas determined as a function of storage. The evaporation rates may be provided for each individual time interval of the overall period-of-analysis, or averages may be provided for each month or season of the year.

Water Management and Use

Reservoir characteristics are specified in a model by:

1. storage capacities defining the pertinent pools

2. storage volume versus water surface area relationships for use in evaporation computations
3. storage volume versus elevation relationships for use in hydropower computations

Reservoir storage capacity is diminished over time due to sediment deposition. Reservoir storage characteristics are reflected in a model based on a specified condition of sedimentation. Discharge capacities of outlet structures and conveyance facilities are also specified in the model. Hydroelectric power plant characteristics must also be furnished as appropriate.

Models contain a variety of mechanisms for defining operating rules that range from very simple to quite complex. Operating rules may involve permanent or seasonal storage allocations, minimum and maximum flow targets, water supply and hydropower requirements, flood control operations, coordination of multiple-purpose operations, multiple-reservoir release decisions, and priorities for allocating shortages to competing demands during periods of insufficient supply.

Water use is modeled as a set of diversion and instream flow targets representing either:

1. actual historical or projected future use for a specified past, present, or future time period
2. water amounts committed to users by water rights, contracts, or other allocation systems
3. hypothetical yields

Water use is often expressed in terms of a constant annual amount that varies monthly or seasonally. Water use may be a function of water availability. For example, certain water uses may be curtailed or reduced in accordance with some triggering mechanism such as reservoir storage falling below specified levels. Diversion return flow specifications are also included in the water use scenario. Hydroelectric energy requirements are specified in a similar manner.

The water resources of a river basin are typically shared by many water users and regulated by complex systems of reservoirs and other facilities. Diversions and return flows of each water user affect water available for other users. Likewise, reservoir storage and evaporation affects downstream flows. Capabilities for representing interactions between the particular storage/use system of concern in a study and other reservoirs and water use activities may be quite important. Removal of the historical effects of basinwide water management is typically a major effort in developing homogeneous sets of unregulated flows provided as input to a model. Reservoirs and other water management and use practices that either affect and/or are affected by the reservoir/use system of primary concern may also be incorporated in the model. Reservoir storage and streamflow may be allocated among numerous water users and types of use.

Model Results

The output of a reservoir/river system analysis model is typically voluminous. Model results can be summarized in various formats such as tabulations and plots of:

1. time series of storage, releases, streamflows, diversions, diversion shortages, energy generated, water quality parameters, and other variables
2. frequency or duration relationships for these variables
3. water supply and hydropower reliability indices
4. economic indices such as flood damages or hydroelectric power revenues

Measures of system performance in meeting water and energy demands, reducing flooding, and otherwise fulfilling water management objectives are formulated to fit the purposes of a particular study. These measures often include expressions of reliability in meeting demands and/or economic consequences of alternative plans.

Period-of-Analysis and Time Step

Reservoir system analysis models are generally formulated in terms of a reservoir system being operated, in the model, during a specified hydrologic period-of-analysis. Unregulated streamflows, reservoir evaporation rates, and possibly water quality parameters and other data representing basin hydrology are inputted for each time step or discrete interval of the overall analysis period. Reservoir releases, storage, regulated streamflows, and other variables are computed by the model for each time step.

Selection of a hydrologic period-of-analysis and computational time interval is a key consideration for a particular modeling application. The choice of analysis period and time step depends on the scope of the application, data availability, and time-variability characteristics of streamflow, water demands, and other factors. The validity of modeling assumptions and the choice of time interval are closely related. For example, flow attenuation in a river reach with a travel time of several days is appropriately neglected in a monthly time step model, but hydrologic or hydraulic routing computations are necessary in a daily time step model.

A several-decade historical period-of-record hydrologic simulation period and one-month computational interval are typically adopted for planning studies involving water supply, hydropower, and other conservation storage purposes. However, weekly or daily computational time steps during the many-year analysis period are also common. In rare cases, a several-month time interval representing wet and dry seasons may be adequate for a particular study.

A model for scheduling irrigation or hydroelectric power releases over the next year might involve a daily or weekly time interval and one-year simulation period, with simulations being repeated for alternative annual sequences of daily or weekly streamflows, and with each simulation starting with present storage levels. The scheduling problem may combine multiple analyses performed at different levels of detail. A monthly interval might be adopted to allocate water over the next year; a daily time step for a particular month; and an hourly interval for analyzing daily operations.

Simulation of flood control operations involves short time intervals since flows are rapidly changing. A major flood event with a duration of several days or weeks is typically simulated with a one-hour, several-hour, or one-day time step. Some models use a variable computational time step, with a daily or shorter interval specified during flood events and a longer interval such as a month adopted during extended periods of more normal hydrologic conditions.

Water Accounting

Computations accounting for the regulation of flow and storage of water are the central core of a reservoir/river system model. Streamflows provide the inflows to the system. Reservoirs regulate the streamflows through storage and releases. Water flows through river reaches, is diverted for beneficial use, and is lost through evaporation. Other gains and losses also occur.

Basic Volume Balance

Water accounting procedures are based upon conservation of mass. Since, for most reservoir/river system analysis applications, water is a constant density fluid, conservation of mass implies conservation of volume as well. For any control point or node in the reservoir/river system

$$S_{t+\Delta t} - S_t = \Sigma I_{vol} - \Sigma O_{vol} \tag{3.1}$$

where S_t and $S_{t+\Delta t}$ denote the storage volume at the beginning and end, respectively, of an interval of time Δt, and ΣI_{vol} and ΣO_{vol} denote the total inflow and outflow volumes during the time period. With no reservoir storage at the river location

$$\Sigma O_{vol} = \Sigma I_{vol} \tag{3.2}$$

Inflows could include regulated flows from upstream, unregulated flows from the incremental local watershed, or return flows from diversions at another location. Outflows include downstream regulated flows, diversions, and net reservoir evaporation.

In modeling of reservoir operations for conservation purposes, Equation 3.1 is expressed as

$$S_{t+\Delta t} = S_t + \text{all inflows - all outflows} \tag{3.3}$$

or

$$\begin{aligned} S_{t+\Delta t} = S_t &+ \text{stream inflows} + \text{other inflows} - \text{withdrawals} \\ &- \text{releases} - \text{spills} - \text{net evaporation} - \text{other losses} \end{aligned} \tag{3.4}$$

Net evaporation is evaporation from the reservoir water surface less precipitation. Reservoir evaporation volumes EV_i for each time period i are typically computed in a model by multiplying a net evaporation rate ER_i by the average water surface area A_i during the time interval, which is determined as a function of storage.

$$EV_i = A_i \, ER_i \tag{3.5}$$

Typical units are m^3 or acre-feet for E_i, meters or feet for ER_i, and m^2 or acres for A_i. The average reservoir water surface area A_i during the time interval can be estimated as:

$$A_i = \frac{A_t + A_{t+\Delta t}}{2} \tag{3.6}$$

where the areas A_t and $A_{t+\Delta t}$ at the beginning and end of the time interval are determined as a function of the corresponding storage volumes at the beginning and end of the interval. Alternatively, the beginning-of-period and end-of-period storage volumes may be averaged and then the average storage applied to the storage versus area relationship to estimate the average area.

Computation of evaporation volume requires an iterative accounting algorithm. End-of-period storage is computed based on Equation 3.1 with net evaporation volume EV being included in the outflows ΣO_{vol}. However, the evaporation volume is of function of end-of-period surface area which is a function of end-of-period storage which is an unknown being computed. Thus, the net evaporation is computed for a best estimate value for end-of-period storage, which is then improved, based on the last computed evaporation volume.

Rainfall and evaporation represent a gain and loss, respectively, which are reflected in the positive or negative sign of net evaporation depth values. With natural unregulated streamflows provided as input to the model, the corresponding net rainfall minus evaporation rates should reflect precipitation that is not already accounted for in the natural unregulated streamflows. Without the reservoir, a portion of the precipitation falling on the land becomes runoff to the stream and the remainder is loss as infiltration, evapotranspiration, and other hydrologic abstractions. With the reservoir, all of the precipitation falling on the reservoir water surface is inflow. Net rainfall minus evaporation rates are sometimes adjusted to reflect the difference between rainfall falling on the reservoir water surface and runoff from rain falling on the land area at the site that contributes to streamflow before the reservoir project is constructed. Evaporation from the free surface of the river, prior to reservoir construction, is usually small relative to reservoir evaporation and thus is neglected in the adjustment.

Other Reservoir and Channel Losses

Losses and gains of water to and from the ground under a reservoir are extremely difficult to quantify. Losses to infiltration or seepage and gains from groundwater or bank storage are typically considered negligible and ignored in reservoir system analysis studies. Most reservoirs are constructed at relatively impermeable sites. Permeability of the reservoir bottom tends to decrease over time with sedimentation. The sediment deposits help seal the bottom and prevent seepage. However, seepage, bank storage, groundwater, and other interactions between the reservoir and underlying ground may be significant at a particular reservoir.

Projects are typically designed and maintained to minimize leakage through the dam and outlet structures. Thus, leakage is typically not a major loss and is neglected in modeling studies. However, leakage through structures could be significant at some dams.

Unauthorized diversions from reservoirs and rivers sometimes are treated as an unaccounted loss. Farmers, businesses, and other individuals without proper water rights or water supply contracts may pump unrecorded amounts of water that are not reflected in the diversions included in the modeling study.

Water supply diversions from a river and instream flows needs are often met by releases from reservoirs located great distances upstream. Water released from a reservoir may be partially lost, as it flows through the downstream river channel, as a result of the natural processes of evaporation, transpiration, and bank seepage. Unauthorized pumpage from the river may also occur. These channel losses are difficult to quantify.

The input data for reservoir/river system analysis models typically include unregulated flows developed from gaged streamflow records. Measured streamflows reflect actual channel losses. However, in a model, reservoirs alter streamflows. Channel losses can be expected to vary with changes in streamflows. The significance of channel losses vary with different reservoir/river system modeling applications. In many cases, channel losses are actually negligible. Losses are also often ignored due to the difficulty in quantifying them.

The typical approach for developing channel loss relationships has been to analyzing stream gage records at upstream and downstream locations. Water budget computations account for all inflows and outflows for the river reach between the gages. Water supply diversions and return flows are recorded. Runoff between the gages is estimated using rainfall-runoff modeling. Historical channel losses or gains are estimated as the remainder of the water budget after accounting for all other inflows and outflows. Losses are then related to streamflow characteristics and river conditions. Losses may be expressed as a variable percentage of streamflow per length of river. The channel loss functions may also be related to factors such as groundwater levels, reservoir release procedures, rate of change of streamflow, and season of the year. Channel loss functions developed for gaged reaches are used for ungaged reaches of the same or similar rivers.

Streamflow Routing

Hydrologic routing consists of computing the outflow hydrograph for a given inflow hydrograph. As illustrated in Figure 3.2, the outflow hydrograph has a smaller peak and broader time base than the inflow hydrograph. Storage routing is a prediction of this attenuation effect of temporary storage on the flow hydrograph. Routing computations are applied to both reservoirs and river reaches. Routing is most often associated with modeling of flood effects. However, routing may also be important in modeling conservation storage operations. For example, water supply diversions often occur at river locations that are great distances below a dam. Several days of travel time may be required for water released from a reservoir to reach the point of diversion from the river. Routing computations are necessary to relate flow versus time at the diversion location to the upstream reservoir releases.

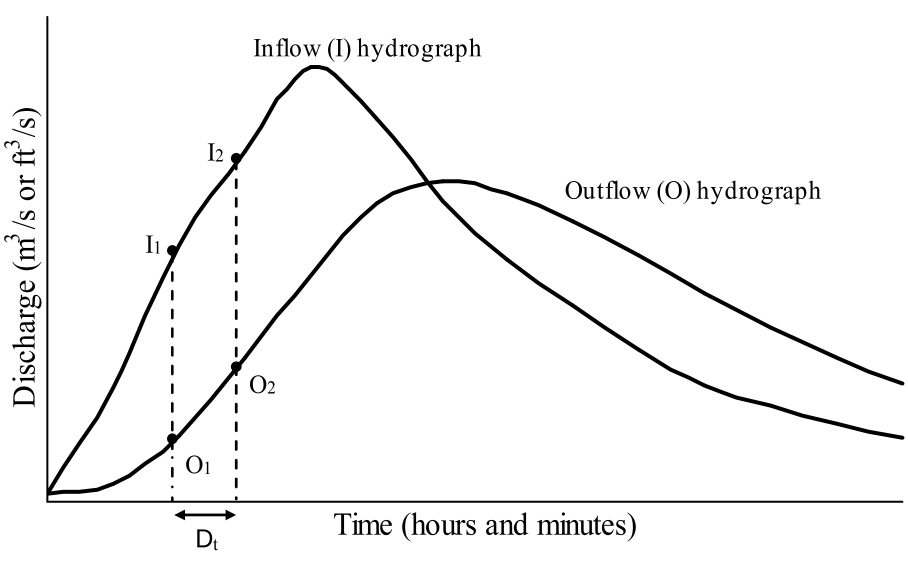

Figure 3.2 Inflow and Outflow Hydrographs

The various hydrologic storage routing methods are based on the conservation of volume equation in the form of Equation 3.7.

$$\frac{S_{t+\Delta t} - S_t}{\Delta t} = \frac{I_t + I_{t+\Delta t}}{2} - \frac{O_t + O_{t+\Delta t}}{2} \tag{3.7}$$

Since there are two unknowns ($O_{t+\Delta t}$ and $S_{t+\Delta t}$) in this equation, it must be combined with some other relationship between storage and discharge. Alternative hydrologic storage routing methods are based on different storage versus discharge relationships. Routing through uncontrolled (ungated) reservoirs is typically based on Equation 3.7 combined with a relationship between storage and outflow developed from reservoir site topography and outlet structure hydraulics. Muskingum routing is one of the simpler of the variety of methods for routing flows through river reaches. Muskingum routing is based on Equation 3.7 combined with the following relationship between storage S in the river reach, inflow I at the upstream end of the reach, and outflow O at the downstream end, where x and K are routing parameters.

$$S = K(xI + (1-x)O) \tag{3.8}$$

For flood control operations of major reservoirs with gated outlet structures, releases are specified by operating rules based on downstream flow conditions. Conservation storage operations are also based on operating rules and water use requirements. Routing is based on Equation 3.1 with the outflows set by operating rules and water management requirements. Water balance computations determine the change in storage.

The two alternative general approaches for modeling the hydraulics of river flows are based on (1) combining hydrologic routing with water surface profile computations or (2) hydraulic routing. Hydrologic routing computes only discharges. Water surface profiles (flow depths) for given peak discharges determined based on hydrologic routing are often computed based on the premises of steady gradually-varied flow using the standard step method solution of the energy equation implemented in the HEC-RAS River Analysis System or other similar models. Hydraulic routing based on numerical solution of the St. Venant equations or simplification thereof simultaneously compute discharges and depths and thus more accurately model flow dynamics. The St. Venant equations are two partial differential equations expressing conservation of mass and momentum. HEC-RAS provides dynamic routing capabilities based on numerical solution of the complete St. Venant equations as well as options based on other simplified hydraulic routing techniques. Hydraulic routing may be used in conjunction with modeling flood control operations.

Hydroelectric Power

For reservoir/river systems with hydroelectric power plants, the reservoir water balance includes releases through turbines for generating energy. The amount of power generated is related to release rates and other pertinent factors as follows:

$$P = \gamma Q H e \tag{3.9}$$

where:
- P = power (N·m/s or ft·lb/s)
- γ = unit weight of water (N/m^3 or lb/m^3)
- Q = flow rate (m^3/s or ft^3/s)
- H = head (m or ft)
- e = efficiency in converting hydraulic energy to electrical energy

Power is the rate of transferring energy:

$$\text{power} = \frac{\text{energy}}{\text{time}} \tag{3.10}$$

Energy is measured in metric units of Newton-meter (N·m) or kilowatt-hr (KW·hr) and English units of foot-pound (ft·lb). Power is measured in units of Newton-meter/second (N·m/s) or foot-pound/second (ft·lb/s). Electrical energy is commonly measured in kilowatts, where a watt is one N·m/s and a kilowatt is 1,000 watts. The English unit of horsepower is used for power, where one horsepower equals 550 ft·lb/s. One horsepower is 746 watts.

The flow through the turbines (Q in the Eq. 3.9) is a component of the outflows in Equation 3.1. With energy demands specified, flows are computed based on Equations 3.1, 3.9, and 3.10. The head H is a function of the average storage which depends on the storage at both the beginning and end of the time interval. Thus, hydropower necessitates an iterative solution of Equations 3.1, 3.9, and 3.10 since both head and end-of-period storage are unknowns being computed.

Water Quality Constituent Loads and Concentrations

Reservoir/river system models may also include water quality. For salinity or other conservative constituents with no chemical reactions or other transformations, the model simply tracks the movement of loads through the river/reservoir system. Constituent loads enter the reservoir/river system with the incoming streamflows and are stored and transported along with the water. Concentrations of regulated flows and water in reservoir storage at each time step are computed. Concentration (C), load (L), and flow (Q) are related as follows:

$$C = \frac{L}{Q} f_C \quad \textit{or} \quad L = \frac{C\,Q}{f_C} \tag{3.11}$$

where f_C is a conversion factor. Tracking of constituent loads may be performed as an adjunct to the water accounting. Water quality models that include chemical and biological transformations in modeling the transport and fate of various constituents may be much more complex.

Reliability Analyses

Reservoir/river system capabilities for satisfying water management requirements must be evaluated from a reliability and risk perspective because streamflow and other variables are characterized by randomness, uncertainty, and great variability. Reliability indices provide a measure of the level of dependability at which water supply, hydroelectric power generation, flood protection, environmental requirements, and other needs can be met. Conversely, risk is a measure of the likelihood of failures in providing these services.

Definitions of the terms *yield* and *reliability* can be formulated in a variety of ways to provide meaningful information for a particular application of concern. In general, yield is a measure of the amount of water which can be supplied by an unregulated stream, a reservoir, or a river system regulated by multiple reservoirs. Reliability is a measure of the level of dependability at which various yield levels can be supplied. Reliability can be expressed in terms of firm yield, percent of time target demands can be met, likelihood or probability of meeting target demands during a specified time interval, risk of failure in meeting specified demands, or the likelihood or percent of time that reservoir storage fall below certain levels. The water use requirements may involve water supply diversions, instream flow needs, generation of hydroelectric power, or maintenance of reservoir storage.

Flood frequency analysis methods provide estimates of the probability of specified flow and volume magnitudes being exceeded during a specified time interval. Expected annual damage analysis methods combine hydrologic, hydraulic, and economic considerations in the evaluation of flooding problems and flood damage reduction measures.

Reliability Indices

Reservoir/river system analyses are usually based on sequential period-by-period hydrologic period-of-record simulations. The reservoir/river system simulation model combines a specified set of water use requirements with historical streamflows representing a specified condition of river basin development typically developed by adjusting gaged flows to remove nonhomogeneities. Simulation results are typically voluminous. Various reliability indices can be computed from the simulation results as concise measures of the capabilities of the simulated reservoir/river system to satisfy the specified water use requirements during a postulated repetition of historical hydrology.

Variations of the concepts of period reliability (R_p) and volume reliability (R_v) are often adopted in modeling studies. These indices are computed from the results of a historical hydrologic period-of-record simulation. Period reliability is based on counting the number of periods of the simulation during which the specified demand target is either fully supplied or a specified percentage of the target is equaled or exceeded. Period reliabilities may be expressed as the percentage of days, months, or years during the simulation during which water supply diversions or hydroelectric energy produced equaled or exceeded specified magnitudes expressed as a percentage of the target demand.

$$R_P = \frac{n}{N}(100\%) \tag{3.12}$$

where *n* denotes the number of periods during the simulation for which the specified percentage of the demand is met, and *N* is the total number of periods considered.

The period reliability represents the percent of time that specified water use requirements are met or the probability of the requirements being met in any randomly selected period. The risk of failure is the complement ($F=1-R_P$) of the period reliability. The risk of failure is the percent of time or the probability that specified water use requirements will not be met.

Volume reliability is the percentage of the total demand that is actually supplied. For water supply, the demand is a volume. For hydropower, the demand is energy generated. Volume reliability R_V is the ratio of volume (energy) supplied to the volume (energy) demanded.

$$R_V = \frac{v}{V}(100\%) \tag{3.13}$$

or, equivalently, the ratio of the mean actual diversion rate to mean target diversion rate.

Performance measures of reservoir/river system capabilities to meet demands are devised to fit the particular modeling and analysis application. Various formulations of water use requirements and failures to meet these requirements can be incorporated in simulation studies. Water use requirements may involve water supply diversions, instream flow needs, hydroelectric energy, or maintenance of reservoir storage levels. Period reliability can be formulated in terms of meeting all of the demand target or, alternatively, at least a specified portion of the demand target. Alternatively, the water use requirements can be defined in terms of meeting demands without reservoir storage falling below specified levels. Reliability can be defined as the percentage of periods during the simulation during which a specified storage level is equaled or exceeded. Water supply failure may be related to necessitating the implementation of emergency demand management measures.

Various definitions of reliability can be formulated for alternative time periods. Monthly periods are typical in planning studies, but other time intervals are common as well. Period reliability may be defined in terms of meeting an annual diversion target on a yearly basis during a simulation performed using a monthly or weekly computational time interval.

Frequency relationships for flow, storage, and other variables are often computed. Exceedance frequencies are determined from the results of a simulation model as

$$\text{Frequency} \;=\; \frac{n}{N}(100\%) \tag{3.14}$$

where *n* is the number of months during the simulation that a particular flow or storage amount is equaled or exceeded, and *N* is the total number of months considered. Thus, the exceedance frequency is an expression of the percentage of time that particular flow or storage amounts can be expected to occur. Equivalently, the exceedance frequency represents the likelihood or probability of a certain amount of water being available.

A simple and informative means of quantifying the yield versus reliability relationship for a run-of-river (no storage) water supply diversion is the conventional flow-duration curve, which shows the percentage of time that specified flow amounts are exceeded. Flow-duration relationships are developed using Equation 3.14 by counting the number of periods (typically days or months) for which the mean flow rate equaled or exceeded specified levels during the period-of-analysis. The primary limitation of the flow-duration curve as a method for quantifying yield is that sequencing of flows is not reflected. The relationship does not indicate whether the lowest flows occurred in consecutive periods or were scattered throughout the period-of-analysis.

Firm Yield

Firm yield (also called safe or dependable yield) is a commonly used measure of water supply and hydroelectric power generation capabilities. Firm yield is the estimated maximum release or diversion rate or hydroelectric energy production rate that can be maintained continuously during a hypothetical repetition of historical period-of-record hydrology. Firm yield is the draft which will lower the storage in a reservoir or multiple reservoir system to a defined failure level during a hydrologic period-of-record simulation. Period and volume reliabilities, as defined in Equations 3.12 and 3.13, are 100% for the firm yield and smaller yields. Yields greater than firm yield have reliabilities of less than 100%. Firm yield estimates reflect all of the premises and assumptions incorporated in the model including hydrologic data, reservoir characteristics and operating rules, water use scenarios, and impacts of other water use and management activities in the river basin. 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.

In citing firm yields, it is always important to emphasize that there is no guarantee of being able to supply this amount of water in the future. Firm yield estimates reflect all the premises incorporated in the model, including hypothetically assuming a repetition of historical hydrology. A future drought more severe than the worst drought during the period of streamflow gaging records will occur at some time in the future though the timing is not known.

Firm yields are commonly determined by repeatedly executing a reservoir/river system simulation model with alternative yields specified in an iterative search for the maximum yield that can be maintained, without failure, continuously during the simulation period. For example, assume that for a particular study, the yield is defined as a constant diversion from a single reservoir, and a failure occurs if the diversion can not be fully met due to drawdowns resulting in an empty reservoir. If the yield (diversion) specified in a run of the simulation model is met continuously without reservoir storage being depleted, the diversion is increased for the next run. Eventually a diversion rate is found that just empties the reservoir, resulting in an imminent diversion shortage. This is the firm yield. Several of the generalized simulation models described in Chapters 5 and 6 contain options which automate the iterative search for the firm yield. Variations of the same iterative simulation approach can be applied to complex multiple-reservoir systems with water use requirements and corresponding failures formulated to fit the scope of the particular study.

The relationship between firm yield and reservoir storage capacity is often of interest. Simulation models are executed iteratively to determine the firm yield provided by a particular storage capacity or, vice versa, the storage capacity required to provide a specified firm yield. Complex multiple-reservoir, multiple-purpose systems may be evaluated. A linear programming formulation for determining firm yields for specified storage capacities and vice versa is discussed in Chapter 4. Rippl presented his graphical mass curve technique for analyzing storage requirements well over a century ago (Rippl 1883).

Combinations of Firm and Secondary (Interruptable) Yield

Many different water users may be supplied by the same reservoir or multiple-reservoir system. Water allocation schemes may involve supplying water at different levels of reliability to the various users. For example, a city may be guaranteed a high level of reliability, while agricultural users are supplied from the same reservoir system at a lower reliability. As discussed in Chapter 2, one or more buffer pools may be designated as a triggering mechanism for curtailing the lower priority diversions. Full demands are met as long as the reservoir water surface is above the designated buffer level, with certain demands being curtailed whenever the water in storage falls below this level. Likewise, this type of triggering mechanism can be adopted for coordinating demand management measures with water supply operations. Emergency demand management plans are implemented whenever reservoir storage falls below specified levels.

Reliability is determined by applying Equations 3.12 and/or 3.13 to the results of a hydrologic period-of-record simulation. Firm yield is the maximum yield that can be supplied with a volume and period reliability of 100%. Additional secondary or interruptable yield can be supplied with a reliability of less than 100%. Reservoir operating rules include setting a top of buffer pool level so as to provide a specified firm yield. The secondary or interruptable yield represents diversions that are curtailed any time storage is below the top of buffer pool.

Other Measures of Reliability

Period and volume reliability as defined by Equations 3.12 and 3.13 are concise indices of supply capabilities. Water use requirements and failures to meet these requirements are complex. Simple indices reflect only limited features of water demands and failures to meet water demands. Other indices can also be devised to measure various aspects of capabilities, or lack thereof, for supplying water needs.

Various models including the HEC-3 Reservoir System Simulation model (Hydrologic Engineering Center 1981) include the following summary measure of failures to meet water supply diversion requirements during a simulation:

$$\text{shortage index} = \left(\frac{100}{\text{years}}\right)\left(\frac{\text{annual shortage}}{\text{annual requirement}}\right)^2 \tag{3.15}$$

as well as volume and period reliabilities, as defined by Equations 3.12 and 3.13.

Performance measures may be formulated that reflect the concepts of vulnerability and resiliency. The precise definition of these criteria and the computational mechanism for their application can vary to fit the scope of the particular study. In general, vulnerability is a measure of the severity of the worst failure. It might be defined as the greatest water supply shortage to occur during any year of a simulation or perhaps the greatest deficit in meeting a hydroelectric energy production target. Resiliency is a measure of the capability for recovery from failure. Resiliency could be defined as the maximum number of consecutive periods of failure to meet water use demands during a simulation. Alternatively, resiliency may viewed in terms of the probability of being in a period of no failure given that there was a failure in the previous period (Hashimoto *et al.* 1982; Moy *et al.* 1986).

Reliability analyses can be expanded to include economic consequences. For example, economic benefits may be assigned to providing a specified water supply or hydroelectric energy requirement at some high level of reliability along with associating costs or losses with occasional failures to meet the demand requirements. Typically, in an economic analysis, the computer model assigns dollars as a function of computed storages, diversions, and instream flows. The difficult time-consuming part of the study is developing a conceptual basis and supporting field data for assigning benefits and costs that can be incorporated in the model input data.

Comparison of Alternative Model Structures

The fundamental structure of a reservoir/river system model provides a framework for organizing its computations and data management. Models are classified in the following outline based on whether or not a standard mathematical programming methodology such as linear programming described in Chapter 4 is used. Without such a formalized methodology, the simulation computations are performed as sets of ad hoc algorithms programmed for each individual model. The models are then further categorized based on the spatial and temporal sequencing of the computations. Reservoir/river system models, including those described in Chapters 6 and 7, are constructed based on the following alternative structures.

- Models may be based on sets of ad hoc algorithms developed specifically to simulate the various aspects of reservoir/river system operations. The sequential order in which the computations are performed is a fundamental consideration.

    1. For each sequential time step, the computations may begin at the upstream extremities of the river/reservoir system and advance by control point (station) in an upstream-to-downstream progression. Most simulation models based on ad hoc methods follow this approach.

    2. Alternatively, for each sequential time step, the computations may be performed in an order based on defined priorities. The WRAP model is based on this approach.

- Models may be based on standard mathematical programming (optimization) algorithms. All locations are considered simultaneously. Whether computations are repeated sequentially for each time step or performed simultaneously for all time steps is a key consideration.

    1. The mathematical programming solution algorithm may repeated at each sequential time step. MODSIM and most other descriptive simulation models are organized in this manner.

    2. All time steps may be considered simultaneously in applying the mathematical programming algorithm. HEC-PRM, the RiverWare optimization option, and most of the system-specific prescriptive optimization models reported in the research literature are based on this approach.

Simulation models based on ad hoc computational algorithms are further categorized based on the order in which the computations are performed. Most of the ad hoc simulation models start at the most upstream control point on a stream branch and work their way downstream adding incremental streamflow inflows. For example, the system in Figure 3.1 is modeled with 12 control points, with reservoirs located at four of the control points and water supply diversions occurring at eight control points. Incremental local unregulated flows enter the system at each control point. Reservoir storage, releases, and evaporation are computed at control points 1, 2, 3, and 8. Diversions are computed at control points 1, 2, 4, 5, 7, 8, 9, and 11. Regulated flows are determined for all 12 of the control points. The computations are performed for one control point at a time.

The upstream-to-downstream computational sequencing could be in the order of control points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12. Alternatively, the upstream-to-downstream sequencing could be control points 3, 4, 5, 8, 9, 1, 2, 6, 7, 10, 11, 12. Iterative simulation algorithms may be adopted to deal with reservoirs being operated for diversion, environmental instream flow, and/or flood control requirements at control points located downstream of the reservoirs.

The alternative sequencing approach adopted for ad hoc simulation models is to sequence the computations based on a user-specified priority system. The WRAP model described in Chapter 8 incorporates a priority system designed to control water allocation and reservoir/river system operating policies that also controls the sequencing of the computations. The computations start with total naturalized flows at all locations rather than accumulating local incremental flows. Water rights (sets of water management/use requirements) are considered in priority order. For each water right, the following computational tasks are performed in WRAP.

1. Water supply, hydropower, instream flow, and storage targets are set as a function of month of the year and also optionally as a function of reservoir storage levels and flows at any location or combination of locations.

2. Water availability is determined by checking a water availability array considering all control points.

3. Operating decisions are made following various rules that may involve multiple reservoirs and/or multiple owners sharing the same reservoirs. Water accounting computations are performed to determine the diversion, evaporation, storage, and related variables.

4. The water availability array is adjusted for the effects of that water right at all pertinent control points.

Mathematical programming is covered in Chapter 4. Simulation/optimization models using linear programming or other optimization methods consider all locations simultaneously. However, the models may be categorized based on time sequencing of the computations. As discussed in the last section of Chapter 4, descriptive simulation models typically step sequentially through time, with the linear programming or other optimization algorithm computations being performed at each time step. In the model, like in the real world, the reservoir system is operated based on user-specified operating rules without knowledge of future river system inflows. The alternative is to solve a optimization problem that considers all time intervals simultaneously. Operating decisions are driven by the objective function considering all inflows with no differentiation between past, present, and future.

Chapter 4
Mathematical Programming Techniques in Reservoir/River System Simulation Models

Many of the models described in Chapters 6 and 7 are based on linear programming (LP), network flow programming (a special form of LP), or other optimization methods. Chapter 4 covers the fundamentals of mathematical programming.

Fundamental Concepts of Optimization

In a broad sense, optimization includes human judgment, use of simulation and/or optimization models, and use of other decision support tools. However, the term *optimization* is often used synonymously with *mathematical programming* to refer to a mathematical formulation in which a standard algorithm is used to compute a set of decision variable values that minimize or maximize an objective function subject to constraints. Optimization models automatically search for an *optimum* set of decision variable values. Optimization techniques are covered by numerous operations research and mathematics books (Vanderbei 2001) as well as civil engineering systems books (ReVelle and McGarity 1997; Revelle et al. 2004) and water resources systems books (Loucks et al. 1981; Mays and Tung 1992; Karamouz et al. 2003; Jain and Singh 2003).

A simulation model is a representation of a system used to predict its behavior under a given set of conditions. Computer models for simulating reservoir operations reproduce the performance of a reservoir/stream system for given hydrologic inputs and operating rules. Simulation is the process of experimenting with a simulation model to analyze the performance of the system under varying conditions. Alternative runs of a reservoir simulation model are made to evaluate alternative storage capacities and operating plans. Simulation models may be constructed either with or without mathematical programming (optimization) algorithms.

Although optimization and simulation are alternative modeling approaches with different characteristics, the distinction is obscured by the fact that most models contain elements of both approaches. All *optimization* models also *simulate* the system. An *optimization* approach may involve numerous iterative executions of a *simulation* model, possibly with the iterations being automated to various degrees. Mathematical programming algorithms are embedded within many reservoir/river system simulation models to perform certain computations. Alternative simulation models may be applied in essentially the same manner even though one incorporates an optimization algorithm to perform certain computations and the other does not.

Terminology

Fundamental terms used in describing optimization models are defined as follows.

optimization - finding the best (optimum) solution. In mathematical programming, a decision policy is determined that minimizes or maximizes an objective function subject to not violating constraints.

decision variables - variables that can be controlled. These are the variables for which optimum values are to be determined.

decision policy - each of the decision variables is assigned a value. A decision policy is a set of values for the decision variables.

constraints - limitations or restrictions on possible decision policies.

feasible policy - a decision policy that does not violate any constraints.

objective function - a statement of the consequences of a decision policy. The objective function is a criterion by which *optimum* is defined and may also be called a criterion function.

optimum solution - a feasible decision policy that optimizes (minimizes or maximizes) the objective function.

The decision variables associated with reservoir/river system models typically include reservoir releases, storage levels, streamflows, diversions, amounts of water allocated to each water user or type of use, and/or the amount of water supplied from each of multiple sources. Constraints typically include representations of volume balances, reservoir storage and release capacities, water availability, and water use requirements.

Objective or Criterion Functions

The objective function of an optimization model may be a penalty or utility function used to define operating rules based on relative priorities or may be a mathematical expression of a planning or operational objective such as the examples listed here. The following water management objectives have been reflected in the objective functions of various reservoir/river system analysis models reported in the literature.

- economic benefits and costs
  - ∗ maximize water supply and/or hydroelectric power revenues
  - ∗ minimize the cost of meeting electric power commitments from a combined hydro/thermal system
  - ∗ minimize economic losses due to water shortages
  - ∗ minimize the electrical cost of pumping water in a distribution system
  - ∗ minimize the damages associated with a design flood event
  - ∗ maximize the net benefits of multiple purpose operations
  - ∗ minimize costs associated with multiple purpose operations

- water availability and reliability
  - ∗ maximize firm yield, yields for specified reliabilities, or reliabilities for specified demands
  - ∗ minimize shortage frequencies and/or volumes
  - ∗ minimize shortage indices, such as the sum of the squared deviations between target and actual diversions
  - ∗ minimize the weighted sum of shortage indices
  - ∗ maximize the minimum streamflow
  - ∗ maximize reservoir storage at the end of the optimization horizon
  - ∗ minimize spills

* minimize evaporation losses
* 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 energy
  * maximize average annual energy
  * minimize energy shortages or energy shortage indices
  * maximize the potential energy of water stored in a system

A key philosophical question is how completely and accurately the criterion function incorporated in a model needs to reflect actual societal objectives in order to provide meaningful information for use in the decision-making process. This is a basic issue in assessing the practical utility of systems analysis tools, particularly optimization models, in general as well as being a key consideration in formulating a modeling approach for a particular application. The usefulness of a model depends on how meaningfully the complex real world can be represented by a set of mathematical equations. Necessary simplifications and approximations severely limit the utility of models. Even if planning objectives can be precisely articulated, which is typically not the case, it will likely not be possible to incorporate a criterion function into a model that 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 criterion function can be a simple index of the relative utility of alternative operating plans, which provide 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.

Although several different objectives will typically be of concern in a particular reservoir/river system analysis study, an optimization model can normally incorporate only one objective function. Multiple objectives can be combined in a single function if they can be expressed in commensurate units, such as dollars. However, the different objectives of concern are typically not quantified in commensurate units. Several of the various multiple-objective decision techniques reported in the literature for analyzing tradeoffs between objectives in water resources systems analysis applications are described in the following paragraphs (Cohon 1978; Goicoechea, *et al*. 1982; Jain and Singh 2003; Revelle et al. 2004).

One 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 user-specified levels. For example, a reservoir operating policy might be developed based on the noncommensurate objectives of maximizing (1) municipal water supply firm yield, (2) firm hydroelectric energy, and (3) average annual energy. The model could be formulated to maximize an objective function representing average annual energy, subject to the constraints that a user-specified water supply firm yield and firm energy be maintained. Alternative runs of the model are made to show how the average annual energy is affected by changes in the user-specified water supply firm yield and firm energy.

Objectives may be prioritized in some applications. Higher priority objectives are more important than those of lesser priority. A multiple-objective optimization strategy called goal programming that has been adopted in a number of models including RiverWare described in Chapter 7 is based on optimizing objectives in priority order. Each objective is optimized subject to the constraint that no other higher priority objectives are adversely affected.

Another 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 weighing factor reflecting the relative importance of that objective. The weighing factors can be arbitrary with 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 weighing factor values to analyze the tradeoffs between the objectives with alternative operating plans.

Mathematical Programming

Mathematical programming models are formulated in a specified format for solution with standard methods. The objective function x_0 and constraints are represented by mathematical expressions as a function of n decision variables $x_1, x_2, x_3, \ldots, x_n$. The general form of the formulation is as follows.

Maximize or minimize an objective function

$$x_0 = f(x_1, x_2, x_3, \ldots, x_n) \quad (4.1)$$

Subject to constraints

$$\begin{aligned} G_1(x_1, x_2, x_3, \ldots, x_n) &= \text{or} \le \text{or} \ge b_1 \quad (4.2) \\ G_2(x_1, x_2, x_3, \ldots, x_n) &= \text{or} \le \text{or} \ge b_2 \\ G_3(x_1, x_2, x_3, \ldots, x_n) &= \text{or} \le \text{or} \ge b_3 \\ &\vdots \\ G_m(x_1, x_2, x_3, \ldots, x_n) &= \text{or} \le \text{or} \ge b_m \end{aligned}$$

Linear programming (LP) is the optimization technique that is most often applied in modeling reservoir/river systems as well as being the most popular optimization method used in many other fields of business, engineering, and science. This chapter focuses on LP, including network flow programming, which is a special form of LP that is used in several generalized reservoir/river system simulation models described in Chapters 6 and 7. Other variations of LP include integer LP with one or more variables restricted to be integers and binary LP with variables restricted to values of zero or one. Variations of LP such as separable programming and successive LP incorporate techniques for dealing with nonlinear terms.

Nonlinear Optimization Methods

Equation 4.1 and inequalities 4.2 may represent complex sets of mathematical and logical expressions incorporating highly nonlinear terms that preclude application of standard linear programming (LP) methods. Other optimization methods that are not restricted to the standard

LP format are briefly discussed as follows prior to focusing the remainder of the chapter on LP. Approaches for solving optimization problems that may be highly nonlinear are categorized as follows:

- separable LP and successive LP methods for applying linear programming to nonlinear problems
- quadratic programming
- dynamic programming
- search algorithms
  - ∗ gradient search algorithms
  - ∗ genetic algorithms

Examples of reservoir/river system models based on each of these optimization approaches are cited in Chapter 6.

Separable LP and Successive LP

Linear programming (LP) objective functions and constraints are restricted to summations of linear terms. Nonlinear terms significantly complicate LP models but can be adequately handled in many cases. Nonlinearities are associated with various features of reservoir operation models, such as evaporation and hydroelectric power computations and benefit/cost functions. Separable LP is based on approximating separable nonlinear terms in an objective function as piecewise linear segments. Successive iterative solutions of a LP model are often used to handle nonlinear terms in the constraints.

Separable programming is applicable to a formulation in which an objective function with separable nonlinear terms is minimized or maximized subject to a set of linear constraints. Separable means that the objective function is the summation of a set of terms with only one decision variable reflected in each term. Each nonlinear term is replaced by a set of piecewise linear terms that approximate the nonlinear term. Additional decision variables and constraints are introduced to define the piecewise linear terms. The resulting formulation is in standard LP format and solved by standard LP algorithms.

Examples 4.1, 4.2, 4.3, and 4.4 presented later are unrealistic because reservoir evaporation is not included in the volume accounting computations. Evaporation volumes are typically computed based on Equation 3.5 as a net evaporation rate multiplied by the mean water surface area during the computational time step. Water surface area is a nonlinear function of storage. The mean storage or area during a time interval, such as a month, is approximated as the average of the values at the beginning and ending of the time interval. Thus, end-of-period storage is computed as a function of evaporation volume, which in turn is computed as a function of end-of-period storage.

Likewise, the nonlinearity of hydroelectric power computations can be reflected in LP models. Hydroelectric power is a function of both head and discharge as expressed by Eq. 3.9. Head is a nonlinear function of storage. End-of-period reservoir storage is computed as a function of releases required to meet hydroelectric energy requirements, which in turn depend upon the available head provided by the reservoir storage.

A common approach is to iteratively execute a LP model with successive approximations of variables associated with nonlinear terms. Again, reservoir evaporation should be incorporated into the models of the examples presented later. Assume the computations are performed for a monthly time interval. The evaporation volume is computed by applying an evaporation rate to the average water surface area during the month. A water surface area versus storage relationship is required as input. The average area during the month is estimated as the average of the beginning- and end-of-month water surface areas determined as a function of the corresponding storage volumes. The areas and evaporation volume is determine by the model in a routine separate from the LP algorithm. An initial estimate of evaporation volume based on the known beginning-of-month storage is input to the LP algorithm. The LP algorithm computes the end-of-month storage, which is then used to developed an improved estimate of the evaporation volume. The LP algorithm is iteratively executed with improved estimates of evaporation inputted until a specified stop criteria is met. The same iterative procedure is used to determine reservoir releases required to meet specified hydroelectric energy requirements.

Quadratic Programming

Quadratic programming is a successive solution algorithm applied to the problem of maximizing or minimizing a quadratic objective function (Equation 4.1) subject to a set of linear constraints (Equations 4.2). An iterative sequential solution procedure is applied to deal with the nonlinear form of the objective function. Examples of using quadratic programming to model reservoir/river systems are cited in Chapter 6.

Dynamic Programming

Dynamic programming (DP) based on state concepts is very different from the other optimization approaches. DP is a general solution strategy based on decomposing a sequential decision problem into stages connected by state variables, with values for decision variables determined for each stage. Decisions at each stage are guided by a recursive objective function. The objective function and constraints may be highly nonlinear. Objective function values for a given decision policy may be computed in essentially any manner ranging from a single simple equation to a complex simulation model. The simulation model from which objective function values are returned for a specified decision policy might be based on LP. Thus, reservoir system models are cited in Chapter 6 for which a LP model is embedded within a DP model.

In dynamic programming, a sequential decision problem is decomposed into stages with a decision required at each stage. In a reservoir/river system DP model, the stages are typically time steps. Stages are connected by state variables. The state variables are storage in each reservoir. Values for decision variables such as reservoir releases are determined for a particular stage (time step). The reservoir storage (state variable) carries forward information regarding the state of the system, which is affected by decisions at preceding stages.

The main advantage of DP relative to LP and quadratic programming is that DP does not restrict the form of the objective function and constraints. A major drawback of DP is the so-called *curse of dimensionality* referring to the dramatic increase in the computational magnitude of a problem that results from increases in the number of state variables. The computational burden of a

DP problem increases greatly with the number of reservoirs in the system. Labadie (2004) outlines the variations and extensions of DP that have been used to develop reservoir system analysis models. Several examples of DP models are included in Chapter 6.

DP models are typically developed for particular reservoir/river systems, rather than being generalized for application to any reservoir/river system. Labadie (1990, 2003) describes a generalized DP package developed at Colorado State University called CSUDP that provides a general framework for building a DP model for a particular application. CSUDP may be applied to modeling reservoir/river systems or any other type of system. In developing a DP model for a particular system using CSUDP, the user writes certain code in the C programming language that defines the objective function and constraints representing the particular problem.

Search Methods

Search methods consist of iteratively determining improved values for the decision variables as measured by an objective function typically evaluated with a simulation model. In gradient search algorithms, the iterative adjustments to the decision variables are based on objective function gradients. Genetic algorithms are search techniques based on probabilistically generating populations of solutions with improving levels of fitness as measured by the objective function. Like DP, search techniques provide more flexibility than linear and quadratic programming methods that are limited to a strict mathematical format. Search methods are combined with simulation models that determine values for the objective function for each of the numerous decision policies considered during the iterative modeling process. The model used to evaluate the objective function for given decision policies may represent any level of complexity and may be based on any methods including LP and/or DP. An LP model could conceivably be embedded within a DP model, which is repeatedly executed by a search algorithm.

Gradient search techniques are based on iteratively adjusting the decision policy based on objective function gradients in a search for the optimal or at least a near optimal solution. At each iteration, numerical approximations of first and second derivatives of the objective function guide adjustments to decision variables. Global optimal solutions are not guaranteed since the search may converge to a local optimum.

Genetic algorithms are search methods based on the mechanics of natural selection and natural genetics in the biological sciences (Goldberg 1989; Coley 1999). Heuristic processes of reproduction, crossover, and mutation are applied probabilistically to discrete decision variables that are coded into binary strings. A genetic algorithm produces groups or populations of solutions whose offspring display increasing levels of fitness as measured by objective function values. Acceptable solutions are obtained without a guarantee of reaching the optimal solution. A disadvantage of genetic algorithms is difficulty in explicitly specifying that solutions not violate constraints.

Linear Programming

Most water resources engineering applications of mathematical programming involve linear programming (LP) or extensions or subsets thereof. The popularity of LP in water resources systems analysis, as well as in other operations research, management science, and systems engineering fields, is due to the following considerations. LP is applicable to a wide variety of types of problems. Efficient solution algorithms are available. Generalized computer software packages are available for applying the solution algorithms.

LP consists of finding values for a set of n decision variables $x_1, x_2, \ldots, x_n$ that minimize or maximize an objective or criterion function x_0 of the form:

$$x_0 = c_1x_1 + c_2x_2 + \ldots + c_nx_n \tag{4.3}$$

subject to a set of m constraint equations and/or inequalities of the form:

$$\begin{aligned} a_{11}x_{11} + a_{12}x_{12} + \ldots + a_{1n}x_{1n} &= \text{or} \le \text{or} \ge \; b_1 \\ a_{21}x_{11} + a_{22}x_{22} + \ldots + a_{2n}x_{2n} &= \text{or} \le \text{or} \ge \; b_2 \\ &\vdots \\ a_{m1}x_{m1} + a_{m2}x_{m2} + \ldots + a_{mn}x_{mn} &= \text{or} \le \text{or} \ge \; b_m \end{aligned} \tag{4.4}$$

and a set of constraints requiring that the decision variables be nonnegative:

$$x_j \ge 0 \quad \text{for } j = 1, 2, \ldots, n \tag{4.5}$$

where a_{ij}, b_i, and c_j are constants. Methods are available for circumventing the non-negativity constraints. The LP model is expressed in more concise notation as:

$$\text{minimize or maximize} \qquad x_0 = \sum_{j=1}^{n} c_j x_j \tag{4.6}$$

$$\text{subject to} \qquad \sum_{j=1}^{n} a_{ij} x_j \le b_i \quad \text{for } i = 1,2,\ldots,m \tag{4.7}$$

$$\text{and} \qquad x_j \ge 0 \quad \text{for } j = 1,2,\ldots,n \tag{4.8}$$

where x_0 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. Maximizing $-x_0$ is equivalent to minimizing x_0. The objective function and all constraints are linear functions of the decision variables. A set of values for the n variables is called a decision policy.

Linear Programming Examples

Considerable ingenuity and significant approximations may be required to formulate a problem in the required mathematical format. However, if the problem can be properly formulated, standard LP algorithms and computer codes are available to perform the computations. Solution techniques are covered in depth by many textbooks.

The following examples illustrate the formulation of reservoir/river system models in LP format (Wurbs and James 2002). The simple examples involve a minimal number of decision variables and constraints. The basic water management concepts illustrated by the simplified examples are incorporated in actual models that may have many thousands of decision variables and constraints. Several of the generalized reservoir/river system simulation models cited in Chapters 6 and 7 are based on the LP formulations illustrated by the following examples.

Example 1 is representative of LP models such as the HEC-PRM (Prescriptive Reservoir Model) that consider all time intervals simultaneously. Unlike Example 1, HEC-PRM includes separable programming methods for approximating nonlinear economic benefit-cost functions as piecewise-linear terms in the objective function. Example 3 is representative of California's CalSim and other LP models cited in Chapter 6 that consider each time step individually.

Generalized models based on the network flow programming formulation illustrated by Example 4 include several Texas Water Development Board models, DWRSIM developed by the California Department of Water Resources, MODSIM developed at Colorado State University, ARSP from Acres International, and others. In these LP models, the water allocation computations illustrated by Example 4 are performed multiple times at each time step in successive iterations designed to deal with nonlinear aspects of evaporation and hydropower computations.

Example 1 – Prescriptive Reservoir Operations Model

As indicated in Fig. 4.1, releases from the storage reservoir flow through a hydroelectric power plant located downstream, supply water for a irrigation diversion further downstream, and maintain instream flows. Flows of up to 180 million m^3/month can be used to generate hydroelectric energy; flows in excess of this amount bypass the turbines. The demands shown in column 4 of Table 4.1 provide upper limits for the irrigation diversion. Irrigation diversions are limited to six months of the year. An instream flow requirement of 20 million m^3 per month must be maintained. The reservoir storage capacity is 600 million m^3. Revenues for supplying irrigation are $900 per million m^3 of water diverted. Each million m^3 of water used to generate hydroelectric power results in revenues of $400. The decision problem consists of determining the set of monthly reservoir releases that maximize revenues, given the inflows tabulated in column 3 of Table 4.1.

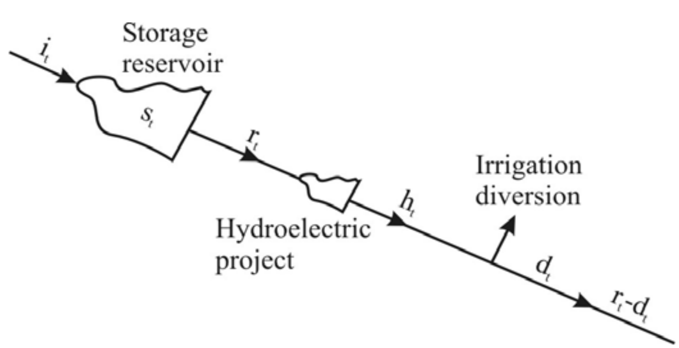

Figure 4.1 Multipurpose Reservoir System of Example 1

Table 4.1 Data (Columns 1-4) and Results (Columns 5-8) for Example 1

Month	t	Inflow i_t ($10^6 m^3$)	Irrigation Demand ($10^6 m^3$)	Storage s_t ($10^6 m^3$)	Total Release r_t ($10^6 m^3$)	Hydropower Release h_t ($10^6 m^3$)	Irrigation Diversion d_t ($10^6 m^3$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Jan	1	95	0	210	20	20	0
Feb	2	112	0	302	20	20	0
Mar	3	170	0	335	137	137	0
Apr	4	250	0	405	180	180	0
May	5	265	50	600	70	70	50
Jun	6	62	150	492	170	170	150
Jul	7	35	260	319	208	180	188
Aug	8	18	260	157	180	180	160
Sep	9	55	190	32	180	180	160
Oct	10	88	100	0	120	120	100
Nov	11	85	0	65	20	20	0
Dec	12	90	0	115	20	20	0

Solution

The following 42 decision variables are incorporated in the linear programming formulation, with t denoting the monthly time interval.

end-of-month storage	s_t for	$t = 1, 2, \ldots, 12$
reservoir release	r_t for	$t = 1, 2, \ldots, 12$
hydropower discharge	h_t for	$t = 1, 2, \ldots, 12$
irrigation diversion	d_t for	$t = 5, 6, 7, 8, 9, 10$

The objective is to maximize total annual revenues, in dollars.

$$\text{Revenues} = 400h_1 + 400h_2 + 400h_3 + 400h_4 + 400h_5 + 400h_6 + 400h_7 + 400h_8 + 400h_9 + 400h_{10} + 400h_{11} + 400h_{12} + 900d_5 + 900d_6 + 900d_7 + 900d_8 + 900d_9 + 900d_{10}$$

In the objective function, the coefficients are \$400 and \$900 per million m^3, respectively, for the 18 decision variables h_t and d_t and zero for the 24 decision variables s_t and r_t. Constraints are as follows. Monthly reservoir mass balances are maintained for each of the 12 months of the analysis for the inflows i_t tabulated in column 3 of Table 4.1. The storages at the beginning and end of the year are set equal (s_0=s_{12}) based on the premise that the annual cycle is repeated.

$$s_t - s_{t-1} + r_t = i_t \quad \text{for } t = 1, 2, \ldots, 12$$

End-of-month storages can not exceed the reservoir capacity of 600 million m^3.

$$s_t \leq 600 \quad \text{for } t = 1, 2, \ldots, 12$$

Diversions do not exceed the demands of column 4 of Table 4.1, and no more than 180 million m^3/month is used for hydroelectric power generation.

$$d_t \leq \text{demand} \quad \text{for } t = 1, 2, ..., 12$$
$$h_t \leq 180 \quad \text{for } t = 1, 2, ..., 12$$

The instream flow requirement is 20 million m^3/month. The flow used for hydropower can not exceed the reservoir release. The irrigation diversion can not exceed the reservoir release.

$$r_t - d_t \geq 20 \quad \text{for } t = 1, 2, ..., 12$$
$$r_t - h_t \geq 0 \quad \text{for } t = 1, 2, ..., 12$$

Nonnegativity constraints specify that the 42 decision variables have values that are zero or positive numbers.

$$s_t, r_t, h_t, d_t \geq 0$$

The complete formulation of the linear programming model is as follows.

Maximize Revenues =

$$400h_1 + 400h_2 + 400h_3 + 400h_4 + 400h_5 + 400h_6 + 400h_7 + 400h_8 + 400h_9 + 400h_{10} + 400h_{11} + 400h_{12} + 900d_5 + 900d_6 + 900d_7 + 900d_8 + 900d_9 + 900d_{10}$$

Subject to

$s_1 - s_{12} + r_1 = 95$	$s_1 \leq 600$	
$s_2 - s_1 + r_2 = 112$	$s_2 \leq 600$	
$s_3 - s_2 + r_3 = 170$	$s_3 \leq 600$	
$s_4 - s_3 + r_4 = 250$	$s_4 \leq 600$	
$s_5 - s_4 + r_5 = 265$	$s_5 \leq 600$	$d_5 \leq 50$
$s_6 - s_5 + r_6 = 62$	$s_6 \leq 600$	$d_6 \leq 150$
$s_7 - s_6 + r_7 = 35$	$s_7 \leq 600$	$d_7 \leq 260$
$s_8 - s_7 + r_8 = 18$	$s_8 \leq 600$	$d_8 \leq 260$
$s_9 - s_8 + r_9 = 55$	$s_9 \leq 600$	$d_9 \leq 190$
$s_{10} - s_9 + r_{10} = 88$	$s_{10} \leq 600$	$d_{10} \leq 100$
$s_{11} - s_{10} + r_{11} = 85$	$s_{11} \leq 600$	
$s_{12} - s_{11} + r_{12} = 90$	$s_{12} \leq 600$	
$r_1 \geq 20$	$r_1 - h_1 \geq 0$	$h_1 \leq 180$
$r_2 \geq 20$	$r_2 - h_2 \geq 0$	$h_2 \leq 180$
$r_3 \geq 20$	$r_3 - h_3 \geq 0$	$h_3 \leq 180$
$r_4 \geq 20$	$r_4 - h_4 \geq 0$	$h_4 \leq 180$
$r_5 - d_5 \geq 20$	$r_5 - h_5 \geq 0$	$h_5 \leq 180$
$r_6 - d_6 \geq 20$	$r_6 - h_6 \geq 0$	$h_6 \leq 180$
$r_7 - d_7 \geq 20$	$r_7 - h_7 \geq 0$	$h_7 \leq 180$
$r_8 - d_8 \geq 20$	$r_8 - h_8 \geq 0$	$h_8 \leq 180$
$r_9 - d_9 \geq 20$	$r_9 - h_9 \geq 0$	$h_9 \leq 180$
$r_{10} - d_{10} \geq 20$	$r_{10} - h_{10} \geq 0$	$h_{10} \leq 180$
$r_{11} \geq 20$	$r_{11} - h_{11} \geq 0$	$h_{11} \leq 180$
$r_{12} \geq 20$	$r_{12} - h_{12} \geq 0$	$h_{12} \leq 180$

$s_t \geq 0 \quad$ for t = 1, 2, ... , 12
$r_t \geq 0 \quad$ for t = 1, 2, ... , 12
$h_t \geq 0 \quad$ for t = 1, 2, ... , 12
$d_t \geq 0 \quad$ for t = 5, 6, ... , 10

The model can be solved using a spreadsheet program such as Microsoft Excel or other LP software. The resulting values for the decision variables are tabulated in columns 5, 6, 7, and 8 of Table 4.1. The objective function is $1,246,000 for this optimum decision policy. This is the optimum objective function value but only one of multiple optimum decision policies. Other sets of values for the decision variables also result in the objective function being $1,246,000.

The model formulated in Example 1, based on one year of streamflows, has 42 decision variables. Reservoir/river system reliability analysis are often based on monthly streamflow sequences covering 50 to 100 years. Using monthly streamflows for the 50-year (600 month) period 1951-2000, instead of just 12 months, increases the number of decision variables from 42 to 2,100. Example 1 has only one reservoir. The same general formulation has been applied to systems of many reservoirs, using hydrologic simulation periods of 50 to 100 years, resulting in LP models with many thousands of decision variables. Weekly or daily, rather than monthly, time steps are often adopted. As discussed later in conjunction with Examples 3 and 4, another common variation of this general type of model applies LP to operate multiple reservoirs and hydropower plants during one sequential time step (month, week, day) at a time. The LP computations are repeated within the model for each time step.

Linear programming is one of several alternative approaches for performing firm yield analyses. Firm yield is the maximum demand that can be met continuously during a sequence of reservoir inflows representing historical hydrology. The relationship between storage capacity and firm yield is fundamental information developed in planning and design of reservoir projects. The storage capacity C required to meet a specified set of water demands y_t representing a firm yield can be computed with the following LP formulation.

$$\text{minimize} \quad C \tag{4.9}$$

subject to

$$s_t = s_{t-1} + i_t - y_t - r_t \quad \text{for } t = 1, 2, \ldots, T \tag{4.10}$$

$$s_t \leq C \quad \text{for } t = 1, 2, \ldots, T \tag{4.11}$$

$$s_t, y_t, r_t \geq 0 \quad \text{for } t = 1, 2, \ldots, T \tag{4.12}$$

where: C = reservoir storage capacity
s_t = storage content at the end of period t
i_t = streamflow inflow to the reservoir during period t
y_t = demand during period t representing the firm yield
r_t = all spills and releases other than y_t during period t
T = number of time periods in the analysis

Thus, the reservoir storage capacity C is minimized subject to constraints which include: the reservoir mass balances; 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 time period t. The known firm yield withdrawals y_t and reservoir inflows i_t are provided as input data. The model computes the value of the storage capacity C and also values of end-of-period storage s_t and other releases r_t for each period t.

Yield analyses require an assumption regarding starting and ending storage conditions. Specification of the storage at the beginning s_0 and end s_T of the overall analysis period could be added to the model formulation. Alternatively, the entire streamflow sequence representing reservoir inflows may be assumed to be repeated as necessary to achieve a repetitive cycle. This is reflected in the model by assuming that the first (t=1) period of a T-period cycle follows the last period (t=T) of the prior cycle and specifying that the beginning (t=0) and ending (t=T) storages be equal ($s_0 = s_T$).

With the above formulation, the reservoir storage capacity C is computed for a user specified firm yield y_t. Alternatively, a model can be formulated to determine a constant firm yield Y provided by a specified storage capacity, by changing the objective function to:

$$\text{maximize } Y \tag{4.13}$$

subject to the same constraints as before. With this formulation, a storage capacity is specified as input, and the model computes the firm yield Y, along with values of s_t and r_t for each period.

Example 2 – Reservoir Firm Yield Model

The reservoir storage capacity required to provide a firm yield of 50 m^3/s for a given sequence of inflows is determined. Monthly inflow volumes are tabulated in column 3 of Table 4.2. The monthly diversion volumes in million m^3 corresponding to a constant diversion of 50 m^3/s are shown in column 4. A LP model is formulated to determine the storage capacity required to meet the monthly demands for the 24-month sequence of reservoir inflows. The final solution is tabulated in Columns 6 and 7 of Table 4.2. The LP formulation is as follows.

The LP problem is formulated with 49 decision variables consisting of the reservoir storage capacity C, end-of-period storage contents s_t and spills r_t for each of 24 months (t = 1, 2, ... , 24). The objective is to:

$$\text{minimize } C$$

In the objective function, the coefficients are 1.0 for the decision variable C and zero for the 48 decision variables s_t and r_t. A set of 24 constraints are formulated to represent the reservoir mass balance for each of the 24 months of the analysis. The mass balance is expressed as:

$$s_t = s_{t-1} + i_t - y_t - r_t$$

which is rearranged with the decision variables on the left of the equal sign:

$$s_t - s_{t-1} + r_t = i_t - y_t$$

The storage s_0 at the beginning of the first month is assumed to equal the storage s_T at the end of the last month. Thus, for the first month (t=1), the mass balance constraint is:

$$s_1 - s_{24} + r_1 = i_1 - y_1$$

With values for i_1 and y_1 from Table 4.2:

$$s_1 - s_{24} + r_1 = 123 - 134 = -11$$

A set of 24 constraints specify that storage content can not exceed capacity.

$$s_t - C \leq 0 \qquad \text{for } t = 1,2, \ldots , 24$$

Nonnegativity constraints specify that the 49 decision variables have values that are zero or positive numbers.

Table 4.2 Data (Columns 1-5) and Results (Columns 6-7)
for the Firm Yield Model of Example 2

Month (1)	t (2)	Inflow i_t (10^6m^3) (3)	Yield Y_t (10^6m^3) (4)	$i_t - y_t$ (10^6m^3) (5)	Storage s_t (10^6m^3) (6)	Release r_t (10^6m^3) (7)
Jan	1	123	134	-11	293	0
Feb	2	172	121	51	304	40
Mar	3	163	134	29	304	29
Apr	4	334	130	204	304	204
May	5	421	134	287	304	287
Jun	6	130	130	0	304	0
Jul	7	37	134	-97	207	0
Aug	8	19	134	-115	92	0
Sep	9	109	130	-21	71	0
Oct	10	88	134	-46	25	0
Nov	11	140	130	10	35	0
Dec	12	134	134	0	35	0
Jan	13	150	134	16	51	0
Feb	14	167	121	46	97	0
Mar	15	230	134	96	193	0
Apr	16	288	130	158	304	47
May	17	362	134	228	304	228
Jun	18	67	130	-63	241	0
Jul	19	32	134	-102	139	0
Aug	20	27	134	-107	32	0
Sep	21	98	130	-32	0	0
Oct	22	276	134	142	142	0
Nov	23	223	130	93	235	0
Dec	24	209	134	75	304	6

The complete formulation of the LP model is as follows.

$$\text{Minimize } C$$

Subject to:

$s_1 - s_{24} + r_1 = -11$	$s_{13} - s_{12} + r_{13} = 16$
$s_2 - s_1 + r_2 = 51$	$s_{14} - s_{13} + r_{14} = 46$
$s_3 - s_2 + r_3 = 29$	$s_{15} - s_{14} + r_{15} = 96$
$s_4 - s_3 + r_4 = 204$	$s_{16} - s_{15} + r_{16} = 158$
$s_5 - s_4 + r_5 = 287$	$s_{17} - s_{16} + r_{17} = 228$
$s_6 - s_5 + r_6 = 0$	$s_{18} - s_{17} + r_{18} = -63$
$s_7 - s_6 + r_7 = -97$	$s_{19} - s_{18} + r_{19} = -102$
$s_8 - s_7 + r_8 = -115$	$s_{20} - s_{19} + r_{20} = -107$
$s_9 - s_8 + r_9 = -21$	$s_{21} - s_{20} + r_{21} = -32$
$s_{10} - s_9 + r_{10} = -46$	$s_{22} - s_{21} + r_{22} = 142$
$s_{11} - s_{10} + r_{11} = 10$	$s_{23} - s_{22} + r_{23} = 93$
$s_{12} - s_{11} + r_{12} = 0$	$s_{24} - s_{23} + r_{24} = 75$

$$s_t - C \leq 0 \quad \text{for } t = 1, 2, \ldots, 24$$
$$s_t \geq 0 \quad \text{for } t = 1, 2, \ldots, 24$$
$$r_t \geq 0 \quad \text{for } t = 1, 2, \ldots, 24$$
$$C \geq 0$$

The model can be solved using Microsoft Excel or any LP software. The results consist of a storage capacity C of 304 million m^3 and the values for s_t and r_t tabulated columns 6 and 7 of Table 4.2.

LP formulations have been incorporated into a number of river basin management models to allocate streamflow and reservoir storage contents among numerous water users in accordance with water rights priority systems. For example, a simulation model might allocate water to several hundred water users during each month of a 60-year (720 month) hydrologic period-of-analysis using a monthly computational time step. The simulation results are used to compute reliabilities for each of the water users. A LP formulation performs the water allocation during each month of the simulation. Thus, the LP algorithm is activated 720 times during a simulation. Examples 3 and 4 have only a few water users but illustrate the general concept of formulating LP models to allocate water among users based on specified priorities.

Example 3 – Water Allocation Model

A schematic of a river/reservoir system is presented in Figure 4.2. Reservoirs A and B, located at nodes 1 and 2, have storage capacities of $750 \text{x} 10^6$ and $900 \text{x} 10^6$ m^3, respectively. The initial storage in Reservoirs A and B at the beginning of the time interval is $460 \text{x} 10^6$ and $215 \text{x} 10^6$ m^3, respectively. Releases are made as necessary to maintain instream flow requirements and then, to the extent possible, to meet water supply diversion targets.

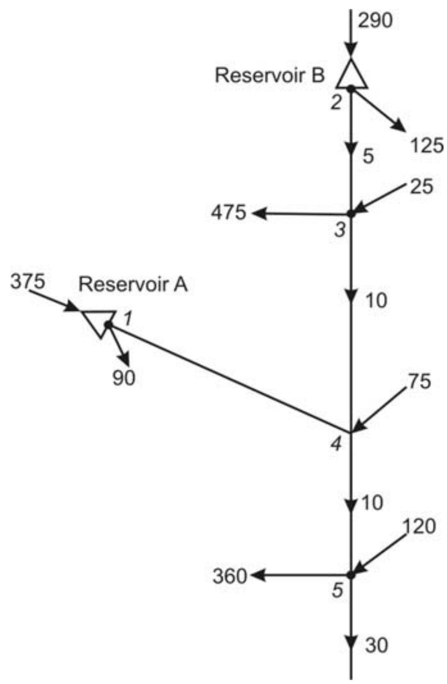

Figure 4.2 System Schematic for Examples 3 and 4

Table 4.3 Given Information for Examples 3 and 4

Location Or Node	Initial Storage ($10^6 m^3$)	Local Inflow ($10^6 m^3$)	Total Supply ($10^6 m^3$)	Demand Target ($10^6 m^3$)	Relative Priority
1	460	375	835	90	4
2	215	290	505	125	3
3	-	25	25	475	2
4	-	75	75	-	-
5	-	120	120	360	5

The supply and demand for water are shown in Table 4.3 for each of the node locations shown in Fig. 4.2. The total supply at each node consists of reservoir storage at the beginning of the time interval and the local flow entering the river between the node and adjacent upstream node(s) during the time period. The demand in Table 4.3 is a target diversion at each node. If supplies are insufficient to meet all demands, allocations are based on the relative priorities tabulated in the last column. For example, with a relative priority of 5, the diversion of $360x10^6$ m^3 at node 5 has the highest priority of the four diversions. Lesser priority diversions are met only to the extent that higher priority diversions are not adversely affected. Instream flow requirements are as follows:

Reach	1-4	2-3	3-4	4-5	below 5
Flow (10^6 m^3)	0	5	10	10	30

The model incorporates the 11 decision variables defined in Table 4.4. The decision variables include instream flows in each of five river reaches (x_1, x_2, x_3, x_4, x_5), water supply diversions at four nodes (x_6, x_7, x_8, x_9), and the ending storage in the two reservoirs (x_{10}, x_{11}).

Table 4.4 Decision Variables for Example 3

Decision Variables	Definition of Decision Variables	Solution (10^6 m^3)
X_1	instream flow from 1 to 4	195
X_2	instream flow from 2 to 3	380
X_3	instream flow from 3 to 4	10
X_4	instream flow from 4 to 5	270
X_5	instream flow below node 5	30
X_6	diversion at node 1	90
X_7	diversion at node 2	125
X_8	diversion at node 3	395
X_9	diversion at node 5	360
X_{10}	reservoir A ending storage	550
X_{11}	reservoir B ending storage	0

The objective function is formulated to reflect relative priorities between water users as follows.

$$\text{maximize} \quad x_0 = 4x_6 + 3x_7 + 2x_8 + 5x_9 + x_{10} + x_{11}$$

The objective function coefficients are used simply to assign relative priorities to guide the allocation of the limited water resources to competing uses. The absolute values of the coefficients are arbitrary. Only the relationship of the coefficient values relative to each other affect the results. Water supply diversion x_9 is assigned the highest priority of the four diversions, as reflected by its coefficient of five. Filling the two reservoirs (x_{10}, x_{11}) is assigned lower priority as reflected by coefficients of one. The diversion targets are fully met prior to filling the reservoirs.

The instream flow requirements (x_1, x_2, x_3, x_4, x_5) are assigned zero priority (coefficient values) in the objective function and are handled as constraints.

$$x_1 \geq 0 \qquad x_2 \geq 5 \qquad x_3 \geq 10 \qquad x_4 \geq 10 \qquad x_5 \geq 30$$

The constraints force the instream flow requirements to be met even if diversion targets can not be fully met. Sufficient water is available to meet all instream flow requirements. Otherwise, there would be no feasible solution, and the model would have to be reformulated.

A volume balance constraint is written for each node. For example, at node 1, initial storage and inflows of 835 m^3 from Table 4.3 supply downstream flows (x_1), diversions (x_6), and reservoir filling (x_{10}).

$$x_1 + x_6 + x_{10} = 835$$

The complete LP model is formulated as follows

$$\text{maximize } x_0 = 4x_6 + 3x_7 + 2x_8 + 5x_9 + x_{10} + x_{11}$$

subject to

$x_1 \geq 0$	$x_2 \geq 5$	$x_3 \geq 10$	$x_4 \geq 10$
$x_5 \geq 30$	$x_6 \leq 90$	$x_7 \leq 125$	$x_8 \leq 475$
$x_9 \leq 360$	$x_{10} \leq 750$	$x_{12} \leq 900$	

$$x_1 + x_6 + x_{10} = 835$$
$$x_2 + x_7 + x_{11} = 505$$
$$-x_2 + x_3 + x_8 = 25$$
$$-x_1 - x_3 + x_4 = 75$$
$$-x_4 + x_5 + x_9 = 120$$

The model can be solved using any LP software. The resulting values for the decision variables are tabulated in the last column of Table 4.4.

Network Flow Programming

Network flow programming is a computationally efficient form of linear programming which can be applied to problems that can be formulated in a specified format representing a system as a network of nodes and arcs having certain characteristics. Network flow programming is addressed in detail by Jensen and Barnes (1980), Ahuja et al. (1993), and others. Several of the reservoir/river system management models cited in Chapters 6 and 7 are based on network flow programming.

The general form of a network flow programming formulation is as follows:

$$\text{minimize} \quad \sum\sum c_{ij} q_{ij} \quad \text{for all arcs} \tag{4.14}$$

$$\text{subject to} \quad \sum q_{ij} - \sum q_{ji} = 0 \quad \text{for all nodes} \tag{4.15}$$

$$l_{ij} \leq q_{ij} \leq u_{ij} \quad \text{for all arcs} \tag{4.16}$$

where q_{ij} is the flow rate in the arc connecting node i to node j; c_{ij} is a penalty or weighting factor for q_{ij}; l_{ij} is a lower bound on q_{ij}; and u_{ij} is a upper bound on q_{ij}.

In a network flow model, the system is represented as a collection of nodes and arcs. For a reservoir/river system, the nodes are locations of reservoirs, diversions, stream tributary confluences, and other pertinent system features. Nodes are connected by arcs or links representing the way *flow* is conveyed. For a reservoir/river system, flow represents either a discharge rate, such as instream flows and diversions, or a change in storage per unit of time.

A solution 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 including maintaining a mass balance at each node and not violating user-specified upper and lower bounds on the flows. Each arc has three parameters: a weighting, penalty, or unit cost factor c_{ij} associated with q_{ij}; lower bound l_{ij} on q_{ij}; and an upper bound u_{ij} on q_{ij}. The requirement for lower and upper bounds results in the term capacitated flow networks. Network flow programming provides considerable flexibility for formulating a particular application. The weighting factors c_{ij} in the objective function are defined in various ways. The c_{ij} may be unit costs in dollars or penalty or utility terms that provide mechanisms for expressing relative priorities. A penalty weighting factor is the same as a negative utility weighting factor.

Network flow programming problems can be solved using conventional LP algorithms. However, the network flow format facilitates the use of much more computationally efficient algorithms that save computer time and allow analysis of larger problems with numerous variables and constraints.

Example 4 – Network Flow Programming

This example consists of repeating the previous Example 3 using the network flow format of Equations 4.14-4.16. Flows q_{ij} are computed for the arcs connecting the set of five nodes shown in Figure 4.3 along with a source node and a sink node. The source node represents the source of water entering the stream/reservoir system. Water leaving the system flows to the sink node. The decision variables q_{ij}, lower and upper bounds l_{ij} and u_{ij} on q_{ij}, and objective function coefficients c_{ij} are shown in Table 4.5. The c_{ij} are the relative priorities, which for the diversions are given in Table 4.5. Five constraints in the form of Equation 4.15 represent the volume balance at each of the five node locations shown in Figure 4.3. Constraints in the form of Equation 4.16 place upper and lower bounds on the decision variables. In order to fit the capacitated network flow format, the given initial storage and inflows are treated as decision variables with both lower and upper bounds set at the values specified in Table 4.5.

The network flow model is formulated as follows:

maximize $$4q_{1,D} + 3q_{2,D} + 2q_{3,D} + 5q_{5,D} + q_{1,S} + q_{2,S}$$

subject to
$$q_{S,1} - q_{1,D} - q_{1,4} - q_{1,S} = 0$$
$$q_{S,2} - q_{2,D} - q_{2,3} - q_{2,S} = 0$$
$$q_{S,3} + q_{2,3} - q_{3,D} - q_{3,4} = 0$$
$$q_{S,4} + q_{1,4} + q_{3,4} - q_{4,5} = 0$$
$$q_{S,5} + q_{4,5} - q_{5,D} - q_{5,S} = 0$$

$$0 \le q_{1,4} \le 999 \qquad 835 \le q_{S,1} \le 835 \qquad 0 \le q_{1,D} \le 90$$
$$5 \le q_{2,3} \le 999 \qquad 505 \le q_{S,2} \le 505 \qquad 0 \le q_{2,D} \le 125$$

$10 \le q_{3,4} \le 999$ $\quad$ $25 \le q_{S,3} \le 25$ $\quad$ $0 \le q_{3,D} \le 475$

$10 \le q_{4,5} \le 999$ $\quad$ $75 \le q_{S,4} \le 75$ $\quad$ $0 \le q_{5,D} \le 360$

$30 \le q_{5,S} \le 999$ $\quad$ $120 \le q_{S,5} \le 120$ $\quad$ $0 \le q_{1,S} \le 750$

$0 \le q_{2,S} \le 900$

The problem is solved using a spreadsheet or LP program. Since the model is formulated in the format of Equations 4.14-4.16, network flow programming algorithms can be used. The solution is tabulated in the last column of Table 4.5.

Table 4.5 Terms in Network Flow Formulation of Example 4

Decision Variable q_{ij}	Definition of q_{ij}	Nodes i	j	Lower Bound l_{ij}	Upper Bound u_{ij}	Priority c_{ij}	Solution ($10^6 m^3$) q_{ij}
$q_{1,4}$	instream flow from 1 to 4	1	4	0	999	0	195
$q_{2,3}$	instream flow from 2 to 3	2	3	5	999	0	380
$q_{3,4}$	instream flow from 3 to 4	3	4	10	999	0	10
$q_{4,5}$	instream flow from 4 to 5	4	5	10	999	0	270
$q_{5,S}$	instream flow below 5	5	sink	30	999	0	30
$q_{S,1}$	inflow + initial storage	source	1	835	835	0	835
$q_{S,2}$	inflow + initial storage	source	2	505	505	0	505
$q_{S,3}$	inflow + initial storage	source	3	25	25	0	25
$q_{S,4}$	inflow + initial storage	source	4	75	75	0	75
$q_{S,5}$	inflow + initial storage	source	5	120	120	0	120
$q_{1,D}$	diversion at node 1	1	sink	0	90	4	90
$q_{2,D}$	diversion at node 2	2	sink	0	125	3	125
$q_{3,D}$	diversion at node 3	3	sink	0	475	2	395
$q_{5,D}$	diversion at node 5	5	sink	0	360	5	360
$q_{1,S}$	reservoir A storage	1	sink	0	750	1	550
$q_{2,S}$	reservoir B storage	2	sink	0	900	1	0

Comparison of Alternative Modeling Approaches

Linear programming is compared with alternative nonlinear optimization methods. Models based solely on ad hoc algorithms are compared with those that incorporate mathematical programming algorithms. Descriptive simulation models (with or without mathematical programming) are compared with prescriptive optimization models.

Alternative Mathematical Programming Methods

Linear programming (LP) dominates as the most widely applied of the various optimization methods. LP has the advantage over other optimization techniques of being a well-defined, easy-to-understand method with well established solution algorithms and readily available solver software. 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 techniques have been used successfully to deal with nonlinearities such as evaporation and hydropower computations. However, the strict linear form of LP does limit its applicability.

Nonlinear properties of a problem can be readily reflected in a dynamic programming (DP) formulation. DP is not a precise algorithm like LP, but rather is a general approach to solving optimization problems. DP is applicable to problems that can be formulated by 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 incorporating ad hoc algorithms and/or mathematical programming algorithms. 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.

Ad Hoc Simulation Algorithms Versus Standard LP Algorithms

Ad hoc simulation algorithms generally provide the advantage of permitting a more detailed and realistic representation of the complex characteristics of a reservoir/river system. Mathematical programming requires adherence to the proper mathematical formulation. Methods for dealing with restrictions on mathematical form are available, such as schemes for linear approximations of nonlinear relationships. However, representing complex reservoir storage allocations and system operating rules, institutional arrangements, and physical facilities in the required format, without unrealistic simplifications, is a particularly difficult aspect of the modeling process which limits the application of mathematical programming techniques.

The advantages of LP relative to ad hoc algorithms are related to:

- using standard systematic methods with readily available solution algorithms
- determining values for numerous variables in a single simultaneous solution
- facilitating a more prescriptive analysis

Many different models, representing diverse applications in engineering, science, and business, can be developed based on the same standard LP algorithms. LP provides useful capabilities for analyzing problems characterized by a need to consider an extremely large number of combinations of values for decision variables. LP 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. For 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 illustrate the motivation for a mathematical programming algorithm.

Descriptive Versus Prescriptive Orientation

System analysis models may be categorized as being descriptive or prescriptive. Descriptive models demonstrate what will happen if a specified plan is adopted. Prescriptive models determine the plan that should be adopted to satisfy specified decision criteria. Although it is desirable for models to be as prescriptive as possible, real-world complexities of reservoir system operations often necessitate model orientation toward the more descriptive end of the descriptive/prescriptive spectrum. In general, models should be as prescriptive as the scope of the study demands and the complexities of the application allow.

Mathematical programming techniques enhance capabilities to develop models that are more prescriptive. Optimization models automatically determine decision variable values which optimize an objective function, which is consistent with the concept of prescriptive modeling. However, capabilities for formulating objectives and assessing performance in meeting these objectives is the driving consideration. Simulation and optimization models should not be rigidly characterized as being descriptive and prescriptive, respectively. Both optimization and simulation models can be more or less oriented toward being either descriptive or prescriptive. Examples of descriptive and more prescriptive models are presented to illustrate this point.

Assume a multiple-reservoir system is operated for flood control and hydroelectric power. The total storage capacity in each reservoir of this existing system is fixed. The problem is to determine the optimal seasonal allocation of storage capacity between flood control and hydroelectric power in each reservoir.

Examples of descriptive simulation and optimization models are noted first. A linear programming model is formulated for computing firm energy for a given storage allocation plan. Linearization techniques are adopted for approximating the nonlinear evaporation and hydropower computations. Likewise, a ad hoc simulation model, incorporating iterative algorithms, can be used to compute firm energy for a given storage allocation plan. Alternative runs of either the LP or ad hoc simulation models can be made to determine firm hydroelectric energy for alternative storage allocations. Firm energy as well as firm water supply yield analyses are quite common. The information provided is very useful in evaluating alternative storage allocation plans. However, the modeling exercise does not directly result in determining the optimal plan, assuming that our objectives entail more than just maximizing firm energy. Thus, both the LP simulation model and ad hoc simulation model can be categorized as being descriptive.

Optimization and simulation models are now formulated that have a more prescriptive orientation. The objective of maximizing economic benefits, in dollars, is adopted. The objective is expressed in terms of maximizing average annual hydropower revenues minus average annual flood damages. A linear programming model is developed which determines releases from each reservoir for each time interval which maximizes the total dollar value of hydropower revenues minus flood damages over the period-of-analysis. The optimization model is executed for a given alternative storage allocation plan, assuming all past and future streamflows are known at the time each release is made. The complexities involved in computing expected annual flood damages for this system necessitates a fairly rough approximation of flood damages in the linear programming model.

A simulation model based on a set of ad hoc computational procedures is also developed which computes both hydroelectric power revenues and flood damages for a given storage allocation plan. The simulation model provides more detailed computational procedures for estimating expected annual flood damages. Other aspects of flood control and hydropower release rules are specified in more detail than in the LP model.

Alternative runs of either the LP model or the ad hoc simulation model result in hydropower and flood control benefits for alternative seasonal storage allocation plans. Since the two alternative models reflect several different basic premises, the results are not equivalent but are meaningful from different perspectives. Multiple alternative runs of these models, combined with adoption of the economic efficiency criterion, represents a more prescriptive evaluation approach than the firm yield analysis of the previous paragraph.

Finding the storage allocation plan, which maximizes the specified objective function, is not necessarily guaranteed with a finite number of executions of either model. None of the models are absolutely prescriptive, since capabilities are not provided for automatically determining the economically optimum storage reallocation plan in a single run of a model.

LP and other mathematical programming models may be classified as either:

1. repeating the mathematical programming solution algorithm at each time step which often involves repeating sets of iterative repetitions of the algorithm dealing with nonlinearities at each time step
2. solving the mathematically programming problem once simultaneously considering all time steps which again may involve iterative repetitions to deal with nonlinearities

Descriptive simulation models (with or without mathematical programming algorithms) step sequentially through time, performing the computations for each time interval in turn. The period-by-period computations result in future streamflows not being reflected in release decisions, except for some models which include features for limited short-term forecasts. The future is unknown as real-world water management decisions are made. Thus, stepping through time sequentially is realistic in this regard. Prescriptive optimization techniques tend to naturally fit the format of computing releases for all time intervals simultaneously based on minimizing or maximizing a specified objective function. Thus, prescriptive optimization models typically make all release decisions simultaneously considering all streamflows covering the entire period of analysis.

Models vary significantly in the mechanisms adopted to represent the water management and use system. Some models provide more flexibility than others in regard to realistically representing reservoir system operating rules and water-use requirements and priorities. Most prescriptive optimization models compute the releases that optimize an objective function without directly using reservoir system operating rules. Descriptive simulation models provide mechanisms for the user to define the operating rules in various levels of detail.

Descriptive simulation models (with or without mathematical programming algorithms) and prescriptive optimization models can be used in combination. For example, a typical reservoir system analysis problem consists of establishing operating rules which best achieve certain water management objectives. A prescriptive optimization model may be used to determine sequences of reservoir release decisions that maximize or minimize a criterion function that provides a measure of performance in meeting the water management objectives. Professional judgment and various analyses are than used to develop operating rules that appear to be consistent with the sequences of release decisions reflected in the optimization model results. These rules are than tested using a descriptive simulation model. In various other types of applications as well, preliminary screening of numerous alternatives using a prescriptive optimization model may be followed by a more detailed evaluation of selected plans using a descriptive simulation model.

Chapter 5
Model Development Software

Modeling systems are constructed using the following types of software tools, which represent different model building approaches or environments in which to work.

- programming languages such as Fortran, C, C++, Java, and Basic
- general-purpose modeling environments
    - spreadsheet software products such as EXCEL
    - simulation software products such as STELLA
    - optimization software products such as GAMS
    - mathematics software products such as MATLAB
- auxiliary software products for data management and analysis
    - geographical information systems such as ArcGIS
    - relational database systems used in business such as ORACLE
    - water resources time series database systems such as HECDSS
- generalized reservoir/river system models such as those described in Chapters 6 and 7
- variations and/or combinations of the above

Programming languages are used to code both customized site-specific and generalized reservoir/river system models. Proprietary software on the commercial market, which is widely used in various business, scientific, and engineering fields, is also applicable to reservoir/river system modeling. These software products have also been created using programming languages.

Generalized reservoir/river system modeling systems provide a framework or environment in which to build a model for a particular river basin. Alternatively, a model for a reservoir/river system may be constructed within a spreadsheet, object-oriented simulation, or mathematical optimization environment using commercially available general-purpose software tools. Software products also provide auxiliary capabilities for compiling, storing, manipulating, organizing, analyzing, and displaying model input and output data. Various types of software are often combined for a particular modeling application.

Programming Languages

A computer system consists of three main layers: hardware, operating system software, and application software (Cezzar 1995, Beekman 2005). The hardware includes the electronics that carries out actions specified by the software. The operating system is a set of programs designed to facilitate operation of the computer. The operating system is normally bundled with the hardware delivered by a vendor since a bare machine without an operating system is quite useless. The application layer consists of programs that accomplish particular functions such as word processing, spreadsheet computations/graphics, and modeling reservoir/river systems. Many thousands of application programs are sold by thousands of companies. Some of these software products are pertinent to reservoir/river system modeling and other water resources engineering applications.

System and applications software directing the actions of a computer are written using programming languages. A *programming language* is a notational system for specifying the operations performed by a computer in a form reasonably-easily understood by humans that can be readily converted to machine-readable form. Machine languages correspond to the instruction set of a particular hardware architecture and are entirely machine dependent. Programming in machine language is extremely tedious, requiring the programmer to keep track of detailed hardware features such as registers, address modes, and memory mapping. Symbolic assembly languages make programming easier by using mnemonics for operations and operands but are still dependent on the specific hardware. High-level languages further facilitate programming by relieving the programmer of many of the details of managing hardware. With high-level languages, programs can be written to run on any type of computer, rather than being machine dependent. High-level implies that the programming language is one or more steps away from machine language.

Software products are available for translating code written in a particular high-level programming language into a form suitable for computer execution. A translator that executes a program directly is called an interpreter. The translation takes place each time the program is run. Translation software that produces an equivalent program in a form suitable for execution is called a compiler. Once translated, the compiled machine language equivalent program can be executed repeatedly. In converting programs to machine-readable executable code, compilers also optimize the efficiency of the program in terms of memory requirements and run time.

Microsoft, Intel, Sun Microsystems, Compaq, Hewlett Packard, and Lahey are among the well-known companies that market compilers, interpreters, and auxiliary software for developing computer programs in various high-level programming languages. Many other companies sell these types of software products as well. An internet search will also reveal various sources of free compilers and related software.

During the 1940's and early 1950's, programming was accomplished entirely with machine and low-level assembly languages with assembler software translating code into instructions for individual types of computers. Machine and assembly languages are still used by professional programmers along with high-level languages. Since the 1950's, many hundreds of high-level languages have been developed. Most of the languages are now obsolete. Languages that are still widely used include: ADA, ALGOL, APL, ASM, AWK, BASIC, BETA, C, C#, C++, CLARION, CLIPPER, CLOS, CLU, COBOL, CPLU, CRASS, DFL, DYLAN, EBONICS, EIFFEL, ESTEREL, FOR, FORTH, FORTRAN, HERMES, ICON, IDL, JAVA, JAVASCRIPT, LABVIEW, LIMBO, LISP, LOGO, MH, ML, MODULA2, MODULA3, MUMPS, OBERON, OBJECTIVE C, OCCAM, PASCAL, PERL, PL1, PLB, POP, POSTSCRIPT, POSTSCRIPT, PROGRAPH, PROLOG, PYTHON, REXX, SATHER, SCHEME, SIMULA, SMALLTALK, SNOBOL, TCL, VERILOG, VHDL, VRML, and YORICK (Louden 2003). The dominant languages are variations of Basic, C, C++, Cobol, Fortran, Java, and Pascal (Conger 2003).

Characteristics of Programming Languages

Procedural and object-oriented are two particular paradigms or organizing characteristics of programming languages. Most languages are characterized as being procedural in nature. Procedural languages are also called imperative. The fundamental concepts of procedural programming date back to the 1950's and have been evolving ever since. The object-oriented programming paradigm has played a key role in the evolution of programming languages during the past 25 years. Many languages are now characterized as being object-oriented. Many languages combine hybrid features of both procedural and object-oriented programming strategies.

A language is categorized as procedural if it has the following properties: (1) sequential execution of instructions, (2) use of variables representing memory locations, and (3) use of assignment to change the values of variables. Procedural languages are also referred to as being imperative since a central feature is a sequence of statements that represent commands or imperatives. A program consists of a list of statements that are executed in sequential order. Programs are organized into algorithmic procedures and control structures. Procedures or subprograms treat complex sequences of operations as a single unit that can be reused. A program is similar to the original mathematical form of a computational algorithm. Variables in a procedural language are similar to variables in mathematics. Variables may be grouped in indexed arrays. Program operations change the values of variables (Cezzar 1995; Louden 2003; Reilly 2004).

The object-oriented paradigm is based on the concepts of objects and classes. An object is a collection of memory locations together with all the operations that can change the values of these memory locations. Instructions and information are coded and stored as objects or modules. Objects can be reused in different programs and subprograms. Each object has a set of values and set of behaviors. The behavior of an object is defined by a set of methods that may operate on the object. Objects are grouped into classes that represent all the objects with the same properties. A class characterizes the structure of states and behaviors that are shared by its objects. Objects are classified into hierarchies through inheritance mechanisms. Inheritance allows reuse of the behavior of a class in the definition of new classes. Classes may be modified through inheritance. Subclasses of a class inherit the operations of the class and may add new operations and new instance variables (Cezzar 1995; Louden 2003; Reilly 2004).

Visual programming refers to a style of programming that relies on graphics-based user interfaces and applies object-oriented principles for manipulating visual objects (Cezzar 1995). Managing input and output receives a great deal of attention in visual programming. Another distinguishing characteristic is being event driven. Events are actions or changing conditions such as a mouse button being clicked on a visual object or text being modified on an edit screen.

A graphical user interface (GUI) is a style of interaction between the user and computer that employs four fundamental elements: windows, icons, menus, and pointers (Torres 2002). Features of GUI's include direct manipulation, mouse or pointer support, graphics, and areas for application function and data. GUI's are very popular for all types of software. Studies have shown that GUI's do not guarantee better usability, but well-designed GUI-based software can be better than non-GUI counterparts in user effectiveness and satisfaction, given the right tasks and skills (Torres 2002).

Computer languages play three different roles in constructing models such as reservoir/river system simulation models.

1. Computational algorithms and data management schemes are implemented to perform the basic modeling computations for which the model is developed.

2. GUI's and interfaces between various software and hardware components of a modeling system are created.
3. Special-purpose languages may be embedded within a model to perform certain specialized tasks.

Different languages may be adopted to develop different parts of the same applications software. The languages cited in the following discussion are all general-purpose languages, but tend to be oriented differently in regard to balancing capabilities for performing the roles listed above.

Reservoir/river system models have been developed in a variety of languages, either completely in a particular language or with various components written in different languages. Historically, Fortran has dominated. C++ has also been used extensively during the past 15 years. Java is the newest language. C and Basic are also relevant to reservoir/river system modeling. All of these languages continue to evolve with various new and improved versions being released fairly frequently.

Fortran

Fortran (FORmula TRANslator) was originally developed by IBM in the 1950's. Fortran is the oldest high-level programming language and continues to be widely used in engineering and science. It is a procedural language designed for efficient and flexible implementation of mathematical modeling algorithms. Most water resources engineering related computer programs developed prior to 1990 and many of the more recent programs are coded in Fortran. Both the Fortran language and the compilers and appurtenant programming software that implement the language continue to evolve over time with updated versions being released periodically.

The American National Standards Institute (ANSI) approved Fortran 66 in 1966 as the first ever standard for a programming language. Subsequent standardized versions of the language are Fortran 77, Fortran 90, Fortran 95, and Fortran 2003. Fortran 90 provided major improvements over Fortran 77. Fortran 95 reflects additional relatively minor revisions. Fortran 2003 incorporates major new additions. Expanded features of Fortran 2003 include object-oriented programming support and interoperability with the C programming language as well as other improvements. The design of Fortran 2003 was completed in 2003 (Metcalf, et al. 2004). Many Fortran 2003 features are incorporated in the latest Intel compiler (Intel Corporation 2004). Compilers fully implementing Fortran 2003 are expected soon. Compilers implementing a particular version of Fortran typically allow use of previous versions of the language as well.

The Intel and Lahey Corporations are leading suppliers of Fortran compilers and related Fortran software development products (http://www.intel.com; http://www.lahey.com). The popular Compaq Visual Fortran development package (Lawrence 2002) was recently integrated with Intel Visual Fortran. Lahey also sells Visual Fortran compilers along with a suite of other compilers and development tools supporting Fortran programming. Recent versions of Intel/Compaq and Lahey Visual Fortran compilers may be integrated with the Microsoft Visual Studio .NET ("dot NET") development environment. Dot NET is briefly discussed later in conjunction with Microsoft Visual Basic. Other companies also market Fortran compilers and supporting software development packages.

C, C++, Objective C, C#

The C language was originally developed at AT&T Bell Laboratories in the 1970's and has since grown into a family of languages. C is an efficient relatively low-level (closer to the machine) language designed for use by professional programmers (Congar 2003). The myriad of software products coded in C include operating system software, wordprocessors, and programs that control communications systems and other types of equipment. The C programming language was used to write the Unix operating system released in 1973, making Unix the first operating system to be written in a high-level programming language rather than machine or assembly language (Reilly 2004). C continues to be popular for use by systems programmers. C is designed as a procedural language. However, the languages discussed below that derived from C incorporate object-oriented programming concepts.

The Objective C language was developed in the 1980's by adding extensions to C that allowed objects to be created and manipulated (Kochan 2004). Development of the C# ("C sharp") language began in 1998 with the goal of providing a modern object-oriented programming language for the new Microsoft .NET platform (Hejlsberg, et al. 2004). Microsoft announced C# in 2000.

C++ was invented in the mid-1980's at the AT&T Bell Laboratories. C++ is an extension of C, which retains all of the C language while adding special features for object-oriented programming (Josuitts 2003). C++ is the most widely applied object-oriented extension of the procedural oriented C language. C and C++ both provide enhanced graphics capabilities while optimizing computational efficiency. The object-oriented programming features of C++ are designed to make programming simpler and reduce the time and effort required to develop software products. Development software with compilers for C and C++ are available from the Microsoft Corporation and many other sources.

C and C++ have been used extensively in recent years to develop water resources engineering models. In some cases, complete models are coded in these languages. In other cases, C or C++ and Fortran are used in combination, with C or C++ providing graphical user interface development capabilities and Fortran being used for developing computational routines.

Java

The Java programming language was introduced in 1995 and quickly became a popular competitor of C++ (Louden 2003; Jia 2003). Initial efforts in developing Java's predecessor called Oak were motivated by embedded consumer-electronics applications. However, Java's popularity has been driven largely by Internet applications (Reilly 2004). Java programming allows use of applets, which are small Java components that run within a Web browser to provide animation and other features. Java is not as efficient as C, C++, and Fortran, from the perspectives of computer run time and memory requirements, for computationally intensive engineering and scientific modeling applications (Louden 2003). However, Java is a general-purpose language that is used for developing various types of software including water resources related modeling systems.

Java resembles C and C++ but omits many unwieldy features (Kak 2003). Whereas C++ is a hybrid procedural and object-oriented language, Java is considered to be a purer implementation of object-oriented programming concepts and perhaps simpler to use. All Java data attributes and functions must be in classes, which define types of objects. Unlike C++, Java permits a class to be a subclass of only one class, but allows any number of class interfaces.

Java was developed by and is a proprietary product owned by Sun Microsystems (http://java.sun.com/). Use of Java is subject to permission from Sun Microsystems, which may impede its adoption by some software development entities (Louden 2003). Because of Java licensing restrictions imposed by Sun Microsystems, Microsoft announced its own Java-like language called C# ("C sharp") in June 2000 (Reilly 2004). C# is designed for implementation with the new Microsoft distributed application framework called .NET ("dot NET").

Java technology is an object-oriented, platform-independent programming environment available from Sun Microsystems (http://wwws.sun.com/software/java/). Programs written in the Java programming language are usually compiled with Java technology. The resulting software will run on any computer on which a Sun Microsystems product called the Java virtual machine is installed. With Java technology and the Java virtual machine, a program coded in the Java language will work on any kind of computer such as a PC, Macintosh, network computer, or new technologies like Internet screen phones.

Visual Basic

Basic (Beginner's All-Purpose Symbolic Instruction Code) is widely applied in many fields including water resources planning and management. Basic was originally created at Dartmouth College in the early 1960's. The various early versions included Microsoft QuickBasic which was popular during the 1980's. The very popular Microsoft Visual Basic was first released in 1991. The seventh version of Microsoft Visual Basic released in 2001, called Visual Basic.NET, is designed for building programs for the Windows operating system or any operating system that supports Microsoft's .NET architecture (Vitter 2001, Shelly, et al. 2003; http://msdn.microsoft.com/vbasic/).

Microsoft announced its .NET initiative in 2000. Dot NET encompasses a series of technologies that allows almost any type of application to run in a common environment. Microsoft is providing a .NET framework class library that is accessible using any .NET-enabled programming language. Classes of modules for common tasks can be obtained from the library rather than recreating code for each different program. Among other benefits, the .NET framework facilitates easier development of graphical user interfaces (GUI's).

Visual Basic is an easy-to-learn, general-purpose, object-oriented language for non-professional programmers. Object-oriented graphical user interfaces can be conveniently created. Web pages may be created that run in almost any Web browser. Visual Basic for Applications (VBA), a simplified version of Visual Basic, is used to develop macros within Microsoft Excel and ESRI ArcGIS. A macro is a relatively small program written to run within a larger program package. Albright (2001) describes use of VBA in developing decision support systems with Microsoft Excel. Burke (2003) explains how to build objects in ArcGIS using VBA. Visual Basic is somewhat cumbersome with limited capabilities compared to Fortran, C, and C++ for developing large complex models. However, Visual Basic can be used for developing graphical user interfaces for programs coded in Fortran or other languages.

<u>Comparison of Programming Languages</u>

Considerations in comparing and evaluating programming languages for a particular application such as developing a reservoir/river system model include the following:

- flexibility in developing a model that performs in detail its intended functions
- efficiency of the executable model in terms of memory requirements and run times
- ease-of-use in applying and understanding the model
- programming expertise and effort required to develop the software
- programming expertise and effort required to modify and maintain the software

As previously noted, computer languages play multiple roles in constructing a model that include:

- implementing computational algorithms and data management schemes to perform the basic modeling computations (computational engine)
- creating graphical user interfaces (GUI's) or other types of user interfaces and interfacing software and hardware components of modeling systems

Programming GUI's and programming the basic computational procedures are very different tasks requiring significantly different programming capabilities. Other specialized interface and data management features of a model may involve programming capabilities that are significantly different than developing the computational engine and GUI. Different parts of a model may be coded in different languages.

Prior to the 1990's, development of water resources engineering models focused on improving capabilities for modeling hydrologic, hydraulic, and water quality processes and water management practices. Improvements in numerical solution techniques were a major emphasis. During the early 1990's the emphasis shifted to using advances in computer technology to develop GUI's. Interfacing components of modeling systems also became a key focus. Developing GUI's and interfacing various model components were found to require considerable effort. Newer development environments are featuring class libraries for building GUI's and other common software components. With continuing advances in computer technology simplifying the development of GUI's and interfaces between modeling system components, the pendulum should eventually shift back toward a greater emphasis on modeling hydrologic, hydraulic, and water quality processes and water management practices.

Object-Oriented Programming

Degree of object-orientation or lack thereof has become a major consideration in comparing programming languages. Object-oriented programming dates back to the 1960's. Simula released in 1967 was the first of many object-oriented languages. Smalltalk is a pure object-oriented language that became popular during the 1970's. Starting in the mid-1980's, object-oriented programming became a very popular term, and hybrid object-oriented dialects of existing languages became to appear, with C++ becoming the most popular. Java was introduced in 1995 and has become a very popular rival of C++.

Object-oriented programming addresses the following aspects of simplifying large time-consuming software development projects (Louden 2003):

- reuse of software components as much as possible
- modification of program behavior with minimal changes to existing code
- making the different components of a software product independent of each other

Objects are more effective than procedural algorithms in creating GUI's and developing distributed and embedded system features (Reilly 2004). Distributed systems involve computers at multiple locations. The Internet is the largest and best-known distributed system. Network client-server systems are also common. An embedded system is a component that is physically embedded within a larger system. Embedded software components are used in a wide variety of systems such as automobiles, aircraft, appliances, weapons, medical devices, and toys. Object-oriented software development environments provide class libraries for developing GUI's and performing other tasks that are common to various applications.

Multiple Alternative Programming Languages

Although computer scientists have dreamed of someday having a single universal programming language that would meet the needs of all computer users, attempts to develop such a language have resulted in frustration and failure (Louden 2003). Although some languages are more popular than others for different types of applications, no one dominant language has emerged. Each language has its strengths and weaknesses depending on the application. Moreover, each language has its avid advocates and adherents (Cezzar 1995). Choice of programming language is a continuing debate in the various applications sectors. The direction that programming will take in the future is highly uncertain. However, reflecting on past experience, a likely future scenario is that there will be a continuing steady process of increasing understanding and refinements based primarily on multiple currently existing languages (Louden 2003).

Historically, development of high-level languages began in the 1950's, over 115 languages had been implemented by 1967, and by 1999 at least 1,000 languages had been in use at some time in the United States, though many were no longer in use (Reilly 2004). The future of any particular language is uncertain. Of the numerous languages developed, relatively few have been widely used or truly significant in the brief history of computer science.

Fortran, C, C++, Java, and Basic

The Fortran, C, C++, Java, and Basic programming languages discussed earlier in this chapter are well established languages that continue to be widely used in water resources engineering and other professional fields. These languages are highlighted in this report as being particularly significant in developing reservoir/river system models. Many other languages are also widely used but not for water resources engineering applications. For example, Cobol (common business-oriented language) is one of the oldest and still most extensively used programming languages. However, Cobol is designed for business applications characterized by relatively simple algorithms that manipulate large amounts of information and has not been used significantly for water resources engineering applications.

Fortran, C, C++, Java, and Basic are all general purpose programming languages that continue to evolve over time with new versions coming out periodically. They all have extensive user communities. They all have advocates and critics. These alternative high-level programming languages may be generally characterized as follows.

Fortran is the leading traditional language designed specifically for engineering and scientific computations. It is a structured procedural language. In the past, Fortran has had no object-oriented programming features. However, modest object-oriented programming features are included in Fortran 2003 with compilers expected to be marketed in 2005.

C has been since the 1970's a leading language for development by professional programmers of operating systems and commercial software products. C is closer to actual machine language than the other high-level languages. C is strictly a procedural language but several languages derived from C incorporate object-oriented programming features.

C++ is based on adding object-oriented programming features to C. C++ became the most popular object-oriented programming language during the late 1980's and early 1990's. The preeminence of C++ as the dominant object-oriented programming language is now being challenged by Java which was introduced in 1995. C++ and Java are widely used in computer science education and many engineering and commercial product development fields. These languages are also used in water resources engineering.

The Basic programming language began as an easy-to-learn general-purpose procedural language. Visual Basic is now an object-oriented language used for many purposes including developing software for Web-based applications and macros for ArcGIS and Microsoft Excel.

General-Purpose Commercial Software

Reservoir/river system models can also be constructed using commercially available general-purpose software that is widely applied in many other areas of engineering, science, business, and education. These modeling environments include spreadsheet programs, object-oriented simulation systems, mathematical programming packages, and mathematics and numerical methods software. These products have been developed by professional programmers using assembly and high-level languages.

The spreadsheet, simulation, optimization, and mathematics software products discussed in this section provide a higher level (more steps above machine language) computing environment than the previously discussed high-level programming languages. Optional programming capabilities are provided along with sets of ready-made computational and graphics features. However, though much simpler to learn and apply, the programming options of these software systems do not provide the flexible programming capabilities of the languages described earlier.

Spreadsheet Software

Numerous spreadsheet-based computation/graphics/database programs have been introduced to the market since the early 1980's. The more popular programs include Excel, Quattro

Pro, and Lotus 1-2-3 marketed by Microsoft Corporation, Borland International, and Lotus Development Corporation, respectively. These spreadsheet programs are used extensively in many fields for a myriad of applications. Almost everyone from high school and college students to professionals in many business and engineering fields seem to be routinely using Microsoft Excel or other spreadsheet programs.

Water management professionals have recognized the potential of electronic spreadsheets since soon after they were first marketed. The software packages are routinely used in a variety of water resources engineering applications. Spreadsheet programs have the advantage of applying the same familiar software to many different types of problems. A reservoir/river system analysis problem can be addressed using software that is already being routinely used in the office for other purposes as well. For relatively simple applications, spreadsheets provide capabilities for developing complete reservoir system analysis models. However, more typically, spreadsheets are used to manage or manipulate input and output data for other reservoir/river system modeling software.

Simulation Software

Object-oriented simulation environments provide another approach for constructing reservoir/river system models. This type of software does not have as vast a market as spreadsheet programs, but is used in a broad range of applications in education, business, science, engineering, and other professional fields. Examples of developing reservoir/river system models within these object-oriented simulation environments include application of VENSIM (Ventana Systems, Inc.) to the Rio Zongo Valley in Bolivia (Cabellero et al. 2001) and application of POWERSIM (Powersim, Inc.) to the Upper Rio Grande (Varvel and Lansey 2002). EXTEND from Imagine That, Inc. (http://www.imaginethatinc.com/) and ITHINK and STELLA marketed by ISEE Systems, Inc. (http://www.iseesystems.com/) are similar software products.

STELLA is an acronym for *Systems Thinking, Experiential Learning Laboratory, with Animation*. It is a general-purpose modeling package designed to simulate time varying or otherwise changing systems characterized by interrelated components. The user builds a model for a particular application, using the operations and functions provided and designs the tabular and/or graphical presentation of simulation results. Karpack and Palmer (1992) used STELLA to analyze the water supply systems of the cities of Seattle and Tacoma, Washington. STELLA was applied to several reservoir systems in conjunction with the Corps of Engineers National Study of Water Management During Drought (Werick 1993; Keyes and Palmer 1993). The Hydrologic Engineering Center (1994) used STELLA to simulate the Missouri River system. Stein et al. (2001) used STELLA to model the Big Sandy River. The software product has been recently applied to the upper Rio Grande.

A model is developed using STELLA by combining four types of icons or objects: stocks, flows, converters, and connectors. Stocks accumulate flows and are used as state variables to reflect dynamic time-varying characteristics of the system. Numerical integration methods are used to solve the mass or volume balance at each stock. The value or amount associated with a stock can change in each time period in response to flows into and out of the stock. For example, if a reservoir system is being modeled, stocks can represent reservoir storage, which is a time-varying function of STELLA flow objects representing stream inflows, water supply diversions, reservoir releases, and evaporation. Converters are used to store mathematical expressions and data. Connectors provide a mechanism to indicate the linkages between stocks, flows, and converters. A system representation may consist of any number of stocks, flows, converters, and connectors. STELLA provides a number of built in functions, which are used in developing the logic and mathematics for the particular application.

Optimization Software

The mathematical programming methods discussed in Chapter 4 provide the advantage of applying standard computational algorithms to many different types of problems. Spreadsheet programs, such as Microsoft Excel, include linear and nonlinear programming capabilities, but are not designed for solving problems with extremely large numbers of variables and constraints. Other optimization packages are available, which are designed specifically for solving linear and, in some cases, nonlinear programming problems, including very large problems. The user inputs values for the coefficients in the objective function and constraint equations for the problem formulation of concern. The optimizer program computes values for the decision variables.

The General Algebraic Modeling System (GAMS) is a notable example of a general-purpose optimization package designed for developing large linear, nonlinear, and mixed integer programming models (http://www.gams.com/). GAMS is a high level language that provides data management and model formulation capabilities as well as a set of linear and nonlinear programming optimizers. Lindo Systems, Inc. is another commercial source of linear and nonlinear programming software (http://www.lindo.com). Reservoir/river system models may be built within the software environment provided by these mathematical programming packages.

Reservoir/river system models are also written in Fortran, C, and C++ with linear programming routines incorporated into the programs. Already-written modules for performing linear programming computations may be incorporated into the coding of various models. The same optimizer routines may be used in any number of different models. The CPLEX linear programming module marketed by the ILOG Corporation (http://www.ilog.com/products/cplex/) and XA optimization solvers from Sunset Software Technology (http://www.sunsetsoft.com) are examples of commercially available optimization products.

Mathematics Software

Integrated environments for numerical computation and graphic visualization are widely used at universities and are also used in various industrial sectors. The many competing software products include:

MATLAB from MathWorks, Inc. (http://www.mathworks.com/)
MATHEMATICA from Wolfram Research, Inc. (http://www.wolfram.com/)
MATHCAD from MathSoft, Inc. (http://www.mathcad.com/)

These programs provide capabilities for solving algebraic and differential equations, matrix operations, differentiation and integration, and statistical computations. Two and three dimensional graphics are provided for data visualization and analysis.

MATLAB, for example, has an encyclopedic collection of subprograms for the solution of various numerical problems, easy-to-use graphing capabilities, and convenient matrix operations (http://www.mathworks.com/products/matlab/description1.html; Chapman 2002; Kuncicky 2004). MATLAB is an interpreter that translates and executes commands as they are entered directly from the keyboard or indirectly from a script file that plays the role of a high-level program. Functions are also available for integrating MATLAB based algorithms with external application software such as Microsoft Excel and programming languages such as C, C++, Fortran, and Java.

These mathematical modeling systems provide a higher level (more steps above machine language) technical computing environment than the previously discussed high-level programming languages. Many common numerical problems can be solved much easier with this type of software than through programming with Fortran or other programming languages. However, the mathematical modeling environments are less flexible than traditional programming languages for developing complicated models and tend to require more memory and run slower than equivalent executable files produced by a compiler.

Supporting Data Management and Analysis Systems

The preceding sections of this chapter focus on software for developing the main reservoir/river system simulation model. A myriad of other commercially available software products may be pertinent to reservoir system analysis applications, in regard to providing capabilities for data compilation, management, and analyses. Streamflow, reservoir storage, water quality, climatic, and other pertinent data may be voluminous. Model input files and simulation results are massive in many typical applications. Data management is important for both real-time operations and planning studies. Many of the reservoir/river modeling systems cited in Chapters 6 and 7 have auxiliary programs that are used to store, transport, organize, manipulate, analyze, summarize, and display model input and output data.

Commercially available relational database management systems such as Microcroft Access and Oracle software from the Oracle Company (http://www.oracle.com/) are widely applied in business, engineering, and other fields and occasionally also used for water management purposes. Database management systems provide storage and access capabilities for large amounts of data that can be used by many different types of applications programs. Most commercially available database systems are said to be relational meaning that each file is considered as a two-dimensional field, and related files are linked via connection fields.

Spreadsheet programs like Microsoft Excel are often used in conjunction with reservoir/river system models to manage data, perform auxiliary computations, and develop graphical displays. The following discussion highlights two other data management systems that have been extensively used with reservoir/river system models, ArcGIS and HEC-DSS. ArcGIS is designed for spatial data. HEC-DSS deals primarily with time-series data.

ArcGIS

A geographical information system (GIS) is a set of computer-based tools for storing, processing, combining, manipulating, analyzing, and displaying data that are spatially referenced to the earth (Longley, et al. 1999). A GIS manages information for which location is a governing concern. Many types of water resources management models are developed within GIS environments or interconnected with GIS. A complete model may be constructed with a GIS software package, but most often the GIS serves to manage voluminous spatial input and output data for other models. Spatial information managed with GIS for water resources management applications include topographic maps, watershed characteristics (drainage area, land use, vegetation, and soil types), river/reservoir system configurations, water distribution system configurations, floodplain delineations, demographic data, precipitation and stream gage locations, and other hydrologic and climatic information. Shamsi (2002) describes databases and GIS resources that are available for water-related applications.

ArcGIS is the most popular of the many available GIS packages. ArcGIS was developed and is marketed by the Environmental Systems Research Institute (ESRI) headquartered in Redlands, California (http://www.esri.com). The original software package called Arc/Info has a long history of many versions and improvements leading to the release in 2001 of a significantly updated system called ArcGIS. The ArcGIS software package contains the following programs (Ormsby, et al. 2001; Price 2004).

- ArcMap provides capabilities for displaying, analyzing, and editing spatial data.
- ArcCatalog is a tool for viewing and managing the spatial data files.
- ArcToolbox is a interface to certain functions including converting between data formats, managing map projections, and performing analysis with commands from the older Arc/Info system.
- Workstation Arc contains the original core software from Arc/Info.

ArcGIS provides different levels of functionality that all use the same basic interface. Users can save money by buying only the functions they need. These levels include the following.

- ArcView provides all of the basic mapping, editing, and analysis functions for shapefiles and geodatabases and is the level of functionality that most users require on a regular basis. ArcView includes ArcMap, ArcCatalog, and ArcToolbox.
- ArcEditor includes all the functions of ArcView but adds the ability to edit coverages and special networks.
- ArcInfo provides access to the original core Arc/Info software as well as to the newer ArcGIS tools.

ArcGIS applies the two alternative approaches of raster and vector models to store spatial information. In the raster format, a set of spatial data is represented by a grid of squares called cells or pixels. The x and y dimensions of each pixel define the resolution of the raster data. Vector data uses a series of x-y locations to store information based on vector objects of points, lines, and polygons. With either the raster or vector approach, information at a point in space is located using x and y coordinate values and sometimes z for height. Data are georeferenced to specific locations on the earth's surface using a specified coordinate system. The various information being stored as a function of location is called the attribute data.

The Visual Basic for Applications (VBA) programming language is provided with ArcGIS (Burke 2003). Many GIS applications are accomplished using features available within ArcGIS without needing special programming. However, more complex data calculations and manipulations may be programmed with VBA.

In conjunction with developing ArcGIS, ESRI sponsored efforts to develop schemes for customizing ArcGIS for particular general types of applications using specially designed data models. Arc Hydro is a data model for hydrology and water resources applications that operates within ArcGIS (Maidment 2002; http://www.crwr.utexas.edu/giswr/). A set of tools associated with Arc Hydro are designed specifically for water-related GIS applications. Hydrologic simulation may involve exchanging data between Arc Hydro and an independent hydrologic model. Alternatively, a simulation model may be attached to Arc Hydro using a dynamic linked library or by customizing the behavior of Arc Hydro objects.

HEC Data Storage System (HECDSS)

The HEC-DSS Visual Utility Engine (HEC-DSSVue) is a graphical user interface program for viewing, editing, and manipulating data in HEC-DSS database files (Hydrologic Engineering Center 2003). The Hydrologic Engineering Center (HEC) Data Storage System (HECDSS) is used routinely with HEC simulation models including those discussed in Chapter 6 and can be used with other non-HEC programs as well (HEC 1995). Development of HECDSS dates back to 1979. HECDSS database management capabilities are oriented particularly toward very voluminous sets of sequential data such as time series. The database can include any type of data, but typically contains hydrologic, hydraulic, climatic, and/or water quality data.

HECDSS and HEC-DSSVue provide capabilities to:

- store and maintain data in a centralized location
- provide input to and store output from application programs and transfer of data between application programs
- perform mathematical and statistical computations
- display data in graphs and tables

HECDSS is designed to easily connect with application programs. A number of HEC generalized simulation models write to and read from DSS files. The same graphics and data management capabilities are shared by multiple hydrologic, hydraulic, and water management simulation models. Essentially any model could be connected to HECDSS. Routines are also provided for retrieving data from other databases such as those maintained by the U.S. Geological Survey and National Climatic Data Center. Utility programs plot graphs and perform various computations. Normal arithmetic operations and many mathematical functions are provided. Statistical analyses can be performed. Missing data can be synthesized. Hydrologic streamflow routing computations can be performed.

HECDSS uses a block of sequential data as the basic unit of storage. The basic concept underlying the data storage system is the organization of data into records of continuous, applications-related elements, as opposed to individually addressable data items. A modified hashing algorithm and hierarchical design is incorporated for database access. This approach is more efficient for water resources applications than that of a conventional relational database system such as Microsoft Access or Oracle because it avoids the processing and storage overhead required to assemble an equivalent record.

HECDSS consists of a package of Fortran subroutines designed to be interfaced to application programs, and a set of utility support routines to aid in interpreting and maintaining data in the database (HEC 1995). The subroutines and support programs read and write data to and from direct access files. Data is stored in blocks or records within a file, and each record has a unique pathname. The HEC-DSSVue graphical user interface program for managing the DSS functions is coded in the Java programming language (HEC January 2003). A HECDSS Microsoft Excel Data Exchange Add-In written in Visual Basic is available from the HEC for transporting data between Excel and HECDSS (HEC November 2003).

Generalized Reservoir/River System Models

This report focuses on generalized modeling systems to support planning and management decision processes regarding reservoir/river systems. *Generalized* means that the modeling system is designed for various types of analyses of essentially any reservoir/river system. The user constructs a model by developing and modifying an input dataset for the particular reservoir/river system of concern. A number of generalized modeling systems are described in Chapters 6 and 7. The majority of these models are available from water agencies and universities, but private consulting firms also develop, market, and apply generalized models. Many models are in the public domain and are available either free of charge or for a nominal handling fee. Some of the models are proprietary.

Most generalized reservoir/river system models developed prior to the 1990's are coded in Fortran. Fortran continues be widely used in building models. However, object-oriented programming and graphical user interfaces became extremely popular during the late-1980's and 1990's. The C++ programming language with its improved features for object-oriented programming and creating GUI's has played a major role in developing reservoir/river system models and other hydrology/hydraulics models during the last 15 years. More recently, Java is establishing a role in developing reservoir/river system modeling systems. C and Visual Basic have also been used to develop components of water-related modeling systems. Connecting reservoir/river system models with data management systems, such as HECDSS and ArcGIS, and with other simulation models has also been a major emphasis in recent years.

The generalized reservoir/river system models described in Chapters 6 and 7 provide tools for building and applying models for river basins or regions of concern. Each of the alternative software packages represents a somewhat different framework environment for modeling reservoir/river systems. Each modeling system has its own peculiar structure and nomenclature.

A model consists of a generalized software system combined with pertinent datasets. Developing the datasets typically represent a major effort. After creation of the basic input dataset, modeling a reservoir/river system consists of adjusting the input data to reflect alternative management strategies and modeling premises of interest.

Comparison of Alternative Model Building Approaches

In developing a model for a particular application, a key question is which modeling environment, or set of software tools, should be adopted. In some situations, one alternative model building approach may be clearly advantageous over the others. In other modeling situations, the relative merits and tradeoffs between the alternative sets of tools will be more balanced. The background and personal preferences of the model builders are typically a major consideration in selecting a software environment. Considerations in comparing the relative advantages and disadvantages of the alternative approaches include:

- flexibility in using mathematical equations, computational algorithms, and data to realistically represent real-world systems and concerns
- efficiency in compiling and managing input data
- effectiveness in organizing, analyzing, displaying, and communicating model results
- expertise, time, and effort required to build a model, and then to apply and maintain the model, and later to modify the model in response to changing analysis requirements

Alternative Modeling Approaches

Given unlimited time, funds, and computer programming expertise, developing programs from scratch using Fortran, C, C++, Java, and/or other programming languages will provide the greatest flexibility to develop a model to fit the particular needs of the water management application. This approach also requires the greatest programming expertise, manpower, and time. Improved and expanded modeling approaches and methods continue to be implemented by writing new computer programs. Specific analysis needs may warrant coding new software specifically for a particular reservoir system and/or a particular type of analysis. Many engineers and scientists naturally prefer the flexibility of working with programs they have coded themselves. However, for complex models, formulating algorithms, devising data management schemes, writing and debugging code, and testing new programs are extremely time consuming and expensive. Thus, time and personnel resources required for detailed model construction drastically reduces the resources available for other more crucial aspects of the modeling study. Application of available general-purpose software or generalized reservoir system analysis models is usually the optimal use of available funding and time resources.

Relatively simple reservoir system analysis models can be constructed using spreadsheet programs such as Microsoft Excel, simulation modeling environments such as STELLA, or optimization software such as GAMS. These commercially available general-purpose software products are widely used in many areas of education, business, engineering, and science. They can be applied to reservoir/river system modeling along with their myriad of other uses. They are polished products that reflect attention to enhanced user interfaces and graphics capabilities. These general-purpose software packages provide programming capabilities for developing computational algorithms, which are simpler than programming directly in languages such as Fortran, C, C++, and Java. The flexible modeling environments can be used for a broad range of applications. However, these software products are most pertinent for simpler problems, with generalized reservoir/river systems analysis models becoming particularly advantageous for more complex applications.

Generalized reservoir/river system models have the advantage of having already developed computational algorithms and data management structures. The same software may be applied to many different reservoirs/river systems in various types of applications. The user provides input data without being concerned with formulating mathematical algorithms and writing code. Most of the generalized reservoir/river system modeling packages provide flexible sets of user-selected optional analysis capabilities. Generalized modeling systems also play an important role in transferring knowledge that is similar to that of books, engineering manuals, and other publications. State-of-the-art concepts and methods are organized into the format of a generalized reservoir/river system model.

Computer Applications in Engineering Academic Curricula

University academic programs both reflect and affect professional practice. Excel and MATLAB or similar software products have replaced traditional programming languages in the undergraduate engineering curricula of most universities. Texas A&M University (TAMU) is probably representative of most engineering programs in this regard. From the 1960's through the mid-1990's, all undergraduate engineering majors at TAMU were required to take a course covering a combination of numerical methods and Fortran programming. During the early 1990's, Fortran was introduced to students in a freshman engineering problem solving course and continued in the sophomore numerical methods course. Fortran was also applied in other courses. During the late 1990's, MATLAB was adopted to replace Fortran programming at TAMU. MATLAB or similar packages have replaced programming languages at most other universities as well. Recent numerical methods textbooks have been written from the perspective of being used in courses along with MATLAB. In addition to MATLAB or a similar mathematics package, Microsoft Excel or a similar spreadsheet package is used in many courses throughout the undergraduate curriculum. Students are introduced to Excel in high school. Excel and MATLAB dominate the undergraduate experience in applying computers for engineering applications.

MATLAB provides essentially all of the computer capabilities needed for calculus and numerical methods in the undergraduate curriculum. Likewise, Excel provides easy-to-learn computational and graphics capabilities to support the subjects covered in most engineering courses. Excel allows macros to be written in Visual Basic. Likewise, MATLAB includes an easy-to-use built-in programming language to supplement its library of already-developed computational and graphics routines. Engineering students have convenient access to dramatically more computational capabilities today than 15 years ago but receive much less exposure to actual programming.

Most graduate students in water resources engineering and other civil engineering specialty fields use Excel routinely in their courses and research. Civil engineering graduate students often apply programming languages such as Fortran, Visual Basic, or C++ in their research. However, formal instruction is minimal with the students learning programming primarily on their own. A few civil engineering graduate students elect to take one or more programming courses offered by the Computer Science Department.

Generalized models such as the HEC-HMS (Hydrologic Modeling System), HEC-RAS (River Analysis System), and EPANET (Water Distribution Network) are routinely used in undergraduate and graduate courses in hydrology, hydraulics, and water resources engineering.

Generalized reservoir/river system models are not incorporated in courses as much as hydrology and hydraulics models. However, the author assigns homework projects using the WRAP reservoir/river system model in his graduate water resources systems engineering course in conjunction with a three-week section of the course covering river basin management. The important role of generalized models in water resources engineering practice are reflected in various recent textbooks, such as Wurbs and James (2002), used in courses.

Geographical information systems (GIS) and related spatial science technology have become well established as an integral part of university curricula in civil engineering, agricultural and biological engineering, geography, forestry, and various other fields over the last ten years. Most graduate students specializing in water resources engineering at TAMU complete at least one graduate course in GIS and are fairly proficient with ArcGIS. A few undergraduate students majoring in civil engineering will take a technical elective course in GIS or geomatics.

Chapter 6
Review of Reservoir/River System Models

The federal water agencies, state and regional water agencies, private firms, research institutes, and universities have developed numerous reservoir/river system analysis models. Development and application of modeling systems are often partnership efforts involving multiple organizations. Models evolve over time with improved and expanded versions. Chapter 6 provides a broad overview addressing both past and current models representative of the evolving state-of-the-art over the past several decades. Although several site-specific models are cited, the emphasis is on generalized models. Although the research literature is also reviewed, the primary focus of the chapter is to inventory available generalized reservoir/river system models that are being applied in actual practice.

Literature of Reservoir/River System Modeling

Pioneering efforts in computer simulation of reservoir/river systems in the United States include a Corps of Engineers study of the operation of the six main-stem reservoirs on the Missouri River initiated in 1953 (Manzer and Barnett 1966). The objective was to maximize hydroelectric power generation subject to constraints imposed by specified requirements for navigation, flood control, and irrigation. Shortly thereafter, both the Corps of Engineers and Bonneville Power Administration conducted simulation studies of hydropower operations on the Columbia River. The International Boundary and Water Commission simulated a multiple-purpose two-reservoir system on the Rio Grande 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 that would maximize the volume of useful irrigation water (Manzer and Barnett 1966). Maass et al. (1966), Hufschmidt and Fiering (1966), and Reuss (2003) discuss the pioneering simulation modeling work of the Harvard University Water Program. Numerous other computer models of river/reservoir system operations have been developed since these early endeavors.

A tremendous amount of work on developing and applying reservoir/river system models has been documented in the published literature during the past 50 years. Much additional work has been accomplished without being reported in the published literature. Several general references that provide a broad state-of-the art review of reservoir/river system modeling capabilities are noted in this section. Other references dealing with specific models are cited later in the chapter.

The several books on modeling and analysis of reservoir operations include those by McMahon and Mein (1986), Votruba and Broza (1989), Wurbs (1996), ReVelle (1999), and Nagy et al. (2002). The author of this report has also prepared previous state-of-the-art reviews of reservoir system analysis methods (Wurbs et al. 1985; Wurbs 1990, 1993, 1994, 1996). The Texas Natural Resource Conservation Commission (TNRCC), its partner agencies, and a team of consultants performed a comparative evaluation of available models in the process of adopting a generalized model for the Texas Water Availability Modeling System (TNRCC 1998). The U.S. Bureau of Reclamation (USBR) maintains a Hydrologic Modeling Inventory (HMI) that provides descriptions of reservoir and river system operations models along with other categories of models. The original USBR HMI was distributed as a printed report (1991). The periodically updated inventory is maintained at the following web site: http://www.usbr.gov/pmts/rivers/hmi/

The published research literature on modeling reservoir system operations is dominated by applications of optimization techniques. The Allies organized interdisciplinary teams during World War II 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 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 management science and systems engineering disciplines, including water resources systems analysis. Mathematical programming is covered by numerous operations research and mathematics books as well as civil engineering systems books (ReVelle and McGarity 1997; Revelle et al. 2004) and water resources systems books (Loucks et al. 1981; Mays and Tung 1992; Karamouz et al. 2003; Jain and Singh 2003).

Reservoir system operations have been viewed by researchers as having high potential for beneficial application of an array of mathematical optimization techniques. Many hundreds of journal and conference papers have been published since the 1960's on applying variations of linear programming, dynamic programming, gradient search algorithms, heuristic programming models such as genetic algorithms, and other nonlinear optimization techniques to reservoir system analysis problems. Various probabilistic methods for incorporating the stochastic nature of streamflows and other variables in the optimization models have been proposed. Yeh (1985) and Labadie (1997 and 2004) provide concise summary reviews of this extensive and complex research literature.

Inventory of Generalized River/Reservoir System Models

The following review focuses on generalized models that have been applied by water management agencies to support actual planning and/or operations decisions. Several models representative of current state-of-the-art modeling capabilities are listed in Tables 6.1 and 6.2. These models have been extensively applied by water management agencies and their consultants to major reservoir systems over many years to support complex decision processes. The ten models listed in Table 6.1 along with a number of other models are briefly discussed in Chapter 6. The five models listed in Table 6.2 are described in greater detail in Chapter 7.

A number of other models not listed in Tables 6.1 and 6.2 are cited in the remainder of this chapter. Many hundreds of other models reported in the literature are not cited at all in this report. The models listed in Tables 6.1 and 6.2 are representative of current modeling capabilities and have a record of successful application by water management agencies in support of actual decision making. In comparing the models listed in the tables to the many others discussed in this chapter or reported in the literature, the other models may fall within one of the following categories.

1. Other models may provide similar capabilities as the models listed. The models listed in Tables 6.1 and 6.2 are representative of capabilities reflected in various other models as well.

2. Other models may provide additional capabilities not provided by those listed. In some cases, the additional capabilities have been adopted in practice. However, most of the many hundreds of models that fall in this category are based on mathematical programming and stochastic modeling techniques that have been explored extensively by university researchers but adopted relatively little by the water management agencies.

Table 6.1 Generalized Reservoir/River System Models Discussed in Chapter 6

Short Name	Descriptive Name	Model Development Organization
	Models Developed by the Corps of Engineers	
HEC-5	Simulation of Flood Control and Conservation Systems	USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/
HEC-PRM	Prescriptive Reservoir Model	USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/
SSARR	Streamflow Synthesis and Reservoir Regulation	USACE North Pacific Division http://www.nwd-wc.usace.army.mil/report/ssarr.htm
	Models Developed by State Agencies	
WRIMS (CALSIM)	Water Resources Integrated Modeling System	California Department of Water Resources http://modeling.water.ca.gov/hydro/model/description.html
StateMOD	State of Colorado Stream Simulation Model	Colorado Water Conservation Board and Colorado Division of Water Resources, http://cdss.state.co.us/
	Models Developed by International Consulting Firms and Research Institutes	
OASIS	Operational Analysis and Simulation of Integrated Systems	HydroLogics, Inc. http://www.hydrologics.net/
ARSP	Acres Reservoir Simulation Program	Acres International, BOSS International http://civilcentral.com/html/arsp_tech_info.html
MIKE BASIN	GIS-Based Decision Support for Water Planning & Management	Danish Hydraulic Institute http://www.dhisoftware.com/mikebasin/
RIBASIM	River Basin Simulation	Delft Hydraulics, http://www.wldelft.nl
WEAP	Water Evaluation and Planning	Stockholm Environment Institute, http://weap21.org

Table 6.2 Generalized Reservoir/River System Models Discussed in Chapter 7

Short Name	Descriptive Name	Model Development Organization
SUPER	SWD Reservoir System Model	USACE Southwestern Division http://www.swd.usace.army.mil/
HEC-ResSim	Reservoir System Simulation	USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/
RiverWare	River and Reservoir Operations	Bureau of Reclamation, TVA, CADSWES http://animas.colorado.edu/riverware/
MODSIM	Generalized River Basin Network Flow Model	Colorado State University http://modsim.engr.colostate.edu/modsim.html
WRAP	Water Rights Analysis Package	Texas Commission on Environmental Quality, USACE, TWRI, http://ceprofs.tamu.edu/rwurbs/wrap.htm

Several of the models cited in the remainder of this chapter are predecessors of those listed in Table 6.2. The models have long histories of improvements in response to expanding applications and advances in computer technology. In the process of continual evolution, several of the models listed in Table 6.2 are gradually replacing other legacy software cited in this chapter.

Models Developed by the U.S. Army Corps of Engineers

The Hydrologic Engineering Center (HEC), Waterways Experiment Station (WES), and the division and district offices of the U.S. Army Corps of Engineers (USACE) have extensive experience in modeling reservoir/river system operations. HEC-ResSim and SUPER are described in Chapter 7. Several other USACE models are cited in the following discussion.

USACE Hydrologic Engineering Center Models

HEC-ResSim, the newest HEC generalized reservoir/river system simulation model, is covered in Chapter 7. HEC-3 and HEC-5 discussed below are HEC-ResSim predecessors. HEC-PRM, also included in the following discussion, represents a significantly different modeling approach and has not been as widely applied as HEC-3/HEC-5/HEC-ResSim. The HEC models are used in combination with the HEC-DSS Data Storage System described in Chapter 5, which provides input data preparation and output analysis capabilities (Hydrologic Engineering Center 1995, 2003). ResSim may be applied either separately or in combination with other HEC models either as an integral component of the Corps Water Management System (CWMS) or independently thereof.

Corps Water Management System (CWMS)

The Corps Water Management System (CWMS) is a modernized version of the HEC water control management software system (Fritz et al. 2002). Development of the CWMS was initiated in FY 1997, and the initial version was completed in 2001. CWMS is a comprehensive system incorporating the acquisition, transformation, verification, storage, display, analysis, and dissemination of information to support real-time operations of Corps of Engineers flood control and multiple-purpose reservoir systems. Components of the CWMS include:

- real-time and static data acquisition systems
- data storage in a database managed with the ORACLE software system
- data visualization tools for creating tables, plots, charts, and maps
- dissemination of information using web sites and other mechanisms
- simulation models

Several simulation models from the HEC family of generalized models are incorporated in the CWMS. This integrated suite of models include:

* HEC-HMS (Hydrologic Modeling System) simulates watershed hydrology using observed and predicted precipitation to generate streamflow hydrographs at pertinent locations.

* HEC-ResSim (Reservoir System Simulation) models reservoir operations for inflows developed with HEC-HMS.

* HEC-RAS (River Analysis System) computes river stages at pertinent locations based on the flows from HEC-HMS and HEC-ResSim.

* HEC-FIA (Flood Impact Analysis) uses the results from HEC-RAS along with economic data to assess the impacts of flooding for various ResSim operating scenarios.

The CWMS is being implemented in the 43 USACE district and division offices (Davis 2003). The Lower Colorado River Authority (LCRA) of Texas is the first non-USACE agency to adopt the CWMS (Ickert and Luna 2004). LCRA and HEC have entered into an agreement for HEC to support LCRA in implementing of the modeling system for the six LCRA operated reservoirs on the Colorado River upstream of the City of Austin. LCRA's initial use of the CWMS was for flood control planning studies. The LCRA CWMS-based modeling system is being expanded to include real-time reservoir operations for flood control.

HEC-3 and HEC-5

The *HEC-3 Reservoir System Analysis for Conservation* program simulates operation of reservoir systems for conservation purposes such as water supply, low-flow augmentation, and hydroelectric power. The initial version of HEC-3 was developed in 1965-1966. The Hydrologic Engineering Center has not distributed HEC-3 in recent years because essentially all of its capabilities have been duplicated in HEC-5. HEC-3 and HEC-5 have similar capabilities for simulating conservation operations, but HEC-3 does not have the comprehensive flood control capabilities of HEC-5. HEC-3 is documented by a users manual (Hydrologic Engineering Center 1981) and other HEC publications.

The *HEC-5 Simulation of Flood Control and Conservation Systems* program has been used in many Corps and non-Corps studies, including investigations of storage reallocations and other operational modifications at existing reservoirs as well as feasibility studies for proposed new projects. The program is also used to support real-time operations. An initial version released in 1973 has subsequently been greatly expanded. The Fortran programs have been run on various computer systems over the years. The HEC-5 package includes several utility programs to aid in developing input data files and analyzing output. Alternative versions of the model exclude and include water quality analysis capabilities. The HEC-5 users manual (Hydrologic Engineering Center 1998) provides instructions for its use. Various HEC publications regarding the use of HEC-5 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-5 simulates the sequential period-by-period operation of a multiple-purpose reservoir system for inputted sequences of unregulated streamflows and reservoir evaporation rates. Multiple reservoirs can be located in essentially any stream tributary configuration. The program uses a variable time interval. For example, monthly or weekly data might be used during periods of normal or low flows in combination with daily or hourly data during flood events. The user specifies the operating rules in HEC-5 by inputting reservoir storage zones, diversion and minimum instream flow targets, and allowable flood flows. The model makes release decisions to empty flood control pools and to meet user-specified diversion and instream flow targets based on computed reservoir storage levels and streamflows at downstream locations. Seasonal rule curves and buffer zones can be included in the operating rules. Multiple-reservoir release decisions are based on balancing the percent storage depletion in specified zones. Hydrologic flood routing options include modified Puls, Muskingum, working R&D, and average lag. HEC-5 has various optional analysis capabilities including computation of expected annual flood damages and single-reservoir firm yields for water supply and hydroelectric power.

HEC-PRM Prescriptive Reservoir Model

The HEC Prescriptive Reservoir Model (HEC-PRM) is a network flow programming model designed for prescriptively oriented applications. Improved network flow computational algorithms have been developed in conjunction with the model. The optimization model minimizes a cost based objective function. Reservoir release decisions are made based on minimizing costs associated with convex piecewise linear penalty functions (dollars versus storage or flow) associated with various purposes including hydroelectric power, recreation, water supply, navigation, and flood control. Schemes have also been devised to also include non-economic components in the basically economic HEC-PRM objective function. User-specified lower and upper bounds on flows and storages are reflected in the constraint equations. HEC-PRM is generalized for application to any reservoir system (Hydrologic Engineering Center 1994).

HEC-PRM applications to date have used a monthly time interval with historic period-of-record streamflows. Unlike most of the other simulation models discussed in this report, HEC-PRM performs the computations simultaneously for all the time intervals. Thus, model results show a set of reservoir storages and releases which would minimize cost (as defined by the user-inputted penalty functions) for the given inflow sequences assuming all future flows are known as release decisions are made during each period. Since in the real-world, future streamflows are not actually known when a release decision is made, the model provides an upper limit or best possible scenario on what can be achieved. Although the model provides only one set of decision variable values, combinations of a range of values for each variable may result in the same value of the objective function. Various strategies are adopted for using HEC-PRM results to develop alternative reservoir system operating plans and then to evaluate the plans in more detail using a descriptive simulation model (Hydrologic Engineering Center 1994 and 1995; Lund and Ferreira 1996).

HEC-PRM was developed in conjunction with USACE studies of major reservoir systems in the Missouri and Columbia River Basins (Hydrologic Engineering Center 1992 and 1993). Recent applications include a study of the Panama Canal (Hydrologic Engineering Center 1999), the USACE Central and South Florida Project Comprehensive Review Study (Watkins et al. 2004), and non-USACE studies in California (Draper et al. 2003; Jenkins et al. 2004).

Both the Missouri and Columbia River studies involved evaluations of the operations of existing reservoir systems motivated by water shortages during droughts that exacerbated the competition among water users. Application of the HEC-PRM to the system of six mainstem Missouri River reservoirs addressed competing interests that included lake recreation, hydroelectric power generation, flood control, water supply, and downstream navigation and environmental concerns (Hydrologic Engineering Center 1992; Lund and Ferreira 1996). The major environmental concern is maintenance of steady flows for sand bar nesting birds.

HEC-PRM was applied in conjunction with the Columbia River System Operation Review, involving 14 reservoirs, that was conducted by the Corps of Engineers, Bureau of Reclamation, and Bonneville Power Administration (Hydrologic Engineering Center 1993; Hayes et al. 1993). For the Columbia River Basin study, the HEC-PRM objective function reflects cost-based piece-wise linear convex penalty functions representing hydropower, flood control, navigation, anadromous fish, water supply, and recreation. The primary environmental concern is maintenance of seasonal flows to aid in the migration of salmon and steelhead. The hydroelectric power penalty function is expressed in terms of dollars versus both flow and storage. The penalty functions for each of the other uses are expressed in terms of dollars per unit of monthly flows. The penalty functions vary monthly to reflect seasonal characteristics. The objective is to minimize total system costs. Basin hydrology is represented by gaged monthly streamflows for the period of 1928 to 1978, adjusted to represent 1980 conditions of basin development. Various alternative system operation scenarios were evaluated.

The HEC applied the HEC-PRM at the request of the USACE Jacksonville District and South Florida Water Management District to the Central and Southern Florida Project (Watkins et al. 2004). This system completed in the mid-1969's includes about 1,000 miles of levees, 150 water control structures, and 16 major pump stations. The project provides flood control, water supply for agricultural and urban uses, prevention of salt water intrusion, water supply for Everglades National Park, and protection of other fish and wildlife resources. The objective of the restudy supported by HEC-PRM was to develop a plan for improving environmental quality and urban and agricultural water supply reliability. The generalized network flow model was used to evaluate several proposed storage and conveyance plans.

Draper et al. (2003) and Jenkins et al. (2004) describe an optimization model of California's major water systems that was performed at the University of California at Davis under the sponsorship of several agencies. The model called CALVIN consists of HEC-PRM, datasets for California, and supporting utility programs. The model covers water use by 92% of California's population and 88% of its irrigated acreage with about 1,200 spatial elements, including 51 reservoirs, 28 groundwater basins, 19 urban water demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links representing most of California's water management infrastructure. Water allocation and system operation are modeled for the 1922-1993 hydrologic period-of-analysis using a monthly time step. Three alternative water use scenarios are considered: (1) 2020 conditions with current operating and allocation policies, (2) economically driven operations and allocations for considering each of five hydrologic regions independently, and (3) statewide economically driven operations and allocations. The optimization studies were designed to support:

- identification of economically promising facility expansions
- assessment of user willingness to pay for water
- identification of promising water transfers
- integration of facility operations
- data assessment and reconciliation
- demonstration of advances in modeling capabilities
- identification of promising solutions for refinement and testing by simulation studies

USACE Waterways Experiment Station Models

The Engineering Research and Development Center (ERDC) at the Waterways Experiment in Vicksburg, Mississippi has a long history of modeling reservoir/river systems with both physical scale models in the laboratory and computer models. Generalized computer models of reservoir/river systems available from WES are designed primarily for simulating hydrodynamics and water quality. Though closely related, the WES generalized simulation models fall outside the primary scope of this report. However, selected WES reservoir/river system hydrodynamics and water quality models are noted as follows.

Numerical models of river/reservoir system hydrodynamics available from the Coastal and Hydraulics Laboratory (http://chl.erdc.usace.mil/) include the TABS System, which is composed of the following models.

- RMA2 is a one-dimensional/two-dimensional model for computing depth-averaged flow velocities and depths.
- RMA4 is a one-dimensional/two-dimensional model for simulating the transport of water quality constituents.
- TABS MDS (RMA10) is a multi-dimensional hydrodynamic model.
- SED2D is a two-dimensional sediment transport model.

Water quality aspects of reservoir/river system operations are simulated by the following models and a number of other models available from the Environmental Laboratory at WES. (http://www.wes.army.mil/el/elmodels/index.html)

* CE-QUAL-R1 is a one-dimensional (vertical) reservoir water quality model that simulates temperature and concentration gradients.
* CE-QUAL-W2 is a two-dimensional reservoir hydrodynamic and water quality model.
* CE-QUAL-RIV1 is a one-dimensional hydrodynamic and water quality model that simulates variations in hydraulic and water quality characteristics longitudinally along a stream.

USACE North Pacific Division Models

The Hydro System Seasonal Regulation (HYSSR), Hourly Load Distribution and Pondage Analysis Program (HLDPA), and Hydropower System Regulation Analysis (HYSYS) models were developed by the USACE North Pacific Division. The models are described in the Hydropower Engineer Manual (U.S. Army Corps of Engineers 1985). Users manuals are available from the North Pacific Division. HYSSR is a monthly sequential routing model designed to analyze the operation of reservoir systems 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 several 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.

The Streamflow Synthesis and Reservoir Regulation (SSARR) model was developed by the North Pacific Division for streamflow and flood forecasting and reservoir operation studies. A program description and users manual (USACE North Pacific Division 1987) documents the current version of the model. Various versions of the model date back to 1956. The SSARR model was originally developed in support of Corps of Engineers studies involving planning, design, and operation of water control projects in the Pacific Northwest. Further development was motivated by operational river forecasting and management activities of the Cooperative Columbia River Forecasting Unit, sponsored by the National Weather Service, Corps of Engineers, and Bonneville Power Administration. Subsequently, numerous river systems in the United States and abroad have been modeled with the SSARR by various agencies, universities, and other organizations.

The SSARR modeling package is composed of two components: (1) a watershed model and (2) a river system and reservoir operation model. The watershed model simulates rainfall-runoff, snow accumulation, and snowmelt-runoff processes. The reservoir/river system model routes flows through river reaches and through controlled and uncontrolled reservoirs.

SSARR is a continuous watershed model designed for large river basins. The computational time step may be varied from 0.1 hour to 24 hours. Streamflows are generated from rainfall and snowmelt runoff. Rainfall data are provided as input. Snowmelt is computed based on inputted data regarding snow depth, elevation, air and dew point temperatures, albedo, radiation, and wind speed. Snowmelt options include the temperature index method and the energy budget method. Application of the model begins with a subdivision of the river basin into hydrologically homogeneous subwatersheds. For each subwatershed, the model computes base flow, subsurface or interflow, and surface runoff. Each flow component is delayed according to different processes, and all are then combined to produce the total subwatershed outflow hydrograph. The subwatershed outflow hydrographs are routed through stream reaches and reservoirs and combined with hydrographs from other subwatersheds to obtain streamflow hydrographs at pertinent locations.

A hydrologic storage routing technique is applied to both reservoirs and stream reaches. The routing method developed for the SSARR conceptually treats a river reach as a cascade of reservoirs. Reservoir release rules may be specified a function of either pool elevation, changes in pool elevation, storage, changes in storage, or outflow. Inflows may also be routed through uncontrolled (ungated) reservoirs. Streamflows may be routed as a function of multivariable relationships involving backwater from tides or reservoirs. Diversions also may be included in a simulation. The SSARR routing method is incorporated as one of several routing options in HEC-ResSim described in Chapter 7.

USACE Savannah District BRASS Model

The Basin Runoff and Streamflow Simulation (BRASS) model was originally developed to provide flood management decision support for operation of a reservoir system in the Savannah River Basin but is generalized for application to other river basins (McMahon *et al.* 1984; Colon and McMahon 1987). It has been used for flood forecasting and other flood management decision support activities. BRASS is an interactive hydrologic/hydraulic simulation model that combines dynamic streamflow routing with aspects of continuous and event rainfall-runoff modeling. For given precipitation input, runoff hydrographs from various subbasins are developed and routed through the stream/reservoir system. This includes storage routing through gated reservoirs and dynamic streamflow routing. BRASS incorporates the National Weather Service (NWS) Dynamic Wave Operational (DWOPER) program for streamflow routing.

USACE Missouri River Division Missouri River System Model

The USACE Missouri River Division initiated in 1989 a several year study to review the water control manual which guides operation of the six main-stem Missouri River reservoirs (Cieslik and McAllister 1994). The study was motivated by a drought in 1987-1992 that affected project uses and environmental resources. The reservoirs are operated for flood control, hydropower, water supply, water quality, irrigation, navigation, recreation, and environmental resources. The system includes a 1,200 km long navigation channel on the Missouri River from its mouth at St. Louis, Missouri, to Sioux City, Iowa. Reservoir operating criteria involve allocation of storage capacity among uses and release rules during navigation and nonnavigation seasons.

Formulation of alternative operating plans focused on (1) the amount of storage reserved for the permanent pool and the resulting size of the carryover multiple use zone available to provide water during droughts and (2) the quantity and timing of releases for navigation, water supply, irrigation, power production, water quality, flood control, recreation, and environmental resources. Operating modifications considered involved: navigation criteria including level of service and length of navigation season; water supply needs during the nonnavigation season; seasonal releases from the most downstream dam to improve the river ecosystem; spring and summer releases to protect threatened and endangered birds that nest on river islands; and intrasystem regulation of the upper three reservoirs to provide favorable conditions for fish reproduction.

The Long Range Study (LRS) Model uses a monthly time interval for simulating operation of the system during 96-year (March 1898 to February 1994) sequences of historical flows at six reservoir nodes and nine other gage locations (Patenode and Wilson 1994). An earlier model developed in the 1960's was updated during the 1990's. A set of supplemental programs are used to process the voluminous simulation results during the process of design, review, and comparison of alternative operating plans. Two input files are used. One contains historic reach inflow and streamflow depletion data and the other contains the various constants and variable parameters that define regulation decisions. The historic input file contains annual evaporation rates for the six reservoirs which are distributed monthly by coefficients contained in the parameter input file. Monthly incremental streamflows are combined with depletion factors that adjust the historic flows to current conditions of water use. The parameter input file contains various information to define the sizes and limits of the river and reservoirs and to establish the guide curves and operating limits of a particular simulation.

The LRS model has been used to simulate and evaluate numerous alternative operating policies. The results of the LRS hydrologic simulation model are used in combination with several other models, including environmental and economic analysis models, in evaluating operations of the mainstem Missouri River system.

Models Developed by the U.S. Bureau of Reclamation

The U.S. Bureau of Reclamation (USBR) sponsorship of development by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado of a series of object-oriented river/reservoir system models dates back to the late 1980's. RiverWare described in Chapter 7 is the most recent product of this effort. The Tennessee Valley Authority and Western Area Power Administration joined with the USBR and CADSWES in developing and applying RiverWare. The USBR has a long history of developing both basin-specific and generalized reservoir/river system models. The majority of the USBR models including those cited below have been replaced with RiverWare or likely will be eventually.

USBR models described in the Hydrologic Modeling Inventory (USBR 1991) in the category of project and river system operations models include the following generalized and basin-specific models. The CRSS, PROSIM, and SANJASM models are briefly discussed later in this section.

Generalized Models

PNMOD – Reservoir Operation and Routing
DROPH – Daily and Hourly Reservoir Operation
HYDROSS – Hydrologic Operations Study System
PNRRN – Monthly Reservoir System Simulation
OPSTUDY – Utility Program for Monthly Operations
SIMULOP – River-Reservoir Operations Simulation
Single Reservoir Operation
River Network Model
Water Operations Technology Package

Models for Specific Reservoir/River Systems

CRSS – Colorado River Simulation System
FAOP – Fryingpan-Arkansas Operations Model
Bighorn Basin Annual Operating Plan Model
North Platte Annual Operating Plan Model
Western Division Hydropower Summary Model
PROSIM – Central Valley Project Simulation
SANJASM – San Joaquin Area Simulation
CVGSM – Central Valley Surface and Groundwater
FORCIS – Central Valley Operational Forecast Model
Truckee-Carson Water Operations Model
BHOPS – Lower Colorado Daily Operations
Colorado River 24 Month Study Model
GLENREL – Operation of CRSP Reservoirs
Animas-La Plata Project Operations Model
Dolores Project Operations Model
SRPSIM – Salt River Project Operations Model
CAPSIM – Central Arizona Project Operations Model
YKMODEL – Yakima Basin Simulation Model

Models Developed at CADSWES Sponsored by the USBR and Its Partner Agencies

RiverWare discussed in Chapter 7 and its predecessors PRSYM, RSS, and CALIDAD discussed below represent pioneering efforts at constructing reservoir/river system analysis models using object-oriented programming. In object-oriented programming, a program is treated as a collection of objects which can be reused in different programs and subprograms. Generalized models can be developed that provide an interactive user-friendly environment for users to build models for their particular applications by selecting from a library of precoded objects. If needs surface for additional types of objects, a programmer can expand the library. C++ is the primary programming language used to develop these modeling systems. The models provide graphical user interfaces and were developed for primarily for workstation environments.

The Power and Reservoir System Model (PRSYM) is a general purpose reservoir simulation and optimization model developed jointly by the USBR, Electric Power Research Institute (EPRI), Tennessee Valley Authority (TVA), and CADSWES. Initial model development efforts included applications to the Colorado, San Juan, and Pecos River Basins. Development of the PRSYM was preceded by the River Simulation System (RSS) and CALIDAD models developed by the USBR and CADSWES and superceded by RiverWare.

The River Simulation System (RSS) developed at CADSWES under the sponsorship of the USBR is a generalized modeling system designed to be adaptable to any reservoir/river system (CADSWES 1992). The interactive graphics based software package was designed to run on workstations using the Unix operating system. The model combines advanced computer graphics and data management technology with river/reservoir system simulation capabilities. Several programs (including S-plus, ARC/INFO, INGRES, HYDAS, and other commercial software) are available within RSS to manage input data and analyze output.

The actual reservoir/river system simulation component of the RSS package is an object-oriented model written in the C and C++ programming languages. River/reservoir systems are represented within the model by node-link components. The user builds a model of a particular system by selecting and combining objects. Preprogrammed instructions for performing computations and data handling functions are associated with each object. For example, the user could select a reservoir object, hydropower object, or diversion object to represent a system component, which results in the model performing certain computations associated with these particular objects. The user defines reservoir system operating rules using "English-like" statements following a specified format. In general, the user can develop a model for a particular system using the preprogrammed objects and functions provided by the RSS. However, the object-oriented program structure also facilitates a programmer altering the software to include additional objects or functions as needed for particular applications.

CALIDAD (Bureau of Reclamation 1994) is also an object-oriented programming model designed for a workstation environment. Initial applications included simulation of the California Central Valley Project (Boyer 1994). CALIDAD was developed in the C programming language and one of its object-oriented extensions, Objective C. The graphical user interface was developed in C using Motif and the X Intrinsics Libraries.

CALIDAD simulates a river basin system and determines the set of diversions and reservoir releases which best meets the management objectives and institutional constraints. A user-specified water use scenario is supplied for sequences of streamflow inflows. In the computational algorithms incorporated in the model, user defined management and institutional constraints are handled using a heuristic technique, called tabu search, to determine permissible diversion and reservoir releases. If the system is over constrained, the tabu search selects a release schedule using weighting factors provided by the user.

A model for a particular river basin is created by combining a collection of objects representing system features such as stream inflows, reservoirs, municipal or irrigation demand sites, or hydroelectric power plants. CALIDAD provides a palette of pre-coded objects which can be used for building models for different river basins. Additional objects may be programmed and added to the library as needed. An object developed for a particular application can then be used for other modeling projects as well. Both computational algorithms and data are associated with each object. The physical data for system features such as reservoir storage capacities and streamflows may be entered as object data. Institutional constraints and management objectives, called rules in the model, are also treated as data and entered through a separate rules editor. The user interactively develops operating rules by relating variables associated with objects using arithmetic and logical operations provided by the editor. The user also assigns weighting factors representing the relative importance of each rule. During the computations for a particular time step of the simulation, it may not be possible to simultaneously meet all of the rules. The weighting factors are used in the computational algorithm in determining which rules to violate whenever conflicts occur.

USBR Colorado River Simulation System

The Colorado River Basin has a long history of being modeled. Studies were performed manually prior to the 1960's. The Colorado River Storage Project model, completed in 1965, was the first computer model of the Colorado River (Schuster 1987). This Bureau of Reclamation model was used to develop annual operating plans for the upper basin reservoirs during the filling of Lake Powell. Over the years, the model was expanded to include lower basin reservoirs, powerplants, salinity, and operating criteria. A second model, called the River Network Model, was developed in 1973 to evaluate the salinity impacts resulting from water resource development and salinity control projects and to aid in establishing salinity standards for the Colorado River. The CRSS, described in the following paragraphs, stemmed from these prior models, motivated by a need to have a flexible, comprehensive model of the Colorado River Basin that would incorporate all areas of interest including legislative requirements.

The Colorado River Simulation System (CRSS), originally developed by the Bureau of Reclamation 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 databases 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." Salt concentrations are also considered.

The main component of the Colorado River Simulation System (CRSS) is the Colorado River Simulation Model (CRSM). The CRSM is a water and salt accounting program. Historical monthly streamflows are inputted at pertinent locations; flows are routed through the system; and water supply commitments are met. Salt is introduced through inflows and return flows, and is routed through the system with the water. The model includes runoff forecasting, reservoir operations (rule curves, evaporation, bank storage, and sediment accumulation), flood control regulations, operating strategies of the system (shortage and surplus strategies), hydroelectric power generation, and legislative requirements.

The hydrology database contains the flow and salt data for the basin. The demand database contains diversion data. Other components of the CRSS include computer programs that process output from the CRSM and data in the hydrology and demand databases.

Models of the Sacramento and San Joaquin River Basins

The California Central Valley Basin includes the watersheds of the Sacramento and San Joaquin Rivers. The water resources of this basin are managed through the storage and conveyance facilities of the State Water Project and the federal Central Valley Project. The Projects Simulation Model (PROSIM) was developed by the Bureau of Reclamation to simulate operations of the Central Valley Project and State Water Project (Bureau of Reclamation 1990; Sandberg and Manza 1991). PROSIM uses a traditional water balance approach, with a monthly time step, to simulate a system represented by 50 nodes which includes 11 reservoirs. Monthly streamflow data is inputted at 24 of the nodes for a 57 year (1922-1978) simulation period. A groundwater routine is included in the model to estimate stream accretion from the groundwater basin in addition to the accretion which occurred historically. A routine is included to analyze hydroelectric power production. Reservoirs operate in accordance with storage allocations, rule curves, powerplant discharge capacities, and water demands. Demand for water comes in four basic forms: nonproject demands, project demands, minimum instream flow requirements, and Delta outflow requirements. Rules are provided to allocate water to competing uses and users in accordance with institutionally established requirements.

The San Joaquin Area Simulation Model (SANJASM) similarly simulates the San Joaquin River system portion of the State and Central Valley Projects plus the Calaveras River. Flood control and conservation operations of federal and private projects are simulated in accordance with user-specified reservoir operating, instream flow requirements, and municipal, industrial, and agricultural water demands. SANJASM and PROSIM are being essentially replaced with CALSIM discussed later in this chapter and RiverWare discussed in Chapter 7.

Models Developed by Regional Water Management Agencies

The Tennessee Valley Authority (TVA) is a unique river basin management agency with a long history of computer modeling. As discussed in Chapter 7, the TVA has adopted RiverWare in recent years to replace its older models. PRISM and associated interagency modeling studies of the Potomac River Basin have been cited as a classic example of the benefits of optimizing the joint operations of existing reservoirs.

Tennessee Valley Authority HYDROSIM Model

Shane and Gilbert (1982) and Gilbert and Shane (1982) describe a model, called HYDROSIM, used to simulate the 42-reservoir Tennessee Valley Authority system based on an established set of operating priorities. HYDROSIM has been used for various purposes including:

- evaluation of the operation of new operating requirements on established objectives
- continual checking of current reservoir system status to warn of possible future problems
- developing of long-range operating guides
- forecasting of reservoir system operation in terms of possible and likely pool level and discharge variations, constraint violations, and hydroelectric generation characteristics anticipated in the next one to 52 weeks of operation

A database includes weekly streamflows at all pertinent locations for the period since 1903. The HYDROSIM model uses LP to compute reservoir storages, releases, and hydroelectric power generation for each week of a 52-week period beginning at the present based on alternative sequences of historical streamflows from the database.

As mandated by the legislative act creating the TVA, the order of priority for operating the system is as follows: flood prevention, navigation, water supply, power generation (energy and capacity assurance), water quality, drawdown rates, recreation, minimization of power production costs, and balancing of reservoirs. The HYDROSIM model is based on these priorities. A series of operating constraints are formulated to represent these objectives. 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.

Potomac River Basin Model

The Potomac River Interactive Simulation Model (PRISM) was originally developed by a research team at Johns Hopkins University (Palmer *et al.* 1982). 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 Corps of Engineers modified PRISM for use in certain drought simulation studies (USACE Baltimore District 1983). The model has not been actively applied in recent years. PRISM simulates the operation of several reservoirs and allocation of water within the Washington Metropolitan Area. Versions of the model alternatively use a weekly and daily time interval. The model determines the amount of water available to each of the several jurisdictions, for given streamflows, demands, and water allocation and reservoir operation rules.

PRISM is designed for use either 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 a regional water supply manager in strict accordance with rules specified by the model user. The interactive model allows participants to engage in a dialogue with the model as it is being executed, thereby changing model parameters and overriding pre-specified 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.

Measures implemented to meet water supply needs in the Washington, D.C. area have been viewed as a classic example of optimizing the beneficial use of existing systems as an alternative to construction of additional major reservoir projects. Various systems analysis techniques including PRISM were used in developing the plan. The Metropolitan Washington Area Water Supply Study Final Report (USACE Baltimore District 1983) summarizes the Corps of Engineers study authorized by the Water Resources Development Act of 1974 as well as the studies performed and actions taken by various nonfederal entities. The Corps of Engineers report resulted in a recommendation of no further federal action since the water supply needs could be satisfied by measures being implemented by nonfederal entities.

The study was motivated by the fact that municipal and industrial water needs significantly exceeded supplies. The primary water supply area is the Potomac River Basin and adjacent Patuxent River Basin. Relatively small portions of these watersheds are controlled by five reservoirs, but the single largest source of supply is unregulated flows in the Potomac River. Construction of additional reservoirs was proposed but concluded to be infeasible for various reasons including lack of public support.

The Interstate Commission on the Potomac River Basin, Corps of Engineers, several water utilities, researchers at Johns Hopkins University, and several committees and task forces all played key roles during several years of studies resulting in the plan finally implemented. The regional water supply plan included a number of components involving: (1) system operation based on coordination of unregulated flows and withdrawals from the existing five reservoirs; (2) long-term and emergency demand management measures; and (3) construction of a small downstream re-regulating reservoir to facilitate improved operation of existing upstream reservoirs. Several contracts and agreements between the various water management agencies were required to implement the plan.

Schwartz (2000) reviews the past history of water management in the Potomac River Basin and associated reservoir system modeling and reports the results of a more recent simulation/optimization modeling study to determine optimal reservoir storage allocations and operating rules. Multi-objective systems analysis techniques were applied to assess yield and reliability for alternative operating strategies under current and projected future conditions of water demand, within the framework of the interagency agreements that have been executed based upon the earlier studies.

Models Developed by State Agencies

Texas, California, and Colorado are notable examples of states that are particularly active in reservoir/river system modeling. They have water agencies with long histories of model development and application with significant expansions in modeling capabilities in recent years.

Texas Water Development Board Models

The Texas Water Development Board (TWDB) has adopted the WRAP modeling system described in Chapter 7 for statewide and regional planning studies conducted in recent years. WRAP supports both the water rights system administered by the Texas Commission on Environmental Quality (TCEQ) and the planning activities led by the TWDB. A number of other generalized models have been developed by the TWDB in the past.

The TWDB began development of a series of models in the late 1960's in conjunction with formulation of the Texas Water Plan. Several generalized models, reflecting pioneering applications of network flow programming, have evolved 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.

SIMYLD-II provides capabilities for analyzing water storage and transfer within a multireservoir or multibasin system with the objective of meeting a set of specified demands in a given order of priority (Texas Water Development Board 1972). If sufficient water is not available to meet competing demands during a particular time interval, the shortage is assigned to the lowest priority demand node. SIMYLD-II also determines the firm yield of a single reservoir within a multiple-reservoir system. An iterative procedure is used to adjust the demands at a reservoir in order to converge on its firm yield.

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. Hydroelectric benefits, which are complicated by nonlinearity, are incorporated by solving successive 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.

Martin (1987) describes the MONITOR-I model developed by the TWDB to analyze complex surface water storage and conveyance systems operated for hydroelectric power, water supply, and low flow augmentation. The LP model uses an iterative successive LP algorithm 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.

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

California Department of Water Resources Models

The CalSim model (Munevar and Chung 1999; Draper et al. 2004) of the combined operation of the State Water Project (SWP) and Central Valley Project (CVP) of California has replaced the earlier DWRSIM model (Chung et al. 1989). The California SWP and federal CVP were constructed and are operated by the California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (USBR), respectively, but are physically interdependent. The two interconnected systems provide flood control, water conservation, power generation, recreation, and streamflow and water quality protection. Maintaining the ecosystem vitality of the Delta region above San Francisco Bay is an important operating objective. Both the SWP and CVP systems have major storage facilities in Northern California that store winter and spring runoff to meet predominately agricultural demand in the Sacramento Valley and San Joaquin Valley and urban demand in the central and southern coastal regions of the state. The CVP includes 20 reservoirs, extensive conveyance facilities, pumping plants, and hydropower plants. Principal components of the SWP include Lake Oroville, the 715 km California Aqueduct, and other storage and conveyance facilities. The San Luis Reservoir is owned and operated jointly by the DWR and USBR. Numerous water suppliers and users hold water supply contracts with the DWR or USBR.

The original Department of Water Resources Simulation Model (DWRSIM) of the combined SWP and CVP was a conventional simulation model developed based on modifying HEC-3. DWRSIM was revised during the 1980's to incorporate the out-of-kilter network flow programming algorithm that had been previously incorporated in Texas Water Development Board models. The versions of DWRSIM with and without the network flow programming algorithm were used for the same types of analyses and had essentially the same input and output formats. The network flow formulation was incorporated into DWRSIM to enhance capabilities for analyzing consequences of different operational scenarios (Chung et al. 1989).

The California Department of Water Resources (DWR) in partnership with the USBR Mid-Pacific Region has replaced DWRSIM with CalSim (Munevar and Chung 1999; Draper et al. 2004; http://modeling.water.ca.gov/hydro/model/index.html). The generalized model is called the Water Resources Integrated Modeling System (WRIMS). The WRIMS model of the operation of combined SWP and CVP is called CalSim (California Water Resources Simulation Model). CalSim is a general-purpose planning and management model currently being applied to the SWP and CVP, focusing on the Sacramento and San Joaquin River Systems with some representation of water deliveries to the Tulare Basin and Southern California urban areas. Ferreira et al. (2004) document a series of interviews with 89 members of the California water management community regarding CalSim. Opinions and ideas discussed range from model mission and administration to the details of implementation, data, and software.

The generalized WRIMS and California CalSim are designed for evaluating operational alternatives for the large, complex river systems. The modeling system integrates a simulation language for defining operating criteria, a linear programming solver, and graphics capabilities.

CalSim is a monthly time step simulation model based on a linear programming formulation that minimizes a priority-based penalty function of delivery and storage targets. Rather than specifying detailed operating rules, the user specifies a series of objectives in the form of relative priorities or weights for water allocation and storage. The LP model is solved for each month. Adjustment computations are performed after the LP solution to deal with more complex nonlinear aspects of modeling complex system operations.

A feature called the Water Resources Engineering Simulation Language (WRESL) was developed for the model based on the Java language to allow the user to express reservoir/river system operating requirements and constraints. WRSEL statements are written by the model-user using any text editor. The user-supplied statements written in the WRESL language are used by the model to define the linear programming formulation. At runtime, the WRESL statements are converted to Fortran code by a parser-interpreter program. Computations are performed by programs written in Fortran. The XA solver (Byer 2001) is incorporated into the model to perform the linear programming solution that is repeated one or more times at each time step. Time series data are stored using the Hydrologic Engineering Center Data Storage System (HECDSS).

State of Colorado StateMod

The Colorado Water Conservation Board and the Colorado Division of Water Resources have developed decision support systems for water management in the Colorado, Rio Grande, South Platte, and Arkansas River Basins. The generalized StateMod serves as the reservoir/river system modeling component of these decision support systems. StateMod is a water allocation and accounting model for simulating alternative water management strategies. Either a monthly or daily time step may be used. Hydrology, water rights, and system operating rules are combined in the model. Water rights are categorized as: direct flow, instream flow, reservoir storage, well, and operational. Water rights are simulated in priority order. The modeling system consists of four major models: base flow, simulation, report, and data check.

Models Developed by International Research Institutes and Consulting Firms

The proprietary OASIS, ARSP, MIKE BASIN, RIBASIN, and WEAP software products were developed and are marketed by organizations that provide consulting services in applying the models. The developers and other organizations have applied the models to reservoir/river systems located throughout the world.

HydroLogics OASIS

HydroLogics is a consulting firm specializing in water resources management with offices in Columbia, MD, Raleigh, NC, and Sacramento, CA (http://www.hydrologics.net/). The Operational Analysis and Simulation of Integrated Systems (OASIS) model is a generalized model based on linear programming that uses operations control language (OCL) for defining operating rules. OCL is a programming language patented by HydroLogics that is similar to a scripting or macro language. OCL is analogous to the WRSEL language incorporated in the California CalSim/WRIMS. Operating rules are expressed as goals and constraints. The modeling system is designed to facilitate connections to other simulation models and data management systems.

Acres Reservoir Simulation Program ARSP

The Acres Reservoir Simulation Program (ARSP) was developed by Acres International Corporation (http://www.acres.com/index.html) and is marketed and supported by BOSS International (http://www.bossintl.com/). The software sells for $1,995. Acres International is headquartered in Ontario, Canada. BOSS International has headquarters in Madison, Wisconsin. Both consulting engineering firms have multiple offices in various countries.

The ARSP network flow programming based model simulates multi-purpose, multi-reservoir systems. Operating policies are defined by prioritizing water demands. Monthly, weekly, daily, or hourly time steps may be used. The software assigns upper and lower bounds and cost functions to the network flow paths for the network flow programming formulation based on the input provided by the user. ARSP has been extensively applied over many years by Acres International and others for both long-term planning and operations studies of reservoir/river systems throughout the world.

Sigvaldason (1976) describes pioneering work in applying network flow programming to reservoir system management that later evolved into the current ARSP model. The original model was developed to assess alternative operation policies for a 48-reservoir multiple-purpose 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, and time based rule curves were specified. The combined rule curve and storage zone representation is similar to HEC-5. However, the Acres model was formulated as a network flow programming problem. Penalty coefficients were assigned to those variables which represented deviations from ideal conditions. Different operating policies were simulated by altering relative values of these coefficients. The out-of-kilter algorithm used to solve the network flow problem is similar to the Texas Water Development Board models cited earlier. Bridgeman et al. (1988) describe applications of a later version of the network flow model designed to forecast inflows, simulate operations, and postprocess results. The Acres International consulting firm continues to apply the ARSP model to various reservoir/river systems for various clients.

Danish Hydraulic Institute MIKE BASIN

The Danish Hydraulic Institute (DHI) is an international consulting and research organization established in 1964 and located in Horsholm, Denmark (http://www.dhi.dk/). DHI has developed and now markets a suite of software covering various areas of hydraulics, hydrology, and water resources management. The DHI provides international consulting services in applying the models. MIKE BASIN is the reservoir/river system component of the DHI family of software. The single-user license fee is $3,000 initially with a $300 annual update.

MIKE BASIN runs within and is an extension to ArcView which is a geographical information system (GIS) software product available from ESRI (http://www.esri.com). MIKE BASIN integrates GIS capabilities with reservoir/river system modeling. Features also facilitate interconnected use of Microsoft Excel with MIKE BASIN. Macros specifying reservoir/river system operating rules may be developed by the model-user in Visual Basic. The model is documented by a guide to getting started tutorial and a on-line help feature providing information describing each window of the user interface.

The model simulates multi-purpose, multi-reservoir systems based on a network formulation of nodes and branches. Although the time step is user-selected, solutions are stationary for each time station without flow routing dynamics. Thus, a monthly time step is common. Time series of inflows from catchments to each branch of the stream system are normally provided as input. However, the model can also be connected to watershed precipitation-runoff capabilities provided by the MIKE11 watershed model also available from the DHI. Discharge from and recharge to groundwater may also be included in the model. An aquifer is modeled as a linear reservoir. Various options are provided for specifying reservoir operating rules and allocating water between multiple water users. Water may be allocated between users at a node based on local priority rules that approximate a riparian water rights system or global priority rules that approximate a prior appropriation water rights system. An extended version of MIKE BASIN has features for modeling water quality.

Delft Hydraulics RIBASIN

Delft Hydraulics is an independent research institute and specialist consultancy in the Netherlands from which several generalized hydraulic simulation software packages are available (http://wldelft.nl). RIBASIN (River Basin Simulation) is their river basin planning and management model. RIBASIN has been applied for a number of river basins throughout the world over the past 20 years. Hydrological water inputs at various locations in a river basin are linked with water users. A water balance for a reservoir/river/use system provides information on water availability and the source composition at all locations and time steps. The flow patterns generated with RIBASIN provide a basis for other water quality and sedimentation analyses for river reaches and reservoirs. RIBASIM may be linked with the HYMOS hydrology model and DELWAQ water quality model also available from Delft Hydraulics. The user interface is designed for compatibility with GIS.

Water Evaluation and Planning (WEAP) Modeling System

The Water Evaluation and Planning (WEAP) System was developed and is distributed by the Stockholm Environmental Institute Boston Center at the Tellus Institute located in Boston, Massachusetts (http://www.weap21.org/). The USACE Hydrologic Engineering Center has funded enhancements to the model. WEAP has been used in studies throughout the world conducted by United Nations agencies, the U.S. Agency for International Development, and other organizations. The software package sells for $2,000 for commercial customers with free or discounted licenses for not-for-profit organizations. WEAP is a reservoir/river/use system water balance accounting model that allocates water from surface and groundwater sources to different types of demands. The modeling system is designed as a tool for maintaining water balance databases, generating water management scenarios, and performing policy analyses.

Generalized Models Developed at Universities

RiverWare, MODSIM, and WRAP described in Chapter 7 were developed at universities with funding support and technical guidance from federal and state water agencies. RiverWare was developed by the Center for Advance Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado sponsored by the Bureau of Reclamation and Tennessee Valley Authority. MODSIM was developed at Colorado State University sponsored by the Bureau of Reclamation and other agencies. WRAP was developed at Texas A&M University sponsored initially by a federal/state research program administered by the U.S. Geological Survey and Texas Water Resources Institute (TWRI) and later by the Texas Advanced Technology Program, Texas Water Development Board, Texas Commission on Environmental Quality, and USACE Fort Worth District under contracts administered through the TWRI of the Texas A&M University System.

Several other models described earlier in this chapter have been developed partially or wholly through university research funded by federal and/or state water agencies. The network flow programming solver incorporated in several of the models was developed at the University of Texas. Other generalized reservoir/river system models developed by university researchers are described by the remainder of this section. A later section reviews other optimization models, most of which are not generalized and most of which were developed by university researchers.

IRIS and IRAS

The Interactive River System Simulation (IRIS) model 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). Model development was motivated by providing a useful tool for water managers responsible for negotiating agreements among individuals and organizations in conflict over water use. IRIS operates in a menu-driven microcomputer or workstation environment with extensive use of computer graphics for information transfer between machine and user. The configuration of the system is specified by "drawing in" nodes (reservoirs, inflow sites, junctions and other key locations) and interconnecting links (river reaches, canals). The model simulates a water supply and conveyance system of essentially any normal branching configuration for inputted streamflow sequences, using a user-specified time step. Hydroelectric power and water quality features are included. System operating rules include: (1) reservoir releases specified as a function of storage and season of the year, (2) allocation functions for multiple links from the same node, and (3) storage distribution targets for reservoirs operating in combination. The model allows the operating rules to be interactively changed by the user during the course of a simulation run. Several alternative sets of inflow sequences to be considered in a single run of the model. Model output includes time series plots of flows, storages, energy generated, and water quality parameters at any node or link in the reservoir/river system and probability distribution displays of magnitude and duration of shortages or failure events.

The Interactive River-Aquifer Systems (IRAS) model was developed as an extension of IRIS (Loucks et al. 1995). IRAS is a generalized program for analyzing regional surface and ground water management systems to address problems involving interactions between ground and surface waters and between water quality and quantity. The model predicts the range and likelihood of various water quantity, quality, and hydropower impacts, over time, associated with alternative design and operating policies, for portions or entire systems, of multiple rivers and ground water aquifers. Simulations are based on mass balances of quantity and quality constituents, taking into account flow routing, seepage, evaporation, consumption, and constituent growth, decay, and transformation, as applicable. A variable computational time step is used. IRAS provides a menu-driven graphics-based user interface.

MITSIM

The MITSIM model was originally developed at the Massachusetts Institute of Technology (Strzepek et al. 1979). Early versions of the model were used in studies of the Rio Colorado in Argentina and the Vardar/Axios project in Yugoslavia and Greece. Subsequent versions have been applied in a number of studies. The model has been updated and adapted to changing computer environments at the Center for Advanced Decision Support for Water and Environmental Systems (Strzepek et al. 1989). MITSIM provides capabilities to evaluate both the hydrologic and economic performance of alternative river basin development plans involving reservoirs, hydroelectric power plants, irrigation areas, and municipal & industrial water supply diversions. A river/reservoir/use system is conceptualized as a collection of arcs and nodes. A variable computational time interval is used. The model assesses system reliability in meeting demands. Economic benefits and costs can also be evaluated. Benefits are divided into long-term benefits and short-term losses. Optional displays of net economic benefits and benefit-cost ratios for the entire river basin and/or sub-regions within the basin can be included in the output.

AQUARIUS

AQUARIUS developed at Colorado State University is an object-oriented modeling system for allocating the water resources of a river basin based on mathematical programming with an economic objective function (Diaz and Brown 1997; Diaz et al. 2000). The model is coded in C++. The computations are based on solving a quadratic objective function subject to a set of linear constraints. Economic benefit functions are reflected in the objective function. A monthly time step is used. AQUARIUS provides a general analysis framework. System components may include storage reservoirs, hydropower plants, agricultural water use, municipal and industrial water use, instream recreation use, reservoir recreation use, and instream flow protection.

Other Models Based on Optimization Techniques

Most of the many hundreds of reservoir/river system models reported in the published literature were developed by university researchers based on mathematical programming techniques. Researchers in the water agencies have also contributed to the massive optimization literature. Yeh (1985) and Labadie (2004) provide summary reviews of the complex literature. Several linear programming models (including several network flow programming models) and one quadratic programming model are described earlier in this chapter. This section of the chapter provides a small representative sampling of the numerous journal papers and other publications on deterministic and stochastic reservoir/river system optimization models.

The following review is organized based on categorizing optimization techniques as being based on variations of linear programming, quadratic programming, dynamic programming, gradient search algorithms, or genetic algorithms. However, models often combine more than one type of optimization method. Computational algorithms that are not optimization methods are also combined in various ways with the formal mathematical optimization methods.

Optimization models may also be categorized as being either deterministic or stochastic. Most models adopted in actual practice are deterministic with sequences of inflows representing historical hydrology provided as input. An array of methods have been proposed in the research literature to probabilistically represent the stochastic nature of streamflows and other variables in stochastic mathematical programming models.

Linear Programming

Numerous reservoir/river system models, including several cited earlier in this chapter, have been based on linear programming (LP). Several other LP models are cited below to further illustrate the variety of ways in which LP has been applied. Network flow programming (Equations 4.14-4.16) is a special form of LP (Equations 4.1-4.8) that allows more computationally efficient solution algorithms. Separable programming and LP with successive approximations are methods for dealing with nonlinear aspects of a model. A separable objective function may be approximated with piece-wise linear functions. Successive executions of an LP algorithm may be repeated with iterative adjustments that deal with non-linear terms through approximations that improve the solution with each successive iteration.

Dorfman (1962) illustrated the use of LP 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. The following alternative approaches for representing inflows are reflected in the three versions of the model: (1) average seasonal flows, (2) critical period flows, and (3) treating flows stochastically.

A number of researchers have developed stochastic LP models with random serially correlated inflows represented by a Markov chain with transition probabilities estimated from historical streamflows. Loucks (1968) developed a stochastic LP model for a single reservoir that determined release rates 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. Houck and Cohon (1978) reported a multiple-reservoir system model with streamflows represented by a discrete Markov structure. A nonlinear formulation was approximated by solving two LP problems.

A number of papers in the research literature have focused on chance-constrained formulations and associated linear decision rules. Revelle et al. (1969) published one of the key early papers on these techniques. Other researchers, such as Loucks and Dorfman (1975) and Houck et al. (1980), built upon and extended the basic concepts. In chance-constrained LP formulations, probability characteristics of inflows and other random variables are reflected in the constraints. Certain constraints are violated a specified percentage of time. A linear decision rule provides a mechanism for reflecting reservoir operating rules in a LP model, which also simplifies solution of the model. Inflows, storage, and releases are related to a decision parameter. For example, for a LP formulation with chance-constraints and a linear decision rule, 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.

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. Reservoir and channel routing equations are incorporated in the model.

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. 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.

Reznicek and Simonovic (1990) developed a successive linear programming approach for analyzing hydroelectric power operations. The model determines releases that maximize system revenue and minimize cost of satisfying energy demands described by a given load duration curve for a given set of stream inflows. A multiple-reservoir system operated by Manitoba Hydro was used as a case study to test the modeling approach.

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 costs; (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. Trade-off curves were developed to show the trade-offs between the four alternative objectives.

The Alameda County Water District in California has used a LP model for long-range planning (Randall et al. 1997). Wilchfort and Lund (1997) report a research study involving application of LP in analyzing management plans for the East Bay Municipal Utility District in California.

Needham et al. (2000) used LP to model flood control operations of a system of three reservoirs on the Iowa and Des Moines Rivers in a study sponsored by the USACE Rock Island

District and Hydrologic Engineering Center. The flood control LP model called HEC-FCLP determines a system-wide set of releases for each daily time step of a flood event that minimize total system penalties for too much or too little release, storage, and flow. A simulation model embedded within the LP model uses given releases to compute storage and downstream flows based on maintaining continuity, Muskingum routing, and hydraulic limitations such as reservoir outlet capacities. HEC-FCLP reads data describing the flood control system from a text file and generates a set of linear equations that constitute the LP model, which is solved with a commercially available general-purpose LP solver called IBM/OSL. HEC-FCLP is linked to the HEC Data Storage System (HEC-DSS) from which it reads incremental flow data and to which it writes the model results.

Tu et al. (2003) used LP to optimize multiple-purpose reservoir system operations in Taiwan. Traditional rule curves and hedging rules are used in combination to allocate water among competing users while minimizing the impacts of drought.

Barros et al. (2003) modeled the Brazilian hydropower system which with 75 hydropower plants is one of the largest hydropower systems in the world. A nonlinear programming was formulated and solved with a quadratic programming algorithm. Two alternative linearization techniques were applied to allow the model to also be solved by LP. Results from the alternative linearized LP models were compare with the nonlinear quadratic programming solution.

Network Flow Programming

The several network flow programming models discussed earlier in this chapter include the Texas Water Development Board SIMYLD-II, AL-V, SIM-V, and MONITOR-I, California Department of Water Resources DWRSIM, Hydrologic Engineering Center HEC-PRM, and Acres International ARSP. MODSIM is discussed in Chapter 6. Other network flow programming models are cited as follows.

Brendecke *et al*. (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. MODSIM served as the basis for development of CRAM, with various improvements pertinent to the particular application being added to CRAM.

The Water Assignment Simulation Package (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 systems as well (Kuczera and Diment 1988). WASP allocates water according to the following criteria in order of decreasing priority: (1) satisfy all demands, (2) satisfy instream requirements, (3) minimize spills, (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.

Hsu and Cheng (2002) applied a similar network flow model for water allocation in a river basin in Taiwan. Israel and Lund (1999), Fredericks et al (1998), and Labadie and Baldo (2001) investigate refinements to network flow programming methods.

Quadratic Programming

Quadratic programming consists of a successive or sequential solution procedure for a problem consisting of minimizing or maximizing a quadratic objective function subject to a set of linear constraints. The previously described AQUARIUS is based on quadratic programming (Diaz *et al.* 2000). 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. Tejada-Guibert (1990) applied quadratic programming to a five reservoir portion of the Central Valley Project of California. Sinha *et al.* (1999) used a quadratic programming model to size storage capacities for reservoirs in India based on minimizing cost. Barros *et al.* (2003) modeled a complex hydroelectric power system alternatively with quadratic programming and with LP with alternative methods for dealing with nonlinear terms.

Dynamic Programming

Dynamic programming (DP) is a general approach to optimization in which a sequential decision problem is decomposed into stages with a decision required at each stage. Stages are connected by state variables. Decisions at each stage are guided by a recursive objective function.

Buras (1966) describes early applications of DP in water resources development. 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. Trezos and Yeh (1987) developed a dynamic programming methodology for improving the operation of systems of multiple hydroelectric power projects. Giles and Wunderlich (1981) describe a model developed by the Tennessee Valley Authority based on dynamic programming that is similar to the previously discussed HYDROSIM model which uses LP.

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

Chung and Helweg (1985) combined DP with HEC-3 in an analysis of operating policies for Lake Oroville and San Luis Reservoir, which are components of the California State Water Project. The HEC-3 reservoir system simulation model 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.

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). 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. Output from one model (monthly ending storages or daily releases) are used as input 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 model 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.

Research studies have explored the complex problem of applying stochastic dynamic programming to multiple-reservoir systems, which involves dealing with state dimensionality. Tejada-Guibert et al. (1995) applied this strategy to the Trinity-Shasta Reservoir System of California. Archibald et al. (1997) applied stochastic DP to a multiple reservoir system, with a sequence of three-dimensional problems solved with states representing the storage in the current reservoir, aggregate of upstream reservoirs, and approximation of downstream reservoirs.

Fontane et al. (1997) combined the theory of fuzzy sets with DP for planning reservoir operations with imprecise objectives. Chandramouli and Raman (2001) modeled the Parambikulam Aliyar Project multireservoir system in India, applying neural networks to the DP results to derive operating rules.

Gradient Search Techniques

Gradient search techniques involve iteratively adjusting the values of decision values based on objective function gradients in a search for the optimal or at least a near optimal solution. Duren and Beard (1972) incorporated a univariate gradient search algorithm, with the Newton-Raphson convergence technique, into a USACE 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 were later also adopted for the parameter calibration and flood damage reduction system optimization options of the HEC-1 Flood Hydrograph Package.

Ford, Garland, and Sullivan (1981) combined a reservoir yield simulation model and the Box-Complex search algorithm in a Corps of Engineers investigation of 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 is used to simulate a given operating policy, satisfying all demands when possible and allocating the available water according to specific priorities when conflicts occur. The simulation model is linked to the search algorithm which automatically selects 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 is then smoothed using engineering judgment based on experience with operation of the system. The system response with the smoothed operating policy is 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 was 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.

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.

Genetic Algorithms

Genetic algorithms are evolutionary search methods based on the mechanics of natural selection (Goldberg 1989; Mitchell 1998; Ranjithan 2005). Esat and Hall (1994) and Wardlaw and Sharif (1999) investigated various alternative formulations of genetic algorithms for analyzing a system of four reservoirs. Oliveira and Loucks (1997) also investigated the potential for evaluating reservoir operating rules using a genetic algorithm. Prasad and Park (2004) and Zyl et al. (2004) applied genetic algorithms to optimize water distribution systems. Burn and Yuliani explore genetic algorithm capabilities for allocating waste loads for a river system. Ilich (2001) and Wardlaw and Bhaktikul (2004) compare linear programming and genetic algorithms. Cai et al. (2001) combine LP and a genetic algorithm.

Generalized Package of Alternative Methods for a Single Reservoir

Simonovic (1992) describes an intelligent decision support system called REZES, which includes a library of 11 models for performing various analyses for a single reservoir. The models utilize various simulation and optimization techniques including LP and DP. REZES is an expert system that facilitates the selection and application of alternative reservoir system analysis methods. The system is structured based on the four phases of the reservoir analysis process: (1) problem identification and formulation, (2) model selection, (3) data preparation and computation, and (4) presentation and evaluation of results. The major components of the expert system are the user interface, knowledge base, model library, input data preparation module, algorithmic routines, and output data analysis module. The model library contains the following single-reservoir models.

* RESER is a simulation-optimization (search algorithm) model for determining the minimum storage capacity required to meet specified demands and to evaluate reliability.
* CYIELD is a LP-based model for minimizing total storage capacity.
* AYIELD is a LP-based reservoir sizing model for within year analysis.
* ILP is an iterative LP model for planning hydroelectric power operations.
* EMSLP is a successive LP optimization model for long-term planning of an interconnected hydro utility.
* DP is a deterministic DP model for long-term planning of a multiple-purpose reservoir.
* CCCP is a chance constrained LP model for long-term planning of a multiple-purpose reservoir.
* RPORC is a reliability programming model for long-term planning of a multiple-purpose reservoir.
* SDP is predictive stochastic dynamic programming for long-term multipurpose planning.
* PROFEXI combines LP with Kalman filtering and multiobjective compromise programming to analyze short-term multipurpose operations.
* FCCP is a fuzzy chance-constrained model for long-term planning that accepts both quantitative and qualitative input information.

Stochastic Storage 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 largely on the theory presented by Moran (1959) and expanded by Gould (1961). Klemes (1981), McMahon and Mein (1986), and Nagy *et al.* (2002) provide in depth overviews and cite many references. Vaugh and Maidment (1987) provide an example of the general approach through application to reservoirs on the Colorado River of Texas.

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.

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.

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

In terms of practical usefulness, the most important storage probability theory models are described as probability matrix methods (McMahon and Mein 1986). Zsuffa and Galai (1987) address probability matrix methods from a practical applications perspective and provide computer programs for implementing the methods. 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) 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."

A nonsteady state analysis can 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 is reduced accordingly. Storage probability theory models 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.

Chapter 7
Selected Generalized Modeling Systems for Simulating Reservoir/River System Management

The SUPER, ResSim, RiverWare, MODSIM, and WRAP modeling systems are described in Chapter 7 and compared in Chapter 8. These five models are representative of state-of-the-art reservoir/river system modeling capabilities in general and are particularly pertinent to practical applications by water resources planning and management agencies in Texas and elsewhere.

Table 7.1 Generalized Reservoir/River System Management Models

Short Name	Descriptive Name	Model Development Organization
SUPER	SWD Reservoir System Model	USACE Southwestern Division http://www.swd.usace.army.mil/
ResSim	Reservoir System Simulation	USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/
RiverWare	River and Reservoir Operations	Bureau of Reclamation, Tennessee Valley Authority, Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) http://animas.colorado.edu/riverware/
MODSIM	Generalized River Basin Network Flow Model	Colorado State University, Bureau of Reclamation http://modsim.engr.colostate.edu/
WRAP	Water Rights Analysis Package	Texas A&M University, Texas Water Resources Institute, Texas Commission on Environmental Quality, USACE Fort Worth District http://ceprofs.tamu.edu/rwurbs/wrap.htm

SWD SUPER Modeling System

The SUPER model was developed by the Southwestern Division (SWD) of the U.S. Army Corps of Engineers (USACE) and has been applied by the SWD office in Dallas and the Fort Worth, Tulsa, and Little Rock District offices of the SWD. SUPER is a system of computer programs designed to simulate the daily sequential regulation of a multipurpose system of reservoirs and the corresponding hydrologic and economic impacts (Hula 1981; USACE Office of the Chief of Engineers 1985). A simulation reflects a specified regulation plan, economic parameters, and long sequences of daily flows and net reservoir evaporation rates. Multiple simulations are performed to compare alternative variations in regulation plans. Simulation results include stage or discharge hydrographs for each reservoir and river control point, which may also be integrated with economic benefit functions. Hydrologic results may be expressed as monthly and annual frequency relationships for maximum and minimum reservoir storage and streamflow; storage and flow duration relationships; and diversion and instream flow shortages. Economic results may include flood damages, recreation benefits, power value, cost of purchased power, dredging costs, and navigation costs.

Software Environment for Model Building

SUPER is a set of Fortran programs that have been compiled and executed on various computer systems over the past 30 years. A particular reservoir/river system is described by a set of data files. The SWD has prepared manuals for database development, operation of the model, and display of results. The model has not been distributed outside of the SWD.

River Basin Hydrology

Hydrologic input to the model consists of total uncontrolled subwatershed daily streamflows at each river control point and each reservoir and daily evaporation depths for each reservoir. The Muskingum method is used for routing flows through river reaches. Development of the hydrologic dataset represents the major part of the effort required for application of the model. Various utility programs are used in processing hydrologic data records. Tasks include computation of:

- reservoir inflow from storage contents or stage and release records
- local flows based on discharge records and storage-discharge routing relations
- data for an ungaged location based on the addition of one or more files each multiplied by a factor
- uncontrolled area flow based on routing and combining local flows, including file smoothing to remove negative flows
- evaporation or net evaporation less precipitation rates based on weather station records, pan coefficients, and geographic factors

Reservoir/River System Operations

Flood control and conservation storage requirements are met within specified operating objectives. Reservoir controls include:

- minimum discharge curves reflecting induced surcharge, minimum release, or uncontrolled spillway release
- seasonal minimum release criteria such as minimum hydropower
- seasonal balancing of reservoir storage levels
- maximum flood release as a function of season and storage level

River controls include:

- seasonal minimum flow requirements
- seasonal withdrawal targets
- seasonal return flow
- maximum regulating discharge for flood releases as a function of season and system storage levels

Capabilities are provided for detailed representation of flood control operating strategies. Flood control reservoirs are regulated on a daily basis to stay within downstream maximum flow limits, which are expressed as a function of season and storage level. Multiple-reservoir release decisions are based on balancing storage levels between specified zones of flood control pools. A forecast feature allows use of knowledge of flows for a specified number of days into the future. On each day of the simulation, a tentative schedule of releases is made for the next several days taking into account downstream maximum flow levels, balancing multiple-reservoir system storage, and maximum daily change in the release rate. The forecast is updated as the simulation progresses to the next day.

Water supply requirements are expressed as seasonal diversion demands and instream flow targets. Diversion and instream flow demands at downstream control points may be served by one or more reservoirs located upstream. Multiple-reservoir release decisions are based on balancing storage levels following specified criteria.

Hydroelectric energy is produced for multiple system loads. Each reservoir is assigned to a specific system. Power loads are expressed as a function of season and storage level. Releases for other purposes are also used to generate power. Any excess energy above specified demands is counted as dump energy. The necessity for thermal purchase is then determined. The remainder of the load is satisfied, if possible, considering available power storage, generating capacity, and remaining available channel capacity. Any deficiencies are accounted for as additional thermal purchase.

Economic Evaluation Capabilities

The model includes features for economic evaluations as well as the basic hydrologic analyses. Economic benefits and costs are determined by combining reservoir storage and streamflow results with:

- flood stage-damage, stage-discharge, and stage-area curves
- cropping patterns and crop values
- navigation costs relative to discharge
- dredging costs relative to flow rates and duration
- reservoir recreation benefits as a function of pool elevation, season, and pool fluctuations
- hydroelectric power value and thermal power purchase costs and a function of season

Applications

The initial implementation of the SUPER model by the USACE SWD dates back to the 1970's (Hula 1981). Coomes (1981) and Copley (1981) describe an early SUPER modeling study of regulation of the Arkansas River System performed by the SWD and Tulsa District. The Fort Worth, Tulsa, and Little Rock Districts and the Division Office have applied the model to many major Corps of Engineers reservoir/river systems in many studies since the 1970's.

HEC-ResSim Modeling System

Development of the Hydrologic Engineering Center (HEC) Reservoir System Simulation (ResSim) Model was initiated in 1996 in conjunction with the Hydrologic Engineering Center's Next Generation (NexGen) Software Development Project. HEC-ResSim will eventually replace the *HEC-5 Simulation and Flood Control and Conservation Systems* model, which has been extensively applied for over 20 years. Version 1.0 of HEC-ResSim was distributed for testing within the Corps of Engineers in 2001. Version 2.0 was released to the public in 2003. Significant new improvements continue to be developed. The public domain software and user documentation may be downloaded free-of-charge from the HEC website listed in Table 6.1. Documentation currently consists of a Quick Start Guide (HEC 2003), Users Manual (HEC 2003), and release notes. The HEC offers a 5-day training course on application of ResSim designed primarily for Corps of Engineers personnel.

ResSim is comprised of a graphical user interface, a computational program to simulate reservoir operation, data management capabilities, and graphics and reporting features. Multipurpose multireservoir systems are simulated using ad hoc algorithms coded specifically for the model rather than formal mathematical programming methods. The user selects the time-step, which may vary from 15 minutes to one day. Various routing options are provided. Features provide flexibility for detailed representation of reservoir system operating rules. Meeting the needs of USACE reservoir control personnel for real-time decision support has been a governing objective in developing HEC-ResSim. The model is also applicable in planning studies. The full spectrum of multiple-purpose reservoir operations is modeled. Particularly detailed capabilities are provided for modeling flood control operations.

Software Environment for Model Building

HEC-ResSim runs in Microsoft Windows. The software has been designed and tested primarily on Windows 2000 but runs on other versions of Windows as well. It has also been compiled and executed under the Sun Solaris 2.8 operating system. ResSim is coded in Java. The graphical user interface provides a map-based schematic development environment. Data are entered through the interface and stored in a file structure defined by the software. HECDSS (HEC 1995, 2003) is used to manage input and output time series data.

ResSim has three sets of functions called modules that provide access to specific types of data within a watershed. These modules are watershed setup, reservoir network, and simulation. Each module has a specific purpose and an associated set of functions accessible through menus, toolbars, and schematic elements. The purpose of the *watershed setup module* is to provide a common framework for watershed creation and definition among different modeling applications. Several HEC models share this module. The *reservoir network module* allows the user to construct a river schematic, describe the physical and operational elements of the reservoir system, and develop alternatives to be analyzed. The *simulation module* is used to configure and perform a simulation and review the results. The graphical user interface allows construction of a reservoir/river system schematic by point-and-click selecting and connecting of icons. Watershed, reservoir network, and simulation data are represented visually in a geo-reference context with interactions with associated data.

The tributary network configuration of the stream system, called the stream alignment, is created in the watershed setup module. The stream alignment consists of stream elements (segments), nodes, and junctions. Other watershed elements include projects, computation points, impact areas, and time-series icons. Projects include reservoirs, levees, diversions, channel modifications, channel storage, and other projects. Computation points are common points where data is exchanged between models. Impact areas are common elements representing areas where flood damages are evaluated. Time-series icons represent sites where time-series data are provided.

The reservoir network schematic is a template for simulation computations that is developed within the reservoir network module based on a configuration created in the watershed setup module. The graphical elements allow the user to access data editors and specify properties of reservoir network components.

River Basin Hydrology

The computational time interval may vary from 15 minutes to one day. Streamflow routing options are coefficient routing, Muskingum, Muskingum-Cunge, modified Puls, and a method from the SSARR model cited in Chapter 6. Time series of stream flows and reservoir evaporation rates are entered in HEC-DSS file format. The streamflow hydrographs provided as input to ResSim can come from any of the normal sources of observed or simulated streamflow sequences. In many typical ResSim applications involving flood control operations, the flows will be generated with the HEC-HMS Hydrologic Modeling System based on precipitation-runoff modeling. Other watershed precipitation-runoff models or other methods may be used as well to develop hydrographs for input to ResSim.

Reservoir/River System Operations

Flood control and conservation storage requirements are met within specified operating objectives. A system may include multiple reservoirs, with each reservoir having multiple outlet structures. Criteria for reservoir release decisions, called an operation set, are based on specified storage zones that divide the pool by elevation and a set of rules that specify the goals and constraints governing releases when the storage level falls within each zone. ResSim version 2.0 features for defining operating rules and modeling reservoir/river system operations include:

- a scheme for defining operating goals and constraints in terms of pool zones and zone dependent rules
- a set of operation rules that include:
  - release requirements and constraints
  - downstream control requirements and constraints
  - pool elevation or inflow rate-of-change limits
  - hydropower requirements
  - induced surcharge emergency gate operations
- operation of multiple reservoirs for a common downstream control with release decisions based on storage balancing
- release overrides of a reservoir release decisions time step by time step

New features being added to the model in 2004 include:

* system hydropower with multiple reservoirs operating for a common hydropower requirement
* pumps and pumpback storage
* period-average release requirements in lieu of current instantaneous values
* release allocation control over multiple-outlet releases
* scheduled outlet outages and outlet capacity overrides
* if-then-else logic for rule validation
* scripting and scripted rules
* critical period and firm yield analysis
* enhancements for period-of-record simulations

Applications

Version 1.0 of HEC-ResSim was distributed for testing within the Corps of Engineers in 2001, and version 2.0 was released to the public in 2003. Significant new features are currently being added. Initial applications include the Sacramento and San Joaquin River Basins in California and the Tigris and Euphrates River Basins in Iraq.

The HEC applied ResSim during 2001-2003 to model the Sacramento and San Joaquin Basins for the Water Management Section of the USACE Sacramento District (Rosenberg 2003). Watershed models of 16 distinct systems in the two basins include a total of 75 major reservoirs. Data sets from pre-existing HEC-5 models were incorporated into the ResSim models. ResSim simulation results were checked against HEC-5 results. The subwatershed systems were simulated using synthetic storm events covering a range of magnitudes.

The HEC is partnering with Development Alternatives, Inc. to model the Tigris and Euphrates river systems, sponsored by the U.S. Agency for International Development (Hanbali 2004). The system includes 6 major multipurpose (flood control, water supply, hydropower) reservoirs, 3 off-channel storage reservoirs, 7 low head dams, and many water supply diversions on the two rivers and their tributaries. The ResSim model is being developed to provide decision support for the Iraq Ministry of Water Resources in its operation of the complex system.

As discussed in Chapter 6, ResSim is a component of the Corps Water Management System (CWMS). ResSim is designed for application either independently of the CWMS or as a component thereof. An initial version of the CWMS was completed in 2001 and is currently being implemented in the Corps of Engineers district offices (Fritz, et al. 2002; Davis 2004). The Lower Colorado River Authority (LCRA) was the first non-USACE agency to apply the CWMS (Ickert and Luna 2004). The LCRA, with assistance from HEC, recently applied the CWMS with HEC-ResSim, HEC-HMS, and HEC-RAS in flood control studies of the Colorado River Highland Lakes system in Texas.

RiverWare Modeling System

The U.S. Bureau of Reclamation (USBR) and Tennessee Valley Authority (TVA) jointly sponsored development of the RiverWare (Reservoir and River Operation) model at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) of the University of Colorado. RiverWare development efforts date back to the mid-1990's, and its predecessors discussed in Chapter 6 date back to the mid-1980's. The modeling system continues to be improved and expanded.

RiverWare provides the basic hydrologic capabilities associated with routing streamflow inflows through a river/reservoir system. Watershed runoff at pertinent river system nodes is provided as input. The primary processes modeled are volume balances at reservoirs, hydrologic routing in river reaches, evaporation and other losses, diversions, and return flows. Features are also provided for modeling groundwater interactions, water quality, and electric power economics. Any number of reservoirs and stream reaches can be modeled.

RiverWare™ is a proprietary software product. Information regarding obtaining the software, documentation, and training is available at the CADSWES web site listed in Table 6.1. License fees in 2004 for a single node are $6,500 for the first year with a $2,500 annual renewal fee. The single node license limits use of the software to one computer. A floating license allowing up to five concurrent sessions running on different nodes of a network has a fee of $11,500 for the first year with a $5,000 annual renewal. The modeling system is described by several papers (Zagona *et al.* 2001 and 2002; Eschenbach *et al.* 2001; and others), a technical manual entitled *Simulation Objects* (CADSWES 2003), and training manuals distributed at short courses. CADSWES provides user support for an hourly fee, offers short courses on applying the model, and organizes annual RiverWare users meetings.

Software Environment for Model Building

RiverWare is an object-oriented software system coded in C++. The software was originally developed to run on a Sun Solaris (Unix) workstation with Solaris 2.9 or higher operating system. Recent versions are also available for personal computers with a Windows NT/2000/XP operating system.

RiverWare provides the model-user with a kit of software tools for constructing a model for a particular reservoir/river system and then running the model. The model-building tool kit includes a library of modeling algorithms, several solvers, and a language for coding operating policies. The tools are applied within a point-and-click graphical user interface.

The centerpiece of the model construction kit is a palette of object icons representing features of a river basin. The objects are listed in Table 7.2. Each object models one or more basic physical processes that are modeled similarly for all instances of an object type. Objects have slots, which contain variables and parameters associated with the physical process models. The model-user selects objects by dragging icons from the palette to the workspace. The model-user then customizes each object by naming it, selecting computational options, and adding data. The objects are linked to form the river system topology.

Table 7.2 RiverWare Objects

Object Type	Processes Modeled
storage reservoir	mass balance, evaporation, bank storage, spill, water quality
level power reservoir	storage reservoir plus hydropower, energy, tailwater, operating head
sloped power reservoir	level power reservoir plus wedge storage for long reservoirs
pumped storage reservoir	level power reservoir plus pumped inflow from another reservoir
reach	routing in a river reach, diversion and return flows
aggregate reach	many reach objects aggregated to save space on the workspace
confluence	brings together two inflows to a single outflow as in a river confluence
canal	bi-directional flow in a canal between two reservoirs
diversion	diversion structure with gravity or pumped diversion
water user	depletion and return flow from a user of water
aggregate water user	multiple water users supplied by a diversion from a reach or reservoir
groundwater storage	stores water from return flows
river gage	specified flows imposed at a river node
thermal object	economics of thermal power system and value of hydropower
data object	user-specified data for policy statements and post-processing
bifurcation	flow junction with single inflow and two outflows
inline power	run-of-river power production
control point	object used to regulate upstream reservoirs based on channel capacity

Input data may be typed manually through the graphical user interface, entered by loading data files, or entered through the data management interface, which allows retrieving large datasets through an external program. Various options are available for tabular and graphical displays of the model results. Output consists of time series associated with the various objects, such as reservoir and reach outflows and reservoir storages, elevations, and other water accounting data. Water quality data may also be output.

Hydrology

The user-selected time step may range from an hour to a year. The hydrologic period-of-analysis may range from a single event to a long continuous record of any length. Inflows at pertinent locations may be entered as input. Alternatively, gaged streamflows and reservoir storage contents may be used to compute the inflows. Reservoir surface evaporation and precipitation rates are also provided as input.

Hydrologic streamflow routing methods include lag, variable time lag, storage, and Muskingum. Hydraulic routing methods include kinematic, Muskingum Cunge, and MacCormick. Bank storage and other gains and losses may be included in routing flows through a river system.

Reservoir/River System Operations

Computational algorithms for modeling reservoir/river system operations are based on three alternative approaches:

1. pure simulation
2. rule-based simulation
3. optimization combining linear programming with preemptive goal programming

Reservoir/river system operating policies are handled differently with each of the alternative solution methods. Water ownership accounting and water quality computations may be coupled with the simulation and rule-based approaches. Operational rules drive the solution for the rule-based simulation and optimization approaches.

Pure simulation solves a uniquely and completely specified problem. Each object must have enough information but not more information than is required. Each object has a number of dispatch methods that map the input/output configuration specified by the user to the correct solution algorithm. Objects may obtain information from user inputs or from other objects through link propagation. The methods associated with an object may also set required values. Based upon the data provided, the appropriate dispatch method is executed and solution computations are performed. Solution results propagate to other objects as appropriate. Multiple links may necessitate iterative solutions. Conflicting information results in an error state and termination of the simulation. Not enough information results in parts of the model being left unsolved.

In rule-based simulation, there is not enough information associated with the objects to obtain a solution. The additional information required is generated by prioritized policy statements (rules) that are specified by the user and interpreted by the rule processor. Slot values for the objects are set based on these rules and the state of the system. The rules are if-then constructs that examine the state of the system as functions of values of slots on the objects in the if-clause. Values are then set depending on that state. The rules are formulated by the model-user in the RiverWare rule language and entered through the graphical editor. The rule language is designed to provide flexibility in expressing reservoir/river system operating rules.

Optimization is the third alternative solution approach. A linear programming (LP) solver is combined with preemptive goal programming. The optimization constraint editor and expression language in RiverWare are designed to allow the model-user to provide required input information without necessarily having to be proficient in linear programming. Objectives and constraints are expressed in terms of physical variables such as pool elevation, flows, or spills or in terms of economic variables such as net replacement cost, future value of used energy, spill cost, and the cost of alternative power sources. The standard LP formulation defined by Equations 4.3 – 4.8 in Chapter 4 is limited to a single objective function. As discussed in Chapter 4, preemptive goal programming is a methodology for incorporating consideration of multiple objectives in a LP model.

RiverWare accesses the CPLEX mathematical programming subroutine library. CPLEX is a proprietary commercially available software product providing computationally efficient linear and nonlinear programming solution routines (http://www.ilog.com/products/cplex/). RiverWare converts user-supplied input to the required LP format with a linear objective function and set of linear constraints and activates CPLEX routines to solve the resulting LP problem.

Preemptive goal programming considers multiple prioritized objectives based on multiple LP solutions. As additional goals are considered, the optimal solution of a higher priority goal is not sacrificed in order to optimize a lower priority goal. In the RiverWare preemptive goal programming procedure, the model assigns a satisfaction variable for each goal or priority level. For each goal, the satisfaction variable is maximized while requiring that all higher priority satisfaction levels be maintained. The maintenance of satisfaction levels is treated as constraints along with all of the other constraints in the model (Eschenbach *et al.* 2001).

Goals are specified by the model-user in RiverWare through an expression editor in the interactive graphical user interface. Each goal can be either a simple objective or a set of constraints that is transformed to an objective to minimize the deviations from the constraints. The goals/constraints specify limitations on the values of various slots (variables) on the objects. The objects reformulate the goals/constraints to be linear expressions of the basic decision variables. Convex nonlinear functions are approximated using piecewise linear functions or by other user-specified optional methods.

Applications

The TVA applies RiverWare in optimizing the daily and hourly operation of the TVA system of multiple-purpose reservoirs and hydroelectric power plants (Biddle 2001; Eschenbach *et al.* 2001; Magee and Goranflo 2002). The USBR uses RiverWare as a long-term planning model and mid-term operations model of the Colorado River as well as a daily operations model for both the Upper and Lower Colorado Regions (Wheeler *et al.* 2002). The Bureau has also applied the model in the Rio Grande, Yakima, and Truckee River Basins. The Lower Colorado River Authority (LCRA) has applied RiverWare in daily time step modeling of water supply operations of the six LCRA reservoirs on the Colorado River of Texas (Brown *et al*. 2004). Other entities have applied the model in various other river basins.

RiverWare was applied to the TVA system by a group of TVA modelers and operators and CADSWES researchers concurrently with development of the generalized RiverWare software (Biddle 2001; Eschenbach 2001). RiverWare optimization capabilities were used to implement a model for scheduling reservoir releases and hydroelectric power generation considering the electric power economics of the hydroelectric power system and other multiple-purpose reservoir system operating requirements related to flood control, navigation, recreation, and water quality. These requirements are defined in RiverWare as prioritized constraints. Hydropower operations are optimized by maximizing the combined value of energy generated during the forecast period and water reserved in storage for future generation.

The RiverWare model of the TVA system is typically run using 6-hour time steps for a forecast period of one week. The optimization can be run several times per day as forecasts of power demands or operational constraints change. The model provides economic information regarding the tradeoffs between using water in the near term versus saving it for future use.

The model includes 35 reservoir objects representing the 35 reservoirs and 35 hydropower plants in the system. The reservoir objects are linked to form the topology of the system, which also includes stream reaches, canals, and confluences. Links allow information to be propagated from one object to another. For example, reservoir outflow may contribute to the inflow to a stream reach. Each reservoir object includes data characterizing the reservoir and hydropower plant, such as operating guide curves and required minimum flows as well as physical characteristics. The resulting linear programming formulation has about 49,300 decision variables and 15,500 constraints. A typical list of TVA-prioritized goals to be modeled in the preemptive goal programming procedure is provided in Table 7.3 (Eschenbach *et al.* 2001).

Table 7.3 Prioritized Goals for a Typical TVA Summer Model Run

Priority	Goal
1	Pool elevation is less than top of gates.
2	Discharge is less than channel capacity.
3	Pool elevation is less than flood guide or top of operating zone.
4	No spill.
5	Discharge is greater than minimum flow requirements.
6	Pool elevation is greater than minimum operating guide or bottom of operating zone.
7	Canal slope is less than upper limit.
8	Discharge change is less than ramp rates.
9	Special operations: Discharge, elevation, or power generation is less than or greater than an upper bound.
10	Maximize avoided power costs.

Initial applications of RiverWare by the Bureau of Reclamation include modeling of the Colorado River System (Zagona *et al.* 2001; Fulp and Harkins 2001;Wheeler *et al.* 2002). Water allocation and reservoir operations in the Colorado River Basin are governed by a collection of international treaties, interstate compacts, court decisions, state and federal statutes, agreements, and operating criteria that are known collectively as the *Law of the River*. Lake Mead impounded by Hoover Dam and Lake Powell impounded Glen Canyon Dam on the Colorado River have the largest and second largest storage capacities of any reservoir in the United States. The long pre-RiverWare history of modeling the Colorado River system include different spatial configurations, time steps, and analysis periods for different types of applications.

System operations have been modeled with RiverWare using a monthly time step and many decade hydrologic simulation period in a planning model that encompasses the Colorado River and nine major tributaries. Eight reservoirs (Flaming Gorge, Blue Mesa, Morrow Point, Crystal, Powell, Mead, Mohave, Havasu) are each modeled as level power reservoir objects. Four storage reservoir objects are used to model eight other reservoirs. Water quality modeling capabilities are used to simulate dissolved solids concentrations. A total of 50 operating policy-based rules and 120 functions were developed by USBR engineers in RiverWare's rule language to match the rules contained in the old Colorado River Simulation System (CRSS) model described in Chapter 5. The operating rules include meeting water use targets, storage targets, and flood control criteria, and equalizing storage between reservoirs.

MODSIM Modeling System

MODSIM is a general-purpose reservoir/river system simulation model based on network flow programming designed for analyzing physical, hydrologic, and institutional/administrative aspects of river basin management. Initial model development at Colorado State University dates back to the 1970's (Labadie *et al.* 1984). Since 1992, the U.S. Bureau of Reclamation Pacific Northwest Region has sponsored continued model improvement efforts at Colorado State University (Labadie *et al.* 2000). The software and documentation may be downloaded free-of-charge from the web site listed in Table 7.1.

MODSIM provides a general framework for modeling. The modeling system is designed to support long-term planning (monthly time step), medium-term management (weekly time step), and short-term operations (daily time step). Water is allocated based on user-specified priorities. The user assigns relative priorities for meeting diversion, instream flow, hydroelectric power, and storage targets, as well as lower and upper bounds on flows and storages. The model computes values for all flows and storages. Optional capabilities are also provided for analyzing water quality (Labadie *et al.* 1994; Dai and Labadie 2001) and conjunctive use of surface and ground water (Fredericks *et al.* 1998). A network flow programming problem is solved for each individual time interval. Thus, release decisions are not affected by future inflows and future release decisions. The out-of-kilter algorithm for solving the network flow programming formulation incorporated in early versions of MODSIM was later replaced with a more efficient algorithm based on a Lagrangean relaxation strategy.

Software Environment for Model Building

MODSIM is coded in C and C++ and is implemented on both UNIX-based workstations operating under X-Window and microcomputers with MS Windows based operating systems. A graphical user interface allows the model-user to build the river/reservoir system topology by clicking and dragging icons. Data structures embodied in each model object are controlled by a data management system that is queried by simple mouse activation. Formatted data files are prepared interactively and the network flow optimization is automatically executed from the user interface. Simulation results are presented as graphical plots or as customized reports available through a scripting language included with the software system. River basin maps may be imported in both vector and raster formats in a separate Window for integration with GIS. MOSIAC style help features and on-line user documentation is provided.

The model-user defines a river/reservoir system as a network of nodes connected by links. Nodes are created in the graphical user interface by clicking the appropriate button on a tool bar and then placing the icon on the canvas. Clicking a node accesses a pop-up spreadsheet for entering data associated with the node. The three types of nodes are (1) non-storage nodes, (2) demand nodes, and (3) reservoir nodes. Non-storage nodes represent points of interest such as river gages, diversion dams, tributary confluences, and sites where return flows enter the river. Demand nodes represent locations of either consumptive diversions or instream flow requirements. Reservoirs, hydropower plants, and appurtenant structures are located at reservoir nodes. A few of the many types of links are artificial, general flow, natural flow, storage ownership, and accrual. Various constructs are provided for modeling complex water allocation schemes.

A model of a particular system consists of the generic MODSIM executable code and a data set created by the model-user through the GUI. The data is stored in a ASCII data file that is command-value oriented with each line of the input starting with a command that the input parsing code associates with a model construct. Data values relevant to the modeled feature follow the command. The input file includes all information about the physical features of the river system and the time series data for the period of record simulated. The GUI includes space delimited data file import capability to facilitate loading large amounts of data. An optional input feature also allows the model-user to specify system constraints through a GUI editor using the Perl programming language.

Hydrology

Sequences of stream inflows and reservoir evaporation rates are provided as input. A monthly, weekly, or daily time step may be used. Streamflow routing using a lag methodology is used with the daily time step. Calibration capabilities are provided for computing local streamflow gains and lag parameters.

MODSIM has a simplified groundwater component and has also been linked with the U.S. Geological Survey MODFLOW groundwater model in studies of conjunctive stream-aquifer management (Fredericks et al. 1998). MODSIM has limited water quality modeling capabilities and has also been linked with the U.S. Environmental Protection Agency QUAL2E streamflow water quality model (Dai and Labadie 2001).

Reservoir/River System Operations

MODSIM is designed to simulate complex water management and allocation systems based on network flow programming. A river/reservoir systems is defined as a network of nodes and links modeled by Equations 4.14, 4.15, and 4.16. The objective function consists of the summation over all links in the network of the flow in each link multiplied by a priority or cost coefficient. The objective function coefficients are factors entered by the model-user to specify relatively priorities that govern operating decisions. The coefficients could be unit costs in dollars or more typically numbers without physical significance other than simply reflecting relative operational priorities. The constraints include equations that preserve the volume balance at each node of the network and various capacities. The optimization algorithm minimizes the objective function while meeting all constraints for a single time step. The computations are repeated iteratively at each time step to deal with nonlinear aspects of the model such as evaporation and hydropower computations. The entire process is repeated sequentially for each time step.

Operational parameters are specified by the model-user in data fields entered into spread-sheet-like tables associated with the nodes and links. Datasets defining networks can be created to simulate operations of a particular river/reservoir in various ways. A relatively simple approach consists of connecting local gain nodes, reservoirs, and demands in a serial on-stream manner with each demand and reservoir node assigned a relative priority number. Nodes with numerically lower priority numbers are satisfied before nodes with higher priority numbers. In this type of network, reservoir content targets directly compete with demands. Links between nodes can be assigned upper bounds to constrain the distribution of flow.

Another approach for simulating water rights consists of placing the demands and reservoirs off-stream and connecting these nodes to the river with links that represent natural or storage rights. Each link that represents a flow right has a priority date that is translated to a relative priority number. Each water right link can have a maximum flow rate (upper bound) and optionally a seasonal capacity or maximum annual volume. Storage contract arrangements are also represented by links from the river to the demand, and data is entered which specify the amount of the contract and the particular reservoir account with which the contract is associated.

A network problem is defined for solution in either a calibration or management mode. In the calibration mode, reservoir targets and demands are input for each time step of the simulation. This mode of simulation is convenient for computing local gains to the river system based on observed river flows, diversions, and reservoir contents. Trial and error simulations are performed to determine routing coefficients, return flow parameters, evaporation, seepage rates, and other parameters, which result in local gains and total flow hydrographs that compare well with observed records. In the management mode, these calibrated parameters and the hydrologic state (wet, average, dry) are defined and the model is used to simulate alternative scenarios.

Applications

MODSIM has been applied in studies of a number of reservoir/river systems in Colorado and throughout the world by university researchers at Colorado State University in collaboration with various local, regional, and international water management agencies. The Bureau of Reclamation has sponsored model improvements and applications in several river basins in the western U.S. Publications describing applications of MODSIM include those reporting studies of the Poudre River System by Labadie *et al.* (1986), Rio Grande Basin by Graham *et al.* (1986), Upper Colorado River System by Law and Brown (1989), Lower South Platte River Basin by Fredericks *et al.* (1998), Piracicaba River in Brazil by Azevedo *et al.* (2000), Snake River Basin by Frevert *et al.* (1994) and the U.S. Bureau of Reclamation Pacific Northwest Region (2000), and Klamath River System by Flug and Campbell (2005). These studies were performed by researchers at Colorado State University in collaboration with sponsoring water management agencies.

USBR Pacific Northwest Region (2000) illustrate MODSIM capabilities through an application to the Upper Snake River Basin in Idaho and Wyoming and the Boise and Payette River Basins in Idaho, which are sub-basins of the Snake River Basin. The Bureau of Reclamation and Idaho Department of Water Resources had been modeling these reservoir/river systems for many years prior to adopting MODSIM. Data from the older models were used as input to MODSIM, and simulation results were compared between MODSIM and the older models.

A 1928-1989 period-of-analysis and monthly time step were used. Historical recorded water use and storage contents were used with various adjustments to determine local streamflow gains representing a 1990 level of basin development and irrigation practices. The hydrologic state index (dry to wet range) feature of MODSIM was adopted to set storage and demand targets as a function of hydrologic state. Exchange limit, storage contract, group ownership, rental pool, and minimum flow features of MODSIM were used in modeling water rights. Most of the reservoirs were modeled as nonchild reservoirs. Three reservoirs (Palisades, Walcott, Anderson Ranch) were modeled as parent reservoirs each having normal active storage space simulated as child reservoirs.

WRAP Modeling System

Development of the Water Rights Analysis Package (WRAP) at Texas A&M University began in the mid-1980's sponsored by a federal/state cooperative university research program administered by the U.S. Geological Survey (USGS) and Texas Water Resources Institute (TWRI). The generalized simulation model was greatly expanded during 1997-2002 under the sponsorship of the Texas Commission on Environmental Quality (TCEQ) in conjunction with implementation of the Texas Water Availability Modeling (WAM) System (Wurbs 2005). The USACE Fort Worth District has also sponsored continued improvements to the model since 2001. The public domain software and documentation (Wurbs 2005) may be downloaded from the website listed in Table 7.1.

WRAP simulates management of the water resources of a river basin or multiple-basin region under a priority-based water allocation system. Basinwide interactions among numerous water uses and diverse water management facilities and practices may be modeled. The original model implemented in the Texas WAM System is designed for long-term monthly time step modeling assessments of hydrologic and institutional water availability and reliability for water supply diversions, environmental instream flow requirements, hydroelectric energy generation, and reservoir storage (Wurbs 2005). An expanded version currently being developed incorporates capabilities for conditional reliability modeling, daily or other sub-monthly time steps, flood control operations, and salinity simulation (Wurbs, et al. 2005). Simulation modes include (1) a single long-term simulation, (2) automatic repetition of the simulation with adjustments to specified targets to develop a yield-reliability table that ends with the firm yield, and (3) conditional reliability modeling based on many short-term simulations starting with the same initial storage condition.

Software Environment for Model Building

WRAP is a set of Fortran programs. Program SIM performs the river/reservoir system water allocation simulation using a monthly time step. SIMD is a recently expanded version of SIM with sub-monthly time step and flood control simulation features. HYD is a set of computational routines for converting gaged streamflows to naturalized flows and compiling sets of net reservoir evaporation less precipitation depths. HYD output consists of monthly hydrology input datasets for SIM. DAY has routines for synthesizing daily or other sub-monthly time interval flows from monthly flows and determining routing parameters. DAY output is input for SIMD. SALT reads a SIM output file and salinity input file and tracks salinity through a river/reservoir system. Program TABLES organizes the SIM, SIMD, and SALT simulation results and develops frequency relationships, reliability indices, and summary statistics. TABLES organizes simulation results into a variety of user defined tables and also provides tabulations for easy export to Microsoft Excel or HECDSSVue.

WinWRAP is an interface for executing the programs on microcomputers within Microsoft Windows. WinWRAP provides the model-user a convenient environment in which to manage data files, WRAP programs, and Microsoft programs. WinWRAP connects WRAP executable programs with each other and with pertinent data files for a particular reservoir/river system. WRAP programs produce data files read by other WRAP programs as instructed by

WinWRAP. WRAP has no editing or graphics capabilities. Input data files are typically created and edited with Microsoft Excel, WordPad, NotePad, or Word. The model-user can create and edit input files and read and manipulate simulation results from WinWRAP using his choice of Microsoft program or any other editor. Simulation results may be manipulated or plotted with HECDSSVue or Excel. ArcGIS has also been applied with WRAP to develop input data and display simulation results, but the connections are through data files without special software interfaces.

Hydrology

River basin hydrology is represented by sequences of monthly naturalized streamflows and reservoir net evaporation less precipitation depths at all pertinent locations for each sequential month of a hydrologic period-of-analysis. A set of computational routines facilitate developing sets of naturalized monthly flows by adjusting gaged flows to remove the historical effects of water resources development and use. Routines are also provided for developing sequences of net evaporation rates. Naturalized flows are distributed from primary control points to all other sites based on watershed parameters. Several optional methods are provided for distributing flows from gaged to ungaged sites. Most applications have used either drainage area ratios or an option based on the Natural Resource Conservation Service relationship between precipitation depth and runoff volume. Channel losses are incorporated in various aspects of a simulation including distribution of flows from gaged to ungaged sites.

WRAP was original developed for applications using a monthly time step. An expanded version of the model under development also allows any sub-monthly time interval with a default of daily. Naturalized flows may be input with a daily or any other time step of less than a month. However, since the TCEQ WAM System includes an extensive database of monthly flows for all the river basins of Texas, capabilities are included in the recent version of WRAP to synthesis daily (sub-monthly) flows from monthly flows. An adaptation of the Muskingum method is used for routing. Capabilities are provided for calibrating routing parameters.

Reservoir/River System Operations

In WRAP terminology, a water right is a set of water use requirements, reservoir storage and conveyance facilities, operating rules, and institutional arrangements for managing water resources. The model is an accounting system for tracking streamflow sequences, subject to reservoir storage capacities and diversion, hydropower, and instream flow targets. Streamflow and reservoir storage is allocated among users based on specified priorities, which can be defined in various ways. Diversion, instream flow, and hydropower targets may be specified as functions of reservoir storage contents or streamflows. Reservoir operations for flood control are based on emptying flood control pools expediently subject to not making releases that contribute to flows at downstream control points exceeded specified maximum allowable operations. Essentially any stream tributary configuration with interbasin and intrabasin conveyance can be modeled. Multiple-reservoir multiple-owner multiple-purpose system operations with off-channel storage as well as major reservoirs and conveyance facilities may be simulated. Flexibility is provided for modeling the various rules specified in water rights permits and/or other institutional arrangements governing water allocation and management.

WRAP is used to assess capabilities for satisfying water supply, hydropower, instream flow, and reservoir storage targets. Simulation results may be organized in various formats including entire time sequences of the various variables included in the simulation results, annual and period-of-analysis summaries, water budgets over various periods, reliability indices, various types of frequency relationships. Concise measures of water availability/reliability useful in analyzing and displaying simulation results include: period and volume reliabilities in meeting targets, period reliabilities associated with exceeding specified percentages of the targets, naturalized, regulated, and unappropriated flow-frequency, reservoir storage-frequency, reservoir drawdown-frequency, and salinity concentration-frequency tables. Peak annual flood flow frequency and storage frequency relationships may also be developed.

In the conventional long-term simulation mode, a specified water management/use scenario is combined with naturalized flows and net reservoir evaporation rates covering the entire hydrologic period-of-analysis in a single simulation. The user specifies the storage content of all reservoirs at the beginning of the simulation, defaulting to full to capacity. An option repeats the simulation setting beginning-of-simulation storages equal to end-of-simulation storages. WRAP also has a yield-reliability analysis feature that iteratively repeats the long-term single simulation multiple times with specified water use targets incremented in each simulation to develop a table of diversion target versus period and volume reliability that ends with the firm (100% reliability) yield.

In the conditional reliability modeling (CRM) mode, reliability and frequency relationships for periods of a month to several months or a year into the future are conditioned upon given preceding reservoir storage contents. The period-of-analysis hydrology is divided into many sequences of a user-specified length. The simulation is automatically repeated with each hydrologic sequence starting with the same specified initial storage condition. Options are provided for assigning probabilities to each hydrologic sequence. The model develops reliability and frequency relationships from the simulation results. The CRM mode supports short-term operational planning studies and real-time management.

Applications

Applications of WRAP by researchers at Texas A&M University date back to the 1980's, but widespread use within the Texas water management community began in 1997 with implementation of the Texas Water Availability Modeling (WAM) System. WRAP is generalized for application anywhere, subject to input files being developed for the river basins of concern. Applications in Texas consist of executing the WRAP model with the WAM System data files altered as appropriate to reflect proposed water management plans of interest, which could involve changes in water use or operating practices, construction of new facilities, or other management strategies.

The Water Availability Modeling (WAM) System developed by the Texas Commission on Environmental Quality (TCEQ), its partner agencies, and contractors pursuant to the 1997 Senate Bill 1 consists of the WRAP model, the 21 sets of WRAP input files listed in Table 1.2 covering the 23 river basins of the state, a GIS, and other supporting databases. The basin number in the first column of Table 7.4 refers to the river basins shown in Figure 7.1.

Table 7.4 Texas WAM System Models

Map ID	River Basin	Period of Analysis	Number of Primary Control Points	Number of Total Control Points	Number of Model Water Rights	Number of Model Reser-voirs	Reservoir Storage Capacity (acre-feet)	Mean Natural Flow (ac-ft/yr)
1	Canadian River Basin	1948-98	12	85	56	47	966,000	190,000
2	Red River Basin	1948-98	50	443	558	240	4,023,000	11,049,000
3	Sulphur River Basin	1940-96	8	83	90	53	753,000	2,498,000
4	Cypress Bayou Basin	1948-98	10	169	151	89	900,000	1,748,000
5	Rio Grande Basin	1940-00	55	957	2,614	113	23,918,000	3,724,000
6	Colorado River Basin and Brazos-Colorado Coastal	1940-98	45	2,263	1,666	503	4,763,000	2,999,000
7	Brazos River and San Jacinto-Brazos Coastal	1940-97	77	3,829	1,7418	663	4,682,000	6,357,000
8	Trinity River Basin	1940-96	40	1,334	1,192	703	7,504,000	6,879,000
9	Neches River Basin	1940-96	20	318	350	176	3,904,000	6,235,000
10	Sabine River Basin	1940-98	27	376	331	207	6,401,000	6,887,000
11	Nueces River Basin	1934-96	41	544	406	122	1,040,000	868,000
12	Guadalupe and San Antonio River Basins	1934-89	46	1,339	1,044	237	808,000	2,101,000
13	Lavaca River Basin	1940-96	7	185	101	22	235,000	943,000
14	San Jacinto River Basin	1940-96	16	410	164	114	637,000	2,207,000
15	Lower Nueces-Rio Grande	1948-98	16	119	76	42	101,700	249,000
16	Upper Nueces-Rio Grande	1948-98	13	78	35	22	102,000	249,000
17	San Antonio-Nueces	1948-98	9	49	14	9	1,480	565,000
18	Lavaca-Guadalupe Coastal	1940-96	2	68	10	-0-	0	134,000
19	Colorado-Lavaca Coastal	1940-96	1	111	31	8	7,230	142,000
20	Trinity-San Jacinto	1940-96	9	83	21	14	4,880	181,000
21	Neches-Trinity Coastal	1940-96	4	245	147	31	58,000	607,000

The WAM datasets listed in Table 7.4 were developed during 1997-2004 by six consulting engineering firms working for the TCEQ as prime contractors with assistance from several other firms serving as subcontractors. Along with compiling the WRAP input datasets, the TCEQ contractors performed simulations for alternative scenarios reflecting combinations of premises regarding water use, return flows, and reservoir sedimentation. The datasets are continually updated by the TCEQ with issuance of new or revised water right permits.

As of April 2005, these datasets contain the 3,415 reservoirs for which a water right permit has been issued. Permits are required to store more than 200 acre-feet. Over 90 percent of the total capacity of the 3,415 reservoirs is contained in the 210 reservoirs that have conservation capacities exceeding 5,000 ac-ft. Modeling is complicated by numerous reservoirs, but most of the storage is contained in a few large reservoirs. Modeling complex operating rules for multiple-reservoir and multiple-owner systems has been a major concern in expanding the WRAP model and implementing the WAM System.

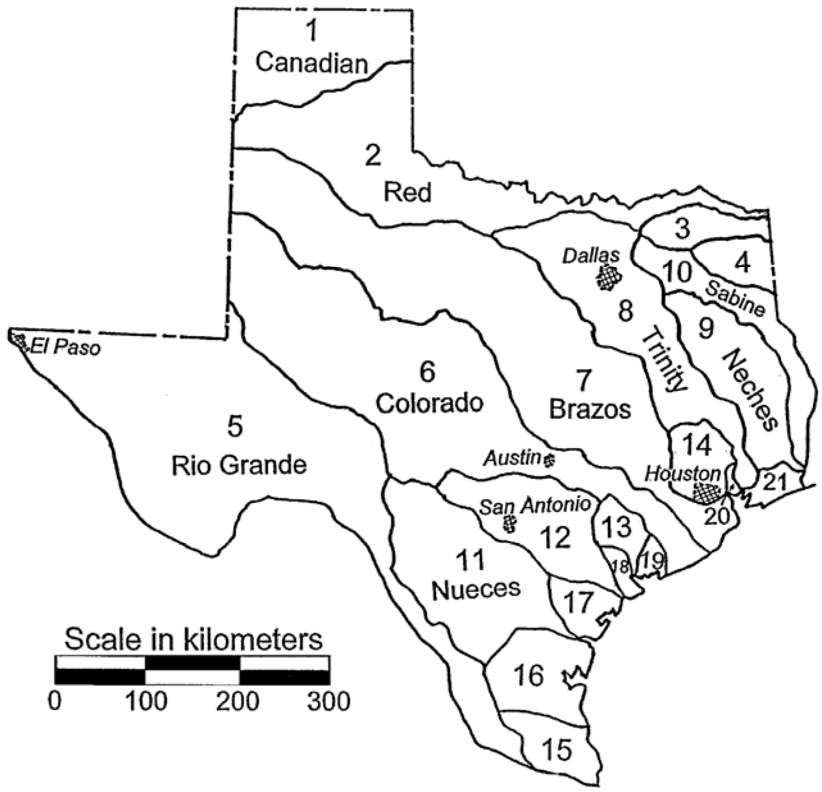

Figure 7.1 Texas WAM System River Basins

Figure 7.2 Major Rivers of Texas

The modeling system is routinely applied by the TCEQ, Texas Water Development Board (TWDB), river authorities, other water management agencies, and consulting firms in preparation and evaluation of water right permit applications, Senate Bill 1 regional planning studies, and various other types of studies. River authorities, other water management agencies, and their consultants have broadened WAM applications to include various types of studies that are not directly mandated by the TCEQ water right permit program or the TWDB Senate Bill 1 planning program described below.

The many regulatory responsibilities of the TCEQ include administering a water rights permit system. Almost 8,000 active permits are in effect, and numerous applications for new permits or changes to existing permits are submitted each year. The 1997 Senate Bill 1 directed that the TCEQ, in conjunction with developing the WAM system, inform all water right permit holders of the reliabilities associated with their permits. Changes in water use or management practices or development of new water projects require TCEQ approval of either new permits or revisions to existing permits. In evaluating permit applications, the TCEQ determines whether sufficient water is available to supply any proposed new use and evaluates the impacts on all other water users in the river basin. TCEQ procedures require that water management entities and their consultants use the WAM System in preparing water right permit applications. TCEQ staff uses the modeling system in evaluating permit applications.

The WAM System is also routinely applied in the regional and statewide planning process established by the 1997 Senate Bill 1. The TWDB administers the process of developing regional water plans that are integrated into a statewide plan. Committees of local water interests have been established to prepare plans for the orderly development, management, and conservation of the water resources of each of 16 regions. The TWDB provides funding, administrative, and technical support to the regional committees. Consulting firms perform much of the technical work. Senate Bill 1 mandated that initial regional plans be completed by 2001 and incorporated into a statewide plan by 2002 (TWDB 2002). Continuing planning is organized based on updated plans being reported at cycles of not to exceed five years. In evaluating water right permit applications, the TCEQ requires that proposed actions must be consistent with regional plans.

Chapter 8
Comparative Evaluation of the Alternative Modeling Systems

The comparative evaluation presented in Chapter 8 builds upon and extends the discussions and comparisons of various aspects of reservoir/river system modeling presented throughout the preceding chapters of this report. The SUPER, ResSim, RiverWare, MODSIM, and WRAP modeling systems described in the preceding Chapter 7 provide a focus for the comparative evaluation. The models described in Chapter 7 and compared in Chapter 8 are listed below in Table 8.1 as well as in Tables 6.2 and 7.1.

Table 8.1 Generalized Systems for Modeling Reservoir/River System Management

Short Name	Descriptive Name	Model Development Organization
SUPER	SWD Reservoir System Model	USACE Southwestern Division
ResSim	Reservoir System Simulation	USACE Hydrologic Engineering Center
RiverWare	River and Reservoir Operations	USBR, TVA, CADSWES
MODSIM	River Basin Network Flow Model	Colorado State University, USBR
WRAP	Water Rights Analysis Package	TAMU/TWRI, TCEQ, USACE FWD

The five alternative models accomplish the same fundamental modeling tasks. The models are all based on volume-balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. A reservoir/river system is modeled as a collection of stations (called nodes or control points) connected by river reaches and perhaps canals and pipelines. Reservoirs, hydropower plants, and water supply diversions and return flows are located at the nodes. A simulation steps through time performing computations sequentially for each time interval. Initial beginning-of-simulation reservoir storage contents and inflows to the river/reservoir system in each time step are provided as input data. The models compute reservoir storage contents and stream flows at pertinent locations for each time internal of the hydrologic period-of-analysis. Each of the five generalized models provides flexible capabilities for simulating complex multiple-purpose, multiple-reservoir system operations.

Although the models are similar in their basic functional mission, each has its own set of modeling strategies and methods and its own terminology or modeling language. The modeling systems are significantly different in their overall organizational structure and the details of their computational algorithms, user interfaces, and data management schemes. The alternative modeling systems are compared in this chapter from the perspectives of their:

1. organizing computational structure
2. modeling environment and user interface features
3. capabilities for various types of applications
4. special modeling features
5. accessibility and documentation
6. institutional dimensions of model evolution

Organizing Computational Structure

The generalized modeling systems are characterized in Table 8.2 based on the organizational structure that serves as the basic foundation and framework for each of the alternative modeling approaches. Each of these different computational strategies provides flexible, computationally-efficient capabilities for modeling complex reservoir/river system operations.

Table 8.2 Structure of the Alternative Modeling Systems

Model	Organizing Computational Structure
SUPER	Ad hoc simulation computations progressing from upstream to downstream.
ResSim	Object-oriented ad hoc simulation progressing from upstream to downstream.
RiverWare	Object-oriented, options for pure and rule-based simulation and optimization.
MODSIM	Object-oriented based on network flow programming.
WRAP	Ad hoc simulation progressing in order of user-defined priorities.

Linear Programming Versus Ad Hoc Algorithms with Alternative Sequencing of Computations

The computational strategies and techniques incorporated in the five modeling systems can be categorized as being based on either:

1. sets of ad hoc algorithms developed specifically for the particular modeling system
2. linear programming (LP) which is incorporated in many models applied in a variety of fields

The computational algorithms in SUPER, ResSim, and WRAP are ad hoc techniques developed specifically for the individual models. RiverWare has two alternative solution options that are based on ad hoc algorithms developed specifically for RiverWare and a third solution option that uses a linear programming (LP) solver. MODSIM is based on network flow programming, which is a computationally efficient form of linear programming. The LP-based models have additional ad hoc computational algorithms used along with their LP solver, but the LP solver accounts for a major portion of the computations. The third column of Table 8.3 indicates whether the model is based solely on ad hoc algorithms or incorporates a LP formulation.

Differences are explored in Chapter 4 between descriptive simulation models that step sequentially through time performing computations for each individual time step without considering the future versus those models that consider all time steps simultaneously. Several optimization models discussed in Chapters 4 and 6 such as the HEC-PRM (Prescriptive Reservoir Model) solve for the decision variables for all time intervals as one solution. Optimization is one of three optional solution approaches in RiverWare. The LP problem is formulated and solved in RiverWare for all time intervals of the period-of-analysis. Thus, decisions reflect complete knowledge of all inflows including future inflows.

Table 8.3 Characteristics of the Alternative Modeling Systems

Model	Language	Method	Time Step	GUI	Graphics	Cost
SUPER	Fortran	ad hoc	day	no	no	free
ResSim	Java	ad hoc	15 minutes to day	yes	yes	free
RiverWare	C++	ad hoc/LP	hour to year	yes	yes	proprietary
MODSIM	C, C++	LP	month, week, day	yes	yes	free
WRAP	Fortran	ad hoc	month, day, any sub-monthly	yes	no	free

With the exception of the RiverWare LP solver optimization option, the five models step sequentially through time with the computations being repeated at each time step. For a given time period, end-of-period reservoir storages, streamflows, diversions, and related variables are computed. With the MODSIM network flow programming model, all variables are computed simultaneously for that time step. With the ad hoc algorithms of SUPER, ResSim, WRAP, and the RiverWare simulation options, the computations progress through sets of water management requirements. SUPER and ResSim generally follow a upstream-to-downstream progression in considering water management requirements for reservoir storage and releases, diversions, and hydropower generation. WRAP computations follow a progression defined by user-specified priorities in considering water management requirements.

SUPER and ResSim computations begin at the upper end of a stream branch and progress in a downstream direction. Computations are performed for all tributaries above a confluence prior to proceeding downstream. Incremental local inflows enter the system at control points. Total flows entering a node consist of computed regulated flows from upstream plus the local incremental flows. Since reservoir releases may depend on requirements at downstream control points, iterative algorithms are built into the computational schemes.

WRAP, like SUPER and ResSim, is a pure simulation model containing no formal mathematical programming algorithm like the LP solvers in RiverWare and MODSIM. However, unlike SUPER and ResSim, WRAP is based on considering water management requirements in priority order. Although WRAP has another option allowing the computations to progress in an upstream-to-down sequence, with the default option normally adopted, the progression of the simulation computations is governed by user-specified priorities. WRAP contains other features for expressing targets as a function of storage levels and flows as well as priorities. WRAP works exclusively with total streamflows, which are checked to determine water availability and adjusted to reflect the basinwide effects as computations are performed for each water right as considered in priority order. WRAP is fundamental different in this regard from the other models that accumulate incremental local flows.

MODSIM is based on network flow programming. The system configuration, system components, and operating rules are expressed in the format of a network of nodes and links. For a given time step, all nodes and links are solved simultaneously by a highly efficient linear programming solver. The objective function coefficients in the network flow LP formulation of MODSIM are expressions of relative priorities.

RiverWare provides three alternative modeling strategies: pure simulation, rule-based simulation, and optimization. Selection between the alternation solution schemes depends on the amount and type of input data provided. Pure simulation solves a completely defined problem that has exactly the required amount of information provided as input. Based upon the data provided, the appropriate dispatch method is executed and solution computations are performed. The objects are interconnected as appropriate, and iterative solutions may be necessary depending on the connections. In rule-based simulation, there is not enough information associated with the objects to obtain a solution. The additional information required is generated by prioritized policy statements (rules), which are specified by the user. Optimization, the third alternative solution approach, combines LP with preemptive goal programming. Multiple objective functions represent different prioritized goals. The LP formulation optimizes individual objectives subject to not adversely impacting higher priority objectives.

The objective function coefficients in the MODSIM network flow formulation and RiverWare LP optimization option and WRAP priorities are somewhat similar but yet distinctly different. The coefficients in the linear objective function of MODSIM simply assign relative priorities to pertinent flow and storage variables. The RiverWare objective function coefficients are also expressions of relative priorities but are designed to be more prescriptive in the context of preemptive goal programming. The prescriptive RiverWare LP formulation solves for all time steps simultaneously. The MODSIM LP formulation solves all variables for a given time step. The priorities in WRAP control the sequential order of the computations.

Repetitive Loops and Iterative Solution Procedures

Repetitive loops and iterative solution procedures are incorporated in all of the models. Computation loops are nested within other computational loops. As computations are repeated for each time step, the end-of-period storage content for a time step becomes the beginning-of-period storage for the next time step. For the LP-based models, all the water management requirements are considered simultaneously. For the simulation models based on ad hoc procedures, computations are repeated for individual sets of water management requirements. With SUPER, ResSim, and the simulation options of RiverWare, iterative solution procedures may be required to capture the interconnections between water management requirements at different locations. For example, reservoir releases from flood control pools depend upon flows at multiple control points located downstream of the reservoirs. Likewise, reservoir releases may be for environmental instream flow or diversion requirements at downstream locations.

Iterative solutions are required for evaporation and hydropower computations in all of the models. Evaporation depends upon end-of-month storage, but end-of-month storage depends upon evaporation. The discharge through a hydropower plant depends upon head, which depends on end-of-month storage, which depends upon the discharge through the hydropower plant. Storage volume versus surface area and elevation relationships are highly nonlinear. In the LP models, the entire LP solution of the whole system is repeated iteratively. With the ad hoc simulation procedures, the computations for an individual reservoir are repeated iteratively.

Further Comparison of LP Versus Ad Hoc Simulation Procedures

The five models are representative of state-of-the-art reservoir/river system modeling capabilities in general. The concept of simulation models with water accounting computations performed by an array of ad hoc algorithms developed specifically for each individual model is quite common. Linear programming is also popular. Network flow programming has been adopted for a number of reservoir/river system models. LP is represented by Equations 4.6, 4.7, and 4.8. Network flow programming is represented by Equations 4.14, 4.15, and 4.16. Network flow problems can be solved by standard LP solution algorithms (Eqs. 4.6-4.7), but the stricter network formulation of Eqs. 4.14-4.16 allows use of more computationally efficient solvers. Network flow models cited in Chapter 6 include the Texas Water Development Board SIMYLD-II, AL-V, SIM-V, and MONITOR-I, California Department of Water Resources DWRSIM, HEC-PRM, and Acres International's ARSP. CALSIM, OASIS, and other models cited in Chapter 6 are based on more general LP formulations that do not fit the strict network flow programming format.

Ad hoc algorithms have the advantage of not being restricted to a particular mathematical format like the linear formulation of LP. The advantages of LP include:

- Already-coded standard solvers are available.
- Models may be more prescriptive with the objective function reflecting economic or other objectives.
- The same general solution framework is common to many different types of problems.

Most models designed for modeling complex water allocation systems reported in the literature are based on network flow programming. The WRAP strategy of determining water availability and adjusting streamflows throughout the river basin as each water right is considered in priority order appears to be somewhat unique. Wurbs and Yerramreddy (1994) describe an investigation in which a network flow version of WRAP, called WRAPNET, was developed for comparison with an earlier version of the conventional WRAP. WRAPNET was based on the same out-of-kilter network flow solver that was incorporated in the several Texas Water Development Board models, California Department of Water Resources DWRSIM, and the original version of MODSIM. The network flow programming WRAPNET and conventional versions of WRAP read the same input files and produced essentially identical results. Both approaches worked fine. The conventional WRAP ran faster. The investigation yielded no clear conclusion on which was the optimal approach. The conventional approach was adopted for further improvements and expansion of WRAP primarily because the developer felt, perhaps correctly or perhaps incorrectly, that the approach provided greater flexibility for expanding the model to incorporate more complex reservoir/system operating rules. However, other investigators such as Chung and Helweg (1985) have demonstrated the flexibility of network flow programming compared to models based solely ad hoc simulation algorithms.

Object-Oriented Versus Procedural Programming

The structured procedural programming approach of Fortran versus the object-oriented programming approach of C++ and Java also affects the organizing computational structure of the reservoir/river system models. The programming language in which a model is coded may be transparent to the user of the executable programs in many respects. However, the structure of computational and data handling procedures may be significantly affected by features of the programming language, and user interfaces may be affected even more.

SUPER and WRAP are coded in Fortran. Fortran programs are organized as structured step-by-step procedures for reading input data from files, performing computations within various repetitive looping algorithms, and writing output to files. Changes to Fortran programs are made by adding and/or revising code. ResSim is coded in Java. RiverWare, and MODSIM are coded in C and C++. The object-oriented programming features are particularly evident in the RiverWare modeling system. Computational methods and data are associated with objects and their slots in an object-oriented environment. Changes to the model may be made by adding or revising objects.

Modeling Environment and Interface Features

A model for a particular reservoir/river system consists of a generalized modeling system such as those listed in Table 8.1 and an input dataset describing the reservoir/river system. The generalized modeling system provides a environment or framework for assembling input data, executing the simulation/optimization computations, and organizing/analyzing/displaying results.

Format of Input and Output

Input data define the configuration of the river/reservoir system; describe the capacities and physical characteristics of reservoirs, hydropower plants, and conveyances facilities; specify water allocation rules and reservoir system operating rules; set water use targets; provide sequences of streamflow inflows and net evaporation rates; and assign values for various parameters. Input data may be entered into the modeling system in the format of:

- files created external to the reservoir/river system model and read as input files
- graphical schematics created within a model's graphical user interface (GUI) by clicking, dragging, and connecting icons
- data entered through a user interface by typing into fields accessed by activating selections from menus associated with objects or other interface features
- operating rules written in a scripting language provided by the user interface in the form of if-then statements and other logic statements

Model output is typically displayed as tables and time series plots and sometimes in a spatial format through a GIS. Graphical displays may be produced by the generalized reservoir/river system model or by other auxiliary graphics software. Model output consists of:

* time series of reservoir storages and releases, unregulated and regulated streamflows, water supply diversions and return flows, hydroelectric energy produced, shortages in meeting diversion and energy targets, and other variables
* water budgets and various other summaries

* reliability indices for water supply diversion and hydropower generation targets
* statistics and frequency relationships for flows, storages, and other variables
* results from special model features such as economic or water quality analyses

User Interfaces

The user interfaces of the alternative models reflect both similarities and significant differences. ResSim, RiverWare, and MODSIM provide sophisticated graphical user interfaces (GUI's) with menu-driven editors for entering and editing input data and displaying simulation results in tables and graphs. WRAP has a simple GUI for managing programs and files, but relies upon standard Microsoft Office programs for entering, editing, and displaying data. All of the models provide options for reading input data from files created external to the model.

ResSim, RiverWare, and MODSIM have a GUI feature that allows a schematic of the river/reservoir system to be created by selecting and connecting icons. Object-oriented programming allows information to be assigned to the objects represented by the icons in the system schematic. Menu-controlled tables for entering and editing data are activated by clicking the objects. The GUI's also provide convenient features for displaying modeling results. These types of GUI features became very popular during the 1990's in water resources engineering as well as in the modeling world in general.

Another option in some models is provision of a simple programming language to allow users to express reservoir/river system operating requirements as a series of statements with if-then-else and similar constructs. RiverWare has its own simulation rule language. A similar scripting feature is being added to ResSim to allow coding of operating rules. MODSIM allows the user to specify constraints using the Perl programming language. Perl (Practical Extraction and Report Language) is a widely used language that originated in the 1980's. Similarly, the OASIS reservoir/river system described in Chapter 6 has an operations control language (OCL) developed and patented by HydroLogics, Inc. The California Department of Water Resources WRIMS/CALSIM model includes a new water resources simulation language that allows reservoir/river system operating goals and constraints to be written as a series of if-then-else statements.

Model development efforts in water resources engineering like other sectors over the last 15 years have emphasized improvements in graphical user interfaces. GUI's have captivated the attention of both developers and users of models. Model documentation in recent years often seems to be focused more on GUI menus and icons than on the physical processes being modeled, governing equations, data compilation, solution methods, and interpretation of model results. Continuing advances in computer technology should result in easier programming of GUI's and more uniformity in GUI's that minimize familiarization time for the user. This hopefully should allow a shifting of emphasis to other important aspects of modeling.

Various features of GUI's are effective in different situations in making models more convenient to apply. The author is biased toward simplicity over sophistication. In comparing legacy models without GUI's to newer versions with GUI's, it seems to the author that, contrary to popular opinion, many of the most popular GUI features have not necessarily made modeling significantly easier. The HEC-1/HEC-HMS watershed hydrology models, HEC-2/HEC-RAS river hydraulics models, and KYPIPE and EPANET water distribution system models have been used extensively in several undergraduate, graduate, and continuing education courses taught by the author over the past 20 years as GUI's were added to the models. Versions of the models both without GUI's (HEC-1, HEC-2, early KYPIPE) and with GUI's (HEC-HMS, HEC-RAS, EPANET, later KYPIPE versions) have been readily applied by students, without pronounced advantages of the GUI versions becoming apparent to their instructor.

The effectiveness of hydrologic, hydraulic, and water management models have been greatly enhanced by data management and analysis software such HEC-DSSVue, ArcGIS, and Microsoft Excel. These auxiliary programs are widely and beneficially applied. The extent to which graphics and other data management capabilities are incorporated into the GUI of a water resources simulation model versus being accomplished by separate programs is a key issue.

Software Interfaces

Reservoir/river system management models are applied with two other categories of software.

1. data management and analysis programs
2. watershed hydrology, river hydraulics, and water quality simulation models

The extent to which software products are integrated/merged versus being maintained as separate modeling system components connected through transfer of data files is subject to continuing investigation.

ResSim has features for connecting with databases and other HEC programs through the HEC-DSS Data Storage System and is designed to serve as a component of the Corps Water Management System (CWMS). ResSim and SUPER are routinely used in combination with watershed hydrology and stream hydraulics models to simulate flood control operations. MODSIM has been connected to the MODFLOW groundwater model and QUAL2E stream water quality model. WRAP is routinely used with Microsoft Excel. HEC-DSSVue and ArcGIS are used with ResSim, RiverWare, MODSIM, and WRAP to compile input data and display simulation results. The models have various features to facilitate convenient connections to other software.

Computer Systems

RiverWare was originally designed to run on a Sun Solaris (Unix) workstation with Solaris 2.9 or higher operating system. Recent versions of RiverWare are also available for desktop computers operating under Windows NT/2000/XP. Memory requirements and run times may be significant in RiverWare applications.

ResSim and MODSIM are also executed on both Microsoft Windows based desktop computers and workstations. ResSim has been run on Unix workstations with the Sun Solaris 2.8 operating system. MODSIM has been run on Unix workstations under X-Windows.

SUPER and WRAP consist of sets of Fortran programs that have been compiled and executed on various computer systems. Development and application of WRAP during the past ten years have been exclusively on desktop computers. The WinWRAP interface is used to connect and manage WRAP executables and data files within Microsoft Windows.

Alternative Frameworks for Model Building

Each of the five modeling systems has its own unique framework within which the user constructs and implements a model for a particular reservoir/river system. SUPER is a set of Fortran programs requiring creation of certain data files in a specified format. With ResSim, the various elements provided by the watershed setup, reservoir network, and simulation modules are used to construct and execute a model. RiverWare has an object/slot-based environment for building models within the context of object oriented programming and provides three optional simulation/optimization solution options. MODSIM is based on network flow programming with a reservoir/river system represented by a network of nodes and links with information compiled through an object-oriented interface. WRAP is about managing programs, files, input records, and results tables, with water management and use practices being described in the terminology of water rights.

This report could be written in English, Spanish, French, Russian, or Mandarin Chinese. Each of these languages probably has certain relative advantages and disadvantages for writing technical reports, though the author has no idea what these might be. The report is written in English because the intended audience understands English and this is the only language the author knows. Likewise, the modeling environments of SUPER, ResSim, RiverWare, MODSIM, and WRAP provide languages with which the user writes a reservoir/river system model. The communication techniques reflected in these languages have some similarities but still are distinctly different. There are certainly real advantages and disadvantages of each language compared to the others. However, personal preferences and familiarity are naturally key factors in selecting a generalized modeling system for a particular application. Unlike the English language and Microsoft Office software, none of the reservoir/river system modeling languages has established a clearly dominant community of subscribers. The modeling systems all have significant communities of subscribers, but none is clearly dominant.

Modeling Capabilities for Various Types of Applications

Modeling applications have grown in complexity. Twenty-five years ago, reservoir simulation studies were most often performed in conjunction with feasibility investigations for construction of new reservoir projects. Typical analyses of conservation storage capacity consisted of determining the firm yield for a single reservoir and performing a period-of-record simulation with a diversion set equal to the firm yield. Flood control studies by the USACE included routing of historical floods and synthetic design storms through reservoir/river systems and estimating expected annual damages. Applications today involve comprehensive detailed modeling of the operations of existing multiple-reservoir systems with complex water allocation and management practices. Typical applications of reservoir/river system models include:

- long-term planning studies focusing on conservation storage operations based on a monthly time step and period-of-analysis of many years

- planning studies focusing on flood control operations based on a hourly to daily time step and multiple discrete historical or synthetic flood events
- operational planning studies focusing on a period-of-analysis of a month to a year following a present or given storage condition
- real-time decision support for reservoir system operations during floods
- decision support for water management during actual droughts
- decision support during the full spectrum of hydrologic conditions for real-time hydroelectric power operations or multipurpose reservoir system operations with hydropower as a major focus

Reservoir system operating rules are different for flood control, water supply, hydroelectric power, navigation, recreation, and environmental management. Computational algorithms and data requirements are also different. Differences are significant between the various conservation storage purposes such as agricultural, municipal, and industrial water supply, hydroelectric power, navigation, recreation, and environmental management. Differences between flood control and conservation purposes are particularly significant.

Each of the five models simulates multiple-purpose reservoir system operations that include both flood control and all of the conservation storage purposes. However, flood control has been a particularly major concern in the development and application by the Corps of Engineers of the SUPER and ResSim models. SUPER and ResSim provide flexible capabilities for detailed simulation of flood control operations. Development and application of RiverWare, MODSIM, and WRAP have been oriented toward comprehensive modeling of the details of complex systems operated for conservation purposes. MODSIM and WRAP provide comprehensive capabilities for detailed simulation of complex water allocation systems. The USACE Fort Worth District recently sponsored work by CADSWES in adding objects to RiverWare for flood control operations. WRAP has also been recently expanded to include capabilities for simulating flood control operations.

The time interval shown in the fourth column of Table 8.3 provides an indication of the types of applications that motivated model development. 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 a computational time step in the range of a hour to a day. Hydrologic and perhaps hydraulic routing methods for modeling flood wave attenuation effects are important. Conservation storage reservoirs supply water during dry seasons with durations of several months and during extreme droughts with durations of several years. Evaporation is important. Different types of applications of modeling reservoir/river system operations for conservation purposes are defined largely by the selection of a daily, weekly, or monthly time step. A monthly interval is typically adopted for long-term planning studies. A daily or weekly may be used for short-term operational planning studies. Real-time decision support for hydroelectric power operations is typically based on a time step ranging from a hour to a day.

Streamflow routing is required to capture lag and attenuation effects for short time steps such as daily but is not required for a monthly time step. Flows completely pass through typical river reaches in much less time than a month. Hydrologic routing is typically adopted for reservoir/river system modeling with a time step of a day or less. Water surface profiles for peak flows are computed with a separate model such as the HEC-RAS (River Hydraulics System) based on the standard step method solution of the energy equation. However, dynamic routing (solution of St. Venant equations also provided by HEC-RAS) or other simpler hydraulic routing techniques may be adopted to more accurately capture the dynamics of a flood event or hydropower release.

SUPER has comprehensive capabilities for detailed modeling of flood control operating rules. It has been applied extensively in simulation studies of flood control operations of Corps of Engineers reservoir systems. SUPER has also been applied in simulating multiple-purpose conservation operations including detailed analyses of hydropower operations. However, it does not have the comprehensive capabilities for simulating institutional aspects of water supply found in the other models. SUPER has a fixed time step of one day. The Muskingum method is used for streamflow routing.

HEC-ResSim is also designed for simulating multiple-purpose reservoir system operations with capabilities provided for detailed modeling of flood control operations. A key area of application for ResSim is serving as the reservoir system operations component of the Corps Water Management System (CWMS). The CWMS is designed to support real-time operations of USACE reservoir systems for which flood control plays a dominant role. The ResSim time interval may vary from 15 minutes to 1 day. Streamflow routing options include coefficient routing, Muskingum, Muskingum-Cunge, modified Puls, and a method from the North Pacific Division's SSARR model

Development of RiverWare was motivated largely by conservation purposes, particularly hydroelectric power operations, but the model also provides capabilities for detailed simulation of flood control operations. It has been applied to Tennessee Valley Authority and Bureau of Reclamation reservoir systems that cover the full spectrum of multiple-purpose operations. The time step may range from a hour to a year. The hydrologic period-of-analysis may range from a single event to a long continuous record of any length. Hydrologic streamflow routing methods include lag, variable time lag, storage, and Muskingum. Hydraulic routing methods include kinematic, Muskingum Cunge, and MacCormick.

MODSIM is designed to model complex institutional and physical systems for managing water for conservation purposes, but flood control can also be included in simulating multiple-purpose reservoir system operations. The time interval may be a month, week, or day. Streamflow routing using a lag methodology is used with the daily time step.

WRAP was originally designed as a monthly time step model used to simulate the complexities of water allocation and management with little or no consideration of flood control. However, features were recently added to use a time step of a day or any other sub-division of a month along with Muskingum routing. Whereas routing is applied to actual total streamflows in other models, adjustments to flows are routed in WRAP. WRAP starts with total unregulated flows, which are then adjusted basin-wide to reflect regulation. Reservoir operation in WRAP is based on emptying flood control pools expeditiously without contributing to flows at downstream control points exceeding flood limits during a specified forecast period.

Special Modeling Features

In addition to the basic water accounting computations, the modeling systems include various optional features for:

- reliability and frequency analyses
- economic evaluation capabilities
- water quality modeling
- surface/groundwater interactions

These features may involve either computations performed during the simulation and/or additional post-simulation computations performed using simulation results.

WRAP provides a set of options for developing various reliability tables for water supply diversion and hydroelectric energy requirements for either individual water rights or various groupings of rights and frequency relationships for flows, storages, and other variables. These analyses may be performed using the results of a conventional single simulation. A yield-reliability/firm yield option is also provided based on automated multiple simulations. A conditional reliability modeling analysis is based on multiple short-term simulations with varying assigned probabilities, all starting with the same specified storage condition. Flood frequency analyses are performed based on applying the log-Pearson type III probability distribution to annual series of peak flows or storage volumes.

SUPER determines economic benefits and costs of flood control, hydropower, and navigation based on functions relating damage, cost, and benefits to flow and/or storage. RiverWare translates economic goals to linear programming objective functions. The relative priorities represented by the objective function coefficients in MODSIM may also be economic costs or benefits.

RiverWare, MODSIM, and WRAP have water quality modeling features. RiverWare models dissolved solids, temperature, and dissolved oxygen. MODSIM and WRAP simulate salinity. MODSIM has also been linked with the stream water quality model QUAL2E.

Groundwater sources and channel losses are included in the models. Surface/ground water interactions have been approximated in various ways. MODSIM has a groundwater routine and has also been linked to the USGS MODFLOW groundwater model.

Accessibility and Documentation

Models vary greatly in regard to the extent to which they are designed to be applied by water management professionals other than the original model developers. Historically, most reservoir/river system models reported in the literature have been both created and applied by the same agency engineers or university researchers. However, the trend in recent years has been to shift toward user-oriented generalized models designed for use by water management practitioners rather than model developers. This report focuses on user-oriented generalized modeling systems. User-oriented generalized models should be convenient to obtain, understand, and use and should work correctly, completely, and efficiently. Documentation, user support, and ease-of-use are key factors in applying a model. Data management efficiency and effective communication of results are also key aspects of modeling.

In the author's experience, the two most important aspects governing the ease-of-use of a modeling system involve (1) clarity and detail of documentation and (2) errors. Documentation includes both instructions for using the software and detailed technical documentation for understanding modeling methods. The error aspect of ease-of-use includes both:

1. an error-free generalized model or at least as near error-free as possible assuming absolutely error-free software may be an idealistic goal yet to be achieved
2. mechanisms for detecting and correcting blunders and inconsistencies in input data

Applying a model that the user does not fully understand can be dangerous as well as frustrating. Dealing with either minor bugs or major errors in the software can also be extremely time consuming and frustrating. The datasets developed for reservoir/river system models can be extremely voluminous. Modeling is greatly facilitated by data checking features build into the software that assist the user in preventing and correcting input errors as well as by clear detailed user documentation. The five modeling systems contain an array of error detecting mechanisms.

With the exception of SUPER, materials describing the models are available at the web sites listed in Table 7.1. The five models are documented by the following materials.

- SUPER is documented by manuals prepared by the Southwestern Division in the past covering database development, operation of the model, and display of results. The manuals have not been disseminated outside of the Corps of Engineers.
- ResSim is documented by a Quick Start Guide (HEC 2003), Users Manual (HEC 2003), and release notes. Unlike other generalized HEC simulation models, a technical reference manual is not yet available for ResSim.
- RiverWare is documented by online help, several papers (Zagona *et al.* 2001 and 2002; Eschenbach *et al.* 2001; and others), and a technical manual entitled *Simulation Objects* (CADSWES 2003) available at the web site listed in Table 7.1. Training manuals are provided at short courses conducted by CADSWES.
- MODSIM is documented by online help and a draft users manual (Labadie et al. 2000). Several journal papers and reports describe particular applications.
- WRAP is documented by detailed users and reference manuals (Wurbs 2005; Wurbs et al. 2005) available at the web site listed in Table 7.1. Journal papers and TWRI reports describe particular applications.

Software and user documentation for ResSim, MODSIM, and WRAP may be downloaded free-of-charge from the websites listed in Table 7.1. SUPER has not been publicly distributed outside of the division and district offices of the USACE Southwestern Division. Documentation of SUPER has not been prepared for public distribution.

RiverWare can be purchased from CADSWES following the instructions provided by the website cited in Table 7.1. License fees in 2004 for a single node are $6,500 for the first year with a $2,500 annual renewal fee. The single node license limits use of the software to one computer. A floating license allowing up to five concurrent sessions running on different nodes of a network has a first year fee of $11,500 for the first year with a $5,000 annual renewal.

The relevance of the proprietary versus public domain nature of generalized models depends upon the particular situation in which the model is applied. Federal and state agencies can afford license fees in situations in which a few people within the agency are performing all of the reservoir/river system modeling work. However, a public domain model is essential for applications such as the Texas WAM System. WRAP is applied by many agencies and consulting firms in the regional planning and water right permit application processes. Developing a broad-based model-user community proficient with WRAP was essential to the success of the Texas WAM System. Public domain software greatly contributes to establishment of a user community. HEC-1/HEC-HMS and HEC-2/HEC-RAS are perhaps the most widely used water resources management related software products in the world. Numerous consulting firms, cities, and agencies routinely apply these HEC models in floodplain management studies in cities throughout the United States and abroad. Easy public domain access contributed significantly to the proliferation of use of HEC models.

Institutional Dimensions of Model Evolution

The evolution of computer modeling of reservoir/river systems that began in the 1950's will likely continue well into the future. The models keep changing in response to advances in computer technology and changing water management practices and associated changes in decision-support needs and modeling applications. A model of a reservoir/river system consists of a generalized simulation model combined with an input dataset describing that particular reservoir/river system. Datasets for input to particular generalized models have been developed for many major river/reservoir systems. Both the datasets and the generalized models continue to be improved and expanded. Institutional capabilities are required to continually maintain and update both the datasets for specific river basins and the generalized modeling systems.

The suite of models available from the Hydrologic Engineering Center of the USACE illustrates the dynamic nature of generalized simulation models. Of the many HEC models, the flagships are:

HEC-1 Flood Hydrograph Package
HEC-2 Water Surface Profiles
HEC-3 Reservoir System Simulation for Conservation
HEC-5 Simulation of Conservation and Flood Control Systems
HEC-DSS Data Storage System
HEC-HMS Hydrologic Modeling System
HEC-RAS River Analysis System
HEC-ResSim Reservoir System Simulation
HEC-DSSVue Visual Utility Engine

HEC-1, HEC-2, and HEC-3 date back to the beginning of the HEC in the mid-1960's. The models were converted to run on microcomputers in the 1980's. HEC-5 essentially replaced HEC-3 in the 1980's. HEC-HMS and HEC-RAS were released in the late-1990's as initial products of the HEC NexGen Project. However, HEC-1 and HEC-2 as well as HEC-HMS and HEC-RAS are still applied extensively by agencies and consulting firms. Likewise, the more recent NexGen product HEC-ResSim is designed to eventually replace HEC-5. ResSim Version 1.0 was distributed for testing within the Corps of Engineers in 2001. Version 2.0 was released to the public in 2003. Major improvements are being added in 2004. Continuing improvements to HECDSS since its original creation in 1979 include the addition of HEC-DSSVue in 2003. All of these HEC models have evolved through many versions over the past 40 years in response to changing computer technology and water management needs. Changes will likely continue in the future.

HEC-1/HEC-HMS and HEC-2/HEC-RAS are widely applied by cities and consulting engineering firms in support of flood plain management activities in communities throughout the United States as well as being applied by the Corps of Engineers and other agencies here and abroad. Reservoir/river system models have not yet acquired the extensive user communities associated with the HEC watershed hydrology and river hydraulics models. However, capabilities for a model to be shared by a group of model-users is growing in importance for reservoir/river system modeling as well as other areas of water resources management.

Partnerships and consensus building are key aspects of water management and likewise have become key aspects in creating and implementing models. User-oriented generalized modeling systems may be shared by multiple agencies as well as by many professionals within each agency. A practical, effective modeling system can serve as a mechanism for addressing issues shared in common by a water management community. Federal and state agencies, consulting firms, and university research entities work together to implement modeling systems.

The Texas WAM System described in Chapter 7 illustrates the concept of a water management community implementing a modeling system consisting of dynamic datasets for individual river basins combined with a generalized simulation model which also keeps changing. The datasets were developed during 1997-2003 by teams of consulting firms working for the Texas Commission on Environmental Quality in collaboration with the Texas Water Development Board and Texas Parks and Wildlife Department. The input datasets continue to be revised by the TCEQ and its consultants in response to both changes in water right permits and refinements that better capturing the details of reservoir/river system operations. The existing WRAP model was already being applied when Senate Bill 1 was enacted in 1997 but was greatly expanded in conjunction with implementation of the statewide WAM System. Model development has been an evolutionary process with extensive interactions between professionals from the agencies and consulting firms applying the model to specific river basins and university researchers responsible for improving the modeling methodology and computer software. Although the WAM System was essentially fully operational by 2003, the generalized WRAP model continues to be significantly expanded.

The five models listed in Table 8.1 are all products of long research and development processes. Development of generalized reservoir/river system models require a tremendous amount of effort expended over many years. Experience gained through practical applications is an essential part of the model development process. The models must be maintained and continually improved and updated. Institutional support is required.

The following considerations are important in selecting a model for a complex water management decision-support application.

1. The generalized model should be the product of an extensive development/application process providing opportunities to correct deficiencies and add improvements.

2. The generalized model should be constructed within a framework that provides a sound technical and institutional foundation for continued future modeling improvements.

Selecting a generalized model that has advanced to a proven stage of maturity and stability is certainly highly advantageous. Institutional and technical capabilities for continued future improvements are also very important.

Chapter 9
Summary and Conclusions

Progress is continuing in the evolution of computer modeling capabilities for analyzing reservoir/river system operations that began in the 1950's. The simulation and optimization methodologies and models described in this report are representative of an extensive published literature as well as often unpublished agency research and application efforts. The generalized SUPER, ResSim, RiverWare, MODSIM, and WRAP modeling systems are representative of current endeavors of the water management community in the United States to improve decision-support for a broad spectrum of river basin management activities.

Modeling Applications

Reservoir/river system modeling applications have grown in complexity from both technical and institutional perspectives. Water management communities are implementing modeling systems that provide detailed analyses of complex physical facilities, water resource allocations, and operating practices. Reservoir/river system models are applied in:

* comprehensive long-term regional or basin-wide planning studies considering environmental instream flow, municipal, industrial, and agricultural water supply, hydroelectric power, recreation, and other water needs
* long-term planning studies focusing on flood damage reduction
* feasibility studies for specific projects that could involve either proposed construction of new facilities and/or storage reallocations or other operational modifications at existing reservoirs
* preparation and evaluation of water right permit applications and administration of water allocation systems
* operational planning studies to periodically reevaluate reservoir system operating policies and practices
* operational planning studies to develop operating plans for the next year or season
* real-time decision support for reservoir system operations during floods
* decision support for water management during droughts
* decision support during the full spectrum of hydrologic conditions for hydroelectric power operations or multipurpose reservoir system operations with hydropower as a major focus

Simulation and optimization modeling strategies, measures of system performance, computational methods, time step length, hydrologic period-of-analysis, and data management schemes vary with the different types of applications.

Modeling Systems

Implementation of a system for modeling reservoir/river system operations consists of the development and continual improvement and maintenance of:

- a generalized reservoir/river system modeling system
- a larger system in which the reservoir/river system modeling system is connected with other software that may include watershed hydrology, river hydraulics, and/or water quality simulation models and/or programs for acquiring, storing, organizing, and displaying input data and model results
- input datasets that describe the particular river basins and reservoir/river systems of concern

The modeling or decision-support system may be applied by multiple model-users over time for various purposes. The modeling system is applied in simulation/optimization exercises that include:

- ∗ adjusting the input data as appropriate to model water management strategies and plans and investigate issues of concern
- ∗ executing the software in as many runs as required to develop the information needed
- ∗ organizing, analyzing, summarizing, displaying, documenting, and communicating modeling results

The scope of the modeling effort may vary greatly between different applications. However, in general, developing and applying a reservoir/river system model involves significant expertise, time, and effort. A generalized model must provide the flexibility required to represent the details of pertinent system operating polices and practices and address complex issues of concern. Data requirements are significant for reservoir/river system models. Developing homogenous sets of unregulated or naturalized streamflows covering the period-of-analysis at all locations of interest is typically a particularly difficult aspect of developing the basic input dataset for a river basin. Model results must be clearly understood and communicated. The worth of a reservoir/river system management modeling system is dependent upon its capabilities to contribute to actual water management decision-making processes.

Alternative Generalized Modeling Systems

A tremendous amount of research, development, and implementation work has been accomplished over the past 50 years dealing with reservoir/river system models. The water management agencies and the university research community have progressed along two distinctly separate pathways, which occasionally merge. The USACE, USBR, TVA, and state and regional water agencies have focused on water management practices and issues as the agencies have developed modeling techniques for their applications. University researchers have focused on a broad array of mathematical programming and stochastic analysis methods and have tended to seek applications for their modeling techniques rather than visa versa. Since publication is fundamental to the academic culture, the published literature has been dominated by the university research side of the water management family. The RiverWare, MODSIM, and WRAP modeling systems described in Chapters 7 and 8 represent partnerships combining the efforts of university researchers and federal and state water management agency professionals that is representative of other institutional partnerships in developing other models cited in

Chapter 6 as well. The USACE Hydrologic Engineering Center has also routinely collaborated with university researchers in the development of the HEC suite of generalized models. This report was written on a university campus under the sponsorship of the USACE Fort Worth District.

A broad review of simulation and optimization modeling strategies, methods, and particular models is presented in Chapters 3, 4, and 6. The software tools used to construct the models are described in Chapter 5. An inventory of available generalized models is outlined in Chapter 6. The comparative evaluation narrows to a focus on the SUPER, ResSim, RiverWare, MODSIM, and WRAP modeling systems in Chapters 7 and 8. Each of these five generalized models provides flexible capabilities for simulating complex multiple-purpose, multiple-reservoir systems operations. All five of the alternative models are water accounting systems based on computing reservoir storages and releases and streamflows. However, the models differ significantly in their overall organizational structure and the details of their computational algorithms, user interfaces, and data management mechanisms. The modeling systems provide general frameworks for constructing and applying models for specific reservoir/river systems. Each of the generalized modeling systems is based upon its own set of modeling strategies and methods and has its own terminology or modeling language.

The details of modeling capabilities are influenced by the setting in which the models have been developed and applied. Implementation of SUPER has occurred within the division and district offices of the USACE Southwestern Division in support of planning and operation of Corps of Engineers reservoir systems. HEC-ResSim serves as the reservoir/river systems component of the new Corps Water Management System (CWMS) being implemented in the Corps district offices nationwide to support real-time operations. ResSim is also designed for use in Corps planning studies. RiverWare was developed as a partnership between CADSWES and the USBR and TVA. The Tennessee Valley Authority uses ResSim to support real-time hydroelectric power system operations within the setting of multiple-purpose reservoir system operations. The Bureau of Reclamation applies RiverWare for both long-term planning and short-term operational planning for its multiple-purpose reservoir systems. MODSIM was developed at Colorado State University in collaboration with the USBR and has been applied primarily by university researchers in studies both in the United States and abroad. WRAP supports local, regional, and basinwide planning and water rights regulatory activities in Texas.

SUPER, ResSim, RiverWare, MODSIM, and WRAP as well as other similar models cited in Chapter 6 are readily available for application anywhere. The choice of a modeling approach for a particular application depends upon various technical and institutional considerations. This report outlines modeling capabilities and issues. Hopefully, the basic background information compiled here will prove useful for adopting and implementing generalized reservoir/river modeling systems or perhaps building upon and continuing to improve existing modeling capabilities.

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Glossary

ad hoc – computational procedures are developed for a particular simulation model rather than being standardized for incorporation in various different models.

algorithm – a prescribed set of well-defined rules or processes for the solution of a problem in a finite number of steps.

ASCII – American Standard Code for Information Exchange

assembly language – a low-level language that uses mnemonic codes instead of binary 0 and 1.

BASIC – an easy-to-learn, easy-to-use high-level programming language.

binary code – a code that makes use of exactly two distinct symbols, usually 0 and 1.

C – a programming language with sophisticated control and data structures for developing both systems and application software.

C++ – a programming language developed at AT&T Bell Laboratories in the mid-1980's by adding object-oriented programming features to the C programming language.

C# – a programming language developed at Microsoft in the late-1990's by adding object-oriented programming features to the C programming language.

COBOL – a programming language developed in the late 1950's that is used primarily for business and administrative information systems.

computer program – a series of instructions or statements in a form acceptable to a computer for acheiving certain results.

conditional reliability modeling – developing indices of the likelihood of meeting water use requirements over a specified period of time and storage-frequency relationships at the end of the time period given preceding storage conditions.

constraints – mathematical programming term referring to limitations or restrictions on possible decision policies.

curse of dimensionality – dynamic programming expression referring to the dramatic increase in the computational magnitude of a dynamic programming problem that results from increases in the number of state variables.

decision policy – mathematical programming term referring to a set of values for the decision variables.

decision variables – mathematical programming term referring to the variables for which optimum values are to be determined.

descriptive – a model demonstrates the consequences of adopting a specified decision policy, as contrasted with prescriptive.

dynamic link library (DLL) – a source-code library of sub programs that is compiled and linked to a unit independently of the application programs that use it.

dynamic programming (DP) – mathematical optimization strategy based on decomposing a sequential decision problem into stages connected by state variables, with values for decision variables determined for each stage.

epilimnion – well mixed surface layer in a thermally stratified reservoir.

feasible policy – mathematical programming term referring to a decision policy that does not violate any constraints.

firm yield – safe or dependable yield is the estimated maximum release or diversion rate or hydroelectric energy production rate that can be maintained continuously during a hypothetical repetition of historical period-of-record hydrology based on all the premises reflected in the model used for the analysis.

flow-duration relationship – expression of likelihood of streamflows falling within various ranges developed by counting the number of periods (typically days or months) for which the mean flow rate equaled or exceeded specified levels during the period-of-analysis.

fortran – a high-level programming language originally developed by IBM in the 1950's that is designed for computationally intensive engineering and scientific applications.

generalized model – a computer modeling system designed for application to a range of concerns dealing with real-world systems at any location as contrasted to customized site-specific models.

genetic algorithms – search methods based on probabilistically generating populations of solutions with improving levels of fitness as measured by the objective function.

geographical information system (GIS) – a set of computer-based tools for storing, processing. combining, manipulating, analyzing, and displaying data spatially referenced to location.

goal programming – an approach for incorporating multiple prioritized objective functions in a mathematical programming model based on solving the optimization problem for each individual objective function while constraining the solution to not worsen the objective function value for any higher priority objective function.

gradient search methods – optimization algorithms based on iterative adjustments to the decision variables that are based on objective function gradients.

graphical user interface (GUI) – a system for entering information to a computer model and retrieving results that is characterized by use of pointing devices such as a mouse, pull-down and pop-up menus, dialog windows, command buttons, and other visual aids.

guide curve – reservoir operating rules defined in terms of target storage levels.

high-level-language – computer programming language designed for programmer convenience as contrasted with assembly and machine languages that more closely reflect the actual operations of a computer.

hydraulic routing – computation of discharges and depths as a function of time and location in a river based on the St. Venant equations or simplifications thereof.

hydrologic routing – computation an outflow hydrograph for a given inflow hydrograph based on the storage form of the continuity equation combined with some other relationship between discharge and storage.

hypolimnion – cold bottom layer in a thermally stratified reservoir.

inheritance – a relationship between two classes of objects such that one of the classes, the child, takes on all relevant features of the other class, the parent.

interpreter – a language-translation program that translates a high-level language into a machine code one line at a time.

interruptible yield – a target water supply or hydropower demand that is supplied with a period reliability of less than 100%.

Java – a popular object oriented programming language introduced by Sun Microsystems, Inc. in 1995.

Java technology – a programming environment available from Sun Microsystems for writing and compiling programs in the Java language.

linear programming (LP) – mathematical optimization formulation that minimizes or maximizes a linear objective function subject to a set of linear constraints.

machine language – a programming language that a computer recognizes and uses directly, based on electronic on/off states represented by a binary number system.

mathematical programming – a mathematical optimization formulation in which a standard algorithm is used to compute a set of decision variable values that minimize or maximize an objective function subject to constraints.

metalimnion – middle layer of high temperature gradient in a thermally stratified reservoir.

Muskingum routing – a hydrologic routing technique based on assuming that storage is a linear function of weighted inflow and outflow.

network flow programming – a special computationally-efficient form of linear programming which restricts the objective function and constraints to a particular format based on treating a system as a connected set of nodes and arcs.

net evaporation depth – reservoir water surface evaporation less precipitation depth which is often adjusted to not double-count the precipitation runoff from the reservoir site that is also reflected in the unregulated stream inflows.

object – an abstraction of a real-world entity.

object class – a set or collection of objects having common features.

object program – the output of a translator program such as a compiler that converts a source program written in a high-level language to code in machine language.

objective function – mathematical programming term referring to a statement of the consequences of a decision policy used as a criterion to define optumum.

object-oriented – pertaining to objects which are abstractions representing real-world entities for convenient manipulation by a computer program.

object-oriented language – a well-defined notation that supports object-oriented methods in programming computers.

operating system – a collection of programs that controls the operation of the computer, manages computer resources, and facilitates human use of the computer.

optimization – finding the best or optimum solution.

optimum solution – mathematical programming term referring to a feasible decision policy that optimizes (minimizes or maximizes) the objective function.

period reliability – percentage of periods during a simulation for which the specified demand target is either fully supplied or a specified percentage of the target is equaled or exceeded.

period-of-analysis – the hydrologic simulation timeframe covered by the streamflow data in a reservoir/river system model.

prescriptive – a model determines the optimal decision policy as measured by minimizing or maximizing an objective function expressing planning or management goals, as contrasted to a descriptive focus on determining the consequences of a particular decision policy.

program – a series of statements and phrases which cause the computer to carry computational actions toward a desired result.

quadratic programming – mathematical optimization formulation in which a successive solution algorithm is applied to the problem of maximizing or minimizing a quadratic objective function subject to a set of linear constraints.

resiliency – a measure of the capability for recovery from failure such as the maximum number of consecutive periods of failure to meet water use demands during a simulation or the probability of being in a period of no failure given that there was a failure in the previous period.

rule curve – reservoir operating rules defined in terms of target storage levels.

search methods – optimization algorithms that are based on iteratively determining improved values for decision variables as measured by an objective function evaluated with a simulation model.

secondary yield – a target water supply or hydropower demand that is supplied with a period reliability of less than 100%.

separable programming – decision variables and constraints are added to a linear programming formulation to approximate separable nonlinear terms in the objective function as piece-wise linear segments.

simplex algorithm – a standard algebraic procedure for solving linear programming problems.

source code – a computer written in a language one or more steps from the machine language of a computer which is translated to an object program prior to execution.

successive linear programming – a strategy for dealing with nonlinear terms in a linear programming formulation by successively repeating the linear programming solutions with adjustments to the variables affected by nonlinearity.

total dissolved solids – measure of the salinity or dissolved minerals in water.

UNIX – a multi-user, multi-tasked operating system developed in the 1970's at Bell Laboratories that is used on many types of computers.

volume reliability – percentage of the total demand amount that is actually supplied during the simulation.

vulnerability – a measure of the severity of the worst failure such as the greatest water supply shortage to occur during any year of a simulation or the greatest deficit in meeting a hydroelectric energy production target.

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