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Integrated Planning and Management for Urban Water Supplies Considering Multiple Uncertainties

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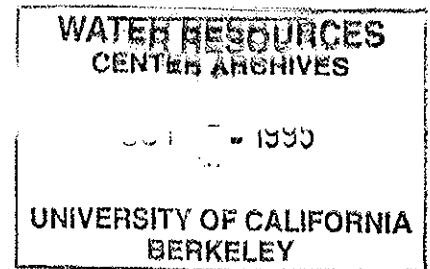
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Preface

Urban water supply planning has changed greatly in recent decades, and has generally become a much more technically serious endeavor. (Urban water supply has always been a politically serious endeavor, with abundant sources of uncertainty (Lund, 1988a, b).) Yet for all the serious and fine technical work and research on urban water supply engineering and economics, it often seems that such work has not provided a clear unified approach for combining the many technical measures available for water supply system planning and management. This report seeks to provide such a unified analytical approach, addressing the integrated economical use of yield enhancement, water transfer, and demand management measures in a context of risk and uncertainty from many hydrologic and institutional sources.

The idea for this research project began under the influence of the authors' involvement in applied research into water transfers in California (Lund, et al., 1992) for the U.S. Army Corps of Engineers and the first author's advisory involvement in urban water supply reliability studies initiated by Lyle Hoag and supported by the California Urban Water Agencies (CUWA). In many ways, this is a technical and applied research spin-off from CUWA's fine efforts in this area.

The idea of pursuing an integrated analytical framework for urban water supply reliability studies was further encouraged by Ray Hoagland's (n.d.) fine pioneering work on urban water supply reliability, to date among the most conceptually complete practical studies of the subject. The work presented here is largely in this tradition, influenced by extensions of this approach by Mark Jensen (Jensen and Lund, 1993) and a 1992 ECI 154 class project. Morris Israel, Ken Kirby, Lore Ruppe, and many other present and former students have contributed ideas and comments along the way as well.

This research effort reported here was financed by the United States Department of Interior, Geological Survey, and the State of California, through the University of California Water Resources Center, Project UCAL-WRC-W-813. Contents of this report do not necessarily reflect the views and policies of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement or recommendation for use by the U.S. Government. Other products of this project include Lund (1995), Lund and Israel (1995), and Lund (1993).

Chapter 1

Introduction

1. Problem Statement

The planning and management of urban water supplies in California has undergone great changes in recent decades with adoption of demand management measures and more recent recognition and use of water transfers. This widened range of planning measures for urban water supply engineering has been a response to increasing urban water demands, increased competition for water from other urban, agricultural, and particularly environmental water uses, and the relative absence of new inexpensive water sources. These changes have made water supply planning a much more complex problem involving a great deal of uncertainty.

In response to this increasingly complex water supply problem, water utilities have adopted increasingly complex and quantitative methodologies for evaluating proposed water supply alternatives. Virtually all major urban water supply planning and engineering studies now involve the use of simulation models. Water supply yield simulation models exist for almost all major urban water supply systems. Separate pipeline network models are typically used for studies involving water supply distribution problems. And it is no longer uncommon for water demands to be estimated using forecasting models. This increasingly quantitative engineering methodology has improved the quality and cost-effectiveness of contemporary urban water supplies. However, these new models for urban water supply engineering have not always been integrated in a way which expeditiously identifies highly promising combinations of diverse water supply management measures.

Uncertainty is a central aspect of urban water supply planning. Uncertainty is an important characteristic in evaluating any other measure of water supply design performance, such as uncertainty in yield or cost. Future water availability is uncertain due to hydrologic variability and, increasingly, due to regulatory changes. Future water demands, over most planning horizons, also are imperfectly known due to uncertainties in future economic, demographic, and land-use conditions and uncertain future uses of different water-using technologies, including changes in plumbing codes. The important costs of different aspects of water management alternatives are often similarly uncertain and incurring additional costs is often desirable to improve the reliability of urban supplies. Various types of water transfers, demand management, and yield augmentation are often sought to improve the reliability and cost of urban water supplies. However, while component models of a water supply all improve the ability to examine uncertainties in each water supply component, they have not yet been well integrated to provide a comprehensive picture of urban water supply reliability and its management. The intent of this work is to develop and apply

for planning water transfers for urban supplies from fundamental legal and economic issues to the more applied, and perhaps more complex, engineering issues. These engineering issues center on how the various types of water transfers can be integrated with various forms of traditional water supplies and water conservation in the planning and management of urban water supply systems given multiple uncertainties.

A by-product of this approach and these methods is an integration of the often mutually oblivious fields of engineering and economics. Important economic issues and problems are implied by these engineering problems and methods. Some fundamental engineering problems also are implied by the fundamental economic nature of this design and planning problem. This research provides an opportunity to apply economic concepts to engineering, and perhaps vice versa.

3. Overview of Proposed Technical Approach

The major product of this report is an integrated technical method for developing economical urban water supply plans. The method is integrated in its explicit consideration of a wide range of water yield enhancement, water conservation/demand management, and water transfer measures within a unified analysis. In doing so, the method considers the entire water supply and demand system. The method also integrates economic and engineering perspectives on water supply planning problems, using economics as a basis for evaluating and designing attractive engineering solutions.

More narrowly, the method presented is technical. The important and multi-faceted public participation, legal, and political aspects of urban water supply problems are represented conveniently as technical assumptions in the model, including explicit representation of institutional uncertainties. It is hoped that this technical approach might contribute technical (economic and engineering) insight to the public, legal, and political decision-making arenas where major water supply decisions are actually made.

The overall methodology is summarized schematically in Figure 1. Here, a fairly traditional water supply yield model is used first to provide a time series of water yields or water shortages, given a historical record of inflows. Such yield models typically represent important institutional uncertainties, such as future instream flow requirements, as model assumptions. This Yield model, in its simplest form, is no exception, but an elaborated form can represent these uncertainties as an assumed subjective probability distribution (discussed in Chapter 5).

alternative sets of system operating rules, and assess the economic value of permanent water transfers and supply system enhancements.

4. Overview of the Report

This report is organized into seven chapters. The next chapter (Chapter 2) reviews the application of contemporary systems analysis techniques to water supply system operations, planning, and management. The material provides the basis of water supply yield modeling for water supply systems. Chapter 3 reviews a variety of approaches to assigning probabilities to shortage events results from a yield model from a perspective of Bayesian probability. This perspective allows a more formal and rigorous approach to assigning probabilities to various shortage events. Chapter 4 presents an integrated shortage management model, which manages probabilistic water supply shortages with a variety of long- and short-term water conservation, water transfer, and water reclamation measures to minimize average annual costs. Chapter 5 is a full presentation of a water supply planning and management framework for integrated management of a variety of traditional water sources, demand management measures, and water transfers from a risk analysis perspective. This approach is applied in Chapter 6 to a realistic hypothetical example based on a simplification of the East Bay Municipal Utility District's (EBMUD) system. Chapter 7 concludes the report.

Chapter 2

Urban Water Supply Planning and Management

"I shall now treat the ways in which water should be conducted to dwellings and cities. ..."
Vitruvius (1st c. B.C., Book VIII, Chapter V)

This chapter reviews the nature of urban water supply problems and the engineering and planning techniques that have been applied to them. The discussion begins with a review of the management measures available for urban water supply engineering, followed by a presentation of the sources of uncertainty involved in water supply planning, and concludes with a brief review of techniques applied to the engineering of management measures to create and sustain urban water supplies.

The management measures available for urban water supply engineering can be divided into three broad categories. Water transfers or markets have received the most attention recently, while demand management or water conservation and yield enhancement are more traditional approaches taken to the problem. The following sections review each of these three categories of water supply management measures.

1. Water Transfers for Urban Water Supplies

Use of Water Transfers in Urban Systems

The integration of water transfers into urban water supply planning and management will be at least as complex a technical task as the still imperfect application of water conservation to urban systems. Some aspects of the use of water transfers in urban water supply planning and management are discussed by Lund, et al. (1992). There is a wide variety of water transfer types, listed in Table 2.1. Each type of water transfer has different operational and planning characteristics for urban supplies. The functions or uses of the many different forms of water transfers are summarized in Table 2.2. However, the integration of these many forms of water transfers into urban water supplies to serve multiple functions has received little attention (Lund, et al., 1992).

Water Transfer Theory and Applications

The theory and application of water transfers have long been explored in the economics and law literature (Milliman, 1959). Water transfers also have received significant attention in the political science literature, although this is less directly relevant here (Nunn and Ingram, 1988).

Economic theory and economic aspects of water transfers have been a frequent topic for over twenty years, and continue to be explored. Much of this literature deals with the economic efficiency of allowing transfers in water systems (Howe, et al., 1986; Brajer, et al., 1989), the use of prices from water markets to represent the marginal value of water in different uses (Colby, et al., 1987), transaction costs (Colby, 1990; MacDonnell, 1990), the institutional organization of particular water markets (Howitt, et al., 1992), and, of course, economic externalities resulting from water transfers (Howe, et al., 1990; National Research Council, 1992). This literature has also extended to examine the relative economic efficiencies of different water marketing institutions (Saleth, et al., 1991). This body of work has established many of the economic values and pitfalls of water transfers, and forms a nice foundation for more applied engineering studies.

Legal aspects of water transfers also have received a great deal of attention (Gray, 1989, 1990; Ellis and DuMars, 1978; O'Brien, 1988). Several legal aspects of water transfers have relevance to the proposed research topic. The legal approval process required for many water transfers is a source of uncertainty and risk in water supply planning. For example, is it likely that a dry-year option contract will not be enforceable or be otherwise stopped when a dry year occurs and the water utility seeks water under the contract? If a water transfer contract is signed, for almost any type of transfer, how will uncertainties in the quantity available to be transferred be handled (Ellis and DuMars, 1978)? These constitute important transaction risks to both parties in the transfer (Lund, 1993).

Engineering aspects and applications of water transfers have been studied in various locations and contexts. The use of water transfers between urban water supply systems has been an occasional topic in water engineering (Capen, 1975; Lund, 1988), as has been the design of water institutions to facilitate water transfers within the context of other water resources infrastructure (Enright and Lund, 1991). There has also been some work suggesting the optimal levels of overall water transfers between regions and water uses (Vaux and Howitt, 1984).

California's use of water transfers has been a frequent topic over the years, with particular focus on legal, economic, third-party, and political aspects (Gray, 1989, 1990; Vaux and Howitt, 1984). The engineering aspects of water transfers in California were recently summarized by Lund, et al. (1992) and Israel and Lund (1995). Others have written of specific experiences with transfers and urban water supplies (Lougee, 1991; Gray, 1990; Reisner and Bates, 1990).

From an applied perspective, one weakness of most of these economic, legal, and engineering studies is the relative neglect of problems of uncertainty in hydrology, water demand,

2. Demand Management

Conservation

Water conservation measures reduce water use. The specific goals of conservation measures can vary depending on the water supply system. Conservation can be used as a short term alternative to reduce demand during episodic shortage events, such as droughts. Conservation programs also can be used to moderate peak consumption, to delay or avoid capital expenditures for new water sources, to reduce the effects of water consumption on the environment, to reduce costs, to defer the need to use inferior quality water, and to provide utilities with more time to develop additional long term supply plans. Conservation measures include: efficient irrigation, xeriscaping, water fixture retrofits, low flush toilet replacements, conservation rate structures, and education programs (California DWR, 1991; CUWA, 1992). As more permanent conservation practices are integrated into the water supply system in anticipation of future shortage, the effectiveness of conservation to mitigate emergency shortages decreases (Lund, 1995). Therefore, short term conservation programs tend to be more drastic and expensive than long term conservation efforts. In assessing the cost of conservation measures both the cost of implementing the measure and the forgone revenue by the water supplier should be considered (Weber, 1993; Mann and Clark, 1993).

Water Reuse

Reused water can function to added to the supply system as a new source of water or can function for pollution control. Reused water has been used for agricultural and landscaping irrigation, industrial process and cooling water, complying with environmental instream flow requirements, groundwater recharge, and direct consumptive use. The use of reused water has been steadily increasing as a result of severe droughts and stringent Federal Water Pollution Control regulations that generally require a minimum of secondary treatment and in some cases, advanced treatment to meet municipal discharge standards. Using reused water for landscaping application generally requires only secondary treatment and disinfection while potable reuse requires much more extensive treatment. Potable reuse requires in addition to primary and secondary treatment, treatment processes such as recarbonation, multimedia filtration, selective ion-exchange, carbon adsorption, reverse osmosis, and disinfection. In general, water reuse for nonpotable purposes is more feasible and cost effective than for potable uses (Asano and Madancy, 1984).

In evaluating the cost of reuse as a water supply source, the costs of additional treatment, the re-distribution system, and operation and maintenance should be considered. The major cost of wastewater reclamation is the cost of distribution (approximately \$300/acre-ft (AF)) to which

Simulation Models of Water Supply Yield

Simulation models have been created for many specific reservoir systems. The Colorado River Simulation Model (CRSM) is an example of a river basin specific simulation model. The CRSM, a component of the Colorado River Simulation System (CRSS), is a deterministic simulation model developed by the Bureau of Reclamation for maintaining storage levels in Lake Powell and Lake Mead in accordance with the "Laws of the River". It is used to model proposed modifications to the river system operation and study their effects on the quantity and quality of water in the river. The model is based on monthly time steps and on meeting end-of-month storage targets (Cowan et al, 1981).

Some simulation models attempt to be more general and can be applied to various system configurations and objectives. For example, HEC-5 is a general simulation model applied to a wide variety of systems. HEC-5 was developed by the Army Corps of Engineers and provides monthly, daily, and hourly simulation of reservoir operation and stream flow routing through a network of conveyance and storage systems. It is used mainly for hydropower and flood control objectives (Feldman, 1981). STELLA (Systems Thinking Experimental Learning Laboratory with Animation) is an interactive graphically oriented program designed to aide in constructing dynamic systems simulation models. Karpack and Palmer (1992) used STELLA to develop simulation models for the Seattle and Tacoma, Washington water supply systems and evaluate the potential value of an intertie between the two major water suppliers. The graphical environment and user interface allowed rapid construction of the models, great flexibility, high quality graphical presentation, and the potential for non-programmers to understand the model contents and assumptions. ResQ is an interactive single reservoir operation simulation model designed for microcomputer use. The program has four components: data acquisition, management and processing, analysis model, and interface with the user. The analysis model is based on a recursive continuity equation and can be used either to determine suitable operating rules to meet specified demands or to determine the effects of specific operation rules on the yield (Ford, 1990). Spreadsheet programs such as Excel have been used for relatively simple reservoir-analysis simulation models.

Yield simulation models can provide estimates of shortage event probabilities given assumptions about water use, system configuration, and operating rules of the system. The GRAM (General Risk Analysis Model) developed by Hirsch (1978), was applied to the Occoquan Reservoir to estimate a set of shortage emergency probabilities. The produced shortage probability distribution can be used by water system managers to better understand their system's reliability, estimate system yield, and reform operating rules to improve system reliability.

Simulation models also can be used in conjunction with optimization. WASP is an

(1995) presented a mixed integer programming model to determine triggers, measured as the reservoir storage volumes plus inflow, for rationing. The objectives of the model were to maximize the number of days without drought and to minimize the number of extreme drought events. The model showed that trigger volumes are sensitive to the number of extreme events allowed. As tolerance for extreme events decreased, the number of small shortage events and the trigger volume value for those events increased.

4. Uncertainties in Water Supply Planning

Uncertainties in environmental regulations, demand, and hydrological forecasts can greatly affect urban water supplies.

Hydrologic Uncertainty

Hydrologic uncertainty arises from the annual and seasonal variability in rainfall, snowfall, evaporation, snowmelt, and, ultimately, runoff. Traditional water resources planning has focused almost exclusively on hydrologic uncertainty in water supply yield (Rippl, 1883; Vogel, et al., 1995). Thus, the effects of hydrologic uncertainty on water system yield are rather well understood. Hydrologic uncertainty also can have considerable effects on water demands (especially where rain-fed lawn watering or "dryland" farming are common) and the ability to complete water transfers, issues of potentially great importance for contemporary urban water supplies.

For water transfers, hydrologic uncertainties affect the availability of water for transfer (also affecting its spot-market price) and the availability of existing and other alternative water supplies (in wet years, transfers may be unneeded). For dry year options, hydrologic uncertainty might affect the availability of water from suppliers with relatively junior water rights.

Water Demand Uncertainties

Water demand uncertainties exist in the long term due to uncertainties in the growth of urban regions, future use of water-using technologies, future plumbing codes and land-use regulations, etc. There is also a degree of short-term uncertainty in urban water demands due to variation in weather patterns. Uncertainty in agricultural water demands may also affect the price and amount of water available for transfer to urban users or the withdrawals of senior agricultural water users. Agricultural water demand is subject to variations in weather patterns, changes in agricultural product prices and subsidies, changes in environmental regulations, and other factors. These uncertainties can have significant impacts on system performance (Ng and Kuczera, 1993).

simple water demand forecasts to be grossly in error and based on unrealistic projections of both population and future per-capita water use (Lund, 1988a, 1988b). Single-valued demand estimates also ignore the flexibility of water demands in the face of shortages. The estimation of yield as a single number also had evident problems. Usually a source provides more water than the firm yield, and as development of new sources became increasingly expensive and demands grew, firm yield became overly expensive and difficult to provide. Basing design on the "worst drought of record" also became somewhat difficult to defend. As years pass, new droughts occur, raising the possibility of lower "firm yields" as the record length increases. Basing design on a system's "firm yield" became increasingly seen as a very expensive and inflexible way of avoiding even the smallest and least expensive shortages (Russell, et al., 1970).

6. Contemporary Water Supply Engineering

Water supply planning has become more sophisticated since the 1960s. Water demands are presently made using better researched and often more sophisticated forecasting methods. While forecasts are still subject to important errors, they are far more reliable and are used with more sophistication and caution. Typically, various water demand scenarios are evaluated, reflecting optimistic, pessimistic, and expected demographic, economic, and water use assumptions. Water demands also are considered to be more flexible through the use of water conservation or demand management measures. Drought or shortage management strategies have become an explicit and well-developed part of most urban water supply plans (California DWR, 1991; CUWA, 1992).

Yield modeling and source management also have become much more sophisticated. Computer models are used to investigate a wider range of potential water source configurations and operations, with yield-reliability studies becoming common. Some qualitative attempts are usually made to find a promising match between measures which enhance yield reliability and those which reduce or modify water demands. Almost all modeling done for these purposes is simulation modeling, with simulation and sometimes forecast models tailored to specific water supply systems.

While these innovations in water supply planning have greatly improved the management of these systems and widened the range of alternatives that are considered, the integration of available water management measures into working systems has been accomplished largely in an informal way. Throughout the years, academic advice has been given to formalize various aspects of water supply planning. In many cases, this advice eventually has become applied widely with great success (Howe and Linaweaver, 1967; Maass, et al., 1966).

(Lund and Israel, 1995).

8. "Integrated Resource Planning"

In recent years, the term "integrated resource planning" or "IRP" has become popular for characterizing the need for and approaches towards a more comprehensive planning and management of water supplies (JAWWA, 1995). While use of the term "IRP" has reached a fever pitch in the consulting world, considerable variation in what is being "integrated" is evident in such studies. Attempts at the following forms of integration are sometimes evident from the literature and presentations of IRP applications to water supply problems:

1. Integration of yield improvement, demand management, and water transfer measures in water supply planning.
2. Integration of planning for multiple resources. Here, water, wastewater, and sludge management might together be the subject of an "integrated" resource plan.
3. Integration of multiple water uses in water planning. Thus, recreational, hydropower, environmental, and multiple water supply uses of a set of water resources might be planned together, in a way similar to traditional multi-purpose water resources planning.
4. Integration of the technical planning process into a social and political context. This form of integration typically strives to improve the prospects for implementing the results of a relatively technical planning process by increased public participation or "consensus-building" in the planning process.
5. Integration of multiple sources of water and their operation for improving supply system yield. This is the most limited, though technically still challenging and important, use of the term "Integrated Resource Planning".

Another distinction of "integrated" resource planning approaches is that they often attempt to make increased use of probabilistic risk assessment, compared to traditional and most contemporary water supply planning applications. Thus, water supply yield and future water demands are more often seen as being probabilistic. This is a technically difficult endeavor and one which, as shown in later chapters, becomes more interesting as attempts are made to "integrate" various uncertainties in a formal technical planning process.

While the call to comprehensiveness, explicit in much of the IRP literature and practice, is philosophically attractive, its technical and procedural difficulties are formidable. The chapters which follow are an attempt to provide a comprehensive technical approach to the integrated

Chapter 3

Plotting Positions for Water Supply Reliability

1. Introduction

Formal estimation of water supply shortage probabilities is becoming more widespread in engineering practice. Typically, this is done by assigning a probability plotting position to each result of a system simulation model which employs historical inflows to represent uncertainty in future streamflows. This chapter compares alternative approaches to assigning probability plotting positions to model results (shortages, costs, yields) and discusses formal approaches to examining the reliability of such probability estimates. The chapter also discusses the problem of assigning probabilities where shortages are scarce and compares the economic and decision-making implications of alternative plotting position formulae.

The overall intent of this chapter is to explore the assignment of exceedence probabilities to the time series of yields or shortages produced by yield models such as those most commonly employed for water supply system studies.

In trying to assess the need for new water supplies or increased demand management, water supply engineers increasingly have gone beyond firm yield studies to more formal estimations of yield and shortage probabilities. Such studies are typically based on system simulation model results, based on the historical streamflow record. A major technical problem in such an exercise is the assignment of formal probability values to the shortage amounts appearing in the simulation results, a problem somewhat similar to selecting a plotting position formula for flood studies. There is considerable uncertainty inherent in the estimates of the probability of simulated yield or shortage results based on short (<100 years) hydrologic records.

This chapter examines alternative plotting positions for such simulation model results, comparing several commonly employed and new plotting position formulae from the perspective of Bayesian inference. Explicit Bayesian analysis is undertaken to assess the probability distribution of non-exceedence probabilities for specific yield or shortage levels.

Significant changes in the shape of yield or shortage probability distributions can result from the different sets of system configurations and operating rules commonly explored in yield reliability studies. Thus, it seems inappropriate to base probability plotting positions for supply-system yield on an assumed distributional form. This situation contrasts with the use of plotting positions for flood flows, where assumed distributional forms are available to guide selection of a plotting position formula (Cunnane, 1978).

An alternative approach, obviating the need for plotting position formulae for water supply, is the use of synthetic hydrologies (Salas, et al., 1988; Vogel and Bolognese, 1995). The use of

The Bayesian approach to developing plotting position formulae for water supply reliability planning presented here provides plotting position formulae which satisfy these criteria fairly well.

3. Bayesian Derivation of Plotting Positions

Several authors have applied Bayesian probabilities to the development of plotting positions (Epstein, 1985; Box and Tiao, 1973; Hirsch, 1978). These approaches begin by considering the probability distribution of an exceedence probability for a yield or shortage event i . Without observations, the exceedence probability of a given level of event is highly uncertain. The uncertainty of these situations is represented by the probability distribution of the exceedence probability of event i , $P(p_i)$, the *prior* in Bayesian analysis. This prior probability distribution is represented variously by different authors.

Bayes Theorem is then applied to use data to update this prior distribution,

$$(1) \quad P(p_i|r_i,n) = \frac{P(r_i|p_i,n) P(p_i)}{\int_0^1 P(r_i|p_i,n) dp_i} = \frac{P(r_i|p_i,n) P(p_i)}{P(r_i|n)},$$

where r_i is the number of occurrences exceeding shortage event i observed in n observations. The denominator $P(r_i|n)$ is a constant, not varying with p_i , and so can be solved later as a scaling constant to ensure

$$(2) \quad \int_{-\infty}^{\infty} P(p_i|r_i,n) dp_i = 1.$$

$P(r_i|p_i,n)$ is the likelihood function, indicating the probability of r_i exceedences out of n trials, given that p_i is the known probability of exceedence. With this interpretation and the assumption that exceedences of shortage event i are independent (a Bernoulli process), $P(r_i|p_i,n)$ is a binomial distribution,

$$(3) \quad P(r_i|p_i,n) = p_i^{r_i} (1-p_i)^{n-r_i}.$$

The posterior distribution of the exceedence probability, $P(p_i|r_i,n)$, then varies with the interaction of the above binomial distribution and the prior distribution $P(p_i)$. The posterior distribution, in this case, is the probability distribution of the probability of exceeding event i , given both the prior distribution and observing that this event was exceeded r_i times out of n observations. For a wide variety of prior probability distributions, the conjugate posterior distribution is a Beta distribution:

$$(4) \quad P(p_i|r_i,n) = \frac{p_i^{a_i-1} (1-p_i)^{b_i-1}}{B(a_i,b_i)},$$

with parameters $1 \leq a_i < \infty$ and $1 \leq b_i < \infty$ and $EV(p_i|r_i,n) = a_i/(a_i+b_i)$ (Abramowitz and Stegan, 1965). The values of parameters a_i and b_i are determined by the interaction of the prior and likelihood distributions. The constant $B(a_i,b_i)$ does not vary with p_i , but does vary with shortage

prior distribution can also be derived by working backwards through Bayes' theorem and the Bernoulli likelihood assumption to find the prior distribution for each plotting rule,

$$(7) \quad P(p_i) = c p_i^a (1-p_i)^b,$$

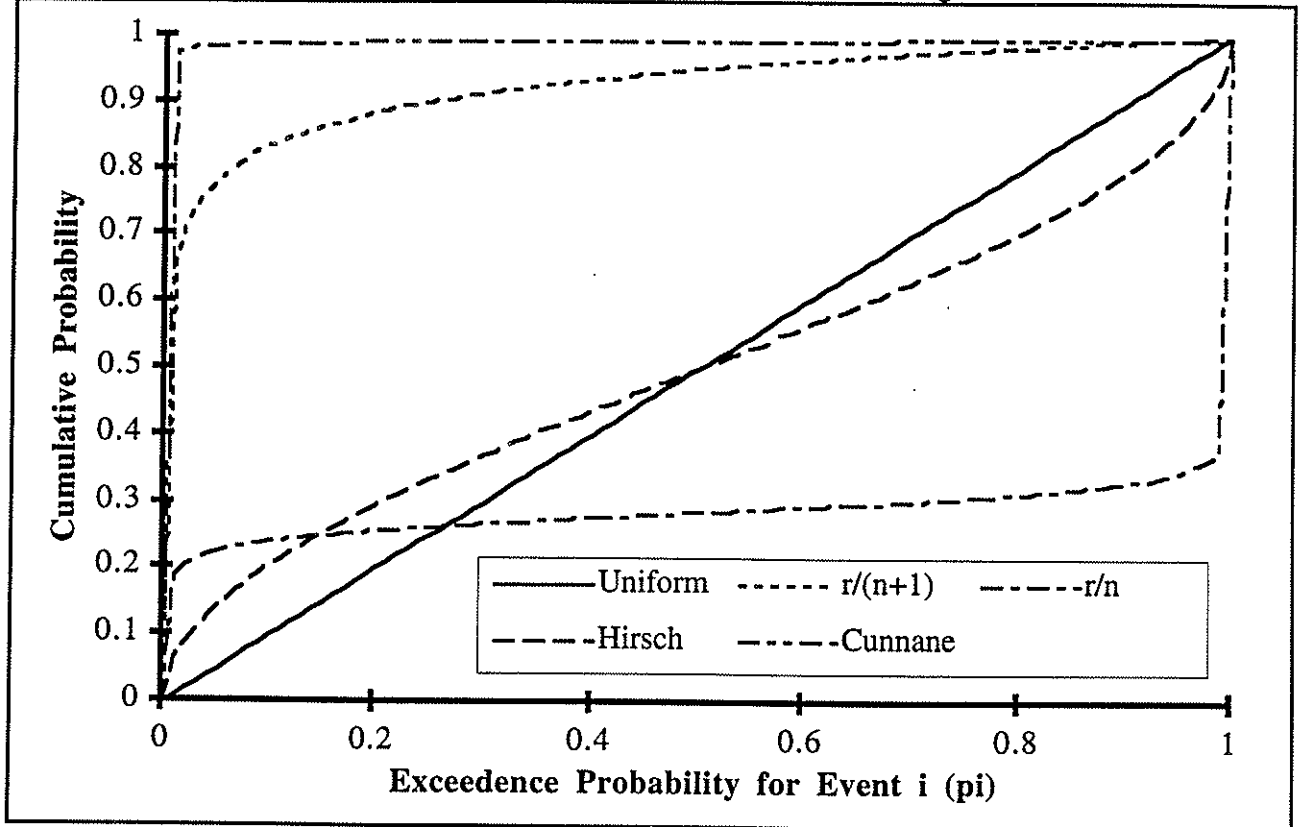
where the parameters $a = a_i - r_i$, $b = b_i - n + r_i$, and c is a constant to ensure that $P(p_i)$ integrates to one over the range $0 \leq p_i \leq 1$.

Table 3.1 contains the priors implied by various plotting position formulae when interpreted in the Bayesian manner described above. The comparison of these priors, from this Bayesian perspective, allows a comparison of the prior information about exceedence probabilities assumed for each plotting position formula. Note that the prior probability distributions do not vary with sample size n , or event rank r_i , or even event i . The prior probability distribution of exceedence probability for an event should represent the analyst's judgment of the subjective distribution of the probability of the event before any data has been collected and before any yield modeling has been done.

For illustrative purposes, these priors are plotted in Figures 3.1a and 3.1b in their density and cumulative forms. (Scaling problems prevent the Cunnane formula appearing in Figure 1a.) For the common probability plotting rules, r/n , $r/(n+1)$, and $(r-0.4)/(n+0.2)$, the "tails" of the prior probability distribution of the exceedence probability are heavy indeed, perhaps reflecting their development and use for conventional flood frequency analysis.

The priors for the $r/(n+1)$ (Weibull) and $(r-0.4)/(n+0.2)$ (Cunnane) imply that all events, presumably shortage events, are rare and have low exceedence probabilities. The r/n rule's prior assumes that events begin mostly with either low or high exceedence probabilities, before data and modeling have been completed. There seems little except perhaps reasonable subjective judgment to establish such seemingly informative priors. The $(r+1)/(n+2)$ rule with a uniform prior has a maximally uninformative prior (Jaynes, 1968).

Figure 3.1b: Implied Prior Cumulative Probabilities of Common Plotting Position Formulae



6. Comparison of Formulae Results

This section provides a comparison of the different posterior distributions of exceedence probability and the expected value (mean) exceedence probability resulting from each of the above prior probability distributions. These results all stem from the Beta distribution in Equation 4, with the appropriate values of a_i and b_i for each plotting position formula's implied prior distribution (Table 3.1).

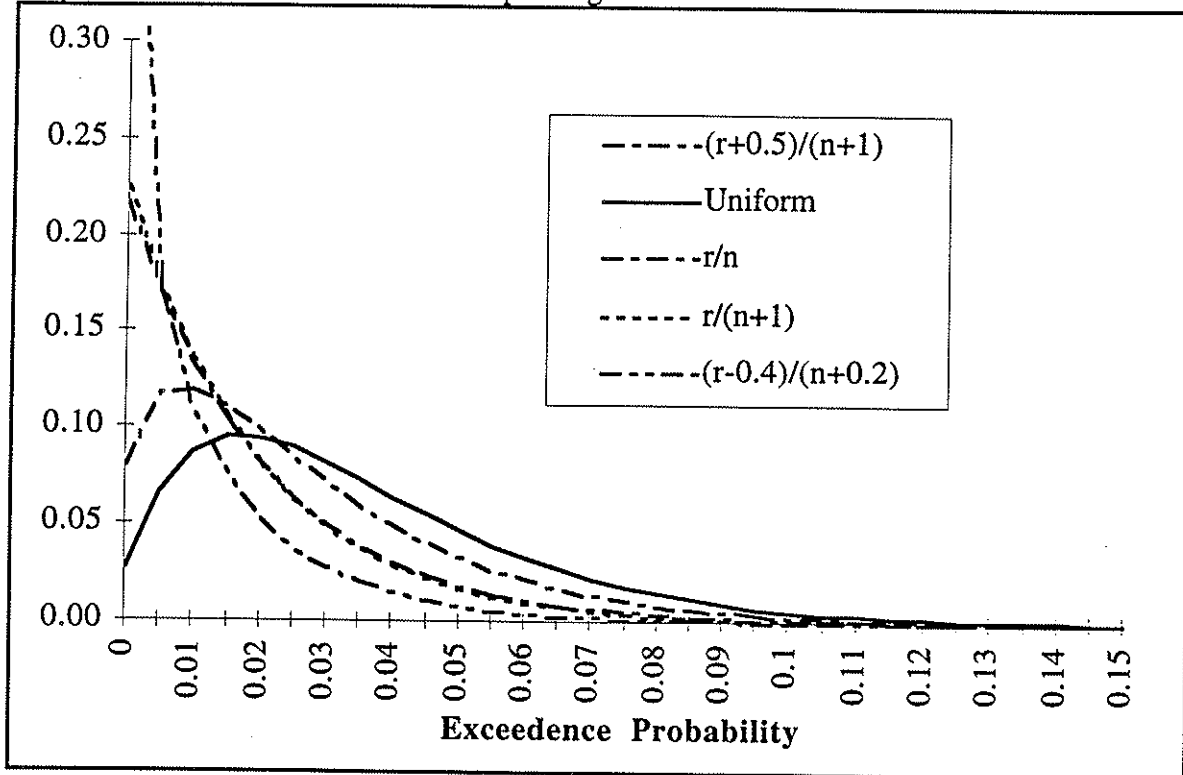
Figure 3.2 below shows the posterior probability distributions of the exceedence probability of the worst yield level observed for a system simulation over a 50-year record for each of the prior probability distributions associated with the plotting position formulae discussed above ($r=1$, $n=50$). The expected value for each of these distributions of exceedence probabilities is the plotting position. These Beta distributions are a probabilistic representation of the uncertainty of the exceedence probability of this worst event, given the different prior distributions.

The effects of increased amounts of data on the uncertainty in the exceedence probability is shown by comparing Figure 3.2 with Figure 3.3, with four times as much data, keeping r/n constant so that $r=4$ and $n=200$ in Figure 3.3. For this case, assuming both sets of r and n

simulated event. The $(r+0.5)/(n+1)$, r/n , $r/(n+1)$, and $(r-0.4)/(n+0.2)$ rules become increasingly "optimistic", expecting lower frequencies of this worst event for any record length, n .

The absolute magnitude of the range in the probabilities assigned to this worst event by the different rules decreases significantly with increased record length. This might be important for the use of these probabilities in planning and decision-making (not necessarily the same) problems, making it less likely that the selection of a probability plotting formula has economic or decision-making importance for long record lengths. An approach to test this condition is presented in a later section.

Figure 3.2: Bayesian probability distribution for the exceedence probability of the worst event in a 50-year historical record for different plotting rules



7. Interpolating and Extrapolating with Rare Shortage Events

Another problem posed in probabilistic planning for water supplies using historical hydrology is that there are rarely shortages that result from a repeat of the historical record. Most water supply systems have been designed using a firm yield approach, often implying that no shortage is expected with a repeat of the worst drought of record. Assigning probabilities to the range of unexperienced and unrepresented severe drought hydrologies requires extrapolation beyond the worst event of record. The remaining cumulative probability, $1 - \bar{P}_{\text{worst}}$, must be distributed over the range of shortages between the worst shortage simulated and 100% shortage, the un-exceedable maximum.

A lesser, but still potentially important problem is distributing probability among shortage or yield levels that fall between shortage or yield events realized in the simulation results. Where shortage events are rare, numbering typically less than half a dozen in a record length of over 50 years, there is likely to be some coarseness to the realized events relative to what would be desirable for planning or decision-making purposes. If a simulation run with a 50-year historical hydrology yields only three shortages, one each of 10%, 40%, and 50%, what is the probability of a 20% or 30% shortage?

This is an interesting, but hopefully unimportant, problem. A maximum-entropy (Tribus, 1969; Englehardt and Lund, 1992) approach to this problem would be to uniformly distribute the differences in cumulative distribution values between realized shortage or yield values, i.e., linear interpolation of probability between shortage result values. Thus, for the question above, the exceedence probability assigned to the 20% shortage level would be that of the 10% shortage level, plus one third of the difference between the exceedence probabilities of the 40% and 10% shortages (found by plotting positions). Still another approach would be to fit a cumulative distribution to those few points estimated by plotting positions formula, perhaps using a spline fit to preserve the plotting positions of the simulated results. This issue appears unresolved.

8. Limitations and Concerns

Two major potential limitations and concerns arise in this analysis. First, is the Bernoulli distribution an appropriate likelihood function for use in this application of Bayes' theorem? The use of a Bernoulli likelihood function in Equation 5 brings the assumption that shortage events are not correlated in time. We know this is frequently not true. Yet, if shortage or yield events are correlated in time, what should be the likelihood function for use in Bayes' theorem? This problem is further compounded by the likely variability of the correlation of yields or shortages with different system configurations or operating policy decisions.

response to these shortages, except for the Uniform $((r+1)/(n+2))$ plotting formula. The differences in willingness to pay to avoid shortages for these first four plotting rules here arise solely from the different probabilities assigned to each shortage level for the expected value calculations. This difference in expected shortage costs estimated from the different plotting position formulae would seem to encourage greater hedging in storage operations where the more "pessimistic" of the first four plotting position formulae are used (such as $(r+0.5)/(n+1)$). In addition, changes in the plotting position rule also affect the overall probability of any shortage, which can affect both shortage management decisions and the expected value costs of any set of decisions.

For this case, the greater shortage probabilities from the use of the Uniform plotting rule change least-cost shortage management decisions as well as further increase the expected value of shortage costs which result from these decisions. The changes in shortage management decisions include a shift from some short-term management measures (emergency water conservation and spot-market water transfers) to more long-term measures (plumbing retrofits and dry-year-option water transfers).

For this moderately severe case, the selection of a shortage plotting position formula appears to have some importance for evaluating alternative system configuration and operation decisions (reflected in differences in the expected shortage cost values). The choice of plotting formula can also be important for the design of least-cost shortage management plans.

Table 3.3: Exceedence Probability Estimates for a 73-year Historical Hydrology

Shortage Level	Rank of Exceedences	Probability Plotting Position Formula				
		$\frac{r}{n}$	$\frac{r}{n+1}$	$\frac{r-0.4}{n+0.2}$	$\frac{r+0.5}{n+1}$	$\frac{r+1}{n+2}$
87%	1	0.014	0.014	0.008	0.020	0.027
64%	2	0.027	0.027	0.022	0.034	0.040
42%	3	0.041	0.041	0.036	0.047	0.053
22%	5 (two)	0.068	0.068	0.063	0.074	0.080
8%	6	0.082	0.081	0.077	0.088	0.093
0%	7	0.096	0.095	0.090	0.101	0.107

Chapter 4

Shortage Management Model

"It is recognized by all water professionals that the science of design and evaluation of water conservation programs has lagged behind the interest in, and need for, these programs."
California Urban Water Agencies (1992)

1. Introduction

This chapter describes the development and application of a shortage management model. This particular shortage management model employs available water shortage management measures to minimize average costs given hydrologic uncertainties. The model is applied to a simplified EBMUD system and expanded to several examples which demonstrate the strengths of the model in incorporating the effects of seasonal shortages, water qualities, and uncertainties relating to the long term and short term management options.

Water shortages and threats of water shortages have resulted in expanded consideration and development of demand management, supply enhancement, and water transfer measures. A wide range of available demand and supply management measures can be considered in devising a management plan to respond to shortage events. In developing shortage management practices, the effects of uncertainties associated with hydrology, water demands, environmental requirements and regulations, and availability of resources ideally should be examined. Other factors that can significantly affect management decisions are the effects of seasonal shortages, limitations on imported water during drought events, the effects of system operation, and the qualities of waters supplied and demanded.

Several methods have been developed to integrate different demand management measures in water supply planning. These methods examined the use of conservation measures to delay the construction of new supply sources (Rubenstein and Ortolano, 1984; Lund, 1987), the trade-off between long term and short term conservation efforts (Dziegielewski, et al., 1992), and the incorporation of water transfers as an option to increase system reliability (Lund and Israel, 1995).

This chapter describes the use of two-stage linear programming optimization to integrate long term and short term demand management and water transfer options for least-cost shortage management, considering yield reliability (Lund, 1995; Lund and Israel, 1995). The effects of hydrologic uncertainty, system operation, the availability of resources, water uses, costs, and available water supply qualities are incorporated into the model.

was diverted to irrigation and lower quality uses while increased treatment was provided to meet high quality water demands.

As drinking water requirements become more stringent, water quality management becomes more important. In this chapter, the two stage linear programming approach is expanded to include options and demands with different water qualities. Water reclamation is added as a source of supply along with water transfers and conservation efforts. Several modifications to the base case are presented to demonstrate the effect of seasonal shortages, water quality, spot market limitations, reservoir operation, and new water supply sources on shortage management.

3. Shortage Management Model Methodology

Two-Stage Linear Programming

The two-stage linear programming model is used to represent least-cost shortage management, given hydrologic uncertainty in supply system yield. This shortage management model is later incorporated, in Chapters 5 and 6, into a larger integrated system model designed to develop least-cost planning alternatives to improve reliability.

The shortage management model integrates demand reduction options and supply enhancement measures for long term and short term periods. Available shortage management decisions are divided into long-term (first stage) and short-term (second stage) management decisions. Long-term decisions must be made in advance of shortages, while short-term decisions are made during shortages and can vary with particular shortage events, as depicted in the decision tree in Figure 4.1.

The first stage decisions in the model represent long term measures such as permanent conservation measures, dry year transfer contracts, additional water treatment, and water reuse. These long-term measures have a long life span and relatively fixed annualized cost.

The second stage decisions consist of short term measures available to augment water supplies or reduce demands for particular shortage levels. Each shortage level corresponds to a different second-stage event (Figure 4.1) whose probability is based on the results of a yield model (as discussed in Chapter 3). Short term decisions are temporary responses to given shortage levels. The costs of short term measures for each shortage level are weighed by the probability of the shortage.

in the first stage. The second component is the sum of all short term measure costs responding to particular shortages weighed by the shortage probability. Equation 1 is the mathematical representation of this cost minimization objective.

$$(1) \quad \text{Minimize } z = \sum_{i=1}^{n_1} (c_{1i} X_{1i}) + \sum_{s=1}^{n_s} \sum_{j=1}^m \sum_{k=1}^{n_2} (c_{2sjk} X_{2sjk}),$$

where,

c_{1i} = unit cost of implementing long term measure i

c_{2sjk} = unit cost of implementing short term measure k in season s and shortage event j

m = number of shortage events

n_1 = number of long term measures available

n_s = number of seasons

n_2 = number of short term measures

X_{1i} = level of implementation of long term measure i (in units of implementation)

X_{2sjk} = level of implementation of short term measure k in season s and shortage event j (in units of implementation)

Decision Variables

The model decision variables are the long term (X_{1i}) and short term (X_{2sjk}) measures available to increase supply system reliability. Long term decisions include water reuse, conservation in the form of xeriscaping and water fixture replacement, additional water treatment capacity, and acquiring dry year transfer options. Short term decisions include drought conservation measures, activating dry year transfer options, and purchasing spot market water. Long term decisions are annual decisions and have units of their implementation. Thus, if a measure is toilet retrofitting, units might be the number of toilets retrofitted. Short term decisions are seasonal decisions in response to shortage events and similarly have units appropriate to their implementation. Thus, reductions in landscape watering might have units of acre-ft per season and event or it might have units of acres unwatered, depending on the chosen formulation of the problem.

The Model Constraints

The principal model constraints are the limits on implementation of long term and short term measures and the requirement of satisfying the demands at each shortage level for both dry and wet seasons. The summed results of implemented long term and short term measures converted to seasonal water volumes must meet seasonal demands (Equation 2). Long term and

xeriscaping,

f_{II} = the loss of ability to implement lawn watering reduction measure II per unit implementation of xeriscaping,

u_{2sjwI} = the upper limit of implementation of lawn watering reduction measure I in season s and event j without xeriscaping being implemented,

u_{2sjwII} = the upper limit of implementation of lawn watering reduction measure II in season s and event j without xeriscaping being implemented,

X_{2sjwI} = the implementation of lawn watering reduction measure I in season s and event j, and

X_{2sjwII} = the implementation of lawn watering reduction measure II in season s and event j.

Another example is where use of water displacement devices and other temporary water demand reduction measures depends on long term water fixture retrofitting decisions (Equation 9). The demand hardening factor (f_D) represents the reduction in the effectiveness of the short term water conservation as more permanent water fixture retrofitting are implemented.

$$(9) \quad X_{2sjD} \leq u_{2sjD} - f_D X_{1R}, \text{ for all } s \text{ and } j,$$

where,

subscript D refers to the particular short-term measure k of temporary installation of displacement devices or other temporary measures,

subscript R is the particular long-term measure i of retrofitting toilets or other plumbing fixtures, and

f_D = the unit reduction of displacement device effectiveness with implementation of plumbing retrofitting.

Water transfers often are limited by the treatment capacity available to accommodate lower quality transferred water. As a long-term measure, water treatment capacity can be expanded to increase the quantity of water that can be contracted as dry year option or purchased from spot markets (Equation 10). For each shortage level, the amount of dry year option activated is dependent on the long term decision of the dry year option contract (Equation 11). The sum of spot market purchases and activated dry year options must not exceed the total transfer limit which might vary with shortage event (Equation 12).

$$(10) \quad TT_s \leq CAP_s + w_s X_{1c}, \text{ for all } s$$

$$(11) \quad X_{2sjO} \leq X_{1O_s}, \text{ for all } s, j, \text{ and option measures } O$$

$$(12) \quad \sum_{l=1}^{n_T} (X_{2sjl}) \leq TT_s, \text{ for all } s \text{ and } j$$

where,

CAP_s = existing water treatment capacity, in volumetric units for season s,

displacement devices in toilets. The effectiveness of these conservation measures will depend greatly on the implementation of long term conservation measures. As more long term conservation measures are implemented, available short term conservation decreases. The activation of dry year options will depend on the amount contracted as a long term measure. Buying spot market water depends on the available water treatment capacity and the quantity of dry year option activated for specific shortage levels. The long term and short term alternatives considered are summarized in Table 4.1.

The base case incorporates seasonal water demands and shortages. The dry season is defined as April through October and the wet season is November through March. These seasons correspond roughly to peak and off-peak urban water demand seasons. A seasonal factor is applied to the long term measures to reflect their water savings contribution during the two seasons. Usually, seasonal factors are proportional to the number of months in each season. The seasonal factors for xeriscaping and lawn watering are based on the different water demands in the two seasons. The model formulated for the EBMUD system has six long term annual decision variables and sixty short term decision variables. Twelve constraints are associated with meeting demand at each event and season and sixty-six constraints reflect the alternatives' limits.

Table 4.1: Limits and Costs

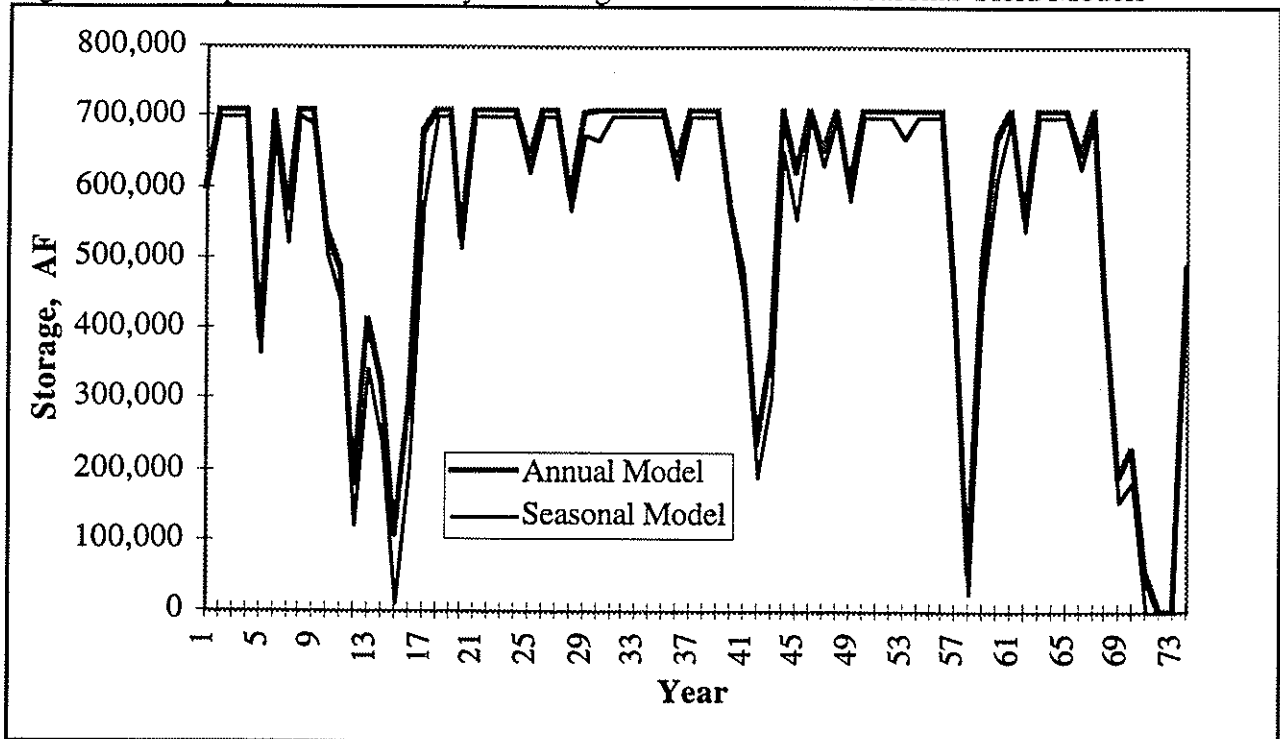
Long Term Measures	Cost (\$/AF)	Limits (TAF)	
Existing Treatment Capacity		70	
Addl. Treatment Capacity	200	50	
Total Transfers		Exist. and addl. treatment capacity	
Dry Year Option Wet Season	20	Total Transfers*seasonal factor	
Dry Year Option Dry Season	20	Total Transfers*seasonal factor	
Water Reuse	1,500	48	
Xeriscaping	150	105	
Water Fixture Retrofit	30	48	
Short Term Measures	Cost (\$/AF)	Wet Season (Nov-Mar) Limits (TAF)	Dry Season (Apr-Oct) Limits (TAF)
Activate Dry Year Option	120	Contract dependent	Contract dependent
Spot Market	Varies with event	Varies with event	Varies with event
Lawn Watering-Part I	300	Xeriscaping Dependent	Xeriscaping Dependent
Lawn Watering-Part II	700	Xeriscaping and LWI Dependent	Xeriscaping & LWI Dependent
Water Replacement Devices	400	Water fixture retrofit dependent	Water fixture retrofit dependent

5. Variations to the Base Case

Seasonal vs. Annual Models

Annual and seasonal yield simulation models can produce significantly different shortage probability distributions. The difference in the distributions can be attributed to the rough averaging and lumping of the annual simulation model. An annual system model will tend to experience less severe shortages and will tend to recover faster than a seasonal simulation model. The differences between annual and seasonal time step simulation models are reflected in Figure 4.2, indicating the difference in the extent of storage depletion and the length of time required for the system to recover under both scenarios. Depletion of storage is more severe for the seasonal model simulation as shown in year 15 and may take longer to recover as shown in years 27 through 31.

Figure 4.2: Comparison of End-of-year Storages for Annual and Seasonal Yield Models



The difference in the probability distribution can affect the results of the shortage management optimization model. A comparison of an annual model and a seasonal model indicates the different decisions and consequences of ignoring the effect of seasonality. Shortage magnitudes and frequencies for the annual and seasonal models are summarized in Table 4.3. The average shortage based on the annual model was 9,744 AF while the average annual shortage based on the seasonal model is 11,795 AF (combined seasons). The seasonal model results

Spot Market Limitations

In formulating the base case, spot market purchases are assumed to be limited by the available water treatment capacity since only limited amounts of high quality water are available if the dry year option contract is activated. During drought conditions, nearby water users will be susceptible to water shortages as well and therefore purchasing spot market water may be limited by water availability as well as treatment capacity. For this example, the base case study is modified for a range of spot market limits during water shortage events and assumes that spot market availability is independent of dry year option contracts.

The long term decisions and expected value cost based on spot market limits are shown graphically in Figure 4.3. The results indicate that limited spot market supplies induce additional long term options at greater expense to accommodate shortage. Based on the constraints in this case study, in addition to transfer options, spot market limits below 70 TAF require the installation of low consumption water fixtures, spot market limits below 60 TAF encourage the use of highly treated reused water, and spot market limits below 40 TAF incorporate conservation by way of xeriscaping. The availability of spot market water during shortages for this case is therefore important if it will be limited to less than 70 TAF, since the costs increase substantially.

This example shows that availability of spot market water can be an important factor in shortage management. As the probability of obtaining spot market water during shortages decreases, more long term measures must be implemented.

Figure 4.3: Effects of Spot Market Limitations

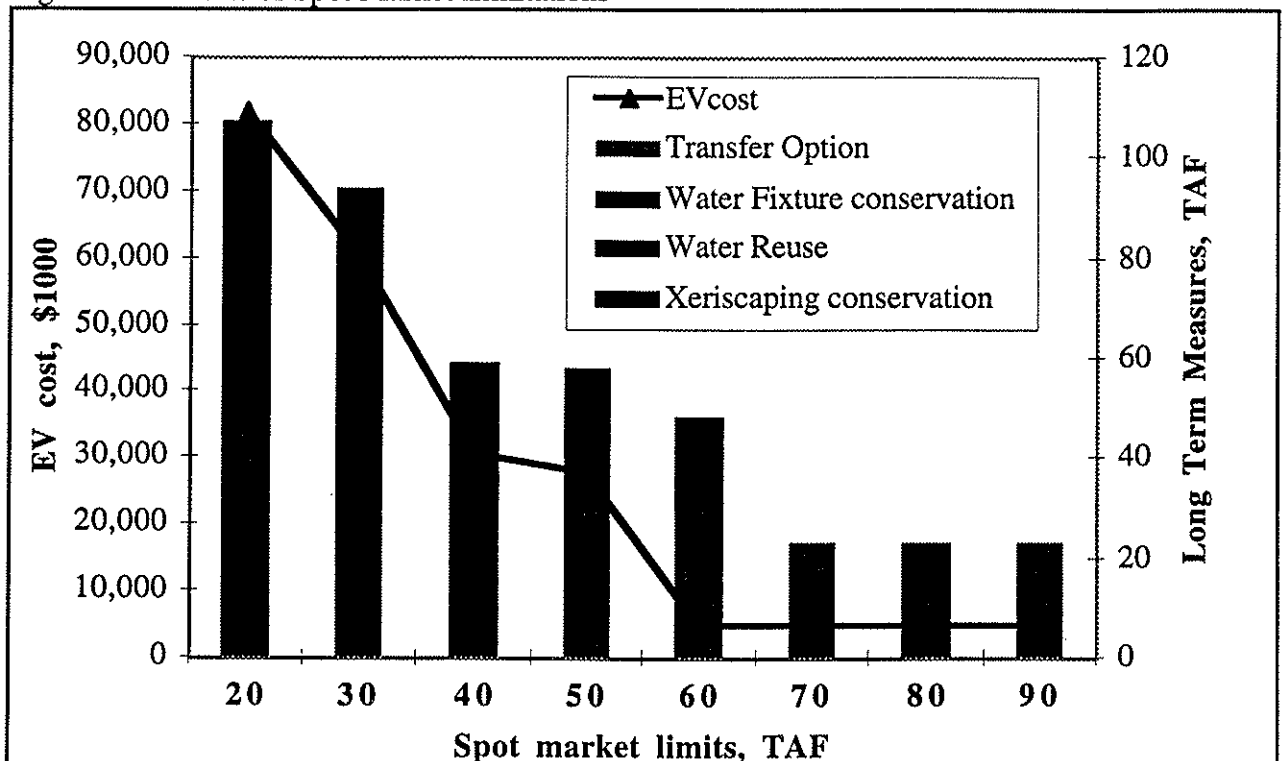


Table 4.5: Hedging Rules Scenarios

Wet Season						
% Hedging	0%	10%	30%	50%	70%	
TAF Hedging	0	14.5	43.4	72.3	101.3	
Cost (\$1000)	11,077	11,182	11,207	9,080	9,113	
Dry Season						
% Hedging	0%	10%	20%	30%	40%	50%
TAF Hedging	0	35.6	71.2	106.9	142.5	178.1
Cost (\$1000)	11,077	11,142	10,476	10,483	10,753	11,008

Table 4.6: Carryover Scenarios with 72.3 TAF Wet Season Hedging

Carryover Storage (TAF)	0	24.8	49.6	74.3	99.1
Cost (\$1000)	9,080	9,083	8,936	8,308	8,246

Hedging in the dry season has a different effect on the system than hedging during the wet season. For this case, hedging in the wet season does not change end of year storage levels significantly or the frequency of shortages but decreases the maximum shortage event in the dry season. Hedging in the wet season induces more frequent shortages in the wet season and reduces the maximum shortage in the dry season. Because shortages in the dry season are more severe, wet season hedging has greater effect on the expected value cost of system reliability than dry season hedging. Incorporating carryover storage rules when storage levels become less than 200 TAF further reduces the overall shortage management cost. Using the different distributions to generate management plans results in the same long term decisions. The difference in overall shortage management cost results from the different extreme event probabilities and the magnitude of the short term measures used. The effects of the various operating rules on shortage frequencies and magnitudes are summarized in Table 4.7.

This example demonstrates the importance of reservoir operations in affecting the supply yield probability and in the planning decisions and costs of demand management and transfers. Depending on other costs associated with altering reservoir operations, it may be cost-effective to change operating rules and decrease the dependency on short term measures to improve supply system reliability.

High quality water demand can be reduced by installing low water consumption fixtures. The difference in cost of dry year options and spot market purchases used for low and high quality water demands is the cost of water treatment required to meet drinking water standards and the additional costs associated with installing a separate distribution system.

To incorporate two types of water qualities into the shortage management model, the objective function was revised and new constraints added. For this water quality example, twenty-five additional decision variables were added and thirty-seven additional constraints. Equation 13 is the mathematical representation of the revised objective function and includes the quality subscript q for decision variables, unit costs, and numbers of long term and short term options. An additional long term decision is increasing the capacity of a dual distribution system for distributing low-quality waters.

$$(13) \text{ Minimize } z = \sum_{q=1}^2 \left(\sum_{i=1}^{n_{1q}} (c_{1qi} X_{1qi}) + \sum_{s=1}^{n_s} \sum_{j=1}^m \sum_{k=1}^{n_{2q}} (c_{2qsjk} X_{2qsjk}) \right)$$

The constraints in Equations 2 through 12 are modified similarly and expanded to reflect water quality aspects and limitations. Equation 2 is expanded in Equation 14 to reflect the interaction between demands for high and low quality waters, with use of low quality water reducing demands for high quality water. Here, $q=1$ represents high quality water. Equation 15 is a modification of Equation 2 for low-quality water ($q=2$), forcing use of low-quality water to be less than its overall availability and use-reduction. Equation 16 limits use of low-quality water to the capacity of the low-quality distribution system plus any conservation within the low-quality distribution system. Ready analogies can be made for generalizing the constraint Equations 3 through 13 for multiple water quality situations. This includes situations, like Equation 10, where long-term measures would be available to expand the low-quality distribution system (thereby expanding CAP_{2s}).

$$(14) \quad \sum_{i=1}^{n_{11}} (e_{11sji} X_{11i}) + \sum_{k=1}^{n_{21}} (e_{21sjk} X_{21sjk}) + a_{1sj} \geq d_{sj} - D_{2sj}, \text{ for all } s \text{ and } j,$$

$$(15) \quad \sum_{i=1}^{n_{12}} (e_{12sji} X_{12i}) + \sum_{k=1}^{n_{22}} (e_{22sjk} X_{22sjk}) + a_{2sj} \geq D_{2sj}, \text{ for all } s \text{ and } j,$$

$$(16) \quad D_{2sj} \leq CAP_{2s} + \sum_{i=cons.} (e_{12sji} X_{12i}) + \sum_{k=cons.} (e_{22sjk} X_{22sjk}), \text{ for all } s \text{ and } j,$$

where,

D_2 = total use of low-quality water to satisfy total water demands

d_{sj} = total water demands (both high and low quality) in season s and shortage event j

CAP_{2s} = the capacity of the low-quality distribution system in season s

shortage management model (Table 4.9). The willingness to pay for the canal construction, operation and maintenance can be calculated as the reduction in expected value cost of providing system reliability associated with having access to American River water. In simulations described in Chapter 6, the number of shortages was reduced from five to two and the probability of the large shortages was reduced. The revised distribution, when used in the shortage management model, reduced the expected value cost for managing shortages by \$306,000/year. The valuation of new supplies or changes in operation that modify the yield reliability distribution are examined in much greater detail in Chapter 6.

Table 4.9: Results of Shortage Management Model with American River Water Supply

Long Term Annual Decisions (TAF)						
Conservation		Dry Year Option Contract		Water Treatment Capacity Expansion	Water Reuse	Total Cost (\$1000)
Xeriscaping	Water Fixture	Dry Season	Wet Season			
0	48	56	0	26	0	7,760
Short Term Seasonal Decisions (TAF)						
Shortage Information				Measures implemented		
Event	% Shortage	probability	Shortage (TAF)	Measures Implemented	Cost*p	
1Wet	0%	0.96	0	none	0	
2Wet	20%	0.003	18	none	0	
3Wet	40%	0.003	37	Spot market	10	
4Wet	60%	0.003	55	Spot market	32	
5Wet	80%	0.003	74	Spot market, conservation	62	
6Wet	100%	0.029	92	Spot market, conservation	1,110	
1Dry	0%	0.96	0	none	0	
2Dry	20%	0.003	38	Dry year option	3	
3Dry	40%	0.003	75	Dry year option	17	
4Dry	60%	0.003	113	Dry year option, conservation	46	
5Dry	80%	0.003	150	Dry year option, conservation	91	
6Dry	100%	0.029	188	Dry year option, conservation	1,640	
Total Expected Value Cost (\$1,000):						10,771

6. Sensitivity Analysis

Varying degrees of uncertainty are associated with determining the costs, limits, and effectiveness of the long term and short term measures used in the shortage management model. And these uncertainties depend on the water system studied. For example, the cost of water reuse which includes treatment cost, conveyance, and the benefit associated with utilizing wastewater effluent instead of discharging to the environment will vary with available technology, existing infrastructure, and changing environmental regulations. The quantity of water that can be saved

from \$150/AF to \$20/AF, in which case it would be more cost effective than short term conservation reductions in lawn watering. Water reuse would be considered as an additional source of water if its unit cost is reduced to \$225/AF in which case it would be more cost effective than implementing water transfers and the required additional water treatment capacity.

Range in Unchanged Basis

The allowable increase or decrease in the coefficients of both the objective function and the constraints is the range in which the same long term and short term decisions are preferred. Increasing the cost of the dry year option contract by \$4/AF or more for the dry season will trigger more spot market purchases to replace the dry year alternative. On the other hand, reducing the cost of a dry year option contract by \$3/AF will prompt use of the wet season contract option. For the base case, knowing the cost of contracting dry year option is important in developing long term and short term planning decisions. The cost of water reuse and increased water treatment capacity will have to be reduced by 80% and increased by 600%, respectively, before affecting the results. Planning decisions are not sensitive to changes in the costs of water reuse and additional treatment capacity and therefore uncertainty associated with these decisions is not significant for this example. As shown in the spot market limit example, the solution is sensitive to the amount of available spot market water in the dry season, particularly in extreme shortage events. Reduction in spot market limits beyond 40 percent will trigger new long term and short term decisions.

7. Conclusions

This shortage management model, based on two stage linear programming, is potentially valuable for identifying promising combinations of long term and short term measures to respond to probabilistic shortages in an economical manner. The model also is valuable as a tool to understand the effects of uncertainties relating to cost, availability and effectiveness of the measures used to improve system reliability. The following conclusions can be made regarding particular measures for the example presented:

1. Limitations on spot market and water transfers during droughts encourage long term conservation measures such as xeriscaping and water fixture retrofit.
2. Water reuse as a means of improving water supply reliability is economically unattractive as long as other conservation measures and water transfers are possible. It may become advantageous to employ water reuse as a water supply option as technology improves (reducing the cost of treatment), demand hardening increases with installation of permanent conservation measures, environmental regulations become more stringent, and/or water demands increase.

Chapter 5

Water Supply Reliability Modeling

"One afternoon they take me from Oraibi to Shupaulovi to witness a great religious ceremony. It is the invocation to the gods for rain." John Wesley Powell (1895, p. 338)

1. Introduction

This chapter explains an engineering-economic-based reliability modeling process suggested for urban water supply planning and management studies. The approach combines traditional water supply yield studies (Chapter 2), whose shortage results have been assigned probabilities (Chapter 3), as inputs to a least-cost probabilistic shortage management model (Chapter 4). Institutional uncertainties also can be incorporated into this modeling framework. The approach presented in this chapter is applied to an example in Chapter 6.

Water supply reliability modeling is an approach to resource planning and management that explicitly incorporates uncertainties and incomplete information into the engineering analysis of alternative water supply strategies. The impact of the interaction of different sources of institutional and hydrologic uncertainty associated with water transfers (presented in Chapter 2) is one of several important considerations in the evaluation and planning of water transfers for urban water supplies. For this study, a water supply system reliability model has been developed that incorporates different forms of water transfers with various traditional water sources and water conservation measures. The purpose of this modeling work is to develop and test a systems analysis approach to identify the least cost mix of different water transfer types, water conservation, and traditional supply augmentation measures for urban water supplies under the combined effects of various sources of uncertainty. This effort demonstrates an important expansion of traditional approaches in water supply reliability analysis through the integration of economic analysis to measure reliability tradeoffs among alternative combinations of measures. In this chapter the modeling procedure and structure are described. A simplified application is developed in Chapter 6 to demonstrate the use of this modeling approach.

Multiple Uncertainties in Urban Water Supply

Typical applications of water supply reliability modeling limit their consideration to hydrologic uncertainty of stream flow, and focus mainly on the evaluation of reservoir system yield. Commonly yield-reliability curves (Figure 5.1) are produced from system simulation models run using the historical record or synthetic stream flows (Hirsch, 1978; Vogel and Bolognese, 1995). Very little work has been done in the area of economic reliability analysis.

Integrated Urban Water Supply Management

In an integrated water supply management context, planning and management measures can be divided by roles into long- or short-term, and supply- or demand-related. Table 5.1 shows such a classification of the many types of urban water supply measures, including different forms of water transfers. The range of solutions identified in Table 5.1 encompasses structural, operational and economic types of management measures.

Long term measures involve decision-making on a planning time scale and include such things as long-term water conservation to suppress demand; the expansion of permanent supplies through the acquisition of new water rights, development of traditional water sources such as reservoirs or ground water, or development of reclaimed waste water systems; and the establishment of dry year option contracts to increase supplies during shortage events. These long term measures must be implemented well before any shortage occurs.

On an operational time scale, when water shortages occur they can be managed through short-term measures that include short-term conservation to reduce demand, the purchase of spot market water, the exercise of dry year options, wheeling of supplies from neighboring systems, or the use of reclaimed water to increase short-term supplies, as well as changes in system operations such as conjunctive use. Many short-term responses to potential shortage require the completion of specific long-term measures. For example, the wheeling of supplies from a neighboring utility requires construction of an intertie which is typically a longer-term measure.

Water transfers have many roles to play in water supply systems, both as a long term measure on a planning time scale and as a short-term measure on an operational time scale. The model presented in this chapter has been developed to integrate these multiple roles of water transfers with other traditional forms of water supply management, while analytically incorporating the effects of institutional and hydrologic uncertainties in a economic-based framework for evaluation. As such, the model provides an organized procedure to examine different types of water transfer opportunities, in the context of the associated uncertainties, for the integrated management of urban water supply system reliability.

Chapter Overview

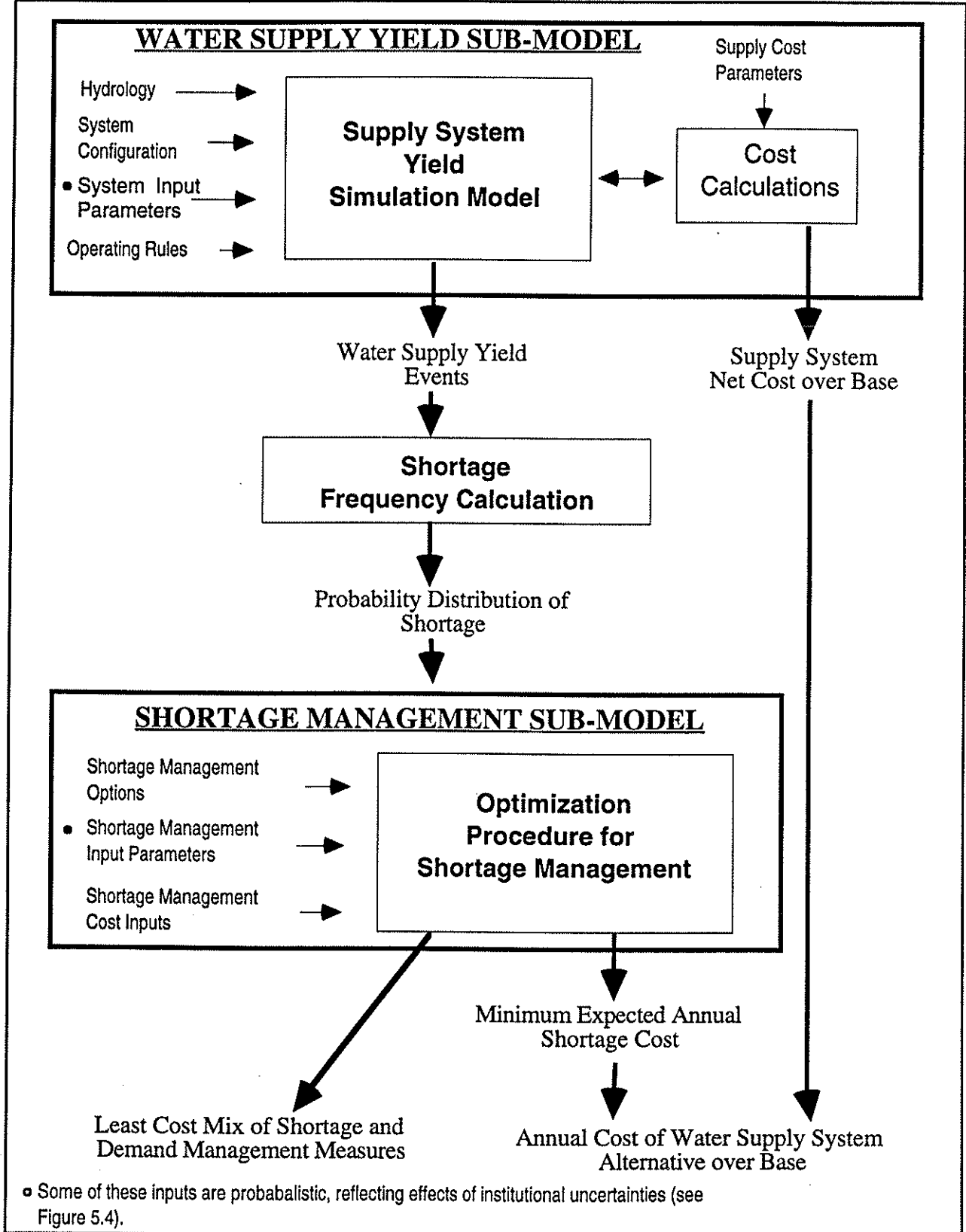
This chapter is organized as follows. Section 2 presents an overview and diagram of the water supply reliability model structure. Sections 3 and 4 explain the details and workings of the two principal sub-models, dealing with supply system yield and shortage management, respectively. Section 5 explains how the sub-models are integrated with each other into a single model and describes the results produced from a single run. Section 6 explains the modeling process of using the integrated model in a routine to evaluate alternatives and the effects of institutional uncertainties. Section 7 concludes the presentation of the general modeling approach.

2. Overview of Integrated Water Supply Reliability Modeling

For analysis and comprehension, the water supply reliability model is organized into two major components or sub-models, representing a separation between the management of physical water sources, i.e. permanent supplies and their operation to meet fixed demand in a predominantly planning context, versus the management of demand and short-term supplies under uncertain shortage in a predominantly operational context. Figure 5.2 shows the overall structure of the model. Part of the rationale for separating an urban water supply system this way is theoretical, based on whether the activity or decision affects the level of supply or of demand. The other part is convenience and adaptation to current practice in water supply modeling. The Water Supply Yield Sub-Model is based on conventional reliability modeling using simulation techniques whereas those activities in the Shortage Management Sub-Model are all amenable to linear optimization.

The sub-model dealing with the operation of the permanent water sources is a simulation model of the physical supply system. Run on a planning time scale, the Water Supply Yield Sub-Model ('Yield sub-model') simulates the effects of long-term water supply augmentation decisions, including the integration of various forms of permanent transfers, on supply system reliability, given a set of system operating policies. The shortage event outcomes of the Yield sub-model, after transformation using the plotting position rule developed in Chapter 3, are passed to the Shortage Management Sub-Model ('Shortage sub-model'). This second sub-model is an optimization procedure that identifies the least cost mix of shortage and demand management decisions that accommodate the probability distribution of shortage from the Yield sub-model. The Shortage sub-model solves this problem using the two-stage linear programming approach presented in Chapter 4. Permanent types of water transfers, having a long term effect on the overall levels of water supply, are handled in the Yield sub-model, while contingent and temporary types of water transfers, conditioned on the possibility of shortages occurring, are handled in the Shortage Management sub-model.

Figure 5.2: Diagram of Water Supply Reliability Model Structure



models, marginal or net operating costs for the supply system (pumping, hydropower, treatment, etc.) also are included.

The uncertain hydrology is represented by time series of stream flows that provide the sequence of uncertain inflow events to drive the simulation model. In the case of multiple inflows to the supply system, including flows associated with a permanent water transfer source, each inflow must be represented by a time-series over the same period. If long enough historical flow records exist for each inflow or most of them, it is preferable to use them directly in the simulation. The possibility of unrepresented extreme events (more severe droughts than recorded in the historical record) can be accounted for in the probability distribution of the resulting shortage events through the choice of a plotting position equation (Chapter 3).

Institutional uncertainties arise from uncertainties in regulatory impacts, the evolution of environmental conflicts, legal outcomes, third party impacts, future economic growth, changes in technology, etc. (Chapter 2). These types of uncertainties can be translated into their probabilistic effects on the levels of various design parameters and/or the likely success/failure of infrastructure construction projects. For example, in a river reservoir operation, instream fish flow requirements may be highly uncertain and dependent on long-term resolution of regional or local environmental issues (as in the Bay-Delta situation), or on future changes in regulatory policy and its implementation, on legal decisions related to water rights, etc. Rates of economic growth affect water use in a shared water resource system, such that in a planning context, the future level of availability of a surface water right entitlement, or of the production level from a well field may be uncertain. While the effects of hydrologic uncertainties are captured with a single simulation run of the Yield sub-model (in the distribution of shortage events), the effects of institutional factors on the integrated performance of the water supply system are evaluated in an analysis framework using the full integrated water supply model. The procedure is described later in Section 6.

Operating Rules and Operation Costs

Changes in operating rules associated with the water sources in the supply system can be investigated separately or jointly with other supply strategies by making appropriate changes to the simulation procedure inputs. For example, the use of hedging in reservoir operations, changes in ground water pumping schedules, changes in the operation of conveyance structures, etc. are operating strategies that may improve supply system reliability in meeting demand. For a given physical supply system configuration, different operating strategies can be simulated on a planning time-scale in the Yield sub-model and their effects captured in changes to the shortage outcome events and to the operating costs of that system.

Each given supply system design alternative has an associated marginal or net cost made up of new capital investments and changes in operations and maintenance which are calculated in the

4. Shortage Management Sub-model

Linear Program Modeling of Shortage Management

The probability distribution of water supply shortages from the Yield sub-model is managed in a least-cost way by the Shortage Management sub-model. Here, strategies to cope with uncertain water shortages, by permanently or temporarily altering the level of demand, or by temporarily increasing supplies via water purchases, are represented as decisions in a two-stage probabilistic optimization procedure (see Chapter 4 for details). Two functional types of water transfers are included in the Shortage sub-model: transfers under a dry year option contract and temporary one-time transfers made on the spot market. Other examples of measures included in this sub-model are those generally categorized as demand-related or short-term supply-related ('(O)' in Table 5.1). An exception would be waste-water reclamation, which despite its long-term supply classification, is easily incorporated into the economic optimization analysis of this sub-model.

First stage decisions of the optimization problem correspond to long-term permanent responses in expectation of probable shortages. Long term decisions may include such irrevocable actions as implementation of various long-term water conservation measures, investment in waste water reclamation capacity, establishment of dry year option contracts, etc.

Second stage decisions are those short-term operational decisions selectively implemented in response to each given shortage event and having a probabilistic likelihood of use. As described in Chapter 4, interaction and tradeoffs between long and short-term decisions are incorporated into the optimization routine through the constraint relationships set on decision variables. Short-term operational decisions may include such temporary actions as implementation of short-term water conservation measures, exercise of a dry year option contract, purchase of water on the spot market, etc.

All decisions included in the shortage management problem are linearizable so that linear programming optimization techniques can be used in the sub-model procedure. The sub-model identifies the least cost mix of demand management and short-term supply-related decisions, and the associated minimum expected annual cost of these decisions, given the set of probabilistic shortage events that are passed to it from the Yield sub-model.

Inputs and Input Uncertainties

User specified inputs to the Shortage Management sub-model are listed in Table 5.2. These external inputs include the array of possible shortage management options under consideration; their design-related parameters such as capacity limits, transaction risk probabilities, efficiencies, season factors, etc.; and their annualized cost coefficients. The sub-model also

shortage as shown in the first four columns of Figure 5.3b. Next using the plotting position formula $(r+1)/(n+2)$ described in Chapter 3, the exceedence probability of each water shortage event is calculated as shown in the last column of Figure 5.3b. These point event exceedence probabilities define the cumulative distribution curve of water shortages for the Yield run (Figure 5.3c). Finally, estimates of the discrete probabilities (or frequencies) of incremental levels of shortage are computed from the cumulative distribution plot by linear interpolation and then simple differentiation (Figure 5.3d). The mid-point of the shortage interval is taken as the average magnitude for that shortage event. Discretization of the shortage events is a matter of choice, depending on technical limits of computing capacity, and consideration of water supply and shortage management operational characteristics.

Integrated Model Results

Model results produced by each integrated run are listed in Table 5.3 and described in the following paragraphs. Two types of results are produced by each Yield sub-model run, after transformation in the Shortage Frequency Calculation procedure. These are the probability distribution of annual (or other time increment selected as the basis of the supply simulation procedure) yield and the probability distribution of annual net operating costs over base case. From the yield reliability and operating cost data, other performance information can be computed. These include the average magnitude of shortage, or system deficit, per year; the likelihood (or marginal probability) of experiencing a shortage in any given year; and the average annual net operating cost.

Results from the Shortage sub-model for each run are the least-cost mix of shortage management options, along with their optimal levels and expected annual cost of implementation. This cost can be understood as the minimum expected annual cost of supply yield failure (i.e. shortage) associated with the particular yield reliability realization for one given Supply Yield sub-model run. In fact, the yield reliability curve or its associated shortage frequency distribution is itself a stochastic distribution contingent on the joint effects of hydrologic and institutional uncertainty for one alternative combination of supply system configuration and operation. Each model run produces one empirical realization of this random shortage frequency distribution.

Economic integration of the two sub-models is done by adding each of their separate cost components into a single annualized total cost. For a particular supply system alternative, each integrated model run produces a final system cost result (see Figure 5.2) composed of (a) fixed new capital investment costs of yield for the supply alternative, (b) expected net operations/maintenance costs (over base case) of yield for the supply alternative, and (c) the minimum expected annual cost of managing probabilistic shortages of yield using the optimally

Fig. 5.3 (c): Cumulative Distribution of Shortage

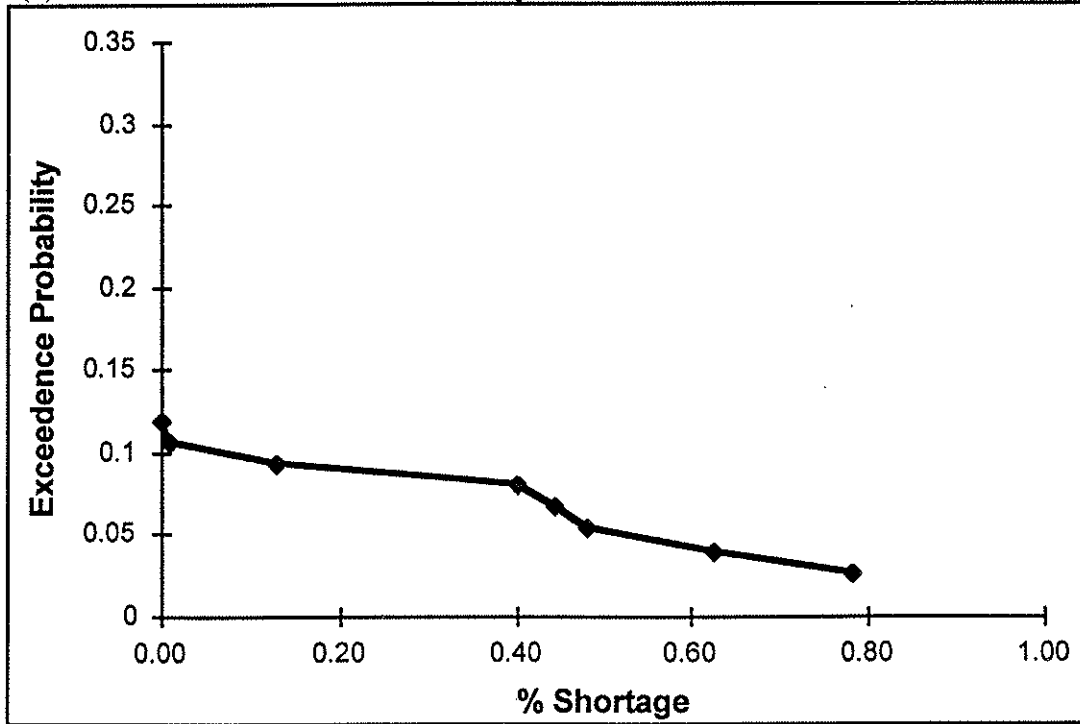
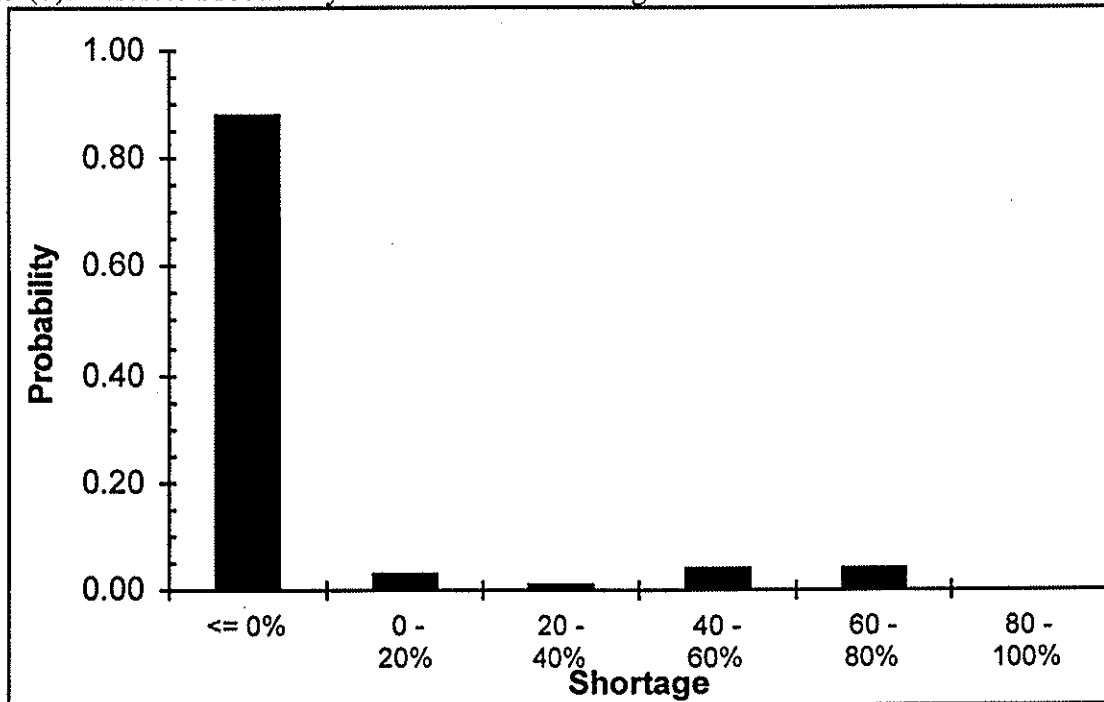


Fig. 5.3 (d): Discrete Probability Distribution of Shortage



Step 1: Evaluate Institutional Uncertainties

The first step in this procedure to evaluate institutional uncertainties involves the construction of the joint probability distribution of the set of institutionally uncertain input parameters (see Figure 5.4). We begin by identifying important design parameter inputs to either the Yield or Shortage sub-models that are uncertain due to underlying unresolved or uncertain institutional outcomes. Next, 'best' estimates of the levels or range of values for each of these uncertain parameters is made, reflecting the range of possible institutional outcomes, or combinations of different institutional outcomes, affecting that parameter. Probabilities are then assigned to each discrete value of the parameter which represent the best guess likelihood of occurrence of the institutional outcome, or combination of outcomes, tied to that value. The result is a discrete probability distribution of the uncertain design parameter constructed from subjective quantification of the effects of the range of probable institutional outcomes. For simplification, the uncertain outcomes of different institutional factors are treated as independent, so that joint probabilities of combinations of levels of uncertain input design parameters can be computed directly from the product of the individual probabilities associated with each level of an input parameter. This seems a reasonable assumption, as the sources of uncertainty are not likely to be correlated in any discernible way.

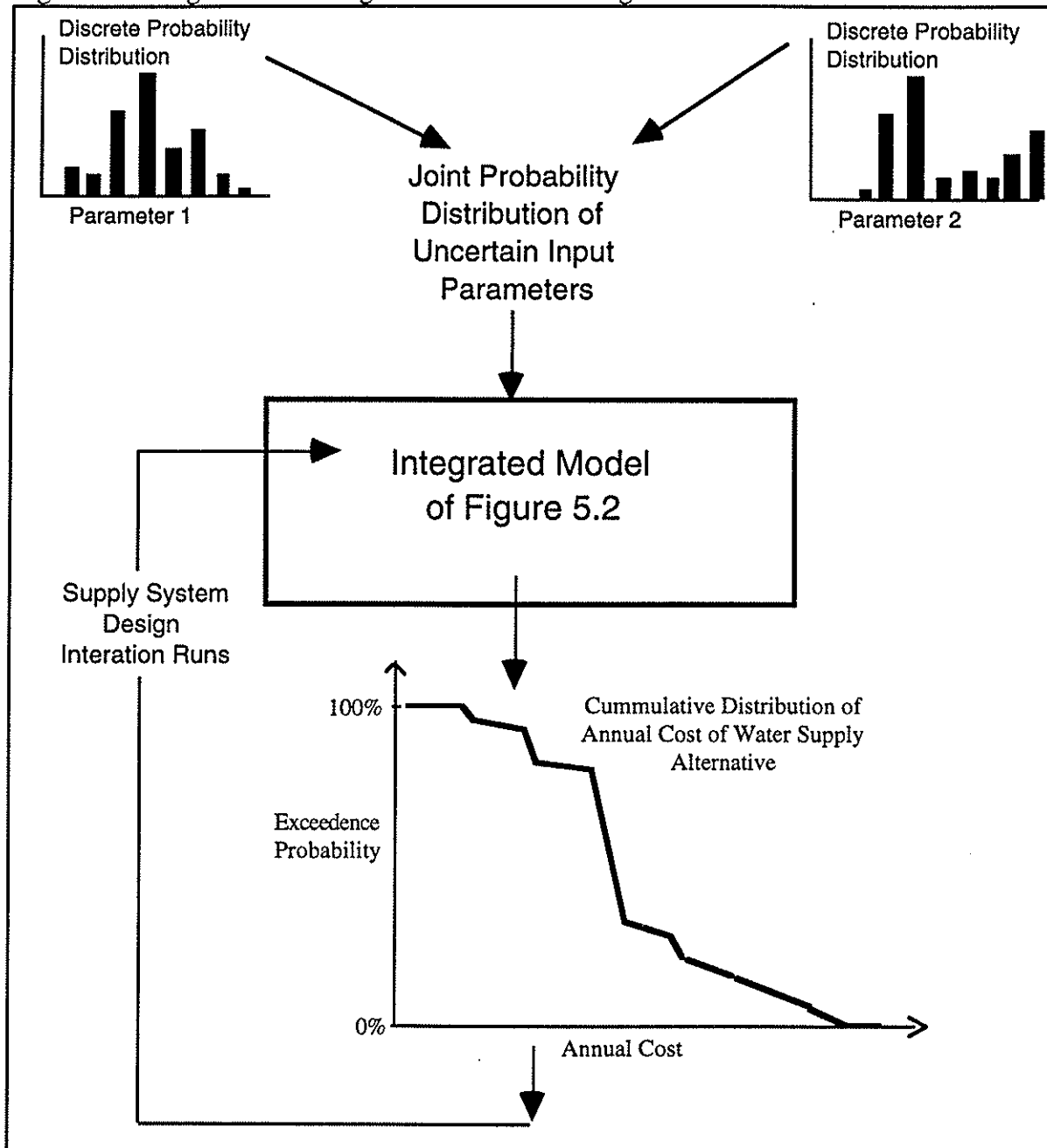
Step 2: Run the Integrated Model for Each Institutional Outcome

The next step in the procedure involves analytically evaluating the impact of this joint probability distribution of uncertain parameters on the integrated model's results. The integrated model is run multiple times in a looped sequence over the full joint probability distribution. Each set of model results is assigned a probability equal to the joint probability of the uncertain input variables. The set of looped runs generates the set of model point results that define the probability distribution of final annual water supply costs for that particular design alternative.

Step 3: Evaluation of Alternatives Considering Uncertainty

Different alternatives can be compared on the basis of these probabilistic annual costs, using their cumulative distribution curves and expected value costs. The annualized capital investment costs for an alternative act as a fixed incremental cost added to each point on the distribution; their addition or removal displaces the cost probability distribution curve (and likewise the distribution's expected value annual cost) further out or back in along the annual cost axis. It is the minimum expected annual shortage and net operating cost components for the supply system alternative being investigated that change for each point on the joint probability distribution of institutionally uncertain parameters.

Figure 5.4: Integrated Modeling Process for Evaluating Institutional Uncertainties



Chapter 6

Simplified Application

to the East Bay Municipal Utility District

"The East Bay Municipal Utility District has a long record of investment choices which forego the lowest-cost source of design because of elements of uncertainty." Bain, et al. (1966, p. 369)

1. Introduction

In this chapter, an application of the water supply reliability modeling framework (Chapter 5) to the East Bay Municipal Utility District (EBMUD) is presented. EBMUD is one of the larger, but less complex, urban water supply systems in California actively attempting to integrate various forms of water transfers, demand management, and yield enhancement into their system planning. EBMUD also faces multiple, complex, and interrelated institutional uncertainties critical in engineering its water supply system and water transfer activities that are typical of the present California water planning environment. As such, it provides an interesting and reasonably simple case study for 1) demonstrating and testing the modeling approach, 2) identifying data and input requirements, 3) interpreting various modeling results, and 4) developing a better understanding of the interactions of selected sources of institutional and hydrologic uncertainty and their impact on integrated urban water supply planning.

East Bay Municipal Utility District

Located on the east side of San Francisco Bay, EBMUD covers 310 square miles and serves roughly 1.1 million people in 20 incorporated cities and 15 unincorporated communities of Alameda and Contra Costa counties (EBMUD, 1995). Present normal-year demand is estimated at 215 million gallons per day (mgd) or 240,000 acre-feet per year (acft/yr). Forecasted demand for 2020 is 250 mgd or 280,000 acft/yr (EBMUD, 1991).

The district receives almost all of its water from the Sierra Nevada Mountains' Mokelumne River Basin. The water supply system consists of a network of two large storage reservoirs on the Mokelumne River (Camanche and Pardee), three aqueducts conveying water from the Mokelumne reservoirs to its service area, five small terminal reservoirs within the service area, and six treatment plants (EBMUD, 1995). No ground water is presently used in the system. In addition to water rights and contracts for about 360,000 acft/yr (325 mgd) from the Mokelumne River, EBMUD has additional contract water rights with the U.S. Bureau of Reclamation's Central Valley Project for 150,000 acft/yr (134 mgd) from the American River. While EBMUD's expectation has been to divert this water through the Folsom South Canal via an extension south to its Mokelumne River aqueducts, current available access to American River water is via the Sacramento River and

Section 4 along with their representation in various model input parameters as discrete probability distributions of those parameter values. Values used in the EBMUD modeling exercise for deterministic input parameters and cost coefficients are presented in Section 5. These values, while not unrealistic for urban water supplies in general, are not necessarily specific for the EBMUD. Model changes from the base case for each of the selected alternatives are also identified in this section. Section 6 presents and discusses the modeling results and their implications. The Chapter concludes in Sections 7 and 8 with a summary of important methodological conclusions and lessons from the EBMUD model application.

2. Potential Roles for Water Transfers in EBMUD's System

EBMUD's Water Transfer History

During the 1976-77 drought, EBMUD gained its first experience transferring 25,000 acft of water from the American River via a diversion at the Delta (EBMUD, 1995). In the most recent California drought, EBMUD aggressively pursued three major efforts to transfer water, each of a different type (Lund et al., 1992). The first involved trading low quality Delta water for high quality Mokelumne River water in 1988 by pumping it upstream through one of EBMUD's aqueducts to its lower Mokelumne Reservoir (Camanche). The Delta water would replace Mokelumne River releases from the upper EBMUD Reservoir (Pardee) designated for downstream requirements, thus freeing an equivalent amount of water for EBMUD users. The transfer effort failed through lack of State approval due to the biological impacts and opposition by downstream users who had rights to the high quality Mokelumne water. The second effort, also in 1988, involved trying to set up dry year option contracts with downstream users on the Mokelumne River to purchase their higher priority water for EBMUD users. However, no transactions or transfers of water were completed. The last and final attempt in early 1989 was similar to the 1976-77 water transfer; it succeeded. This transfer involved the purchase of 60,000 acft from the Yuba County Water Agency to be pumped directly from the Delta for treatment and use in EBMUD's service area. While the transaction succeeded, none of this water was actually used by EBMUD after unusually heavy March rains removed the immediate crisis. EBMUD resold the water to other buyers on the spot market.

As evident from these attempts, water quality issues play an important part in EBMUD transfers. Motivation, due to customer preferences, treatment costs, and treatment capacities, is very strong to preserve the high quality of water entering the service area. EBMUD faces significant operational limitations on treating lower quality Delta water in its system. Existing treatment facilities would require major modifications to operations and possibly some infrastructure to accommodate frequent or substantial use of Delta water.

Dry Year Options

The second type of water transfer included in this application is dry year option contracts to provide access to additional water during shortage events. The EBMUD system has two distinct sources of water for contracting dry year options: senior water rights holders on the Mokelumne River and water sellers anywhere using Sacramento River or Delta water. The first source would provide water of the same high quality as existing supplies through EBMUD's existing network of aqueducts. Water from this source would have a purchase cost, but few additional operating requirements over existing supplies. The second source of dry year option water transfers would entail low quality water withdrawals from the Delta if no additional conveyance facilities are constructed. Here additional treatment costs and treatment capacity would be involved.

Spot Markets

Spot market transfers or one-time purchases of water on the spot market are the last type of water transfer considered in this application. Sources of spot market water would be the same as those for dry year option contracts as well as some kind of drought emergency water bank. Treatment issues are the same as those for the dry year option sources.

Many other possibilities for water transfers exist, some more obscure, less feasible or variations on those identified above. For example the exchange of low for high quality water that EBMUD attempted in 1988 is similar to the third way suggested above for operationally integrating a permanent transfer of American River water into EBMUD's supply system through the Folsom South Canal, pumping water into Camanche Reservoir). The water supply reliability modeling structure and framework of Chapter 5 is flexible, comprehensive and fully integrated to permit the evaluation of any of these water transfer possibilities.

Modeled Water Transfer Alternatives

For the application presented in this chapter, only a few representative alternatives for evaluating water transfers have been selected. Permanent transfer of American River water to the EBMUD system through either the Delta (Alternative AR via DELTA) or an extension of the Folsom South Canal (Alternative AR via CANAL) will be evaluated against base case operation (BASE). Both of these American River supply alternatives will be operated only as backup supply to the existing supplies in the Yield sub-model. In the context of shortage management, dry year option contracts and spot market purchases will be included as options, along with other non-transfer measures, in the optimization procedure of the Shortage Management sub-model. Consideration of two levels of water quality is made only in the specification of both dry year contract and spot market water transfers during shortage. The two levels are 'high' and 'low' and

Conservation District (20,000 acft/yr), the Woodbridge Irrigation District (60,000 acft/yr), and riparian and other senior appropriative water rights holders (21,000 acft/yr estimated) (EBMUD, 1991). EBMUD withdrawals (component 6) are based on meeting a target demand of 280,000 acft/yr for the 2020 planning scenario. Monthly requirements are based on the current average fraction of annual deliveries made in each month to EBMUD (California Department of Water Resources, 1994).

Additional components of the BASE case are needed to model the integration of a permanent transfer of American River water under the two selected alternatives. These consist of runoff or flow for the American River (component 7) represented by the monthly historical unimpaired streamflow (California Department of Water Resources, 1995) for 1921-1993, a diversion point at the Folsom South Canal and its extension and tie-in to EBMUD's aqueducts (component 8) for Alternative AR via CANAL, a diversion point in the Delta at EBMUD's service area (component 10) for Alternative AR via DELTA, minimum instream flow requirements in the American River for fish flows, senior appropriators, channel losses and meeting Bay/Delta quality standards before EBMUD can make diversions at either point (component 9), and consideration of EBMUD water treatment facility constraints (component 11) on treating low quality water from the Delta for Alternative AR via DELTA.

The BASE supply system and both permanent water transfer alternatives are operated using a linear hedging operation rule (component 3) for making releases from the Mokelumne River reservoir. The operating rule allows modification for two simple hedging features, one consisting of wet season carryover storage triggered by low forecasted inflow in the dry season, and the other consisting of a reduced dry season drawdown rate of storage triggered by low projected end-of-period storage. No consideration has been given to flood control, hydropower or terminal storage regulation of and inflows into the 5 terminal reservoirs in this simplified operating rule developed for our model application.

Table 6.1: Modeling Inputs for Yield Sub-Model for EBMUD Application

Component:	Parameter:	Value:	Description:
1. Mokelumne River Flow	<ul style="list-style-type: none"> runoff inflow to reservoir 	uncertain	historical monthly unimpaired streamflow data for 1921-1993
2. Mokelumne River Reservoir	<ul style="list-style-type: none"> active storage capacity average wet season evaporation (Nov - Mar) average dry season evaporation (Apr - Oct) 	720,000 acft 7,600 acft 18,000 acft	a single reservoir has been used to represent system storage and operations for Camanche, Pardee, and the 5 East Bay terminal reservoirs; evaporation is a fixed amount taken each season independent of storage volume
3. Reservoir Operating Rule	<ul style="list-style-type: none"> wet season target release dry season target release wet season hedging dry season hedging wet season carryover storage to dry season trigger for wet carryover storage 	targets vary with total release requirements 0 35% of dry target 175% of dry season instream flow requirement dry season inflow <= 200,000 acft	a standard linear operating rule is used allowing adaptation for seasonal hedging by reducing rate of drawdown and/or wet season carrying over storage; target release equals the sum of instream requirements, downstream withdrawals and EBMUD demand for the given season
4. Instream Requirements on Mokelumne	<ul style="list-style-type: none"> annual instream flow requirements percentage requirement in wet season (Nov - Mar) 	uncertain 41 %	fish and wildlife habitat and production, Delta flows, channel losses
5. Mokelumne River Withdrawals	<ul style="list-style-type: none"> annual downstream withdrawals percentage withdrawal in wet season (Nov - Mar) 	uncertain 8 %	senior water rights on the Mokelumne River for which reservoir releases must be made (mainly for irrigation districts, farmers, and small communities)
6. EBMUD Withdrawals	<ul style="list-style-type: none"> annual target demand percentage demand in wet season (Nov - Mar) 	280,000 acft/yr 33 %	year 2020 planning scenario for EBMUD demand
7. American River Flow	<ul style="list-style-type: none"> runoff at Folsom Reservoir 	uncertain	historical monthly unimpaired streamflow data for 1921-1993
8. Folsom South Canal Diversion Point	<ul style="list-style-type: none"> availability 	0 or 1	an on/off switch indicating extension and tie-in of the Folsom South Canal to the Mokelumne aqueducts for Alternative AR via CANAL
9. Minimum Instream Requirements on American	<ul style="list-style-type: none"> wet season minimum runoff before EBMUD diversions are permitted dry season minimum runoff before EBMUD diversions are permitted 	uncertain uncertain	wet and dry season minimum instream flow requirements that must be met in the American River before EBMUD can divert water under its Bureau contract for either Alternative
10. Delta Diversion Point	(none)		direct intake to EBMUD service area of American River water for Alternative AR via DELTA
11. EBMUD Water Treatment Facilities	<ul style="list-style-type: none"> maximum percentage Delta water 	35 %	operating quality constraint on treating low quality Delta water expressed as a percentage of mix with high quality Mokelumne water

N.B. Parameters whose values are uncertain are either hydrologic inputs or those whose levels are uncertain due to institutional factors. Probability distributions for those institutionally uncertain parameters treated in this modeling study are discussed in Section 4 and presented in Table 6.4.

Wet season is November to March. Dry season is April to October.

Table 6.2: Modeling Inputs for Shortage Management Sub-Model for EBMUD Application

Measure:	Parameter:	Value:	Description:
<i>Additional Water Treatment Capacity</i>	<ul style="list-style-type: none"> • limit on capacity expansion • wet season capacity factor • dry season capacity factor 	50,000 acft/yr 42% 58%	water treatment capacity expansion to accept additional low quality transfers through dry year option or spot markets beyond existing treatment limits
<i>Dry Year Option Contract</i>	<ul style="list-style-type: none"> • limit on volume of 'high' quality water transferred in dry season (1st increment) • limit on volume of 'low' quality water transferred in dry season (2nd increment) • limit on volume of 'high' quality water transferred in wet season (1st increment) • limit on volume of 'low' quality water transferred in dry season (2nd increment) • probability of transaction completion/success 	41,000 acft amount of additional treatment capacity (x 58%) 29,000 acft amount of additional treatment capacity (x 42%) uncertain (0 to 1)	Dry year option transfers are limited by the available water system treatment capacity consisting of existing capacity to treat water transfers (70,000 acft/yr) and any additional water treatment capacity selected as long term decision (up to 50,000 acft/yr) Model runs use a transaction completion probability of 1 for the analysis made in this chapter.
<i>Spot Market Water Transfer</i>	(same as above for dry year options)	(same as above for dry year options)	Spot market transfers are limited by the available water treatment capacity (as above) and the amount of transferred water from dry year option contracts.
<i>Long Term Conservation</i>	<ul style="list-style-type: none"> • maximum contribution of toilet/plumbing retrofits • wet season retrofit factor • dry season retrofit factor • maximum contribution of xeriscaping • wet season xeri factor • dry season xeri factor 	40,000 acft/yr 42% 58% 100,000 acft/yr 20% 80%	measures used to permanently decrease water consumption through plumbing retrofits and xeriscaping (landscape modifications); expressed on an annual basis with seasonal factors used to compute equivalent seasonal contribution
<i>Short Term Conservation</i>	<ul style="list-style-type: none"> • maximum contribution of reduced in-house water uses w/ no fixture retrofit in place • demand hardening factor for long term fixture retrofits • maximum contribution of reduced lawn watering I and II • demand hardening factor for long term xeriscaping 	40,000 acft/yr 30% 100,000 acft/yr 100%	Reduced in-house water uses depends on long term toilet/plumbing retrofits; Seasonal factors are the same as those for long term fixture retrofits; 1 unit of retrofit eliminates 0.3 units of reduced use capacity; Reduced lawn watering depends on long term xeriscaping; two levels of lawn watering reduction are used to represent the severity of high levels of reduction; Seasonal factors are the same as those for long term xeriscaping 1 unit of xeriscaping eliminates 1 unit of reduced lawn watering capacity
<i>Water Reuse</i>	<ul style="list-style-type: none"> • maximum contribution of water reuse • wet season reuse factor • dry season reuse factor 	40,000 acft/yr 42% 58%	Additional water supply source from water reclamation system

Figure 6.2: Historical Seasonal Flow Exceedence Probabilities

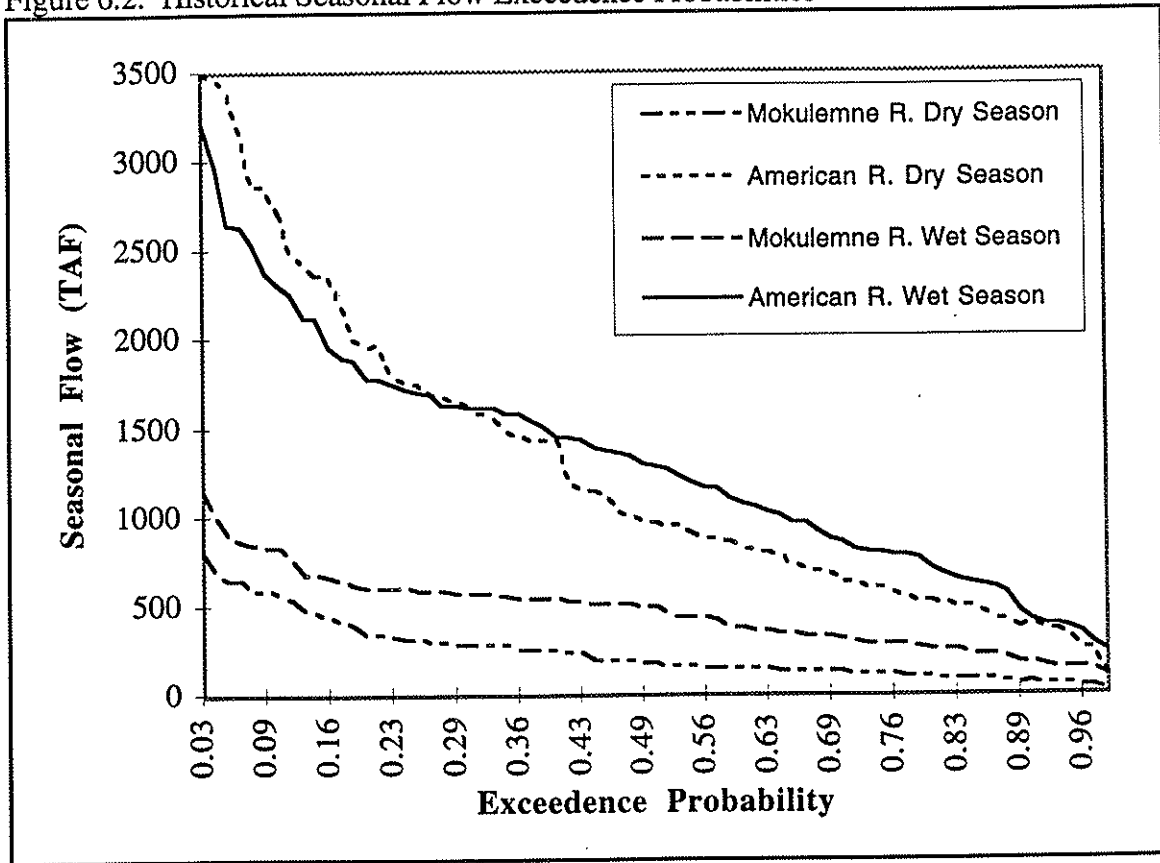
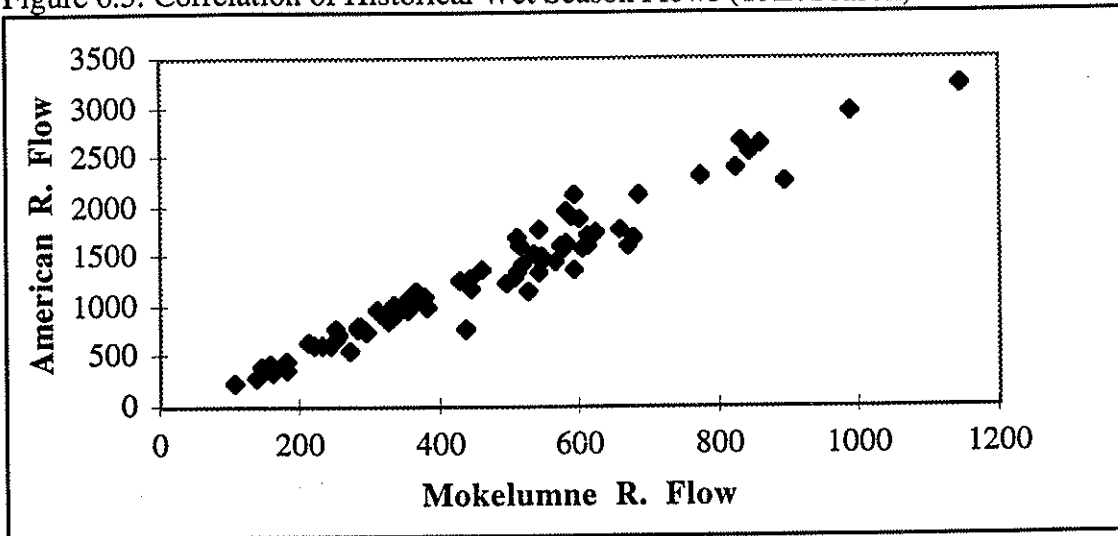


Figure 6.3: Correlation of Historical Wet Season Flows (TAF/Season)



IFR - Lower Mokelumne River Instream Flow Requirements

Over a planning horizon relevant for facility planning and operations studies, instream flow requirements for the lower Mokelumne River are highly uncertain. These uncertainties are driven by environmental regulations and California Department of Fish and Game implementation of those regulations, by eventual implementation of Bay/Delta water quality standards, and by other developments on the Mokelumne River affecting inflow levels (EDAW, Inc., 1992). The range of potential values for this annual instream flow requirement is taken to be 32-131 TAF, based on numbers given in various EBMUD reports, and the most likely value is 105 TAF/yr. This requirement is disaggregated into seasonal values for modeling. The assignment of probabilities appearing in Table 6.3 and plotted in Figure 6.4 is subjective, and could be modified to reflect different opinions of the relative likelihood of institutional outcomes affecting different levels.

DSW - Mokelumne River Senior Withdrawals

There are significant senior downstream and upstream withdrawals on the Mokelumne River and some uncertainty regarding their future use levels responding to potential use of full entitlements, future changes in irrigation and agricultural practices, and growing demands in the basin. Other factors include a number of pending projects by upstream appropriators that will uncertainly affect inflows to EBMUD's Mokelumne River reservoirs depending on approval of water use petitions. A range of 91-136 TAF/yr was assumed based on the literature, with subjective probabilities assigned to each level in Table 6.3 and plotted in Figure 6.4. The most likely value is 116 TAF/yr. Seasonal disaggregation assumes predominantly agricultural use.

IA2Min - Lower American River Instream Flow Requirements

Dry season minimum instream flows on the lower American River are based on legal decisions, but are under revision by the State Water Resources Control Board in planning for future additional diversions by the Sacramento metropolitan area and other factors. These flow requirements might limit the ability of EBMUD to withdraw water from the American River downstream of Folsom Dam during many years. There is much uncertainty regarding the exact limit that will apply in the long term as well as uncertainty about the future withdrawals of more senior right-holders in the basin. Finally, proposed solutions to flood control problems in the Sacramento Area, including construction of Auburn Dam and modifications to Folsom Dam flood control operations, would affect availability of EBMUD's American River entitlement in uncertain ways (EDAW, Inc., 1992). A range of 300-1,200 TAF for the minimum dry season instream flow requirement was assumed for this exercise, with the mostly likely value at 470 TAF. These values are based on dry season historical low flows ranging from a 2.5% non-exceedence event (300 TAF) to a 46% non-exceedence event (1,200 TAF), with the most likely being the 10% non-

Shortage Management Sub-model Uncertainties

There are of course many other sources of uncertainty for the planning and management of the EBMUD system. These are not included mostly for practical reasons of the limited effort of this work and its primarily conceptual and methodological intent. Still it might be useful to mention some additional sources of uncertainty and how they could be incorporated into this modeling approach for a real system study, as opposed to the simplified study presented here.

Completion of Water Transfers

Uncertainty regarding the ability to complete water transfer transactions has been found to be potentially significant for water transfer planning (Lund, 1993). Indeed, there is considerable uncertainty regarding the ability of EBMUD to complete and implement particular dry year option or spot market water transfers given variable economic, hydrologic, and regulatory conditions, as demonstrated by EBMUD's history of water transfers (Lund, et al., 1992). The likelihood of completing a water transfer transaction is likely to vary with its location and context.

Some of these uncertainties can be incorporated directly into the formulation of the two-stage decision process modeled in the shortage management sub-model, accompanied by the development of a probability distribution of the relevant uncertain shortage parameter (i.e., probability of transaction completion). This essentially enlarges the number of second stage events, reflecting the combination of both different hydrologic/shortage events and the different completion scenarios for different water transfer efforts, which might be wholly or fractionally effective or ineffective. For more complex situations additional stages might be required of the shortage management decision model. In either case, the addition of transaction completion uncertainties can greatly enlarge the computational size of the shortage management linear programming sub-model.

Water Transfer Availability

There is likely to be some uncertainty regarding the availability of water for transfer. In addition, there are likely to be differences in the uncertainty of water availability for various qualities of water, such as water available in the Delta versus above the Delta versus from the Mokelumne River. In the case of high quality transferred water from the Mokelumne, availability is likely to depend on outcomes of some of the same institutional issues affecting lower Mokelumne River instream flow requirements. As in the previous case, these uncertain limits would require expanding the number of events in the second stage of the two-stage formulation, or adding another stage. Either of these approaches can greatly expand the computational demands of the shortage management sub-model.

Seasonal fractions of the annual level of IFR (lower Mokelumne River instream flow requirements) are set at 42% in wet and 58% in dry, based on the assumption of a constant monthly requirement. Seasonal fractions of the annual level of DSW (Mokelumne senior withdrawals) are set at 8% in wet and 92% in dry, derived from the seasonal pattern of predominantly agricultural demands in the basin (EDAW, Inc., 1992). Seasonal fractions of EBMUD's demand are 33% in wet and 66% in dry (California Department of Water Resources, 1994). A capacity limit of 35% is assumed for treating low quality water taken from the Delta in EBMUD's existing treatment facilities for the alternative AR via Delta. This limit is stated in terms of the maximum percentage of Delta quality water on a seasonal basis in any mix with present quality Mokelumne water.

Annual cost parameters are needed to represent increased operating costs over BASE operations, associated with the two permanent American River water transfer alternatives considered. The two cost parameters used in the Yield sub-model are \$150/acft of water diverted at the Delta (AR via Delta) for additional pumping and treatment costs over BASE case, and \$10/acft of water conveyed by the Folsom South Canal to the Mokelumne Aqueducts (AR via Canal) for additional pressurization and pumping costs, but no additional treatment over BASE case.

Throughout this study, the fixed capital investment costs for infrastructure, which would be required for the Canal alternative (AR via Canal), are not included in any of the modeling results. Instead a willingness-to-pay approach is used to estimate the maximum economical investment cost for the Canal alternative. Thus, Yield sub-model cost results represent only excess operating costs over the BASE case for each permanent transfer alternative, while the BASE case has no Yield sub-model costs.

Shortage Management Sub-Model Parameter Values and Costs

The input parameters to the Shortage Management sub-model include EBMUD urban water demand, the shortage probability distribution, and the limits and costs of short term and long term shortage management measures. EBMUD total annual demand is 280 TAF. Seasonal demands assume a 33% wet season fraction, resulting in 92 TAF and 188 TAF for the wet and dry seasons, respectively. The model accounts for six levels of shortages at intervals of 20 percent for each season. The probabilities of these 12 events are estimated in the shortage frequency calculation procedure (see Figure 5.3) from each season's results of the Yield sub-model, using the probability plotting formula presented in Chapter 3. The magnitude of each shortage event is assigned the mid-point value of the interval, so that the six events have magnitudes of 0%, 10%, 30%, 50%, 70% and 90% shortage.

Table 6.5: Scenarios Examined Representing Different Institutional Uncertainties

Scenario	Mokelumne R. Instream Flows (IFR)	Mokelumne R. Downstream Use (DSW)	American R. Dry Season Min. Flows (IA2Min)	Reservoir Operations
Rosy	M	M	M	A
0	-	-	-	A
1	X	-	-	A
2	-	X	-	A
3	-	-	X	A
4	X	X	-	A
5	X	-	X	A
6	-	X	X	A
7	X	X	X	A
8	X	X	X	B

A - Base case variable carryover storage rule derived for Scenario 0

B - Fixed carryover storage rule

M - Minimum value from Table 6.3 assumed deterministically

X - Probability distribution used, otherwise "most likely" (i.e. expected value of probability distribution in Table 6.3) value was used

Cost results from all scenarios of the two permanent American River water transfer alternatives represent the sum of supply system net operating and maintenance costs over BASE case plus the minimum expected value cost of shortage management. For the BASE case, the cost results represent only the minimum expected value cost of shortage management as the BASE case supply system is the reference for supply yield operating and maintenance costs.

Under each scenario where institutional uncertainties are examined, the integrated model is run for each of the three alternatives, following the approach laid out in Figure 5.4, to produce a cumulative probability distribution of water supply system annual costs for each alternative. Figure 6.5 shows a typical plot of these results for one scenario (#7), in which the cumulative distribution curve is used to display probabilistic costs for each alternative. These probability distributions of annual cost are summarized by their expected value costs in Table 6.6. This allows rapid and rigorous assessment and comparison of alternatives and scenarios based on a single value measure of cost (Park and Sharp-Bette, 1990). The range of the annual cost distributions for each scenario appear in Table 6.7.

For all cases, connection with the American River via a Canal had the lowest expected value cost, including both supply system operation and demand management and water transfer costs. The AR via Canal costs in all scenarios do not include additional capital investment costs required to build the canal structures needed to physically convey and transfer this water to EBMUD.

Table 6.7: Range of Annual Costs For Each Alternative (\$ millions)

Scenario	BASE	AR via Delta	AR via Canal ^a
Rosy	0.1*	0.1*	0.1*
0	8.2*	8.2*	6.7*
1	0.6-9.9	0.6-9.3	0.6-7.6
2	7.0-9.5	6.8-9.2	2.0-7.4
3	8.2*	7.5-8.2	1.4-7.1
4	0.1-10.6	0.1-10.8	0.1-8.3
5	0.6-9.9	0.2-9.9	0.1-8.9
6	7.0-9.5	6.2-9.5	0.7-8.3
7	0.1-10.6	0.1-10.8	0.1-9.6
8	0.1-10.7	0.1-9.7	0.1-10.8

* = Single value (represents only hydrologic uncertainty)

a = cost does not include capital investment for canal structures, etc.

Scenario Rosy - Only Hydrologic Uncertainty, Minimal Flow Requirements

It is sometimes useful to define the "best" possible, though unlikely, cost outcome in a system analysis. Scenario Rosy assumes only hydrologic uncertainty represented by the historical record and all values for the institutionally uncertain parameters (IFR, DSW, and IA2Min) were set at their lowest, most favorable-to-EBMUD values in Table 6.4. Institutionally, this is the best possible cost outcome for EBMUD system operations. Indeed, for all three planning alternatives, the expected value cost is about \$0.1 million/year.

There are no shortage events in this Rosy scenario for the BASE case Yield sub-model, so that neither American River alternative is needed. The cost result is the same for all three alternatives because no shortages occur in a 73-year repeat of the historical record. Nevertheless, the Bayesian plotting rule still gives a 2.7% chance of some shortage which converts to a small expected cost of managing shortage.

For each alternative, even where a Folsom South Canal is present, no American River water is employed in any hydrologic year. An exclusively Mokelumne River supply is sufficient to meet EBMUD demands and Mokelumne River requirements. The average \$0.1 million/year cost results solely from the probabilistic use of some short-term water conservation measures during future expected droughts. The subjective joint probability of the Rosy Scenario is about 1%, reflecting several potential combinations of very favorable institutional outcomes.

Decisions with Only Hydrologic Uncertainty

With only hydrologic uncertainty, the addition of American River water via the Delta (AR via Delta) has only minimal improvement in expected value cost at \$8.18 million/year over the present Mokelumne River only system (BASE) at \$8.19 million/year, as seen in Table 6.6. This minuscule improvement in cost arises from the limited access and use of Delta water arising from the limitations of dry season American River flows (IA2Min) and treatment constraints on use of Delta water. When used as a backup to Mokelumne River supplies, Delta water provides very little additional yield in times of shortfall, as shown in Figure 6.6. Considering cost, Delta water has a high marginal operating cost over Mokelumne River or American River water via a canal.

For these alternatives, almost 50,000 acft of wet season dry-year options are purchased and 40,000 acft/yr of long-term water conservation is implemented through improvements in water fixture efficiency. Over 14,000 acft/year of improved treatment plant capacity is also constructed to allow the use of additional low quality water transfers (from dry year options or spot markets). Short-term water conservation and spot market purchases make up the remainder of shortages, depending on the severity of the shortage event.

Valuing a Folsom South Canal

The availability of American River water via a Folsom South Canal (AR via Canal) has a much improved average annual cost of \$6.65 million/year. This reflects improved yield reliability over BASE alternative (Figure 6.6), without the additional treatment costs and limitations of the AR via Delta alternative. With the model excluding the capital cost of constructing such a canal, the difference between this cost and that of the next least expensive alternative (\$8.18 million/year) would be EBMUD's expected annual willingness to pay for completion of the Canal project. In this case, this annual willingness to pay would be \$1.53 million/year. This has a present value of \$30.6 million at a 5% interest rate over an infinite life-span for the canal. Greater costs to EBMUD for completing a canal would presumably result in disinterest in the Canal option, for expected value decision making under these unit cost and institutional assumptions.

Cost Variation with Institutionally Deterministic Assumptions

These results are very dependent on the deterministic assumptions made for the institutionally uncertain parameters. Here, the expected values of the distributions shown in Table 6.4 were used, and are the "most likely" levels for these parameters suggested in EBMUD reports. If these institutional considerations were substantially relaxed, in the form of a rosy deterministic scenario, where each institutional parameter was set at its least restrictive level representing the most favorable outcomes to EBMUD of institutional uncertainties, then the costs for all alternatives would be identical at less than \$0.1 million/year. Thus, the cost to EBMUD of these expected

While consideration of institutional uncertainty lowered expected value costs in all cases, the effects of different institutional uncertainties vary with the alternative considered. For instance, in Scenario 3 uncertainties in IA2Min have much less effect on the expected value cost of AR via Delta than on that of AR via Canal from Scenario 0. Adding DSW uncertainties to IA2Min uncertainties (Scenario 4 becomes Scenario 6) reduces the expected value cost of AR via Canal while increasing that of AR via Delta.

Adding institutional uncertainties in Scenarios 1-7 widens the range of cost outcomes. The institutionally deterministic Scenario 0 has a single value for expected value cost with hydrologic uncertainty and no institutional variability. However, with the incorporation of all institutional uncertainties in Scenario 7, the variability in expected value cost is over a factor of 100 (Figure 6.5). This widening of the range of cost outcomes with addition of institutional uncertainties contrasts with the effects of additional uncertainties on overall expected value costs for each scenario, where additional uncertainties lowered expected value costs. This behavior also highlights the importance of the subjective probabilities used to weight different uncertain institutional outcomes in Table 6.3.

Including additional sources of uncertainty never increases expected value costs for Scenarios 1-7, and usually decreases costs. For all these cases, additional uncertainties increase the likelihood of lower costs more than they increase the likelihood of higher costs.

Scenario 8 - The Importance of Operating Rules

Scenario 8 incorporates the same representation of all three institutional uncertainties as Scenario 7, but with a slight change in reservoir operating policy that fixes the carryover storage volume from wet to dry season instead of varying it proportionally with Mokelumne River instream flow requirements. Little effort was made to optimize reservoir operating policy, in terms of minimizing the expected value costs in Table 6.6. In the case of modeling all three institutional uncertainties, AR via Delta performs economically better under operations policy "A" than "B", while for BASE and AR via Canal alternatives, the reverse is true.

Further examination of the importance of reservoir hedging was carried out by re-running Scenarios 2, 5 and 7 under operation policy "B" for a fixed volume of carryover storage. The resulting expected value costs are compared with the costs under operation policy "A" in Table 6.8. While in many cases the changed operating policy "B" is superior to policy "A", this is not always true.

The least-cost operating policy (between "A" and "B") can vary both with planning alternative and sources of institutional uncertainty considered. This is particularly true for the AR via Delta alternative, where the preferred operating policy varies with the uncertainties considered.

alternative. These annual willingness-to-pay estimates appear in Table 6.9 along with their equivalent present values computed using a 5% interest rate over an infinite project life-span. These values are for illustrative purposes only, given the preliminary yield and shortage management sub-models used in the analysis.

Table 6.9: Expected Value of Annual Willingness to Pay for a Folsom South Canal (\$ millions/year) and Present Value Willingness to Pay (\$millions)

Scenario	AR via Delta	AR via Canal	Annual WTP	Present Value WTP ^a
Rosy	0.1	0.1	0.00	0
0	8.18	6.65	1.53	30.6
1	7.75	5.31	2.44	48.8
2	8.04	5.66	2.38	47.6
3	7.70	3.68	4.02	80.4
4	7.39	5.05	2.34	46.8
5	7.27	3.44	3.83	76.3
6	7.68	3.37	4.31	86.2
7	7.05	3.29	3.76	75.2
8	7.20	3.18	4.02	80.4

a = Based on annual WTP with 5% interest rate over an infinite canal project life-span.

The removal of some institutional uncertainties often raises the value of a Folsom South Canal. In these cases, presumably EBMUD would be willing to pay for mitigation or other programs which would reduce these uncertainties and improve the value of a Canal. For example, removing uncertainty in IFR from the set of all uncertainties (Scenario 7 vs. 6) raises the value of a Folsom South Canal project by \$11 million; removing uncertainty in DSW (Scenario 7 vs. 5) raises the Canal's value by \$1.1 million; and, eliminating uncertainty in both IFR and DSW (Scenario 7 vs. 3) raises the Canal's value by \$5.2 million.

However, the addition of institutional uncertainties raises the value of a Folsom South Canal substantially compared to the cases examined with no institutional uncertainties (Scenarios Rosy and Scenario 0). Where the addition of uncertainties raise the value (WTP) of a Folsom South Canal, the Canal serves to take advantage of favorable outcomes or as a hedge against unfavorable outcomes. For example, with all institutional uncertainties considered probabilistically (Scenario 7), a Folsom South Canal has more than twice the cost-reduction value as under the deterministic values used in Scenario 0.

3. For the case of EBMUD, the operations of the reservoir system and water sources has a great impact on the water transfers, demand management measures, costs, and reliabilities of the integrated system. The American River permanent water transfer alternatives were made far less attractive in the Yield Sub-model by requiring that this source act only as a back-up to Mokelumne River supplies when they were inadequate. An actual study should examine a much wider range of operating rule alternatives than could be examined here.

4. Some activities in the model that are now artificially separated by model structure should perhaps be linked. For example, water quality treatment tradeoffs for involving different water transfer types might be linked. Water quality issues for permanent transfers in the Yield sub-model currently are not integrated with water treatment issues related to shortage management transfer decisions.

5. Discretization levels of shortage events used in the Shortage Management sub-model can be very important when evaluating performance of alternatives. Ideally, a much finer discretization would reduce the effects of shortage discretization on jumps or discontinuities in overall costs as uncertain parameters change. Discretization was limited in this case primarily by the need to retain the linear program-based Shortage Management sub-model within the limits of the spreadsheet optimizing software.

6. Discretization of levels of institutional parameters can have great importance for overall results and affect their probability levels as well. Here a fairly coarse, five point, discretization was used. While such a coarse discretization can result in jumps in model results, a finer discretization is costly in two ways. First, finer discretization of institutional parameter values can greatly increase the number of Yield and Shortage Management sub-model runs required. In this case, we considered three institutionally uncertain parameters, each having five possible values; this required a total of 5^3 (= 125) runs of the combined Yield and Shortage Management sub-models. Had the discretization been made finer at 10 levels per parameter, examination of three such uncertain parameters would require 10^3 (= 1,000) combined-model runs. A second, and perhaps ultimately greater problem from fine discretization of institutional uncertainties is assessing the subjective probability values for such distributions. A finer discretization might give undue confidence in these distributions and probably would entail more human effort and daring to estimate.

7. Parameter values are undoubtedly correlated through shared institutional issues. The minimum instream flow requirements IFR and IA2Min are likely to be correlated as a result of common agency, judicial, and political decision making. It is difficult and awkward to establish a necessarily subjective correlation between these outcomes. However, it would be possible to extend this technical planning method to examine the importance of prospective correlations.

Chapter 7

Conclusions

1. Conclusions

This report has four major conclusions. Many other and more specific conclusions appear at the end of each chapter.

1. *It is technically possible to perform integrated economic-engineering studies of urban water supplies.* The approach developed here extends common yield-reliability studies to:
 - a. integrate yield enhancement, demand management, and water transfer decisions,
 - b. provide an economic and risk-based approach to planning, as opposed to an approach based solely on yield, and
 - c. examine explicitly institutional uncertainties inherent in urban water supply planning.
2. *The proposed technical approach (summarized in Chapter 5) is practical for actual urban water supply problems.*
 - a. Historical streamflows are used to estimate yield-reliability using common yield simulation models with an enhanced Bayesian interpretation of shortage and yield probability plotting positions.
 - b. A cost-minimizing shortage management model is used to integrate long and short term demand management and water transfer responses to shortages.
 - c. The approach is very feasible computationally; here, an entire analysis of the East Bay Municipal Utility District (EBMUD) system was performed with common spreadsheet software.
 - d. Little is required in the way of new data.
3. *It is possible to examine the joint effects of multiple institutional and hydrologic uncertainties for urban water supply planning.*
 - a. Institutional uncertainties are complex and interact in ways which are not always intuitive and which are too complex for simple analytical methods.
 - b. Modeling studies are needed to fully understand the implications of institutional uncertainties for urban water supply planning. Model analyses of the most worrisome uncertainties can be done without unrealistic amounts of effort. However, it is probably impossible to explicitly include all institutional uncertainties in a modeling analysis.
 - c. Least-cost planning and management decisions, and their overall cost, can vary with both institutional and hydrologic uncertainties.

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