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Water Resources Planning and Management

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39.1 Introduction

Water resources planning and management engineering is concerned with conceptualizing, designing, and implementing strategies for delivering water of sufficient quality and quantity to meet societal needs in a cost-effective manner. Alternatives that can be engineered to accomplish these functions include development of new water supplies, regulation of natural sources of water, transfer of water over large distances, and treatment of degraded water so that it can be reused. The challenges for water resources engineers are: (1) to identify the essential characteristics of a given water resources problem, (2) to identify feasible alternatives for resolving the problem, (3) to systematically evaluate all feasible alternatives in terms of the goals and objectives of the decision makers, and (4) to present a clear and concise representation of the trade-offs that exist between various alternatives.

Water Resources Decision Making

Because large-scale planning, development, and management of water resource systems generally take place in the public sector, the individual responsible for making decisions about, or selecting from, a set of development alternatives is usually not the engineer(s) who perform the technical analyses related to the given problem domain. The decision-making topology is rather more like that presented in Fig. 39.1. At the top of the topology is the decision maker, usually an elected official or his or her appointee. This individual assumes the responsibility for selecting a course of action that best achieves the goals and

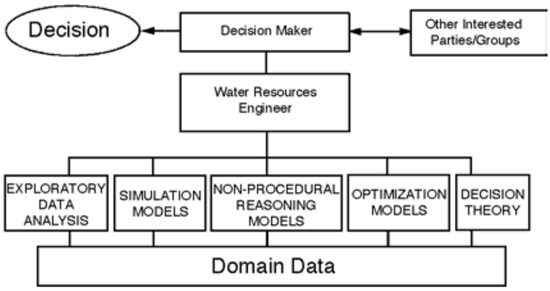

FIGURE 39.1 The water resources engineer uses a wide range of analytical tools and techniques to identify and evaluate alternative development plans and management strategies. The selection of a particular project or plan from a set of alternatives identified by the engineer is the responsibility of the decision maker.

objectives of his or her constituency. During the course of the decision-making process, the decision maker interacts with other interested parties, such as local, state, and federal government agencies; non-governmental organizations and groups; industry; and individuals.

At the bottom of the hierarchy are all data that pertain to the problem domain, including hydrologic data, economic and other cost data, demographic and historic data, and information about relevant structural and management technologies. The water resources engineer selects, from a wide range of modeling and analysis technologies, those that can best evaluate these data and provide the decision maker with information about the trade-offs that exist among and between multiple and conflicting management objectives. In addition, the water resources engineer may interact with other interested parties, including social scientists, economists, and environmentalists, to ensure a comprehensive consideration of the system and its impacts. Consequently, the water resource systems analyst must be skilled in problem identification; proficient in the use of different modeling methods and technologies; and willing and able to interact with technical, and non-technical managers and decision makers.

Comprehensive water resource, planning and management is generally conducted in several separate but related phases requiring input from a wide range of specialists including urban and regional planners, economists and financial planners, government agency personnel, citizen groups, architects, sociologists, real estate agents, civil engineers, hydrologists, and environmental specialists. The National Environmental Policy Act of 1969 (NEPA) requires the preparation of an environmental impact statement for every major federal action (program, project, on licensing action) "significantly" affecting the quality of the human environment. Most water projects fall under this legislation and most states have prepared regional guidelines for complying with NEPA. Special-purpose developments often require the assistance of specialists from disciplines such as soil scientists, agricultural specialists, crop experts, computer specialists, and legal experts. These individuals are involved in one or more of several planning and management phases

- Establishment of project goals and objectives
- Collection of relevant data
- Identification of feasible best-compromise alternative solutions
- Preliminary impact assessment
- Formulation of recommendation(s)
- Implementation (detailed structural design, construction, and/or policy implementation)
- Operation, management, and sustainment

Because most large-scale water resources projects involve many different constituencies having different goals and objectives, a multiobjective perspective through this process is essential. Consider, for example, the problem of developing an operating strategy for a large multipurpose reservoir designed to provide water for irrigated agriculture, municipal and industrial water supply, water-based recreation, and power generation (see Chapter 37 for a comprehensive discussion of water resource structures). The reservoir may also be a critical component in a regional flood control program. The decision maker in this context might be a regional water authority which reports to a state water agency or to the state governor. Clearly, the decision maker has responsibilities to a range of constituencies that might include the citizens at large, industry special interest groups, the environment and future generations, and perhaps a present political administration. The operating strategy that best meets the needs of one interest may prove disastrous for another. (For a thorough discussion of multiple and conflicting objectives in water resources planning and management, see Cohon and Rothley, 1997; Goodman, 1984; and Linsley et al., 1992.) The selection among alternatives is thus the responsibility of the decision maker who represents these groups. The role of the engineering analyst is to develop a clear and concise documentation of feasible alternatives. The focus of this chapter is the use of analytical engineering management tools and techniques for developing these alternatives.

Water Resources Modeling

The main tool of the water resources engineer is the computer model, which can be classified by: (1) structure and function (optimization or simulation), (2) degree of uncertainty in system inputs (deterministic or stochastic), (3) level of fluctuation in economic or environmental conditions being modeled (static or dynamic), (4) distribution of model data (lumped or distributed), and (5) type of decision to be made (investment or operations/management). Each model configuration has inherent strengths and weaknesses, and each has its proper role in water resources planning. The challenge for the water resources engineer is not to determine which is better, but which is most appropriate for a particular situation given available resources including time, money, computer capability, and data.

Optimization vs. Simulation Models

A variety of water resources management and planning models can be formulated and solved as optimization models. Optimization models have the following general structure:

$$\text{Optimize } Z = f\left(x_1, x_2, \ldots, x_n\right) \tag{39.1}$$

Subject to:

$$g_1\left(x_1, x_2, \ldots, x_n\right) \le b_1 \tag{39.2}$$

$$g_2\left(x_1, x_2, \ldots, x_n\right) \le b_2 \tag{39.3}$$

$$\cdots$$

$$\cdots$$

$$g_m\left(x_1, x_2, \ldots, x_n\right) \le b_m \tag{39.4}$$

$$x_j \ge 0 \qquad j = 1, 2, \ldots, \text{J} \tag{39.5}$$

Equation (39.1) is called the objective function and is specified as a mathematical criterion for measuring the 'goodness' of any given solution. The objective function is a function of a set of non-negative variables known as decision variables (x_1, x_2, …, x_n), which typically represent the choices available to the decision makers. The optimal solution to the optimization model is the set of values of the decision variables that provides the "best" (e.g., maximum or minimum) value for the objective function.

The quality of the solution as measured by the objective function is constrained by a set of equations, appropriately called constraint equations or constraints — Eqs. (39.2–39.4) above. The constraints represent all the real-life restrictions on the values of the decision variables. The functions g_1, g_2, … g_m depend on the values of the decision variables, and are restricted to be less-than-or-equal-to a set of constants b_1, b_2,…, b_m. This is the typical presentation of an optimization model; however, equalities and greater-than-or-equal-to inequalities in the constraints are allowed.

Finally, the optimization model typically includes the requirement that all decision variables are non-negative — Eq. (39.5). From an engineering management standpoint, decision variables represent those factors of a problem over which the engineer has control, such as the amount of resource to allocate to a particular activity the appropriate size of a component of a structure, the time at which something should begin, or cost that should be charged for a service. Clearly negative values for such things have no physical meaning. However, if there are decision variables that should be allowed to take on negative values, then this can be accommodated within an optimization model.

If a water resources planning or management model can be constructed to adhere to the rigid structure of the optimization model, a variety of solution methodologies are available to solve them [Hillier and Lieberman, 1990; Sofer and Nash, 1995]. These techniques are continuously improving in scale and efficiency with the ongoing improvements in information technology (e.g., object oriented programming, increasing computational speeds of computer processors). New techniques such as artificial neural networks, or evolutionary computing — an offshoot of artificial intelligence — are offering an even greater range of solution options (e.g., Wardlaw and Sharif, 1997).

Undoubtedly the most widely used analytical procedure employed in the area of water resources systems engineering is simulation (or descriptive) modeling. The main characteristics of this modeling methodology are: (1) problem complexities can be incorporated into the model at virtually any level of abstraction deemed appropriate by the model designer or user (in contrast to the more rigid structure required by optimization models), and (2) the model results do not inherently represent good solutions to engineering problems. These models reflect the structure and function of the system being modeled and do not attempt to suggest changes in design or configuration towards improving a given scenario.

Simulation models may be time or event sequenced. In time-sequenced simulation, time is represented as a series of discrete time steps ($t = 0, 1, 2,\ldots, N$) of an appropriate length perhaps hours, days, weeks, or months depending on the system being modeled. At the end of each time period t all model parameters would be updated (recomputed) resulting in a new system state at the beginning of time step $t + 1$. The relationships among and between model parameters may be deterministic or stochastic through this updating process, again depending on the design of the system and the level of abstraction assumed by the model. Model inputs, both initially and throughout the simulation, may follow parameter distributions as discussed in the previous section or may be input from external sources such as monitoring instrumentation or databases.

Models that simulate physical or economic water resource systems can also be event sequenced, wherein the model is designed to simulate specific events or their impacts whenever they occur. These events might be input as deterministic or stochastic events or they might be triggered by the conditions of the system. In any case, the model responds to these events as they occur regardless of their timing relative to simulated real time. Regardless of the treatment of time through the simulation process, these models can be either deterministic or stochastic.

With increasingly powerful computer technology, extremely complicated simulation models can be developed that emulate reality to increasingly high levels of accuracy. Very complicated systems can be modeled through many time steps and these models can be "exercised" heavily (can be run many times with different parameter settings and/or data inputs) to understand the system being modeled better. A number of commercial vendors market simulation systems that can be used to design and develop simulation models.

Historically, optimization models have been used as screening models in water resources planning and management analyses. The gross level of abstraction required to "fit' a particular problem to this rigid structure, coupled with the heavy computational burden required to solve these models, precluded the construction of large and accurate systems representation. Once a general solution strategy or set of alternatives was identified, simulation models could be constructed for purposes of more detailed analysis and "what-if" -type analyses. With the advent of increasingly powerful computing capability there is a much tighter integration of these and other modeling technologies.

Deterministic vs. Stochastic Models

Water resources models can also be classified by the Ievel of uncertainty that is present in model parameters and hydrologic inputs. A model is said to be deterministic if all input parameters and expected future unregulated streamflows and other time series are assumed to be known with certainty and defined specifically within model constraint equations. If, on the other hand, only the probability distributions of these streamflows are assumed to be known within the model, the model is said to be stochastic (see Chapter 31 for a more complete discussion of statistical hydrologic analysis).

Both optimization and simulation models can be either deterministic or stochastic. Stochastic models are generally more complex than deterministic models, having more variables and constraints or limiting conditions. But deterministic models, having parameters and inputs based on average values over potentially long time periods, are usually optimistic; system benefits are usually overestimated, while costs and system losses are generally underestimated. If sufficient information and computational resources are available, stochastic models (either optimization or simulation) are generally superior (Loucks et al., 1981).

Static vs. Dynamic Models

Models vary in the manner in which changes to model parameters occur over time. In a particular watershed, for example, while actual or predicted streamflows might vary over time, the probability distribution for the streamflows may not change appreciably from one year to the next, and may thus be considered static within the corresponding model. Dynamic models, on the other hand, assume changing conditions over time and attempt to incorporate such changes into the analyses being conducted (e.g., climate change models [Lane et al., 1999; Lettenmaier et al., 1999]). Dynamic models tend to be more complex and require more computational effort to solve, but usually provide more accurate results, assuming that adequate data are available to calibrate the models appropriately; this is particularly true for investment models. Static models can be significantly larger in scope. Models may be static in terms of some factors (e.g., physical characteristics) but dynamic in terms of others (e.g., economies).

Investment vs. Operations/Management Models

Models may also be classified in terms of the time frame within which the analysis is being performed and for which the resulting decision will be made. Long-term decisions dealing with selecting investment strategies including things like physical changes to facilities (reservoir capacity expansion or hydroelectric facility development, for example) are characteristically different from short-term decisions, such as determining the appropriate reservoir release at a particular point in time. Models used to develop operating or management strategies for a water resource system can generally be more detailed than those designed to recommend longer-term investment decisions, which frequently consider actions taken over multiple time periods.

Lumped vs. Distributed Data Models

Lumped data models are those that assume single values (e.g., average monthly rainfall or average hydraulic conductivity for a 1 km^2 area) for parameters that might be represented better with a finer discretization of space or time. Distributed data models use a finer resolution of parameters through time or space (e.g., daily rainfall or hydraulic conductivity for each 100 m^2 area) to represent the same system. Clearly, distributed data models require considerably more data and probably computational effort while potentially providing a much more realistic representation of the physical system being studied. Lumped parameter models are generally much more efficient to solve and may be appropriate in cases where insufficient or incomplete data sources are available. With the explosive growth in the use of geographic information systems and corresponding availability of spatial data, distributed data models are becoming much more popular, at least within the research arena [Maidment, 1993].

39.2 Evaluation of Management Alternatives

For any given water resources problem, an alternative may be represented as a set of investment decisions, each having a specific time-stream of costs and benefits. The level of each investment is a variable, the best value of which depends on the values of other variables and the goals and objectives of the decision maker. Hence, each alternative may have many impacts that result in numerous economic gains and losses (benefits and costs) that occur at different times, different locations, and accrue to different individuals or groups. The evaluation of the gains and losses associated with any particular alternative may be complex. However, without this analysis, the selection of the best alternative will be impossible.

The questions that must be considered systematically by the water resources engineer in providing meaningful guidance to the decision maker are: (1) how should each variable be evaluated economically? (2) what is the set of values for these variables such that the resulting alternative best satisfies a given objective? and (3) what is the best set of alternatives, and how can one be assured that there are no better alternatives? A number of proven modeling techniques are available to address these questions.

Consider a set of alternate water resources projects P consisting of individual projects $p \in P$. Each project may be specified as a set of values for a discrete number of decision variables x_p^j, $j = 1, 2, \ldots, n_p$. Each project is fully specified by a vector of these decision variables and their values, represented by X_p. A common goal of water managers is to identify that plan which maximizes net benefits (NB):

$$Maximize \sum_{p \in P} NB(Xp) \tag{39.6}$$

When the benefits (or costs) of a particular project alternative are most properly evaluated in economic terms, the value of a particular investment component of any given project depends at least in part on the timing of that particular investment. Because different water resources investment alternatives may have different useful lives, it is important that they be compared using a common framework. While a comprehensive treatment of engineering economic analysis is beyond the scope of this handbook, a brief outline of an approach to valuing alternatives is offered. Basic understanding of the time value of money, as well as finance principles, is important in an overall analysis of complex investment strategies. The interested reader is referred to Jenkins et al. [2001]; Blanchard and Fabrycky [1990]; Fabrycky and Blanchard [1991]; Grant et al. [1990]; and White et al. [1989] for additional information on performing comprehensive engineering economic analysis.

Discount factors are used to determine the value of a particular investment over time.

Let PV = the present value of an amount of money (principal)
FV = the future value of an amount (or value) of money,
i = the interest rate each period, and
n = the life (in periods) of the investment.

Given an investment at the present time, the future value of that investment n time periods into the future is given by the single-payment, compound-amount factor

$$\mathrm{FV} = \mathrm{PV}(1+i)^n \tag{39.7}$$

The present value of costs (or benefits) resulting from some future payment is computed using the reciprocal of this factor, which is referred to as the single-payment, present-worth factor:

$$PV = FV(1+i)^{-n} \tag{39.8}$$

Suppose that a particular investment (water resources project, for example) is anticipated to return a stream of future net benefits NB_t over T discrete time periods, $t = 1, 2, \ldots, T$. The present value of this stream of benefits is computed:

$$PV = \sum_{t=1}^{T} NB_t (1+i)^{-t} \tag{39.9}$$

It is also possible to represent the present value of net benefits (PV) of a project as an equivalent uniform or constant stream of net benefits over a horizon of T periods. Let A equal a constant amount of money each period. Then,

$$A = PV * CR \tag{39.10}$$

where CR is the capital recovery factor defined as:

$$CR = \left[i(1+i)^T\right] \Big/ \left[(1+i)^T - 1\right] \tag{39.11}$$

As a supplement to using present value of net benefits as a criterion to evaluate projects, the computation of a benefit-cost ratio — present value of benefits (PVB) divided by present value of costs (PVC) — is often used to perform preliminary screening of alternatives:

$$B/C = PVB/PVC \tag{39.12}$$

Alternatives having a benefit-cost ratio less than 1.0 should be removed from further consideration. However, because costs are typically easier to identify and estimate, care should be used in itemizing and valuing project benefits for this purpose.

For public investments, the appropriate interest rate to be used in comparing projects is a matter of public record and is based on the average yield on federal government bonds having approximately the same maturity period, the economically useful life of the project being evaluated [Water Resources Development Act of 1974 (P.L. 9302511)]. The assumption of a constant interest rate is standard practice for these types of investments. A comprehensive discussion of inflationary considerations in project evaluation is presented in Hanke et al. [1975].

39.3 Water Quantity Management Modeling

Among the largest public investments are those designed to stabilize the flow of water in rivers and streams. A stream that may carry little or no water during a significant portion of the year may experience extremely large (perhaps damaging) flows during peak periods. A storage reservoir may be employed to retain water from these peak flow periods for conservation use during low-flow periods (water supply, low-flow augmentation for environmental protection, irrigation, power production, navigation, recreation, etc.) or to contain peak flows for purposes of reducing downstream flood damage (flood control). In this section, methods for managing surface-water quantity pursuant to the development of comprehensive management alternatives are presented.

The management of a reservoir or system of reservoirs is achieved through a set of operating rules, that govern releases from the reservoir as a function of such things as inflows into the impoundment, demand for water, storage volumes, and reservoir elevations. Design of the reservoir storage volume, the spillway, and other reservoir components depends on these rules.

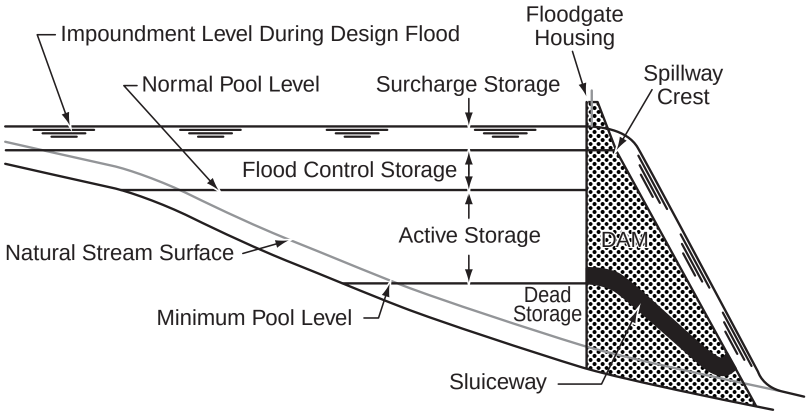

FIGURE 39.2 Schematic cross section of a typical reservoir system showing the relative location of different storage types.

Deterministic Reservoir Models

While there is always a significant amount of uncertainty in any hydrologic system, preliminary analysis of alternatives may be accomplished using deterministic models — models that do not explicitly consider uncertainty in hydrologic variables. Deterministic methods are particularly useful as screening models, which can identify alternatives for further analyses using more complete and thorough system representations.

Reservoir Storage Requirements

The factors that determine the extent to which streamflows can be stored for future use are: (1) the capacity of the impoundment, and (2) the manner in which the reservoir is operated. It is important to realize that the use of a reservoir to manage streamflows will necessarily result in a net loss of total water due to evaporation and seepage. Only if the benefits of regulation will be greater than these losses should a reservoir be utilized. Thus, the main goal of storage-reservoir design is a thorough analysis of the relationship between firm yield — the maximum quantity of flow that can be guaranteed with high reliability at a given site along a stream at all times — and reservoir capacity.

The impoundment behind a reservoir consists of three components (Fig. 39.2): (1) dead storage — that volume used for sediment control and retention of a permanent pool; (2) active storage — that volume used to meet water demands such as water supply irrigation, conservation, recreation, and power production (head); and (3) flood control storage — that volume of the reservoir reserved to contain flood flows, thereby protecting downstream assets. The determination of reservoir capacity and operating strategy should consider all three storage components with a goal of achieving a least-cost design strategy (total storage volume) that satisfies a predetermined set of operational constraints.

A variety of methods are available for performing these analyses including the mass diagram analysis [Rippl 1883; Fair et al., 1966], which finds the maximum positive cumulative difference between a sequence of specified reservoir releases and known historical (or simulated) inflows; the sequent peak procedure [Thomas and Fiering, 1963], which is a bit less cumbersome than the mass diagram method; and a variety of optimization methods [see, for example, Yeh, 1982], which can consider multiple reservoir systems.

The optimization methods incorporate mass balance constraints of the following form:

$$ST_{t+1} = ST_t + PP_t + QF_t - RR_t - EV_t \tag{39.13}$$

where ST_t = storage volume in the reservoir at the beginning of time period t
PP_t = precipitation volume on the reservoir during time period t

QF_t = reservoir inflow volume during time period t
RR_t = reservoir release volume during time period t
EV_t = evaporation volume from the reservoir during time period t

Defining K_a as the minimum active storage capacity of the reservoir for a specified firm yield release level R^* the optimization model, with variables on the left-hand-sides of the constraints and known quantities on the right-hand-sides is:

$$\text{minimize } K_a \tag{39.14}$$

subject to:

conservation of mass in each period

$$ST_{t+1} - ST_t + R_t = -R^* + PP_t + QF_t - EV_t \qquad t = 1, 2, \ldots, T \tag{39.15}$$

reservoir capacity cannot be exceeded:

$$ST_t - K_a \le 0 \qquad t = 1, 2, \ldots, T+1 \tag{39.16}$$

storage and release volumes cannot be negative.

$$\begin{aligned} ST_t \ge 0 \qquad t = 1, 2, \ldots, T+1 \\ R_t \ge 0 \qquad t = 1, 2, \ldots, T \end{aligned} \tag{39.17}$$

where R_t is the volume released in period t in excess of the firm release R^*.

The model can be solved to find optimal values for K_a, S_t, and R_t, and can be solved repeatedly with different values of R^* to find the relationship (trade-off) between minimum reservoir storage and firm yield. This is a deterministic model that uses a particular sequence of streamflows and the estimates of required storage volume are dependent on the adequacy of this streamflow sequence to represent the actual stochastic nature of the streamflows. In addition, because the entire sequence of streamflows is assumed to be known in advance as far as the optimization model is concerned, the results may be less conservative than expected.

Flood Control Planning

Prevention (or mitigation) of damage due to flooding may be achieved by: (1) containing excess streamflow in upstream reservoirs, or (2) confining the excess flow within a channel using levees, flood walls, or closed conduits. Flood flows generally occur during certain periods of the year and last for relatively short periods. The likelihood of a flood event of a given magnitude is described by its return period: the average interval in years between the occurrence of a flood of a specified magnitude and an equal or larger flood.

The probability that a T-year flood will be exceeded in any given year is $1/T$. Let PQ be a random annual peak flood flow and PQ_T a particular peak flood flow having a return period of T years. Then the probability of PQ equaling or exceeding PQ_T is given by:

$$\Pr\left[\text{PQ} \ge \text{PQ}_T\right] = 1/T \tag{39.18}$$

For continuous distributions

$$\Pr\left[\text{PQ} \ge \text{PQ}_T\right] = 1 - F_{PQ}\left(\text{PQ}_T\right) \tag{39.19}$$

TABLE 39.1 Reservoir Operation Priorities in HEC-5

Condition	Normal Priority	Optional Priority
During flooding at downstream location	No release for power requirements	Release for primary power
If primary power releases can be made without increasing flooding downstream	Release down to top of buffered pool	Release down to top of inactive pool (level 1)
During flooding at downstream location	No releases for minimum flow	Release minimum desired flow
If minimum desired flows can be made without increasing flooding downstream	Release minimum flow between top of conservation and top of buffered pool	Same as normal
If minimum required flows can be made without increasing flooding downstream	Release minimum flow between top of conservation and top of inactive pool	Same as normal
Diversions from reservoirs (except when diversion is a function of storage)	Divert down to top of buffered pool	Divert down to top of inactive pool (level 1)

Source: US Army Corps of Engineers, 1982.

Or

$$F_{PQ}\left(\mathrm{PQ}_T\right) = 1 - \left(1/T\right) \tag{39.20}$$

where $F_{PQ}(\mathrm{PQ}_T)$ is the cumulative distribution function of annual peak flows.

The peak flow at any potential damage site resulting from a flood of return period T will be some function of the upstream reservoir flood storage capacity K_f and the reservoir operating policy:

$$\mathrm{PQ}_T = f_T\left(K_f\right) \tag{39.21}$$

By assuming a reservoir operating policy for flood flow releases and using an appropriate flood routing simulation model, the function $f_T(K_f)$ can be defined by routing different floods through the reservoir using different storage capacities K_f. Damage functions can then be derived using field surveys at potential damage sites [James and Lee, 1971].

As an alternative to containing peak flows in upstream reservoirs in order to protect downstream sites, channel modifications at the potential damage sites can be implemented. Frequently, combinations of upstream containment and at-site improvements are considered.

In addition, a number of nonstructural measures have been adopted to reduce the impact of flooding [Johnson, 1977]. Nonstructural measures include moving people and damagable facilities out of the flood plain, thereby incurring the costs of relocation but reducing the losses of flooding.

If cost functions can be assumed for various improvement alternatives — structural and nonstructural, optimization models can be constructed to identify least-cost options for improvements or for determining optimal strategies using benefit-cost analyses [Loucks et al., 1981].

Among the most widely used reservoir simulation models is the U.S. Army Corps of Engineers Hydrologic Engineering Center HEC-5 program [U.S. Army COE 1982]. This model was developed to assist in the analysis of multipurpose, multireservoir systems, and contains routines to model flood control operation (including the computation of expected annual damages), determination of firm yield, hydropower systems simulation, multiple-purpose multiple-reservoir system operation and analysis, and simulation of pumped-storage projects. The model incorporates an operating priority as set forth in Table 39.1.

Water Supply Objectives

The model, discussed above may explicitly consider the net benefits that would result from the provision of water for domestic, commercial, and industrial water supplies, as well as supplies for irrigation and other agricultural uses. Nonagricultural water users generally base their investments on the availability of firm water yields because of the importance of the water input. A benefit function can be incorporated directly into the model (usually as an objective function in an optimization model), provided that the expected net benefit of some specified target allocation can be assumed. Constraints are included to ensure that the allocation to meet demand in any period not exceed the available yield at that time and location. For those water uses for which economic benefit/loss data are available, constraints specifying minimum acceptable allocations can be used.

Analysis of agricultural investments is generally more activity-specific than for nonagricultural users of water and should thus consider additional input factors such as the availability of capital, labor, and seasonal availability of water. Frequently, a detailed model is used for each irrigation site within a region or watershed and may contain detailed information about soil types, cropping patterns, rainfall and runoff profiles, variation in crop yield as a function of water allocation, and perhaps market crop pricing. In cases where detailed irrigation analyses are not possible, a general benefit function may be assumed and incorporated into the planning model. A more complete discussion of the factors to be included in the analysis of water use for irrigation may be found in Chapter 14 of Linsley et al. [1992].

Power Production Objectives

The potential for power production at a reservoir site depends on the flow rate of water that can pass through generation turbines and the potential head available. Power plant capacity is the maximum power that can be generated under normal head at full flow, while firm power is the amount of power that can be sustained, available 100% of the time. Firm energy is the energy produced with the plant operating at the level of firm power. Power that is generated in excess of firm power is called secondary or interruptible power.

The problem of determining reservoir storage sufficient to produce a specified firm energy (or some surrogate benefit function) is similar to that of determining firm yield but, because firm energy, flow rate, gross head, and storage are nonlinearly related, it is more difficult to estimate. Nonlinear optimization models and, in some cases, mass curve analysis, may be used to estimate the minimum storage necessary to provide a given firm yield. More common linear optimization models may be used to analyze hydropower potential: typically, a value of head is assumed, thereby linearizing the power equations; the resulting optimization model is solved; and the actual heads are compared to the assumed values. Adjustment of the assumed values can be made if the discrepancy is too large, and the process is repeated. Simulation models may also be used to evaluate power potential, but they require an explicit specification of the operating rules for the reservoir. A more complete discussion of the use of optimization models to size and control hydropower reservoirs can be found in Major and Lenton [1979]; Loucks et al. [1981]; and Mays and Tung [1992].

Flow Augmentation and Navigation

It is often desirable to use water stored in a reservoir to augment downstream flows for instream uses such as natural habitat protection, recreation, navigation, and general water quality considerations. Not only is the volume of flow important, but the regulation of water temperature and other quality characteristics may also be of concern. Dilution of wastewater or runoff such as from agricultural sources is another potential objective of reservoir management. Assuming that appropriate target values can be established for flow augmentation during different times of the year, these considerations may readily be incorporated into simulation and optimization models used for developing reservoir-operating strategies. By constraining the appropriate streamflow yields at a specific time and location to be no less than some minimal acceptable value, it is possible to estimate the degradation in the resulting value of the objective function (or quantifiable net benefits) that would result from such a policy.

Real-Time Operations

Long-term operation, and planning models attempt to address questions such as: how large should the storage volume (reservoir) be? what type, and capacities of turbine, would be best for hydroelectric energy production? and how much freeboard should be allocated for flood control? Many long-term operations and planning models are based on a time scale of months or seasons (and sometimes, weeks), so that any operating rules from these models serve as guides to real-time operations but do not well define the operating policy to be followed in the short term.

Real-time operations models attempt to answer the question of how best to operate a reservoir or water control system in the short term (perhaps hours or days), using the existing physical system. Real-time operations models can have all of the model characteristics already described but they typically differ because: (1) they have a short time horizon (days, or weeks compared to years); and (2) they are used repeatedly. For example, at the beginning of a particular day, the system state — current storages, anticipated flows for the next week, etc. — is input to the model; the model is solved to determine the optimal releases to be made during each of the next seven days; the recommended release for today is actually made and at the beginning of tomorrow, the whole process is repeated with the actual new system state and forecasts.

System Expansion

The water resources management models discussed thus far have assumed a single (static) planning horizon with constant parameters (demand, release targets, etc.). More typically, investments of this magnitude span many years, during which change is continuous. While these models provide reasonable solutions for a particular future time period, they are not well suited for analyses over multiple time periods or when multiple stages of development are required. When longer-term planning is required, dynamic expansion models should be considered. Two types of optimization models are used most frequently to select an investment sequence: integer programming, and dynamic programming.

The capacity expansion integer program assumes a finite set of expansion investments for each project site over a finite number of time periods, $t = 1, 2, \ldots, T$. If the present value of net benefits of each investment is known as a function of when that investment is undertaken (NB_{st} = net present value of benefits if investment at site *s* is undertaken in time period *t*), then an objective function can be written to maximize total benefits across all project, during the planning period:

$$\text{Maximize} \sum_t \sum_s NB_{st} * X_{st} \tag{39.22}$$

where $X_{st} = 1$, if investment *s* is undertaken in period *t,* and 0, otherwise.

Constraints ensuring that each investment can be undertaken only once (or that each must be undertaken exactly once), constraints on total expenditures, and constraints that enforce requirements for dependencies among investments may also be included if necessary in this capacity expansion model. This model can also be used to determine the optimal magnitude of a particular investment, such as determining the optimal net increase in storage to add to a particular reservoir. [Morin, 1973; Loucks et al., 1981].

Integer programs are relatively easy to develop but computationally expensive to solve. In contrast, dynamic programming is an alternate approach for solving capacity expansion problems, and one that has become extremely popular among water resources professionals. Dynamic programming is particularly useful for determining strategies for making decisions about a sequence of interrelated activities (investments) where nonlinearities in the objective function or constraints are present. These models tend to be more efficient to solve but, because there are only limited commercial solution packages available for dynamic programs, they may require more time and care to develop [Mays and Tung, 1992; Esogbue, 1989].

Stochastic Reservoir Modeling

The deterministic modeling approach discussed above is based on an assumed profile of system inputs (e.g., streamflows). However, the historical record of streamflows upon which these analyses are typically based may not be sufficiently representative of long-term conditions. In stochastic reservoir modeling, available records are considered to be only a sampling of long-term hydrologic processes and are thus used to estimate the statistical properties of the underlying stochastic process. Two approaches have been developed to use the resulting stochastic model: (1) incorporate the stochastic model (e.g., a Markov model of streamflow) directly in an optimization model; and (2) use the stochastic model to generate synthetic records, which are then used as inputs for a set of deterministic models.

Consider the second option — generating synthetic records that reflect the main statistical properties of the observed historic flows (mean, standard deviations, first-order correlation coefficients, etc.). Multiple sets of these streamflow records may then be used in a variety of river basin models. (Synthetic sequences of other processes are frequently used in river basin simulation modeling, including rainfall, evaporation, temperature, and economic factors.) There are two basic approaches to synthetic streamflow generation. If a representative historic record is available, and if streamflow is believed to be a stationary stochastic process (wherein the main statistical parameters of the process do not change with time), then a statistical model can be used to generate sequences that reproduce characteristics of that historic record [Matalas and Wallis, 1976]. For river basins or watersheds that have experienced significant changes in runoff due to such factors as modified cropping practices, changing land use, urbanization, or major changes in groundwater resources (see Chapter 32), the assumption of stationarity may not be valid. In these instances, rainfall runoff models may be useful in generating streamflow sequences that can be used effectively for water resources engineering [Chow et al., 1988].

The use of synthetic sequences in simulation models is an acceptable way of dealing with uncertainty in the analysis of water resource planning and management alternatives. Recall, however, that simulation models are unable to generate optimal alternatives. The optimization modeling methodologies discussed previously can also incorporate hydrologic variability (and process uncertainties) for solution by the appropriate optimization algorithms.

The direct incorporation of the stochastic model within an optimization model permits explicit probabilistic constraints or objectives to be included [Loucks et al., 1981]. One example of this approach to the incorporation of hydrologic uncertainty into surface-water optimization models is through the use of chance constraints, which can suggest optimal reservoir size and operating strategy while enforcing prespecified levels of reliability for release and storage requirements [ReVelle et al., 1969; ReVelle, 1999; Sniedovich 1980). This technique involves the transformation of probabilistic constraints into their deterministic equivalents. Here is a probabilistic constraint on storage volumes:

$$\Pr\left[S_{\min,t} \le ST_t\right] \ge \alpha_{STt} \qquad t = 1, 2, \ldots, T \tag{39.23}$$

which ensures that the probability of the storage at the beginning of time period t being greater-than-or-equal-to a minimum storage value ($S_{\min,t}$) will be greater than or equal to some specified reliability level (α_{STt}). Similarly, for reservoir release levels:

$$\Pr\left[R_{\min,t} \le R_t \le R_{\max,t}\right] \ge \alpha_{Rt} \qquad t = 1, 2, \ldots, T \tag{39.24}$$

The result is a set of decision rules (often linear) that relate releases from the reservoir to storage, inflows, and other model decision variables [ReVelle, 1999]. This methodology can be extended to help determine strategies for planning and operating multiple reservoir systems having multiple water uses.

Water Quality Modeling

The quality of water in a stream, lake, or estuary, or the quality of groundwater is often as important as the quantity of water available. The range of pollutants of concern (e.g., heavy metals, solids, organics, heat), water quality indices (e.g., biochemical oxygen demand — BOD, temperature, total suspended solids — TSS), and specific treatment methodologies are extensive, and are described in the "Environmental Engineering" section and the "Quality of Urban Runoff" chapter of the Handbook. The impacts of these pollutants range from negligible to life-threatening.

The ability to model water quality in the natural environment has improved rapidly over the past century [see for example, Thomann, 1997]. For example, the Enhanced Stream Water Quality Model (QUAL2E) from the US Environmental Protection Agency can be used to simulate the major reactions of benthic and carbonaceous demands, atmospheric reaeration, nutrients, and algal production, and their effects on the dissolved oxygen balance in well-mixed, dendritic streams. More than a dozen water quality constituent concentrations can be modeled (www.epa.gov/docs/QUAL2E_WINDOWS). QUAL2EU is an enhancement of QUAL2E that allows uncertainty analysis to be performed.

Three-dimensional water quality models have also been developed and are in regular use. One example is the Chesapeake Bay Estuary Model (www.chesapeakebay.net/model.htm) that is three-dimensional and includes a hydrodynamics submodel as well as a water quality submodel. In addition, the estuary model is directly linked to a watershed model that predicts inputs to the estuary based on land use and other factors. It is also linked to an airshed model that predicts inputs to the estuary coming from the atmosphere. Thus, water quality models can be incorporated directly into larger and more comprehensive simulation and optimization modeling programs.

Groundwater Modeling

Comparable modeling approaches have been developed and used to solve quantity and quality problems associated with groundwater. The modeling approaches include optimization and simulation, lumped and distributed, deterministic and stochastic, and static and dynamic modeling. Further, the coupling of surface water and groundwater models to represent the actual surface and groundwater systems better is now routinely considered. For a complete description of these problems and the modeling methods used to solve them, see Freeze and Cherry [1979], Willis and Yeh [1987] and Delleur [1999].

39.4 Data Considerations

For at least four reasons there is a continuing great deal of interest in the use of spatial data as a framework for conducting water resources engineering: (1) enormous resources are being expended to collect and maintain water resources and physical attribute data within a spatial context; (2) there is a clear relationship between physical land features, which are spatially distributed, and hydrologic surface and subsurface processes [Maidment, 1993]; (3) geographic information systems (GIS) have matured to the point that they can be used to simulate hydrologic processes [Engel et al., 1993; Englund, 1993]; and (4) the integration of water resources models, spatial databases, and sophisticated user interfaces has resulted in the development of powerful (spatial) decision support systems that can be understood and used by water professionals [Fedra,1993].

Geographic information systems is a technology for storing, manipulating, and displaying geo-spatial data. While the data manipulation capabilities of GIS are still improving, the computational sophistication of these systems and the efficiency with which they can store and display data are impressive [Star and Estes, 1990]. A framework for integration of these spatial databases, traditional lumped parameter data and contextual information, with specialized water resources models is presented in Fig. 39.3. Physical, hydrologic, and possibly biological and economic data are represented as attribute maps or "layer" (A_1 - slope, A_2 - soils type, A_3 = vegetation, A_4 - depth to aquifer, etc., for example). Lumped parameter information and model parameters might be stated in a database or provided by monitoring instrumentation. The model base might include optimization screening models, or more detailed simulation models. The user would interact with the models through a graphical user interface that would allow such options as display of systems status, modification of system parameters and data sets, and display of model results.

In addition to advances in spatial data management and conventional (simulation and optimization) modeling technologies, the use of other nonprocedural modeling technologies is also being explored to improve our understanding of water resource, systems. Though simulation models have become a more important part of the technology of water resources systems engineering, many well-known and -accepted

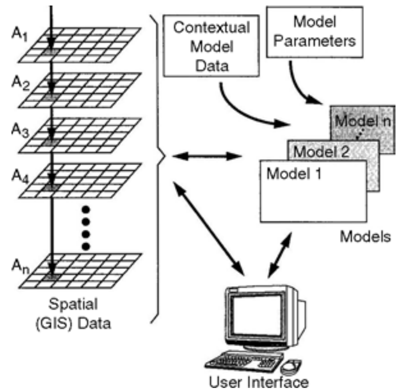

FIGURE 39.3 Functional representation of a spatial decision support system for water resources planning and management that integrates geo-referenced spatial and non-spatial data, one or more specialized models, and a custom user interface.

programs have become extremely large and complex precluding the use by inexperienced professionals. In addition, some system relationships are too poorly understood to be simulated, but may be well understood (or at least expertly managed or operated) by an individual, who possess special knowledge and expertise. Expert systems and other techniques from the field of artificial intelligence, such as artificial neural networks may be used to model water resources systems when such is the case [see, for example Bender et al., 1993; Fernandez and Naim, 2001; Davis et al., 1990].

Defining Terms

Active storage — The portion of water in a reservoir that is used to meet societal needs, such as for water supply, irrigation, etc.

Conservation — The confinement of excess flows for future societal use.

Constraints — Functional relationships that limit collective values of decision variables in optimization models.

Dead storage — The portion of water in a reservoir that is used for sediment collection and retention of a permanent pool.

Decision variable — An operational or design parameter the value of which is to be determined through formal analysis (for example reservoir capacity).

Deterministic models — Models whose inputs and parameters are assumed to be known with certainty.

Dynamic models — Models of processes the main characteristics of which are believed to change significantly over time.

Expansion model — Models that can analyze water resources investments over multiple time or planning horizons.

Firm energy — The energy produced with the plant operating at the level of firm power.

Firm power — The amount of power that can be sustained available 100% of the time.

Firm yield — The largest flow of water that can be provided continuously from a stream or reservoir.

Flood control storage — Portion of volume in a reservoir that is reserved for storing excess flow during flooding to protect downstream assets.

Future value, FV — The future value of an amount (or value) of money.

Geographic information systems, GIS — Spatial database technology used increasingly for water resources planning and management.

Gross head — The difference in elevation between the water surface immediately upstream of the reservoir structure and the elevation of the point where the water enters the turbine.

HEC-5 — A simulation model developed by the U.S. Army Corps of Engineer, designed to be used in evaluating multipurpose, multireservoir systems.

Impoundment — The volume of water stored behind a water resources reservoir.

Interest rate, i — The fraction of borrowed capital paid as a fee for the use of that resource.

Interruptible (secondary) power — Power that is generated in excess of firm power; cannot be sustained.

Optimization model — A rigid modeling structure commonly used for water resources planning and management.

N — The life (in periods) of an economic investment.

NEPA — The National Environmental Policy Act of 1969.

Net benefits, NB — The total value of benefits expected to result from some investment minus total costs.

Objective function — The function used to evaluate feasible management alternatives.

Operating rules — The policy for operation of a water resource system expressed as a set of management rules.

Optimization — A modeling procedure that determines the optimal values of the decision variables of a model.

Plant capacity — The maximum power that can be generated under normal head at full flow.

Present value, PV — The present value of an amount of money (principal).

Return period, T — The average interval in years between the occurrence of a flood of a specified magnitude and an equal or larger flood.

Rule curve — A guide to reservoir operation typically depicted as a graph showing target storage volume vs. time of the year.

Simulation — A modeling methodology that is used to describe the structure and function of a system. The model may be used to find good solution strategies for a variety of management problems.

Static models — Models of processes the major characteristics of which are assumed to not change significantly ever time.

Stochastic models — Models whose inputs and parameters are assumed to follow specified probability distributions.

Synthetic record — A streamflow sequence that is generated based an statistical properties from the historic record of streamflows.

References

Bender, M.J., Simonovic S.P., Burn, D.H., and Mohammed, W. 1993. Interactive computer graphics for expert-system verification, *ASCE Water Res. Plan. Manage*. 19(5): 518–530.

Burde, A.M., Jackel, T., Hemker, H., and Dieckmann, R. 1994. Expert system shell SAFRAN and its use to estimate the contaminant load of groundwater and soil caused by deposition of air pollutants: System we for decision making in a practical planning problem. *European Water Pollution Control.* 4(1):20–24.

Cohon, J., Rothley, K. 1997. Multi-objective Methods. In *Design and Operation of Civil and Environmental Engineering Systems*, ReVelle, C., McGarity, A. (eds.). John Wiley, New York.

Davis, R., Cuddy, S., Laut P., Goodspeed, J., and Whigham P. 1990. Integrated GIS and models for assisting the managers of an army training area. *Proc. ASCE Symp Watershed Plan. Anal. in Action*. Derange, CO. July 9–11.

Chow, V.T., Maidment D.R., and Mays, L.W. 1988. *Handbook of Applied Hydrology*, McGraw Hill, New York.

Delleur, J.W. Ed. 1999. *The Handbook of Groundwater Engineering*, CRC Press, Boca Raton, FL.

Engel, B.A., Raghavan S., and Rewerts C. 1993. A spatial decision support system for modeling and managing non-point source pollution. In Goodchild, M.F., Parks, B.O., and Steyaert, L.T. (eds.) *Environmental Modeling with GIS*. Oxford University Press, New York.

Englund, E.J. 1993. Spatial simulation: Environmental applications. In Goodchild, M.F., Parks, B.O., and Steyaert, L.T. (eds.) *Environmental Modeling with GIS*. Oxford University Press, New York.

Esogbue A.O. (ed.) 1989. Dynamic Programming for Optimal Water Resources System, Analysis. Prentice Hall, Engelwood Cliffs, N.J.

Fair, G.M., Geyer, J.C., and Oken, D.A. 1966. Water and Wastewater Engineering Vol. 1: Water Supply ad Wastewater Removal. John Wiley & Sons, New York.

Fedra K. 1993. GIS and environmental modeling. In Goodchild, M.F., Parks, B.O., and Steyaert, L.T. (eds.) *Environmental Modeling with GIS*. Oxford University Press, New York.

Fernandez, L.F.S., Haie, Naim, 2001. Neural Networks in Water Resources Management, *Proceedings of the World Water and Environmental Resources Congress ASCE*, Orlando, Florida, May.

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

Goodman, A.S. 1984. *Principles of Water Resources Planning*. Prentice Hall, Englewood Cliffs, NJ.

Hanke, S.H., Carver, P.H., and Bugg, P. 1975. Project evaluation during inflation. *Water Resources Research*. 11(4):511–514.

Hillier, F.S. and Lieberman G.J. 2000. *Introduction to Operation, Research*, 7th ed. McGraw Hill, New York.

James, L.D. and Lee, R.R. 1971. *Economics of Water Resources Planning*. McGraw-Hill, New York.

Jenkins, M.W., Draper, A.A., Marques, G.G., Ritzema, R.S., Tanaka, S.K., Kirby, K.W., Fidell, M.S., Msagi, S., Howitt, R.E., Lund, J.R. 2001, Economic Valuation of California's Water Resources and Infrastructure. *Proceedings of the World Water and Environmental Resources Congress ASCE*, Orlando, Florida, May.

Johnson, W.K. 1977. *Physical and Economic Feasibility of Non-structural Flood Plain Management Measures.*Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA.

Lane, M.E., Kirshen, P.H., Vogel, R.M. 1999. Indicators or impacts of global climate change on U.S. Water Resources. *Journal of Water Resources Planning and Management.* 125(4):194–204.

Lettenmaier, D.P., Wood, A.W., Palmer, R.N., Wood, E.F., and Stahkiv, E.Z. 1999. Water resources implications of global warming; a U.S. regional perspective. *Climatic Change*. 43:537–579.

Linsley, R.K., Franzini J.B., Freyberg D.L., and Tchobanoglous G. 1992. *Water Resources Engineering*, 4th ed. McGraw-Hill, New York.

Loucks, D.P., Stedinger, J.R., and Haith D.A. 1981. *Water Resource Systems Planning and Analysis*. Prentice Hall, Englewood Cliffs, NJ.

McKinney, D.C., Maidment D.R., and Tanriverdi M. 1993, Expert geographic information systems for Texas water planning. ASCE Water Resource, Plan. Manage March-April pp. 170–183.

Maidment D.R. 1993. GIS and hydrological modeling. In Goodchild, M.F., Parks, B.O., and Steyaert, L.T. (eds.) *Environmental Modeling with GIS*. Oxford University Press, New York.

Major, D.C. and Lenton, R.L. 1979. *Applied Water Resources Systems Planning*. Prentice Hall, Englewood Cliffs, NJ.

Matalas N.C. and Wallis, J.R. 1976. Generation of synthetic flow sequences. In Biswas A.K. (ed.) *Systems Approach to Water Management*. McGraw-Hill, New York.

Mays, L.W. and Tung, Y.-K. 1992. *Hydrosystems Engineering and Management*. McGraw-Hill, New York.

Morin, T.L. 1973. Optimal sequencing of capacity expansion projects.*J. Hydraul. Div. ASCE.* 99(9).

ReVelle, C.S. 1999. Opti*mizing Reservoir Resources*. John Wiley & Sons, New York.

ReVelle C.S., Joeres E., and Kirby, W. 1969. The linear decision rule in reservoir management and design: Development of the stochastic model. *Water Resources Research*. 5(4):767–777.

Rippl, W. 1883. The capacity of storage reservoirs for water supply. *Proceedings Institute of Civil Engineers* (Brit.) 71:270–278.

Schultz, G.A. 2000. Potential of modern data types for future water resources management. *International Water Resources Association*. 25:1.

Sniedovich M. 1980. Analysis of a chance-constrained reservoir control model. *Water Resources Research*. 16(4): 849–854.

Star, J. and Estes, J. 1990. *Geographic Information Systems: An Introduction*. Prentice Hall, Engelwood Cliffs, NJ.

Thomas, H.A., Jr. and Fiering, M.B. 1963. The nature of the storage yield function. *Operations Research in Water Quality Management*. Harvard Water Resources Group, Cambridge, MA.
Thomann, Robert V. and Mueller, John A. 1997. *Principles of Water Surface & Quality Modeling Control*. Addison-Wesley Educational Publishers, Inc., New York, NY.
U.S. Army Corps of Engineers. Hydrologic Engineering Center HEC-5. 1982. Simulation of Flood Control and Conservation Systems Users Manual. Davis, CA.
Wardlaw, R., Sharif, M. 1997. Evaluation of genetic algorithms for optimal reservoir system operation, *Journal of Water Resources Planning and Management*, ASCE, 125(1):25–33.
Willis, R. and Yeh, W.W-G. 1987. *Groundwater Systems Planning and Management*. Prentice Hall, Englewood Cliffs, NJ.
Yeh, W.W-G. 1985. Reservoir Management and Operations Models: A State of the Art Review. *Water Resources Research*. 21(12):1797–1818.

Further Information

Ang, A.H-S. and Tang, W.H. 1984. Probability Concepts in Engineering Planning and Design, Volume 1: Decision, Risk and Reliability. John Wiley & Sons, New York.
Blanchard, B.S. and Fabrycky W.J. 1990. *Systems Engineering and Analysis*. Prentice Hall, Englewood Cliffs, NJ.
Cohon, J. 1978. Multi-objective Programming and Planning. Academic Press. New York.
Fabrycky W.J., and Blanchard, B.S. 1991. *Life-Cycle Cost and Economic Analysis*, Prentice Hall, Englewood Cliffs, NJ.
Grant, E.L., Ireson, W.G., and Leavenworth, R.S. 1990. *Principles of Engineering Economy*, 8th ed. Ronald Press, New York.
Moore, J.W. 1989. *Balancing the Needs of Water Use*. Springer-Verlag New York.
Nicklow, J.W. 2000. Discrete-time optimal control for water resources engineering and management. Water International. 25(1):89–95.
ReVelle, C., McGarity, A. (eds.). 1997. Design and Operation of Civil and Environmental Engineering Systems, John Wiley, New York.
Sofer, A., Nash, S.G., 1995. *Linear and Nonlinear Programming*. McGraw-Hill, Englewood Cliffs, NJ.
Viessman, W., Hammer, M.J., Sr., 1998. Water Supply and Pollution Control, 6th edition. HarperCollins, New York.
White, J.A., Agee, M.H., and Case, K.E. 1997. *Principles of Engineering Economic Analysis*, 4th ed., John Wiley & Sons, New York.