# INTEGRATING YIELD AND SHORTAGE MANAGEMENT UNDER MULTIPLE UNCERTAINTIES

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**Abstract:** An economic-engineering modeling approach is presented for integrating urban water supply reliability analysis with shortage management options such as dry year option and spot market water transfers, water reuse, and long- and short-term water conservation. The integrated model links supply-side yield simulation to probabilistic shortage management optimization, using a probability plotting position formula. The approach can help joint planning of supply and demand management and estimate the economic value of expanding infrastructure and changing institutional constraints. Results from a case study show that jointly managing supply capacity and operating rule decisions with shortage management decisions within a risk analysis framework can create significant economic savings. The importance of hydrologic and institutional uncertainties is explored. Tuning supply system and reservoir operating policies to match the seasonal and cost characteristics of available shortage management measures is shown to be essential to least-cost planning.

## INTRODUCTION

Increasing competition for water among urban, agricultural and environmental water users and the relative absence of new inexpensive water sources, has led to the need to jointly consider a widening range of options to improve the reliability and reduce the costs of water supplies. These options may involve structural, operational and economic solutions involving yield enhancement, demand management, and water transfers. This study addresses how to integrate the economic analysis and engineering modeling of demand management and water transfer measures, with the traditional analysis and modeling of water yield for urban water supply systems. The modeling framework presented provides an integrated resource planning approach to expeditiously identify promising combinations of different water transfer, water conservation, and traditional supply augmentation options for least-cost urban water supplies under hydrologic uncertainties. The approach is demonstrated by application to a large urban water supply system in the West. Full details of the model's development and application appear in a separate research report (Lund et al. 1998). Details of the shortage management model appear in Wilchfort and Lund (1997).

### Systems Analysis and Integrated Resource Planning

In recent decades traditional systems analysis, based primarily on in-stream surface water reservoirs, has been extended using various simulation and optimization techniques to include the engineering of more complex forms of water storage, including multiple reservoirs and the

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conjunctive use of ground and surface water (Willis and Yeh 1987; Palmer et al. 1982). The use of demand curbing and shaping options has been addressed in systems analysis of urban water supplies, showing significant water and cost savings from managing demand and demonstrating the trade-off between long-term and short-term demand management options (Rubenstein and Ortolano 1984; Dziegielewski and Crews 1986; Lund 1987).

Water transfers can take many forms (e.g., dry year contingent transfers, exchanges, spot market purchases) and fulfill different functions in an urban water supply system (Lund and Israel 1995b). There is some work on optimizing inter-regional water transfers and on optimizing different forms of water transfers to meet urban water shortages (Vaux and Howitt 1984; Lund and Israel 1995a).

This paper combines traditional water supply yield simulation modeling with a least-cost shortage management model to provide a modeling framework encompassing both water supply and demand systems. The approach explicitly considers engineering and economic aspects of system performance and management. (For another approach, see Hoagland, 1996). Hydrologic uncertainty is commonly addressed by generating yield reliability curves from system simulation models using the historical record or synthetic stream flows (Hirsch 1978; Vogel and Bolognese 1995). This work extends traditional water supply reliability modeling by converting a yield probability distribution to economic values based on least-cost shortage management (Wilchfort and Lund 1997). The approach's structure and flexibility allow for the integrated planning and economic analysis of a wide variety of traditional water sources and their operations, water conservation options, water reuse, consumer cutbacks, and water transfers to identify promising combinations of these diverse options. The explicit integration of such wide-ranging resource management options into a unified analytical framework contrasts with more indirect integrated resource planning (IRP) methods (*JAWWA* 1995). This paper develops this framework and, through a case example, illustrates the importance of jointly managing supply and demand systems within least-cost planning and the roles of hydrologic and institutional uncertainties.

The following section describes the structure and components of the integrated modeling framework, the model inputs, and results. Next, an illustrative application of this approach to a major western urban water system is presented. A discussion of the modeling results and their uses for urban water supply planning follows. The final section provides concluding remarks.

## INTEGRATED MODELING FRAMEWORK AND PROCESS

The modeling framework combines two major components or sub-models, as shown in Figure 1: (1) a water supply yield sub-model (yield sub-model) and (2) a shortage management sub-model (shortage sub-model). The two sub-models are run sequentially, with the water supply yield simulation sub-model producing a probability distribution of shortages that enters the shortage management optimization sub-model. Each sub-model is briefly presented and discussed in more detail in later sections.

Management of physical water supplies (i.e., permanent supplies and their operation) is accomplished in the yield sub-model. The core of this sub-model is a fairly conventional simulation model of the physical supply system that produces a time series of water yields or

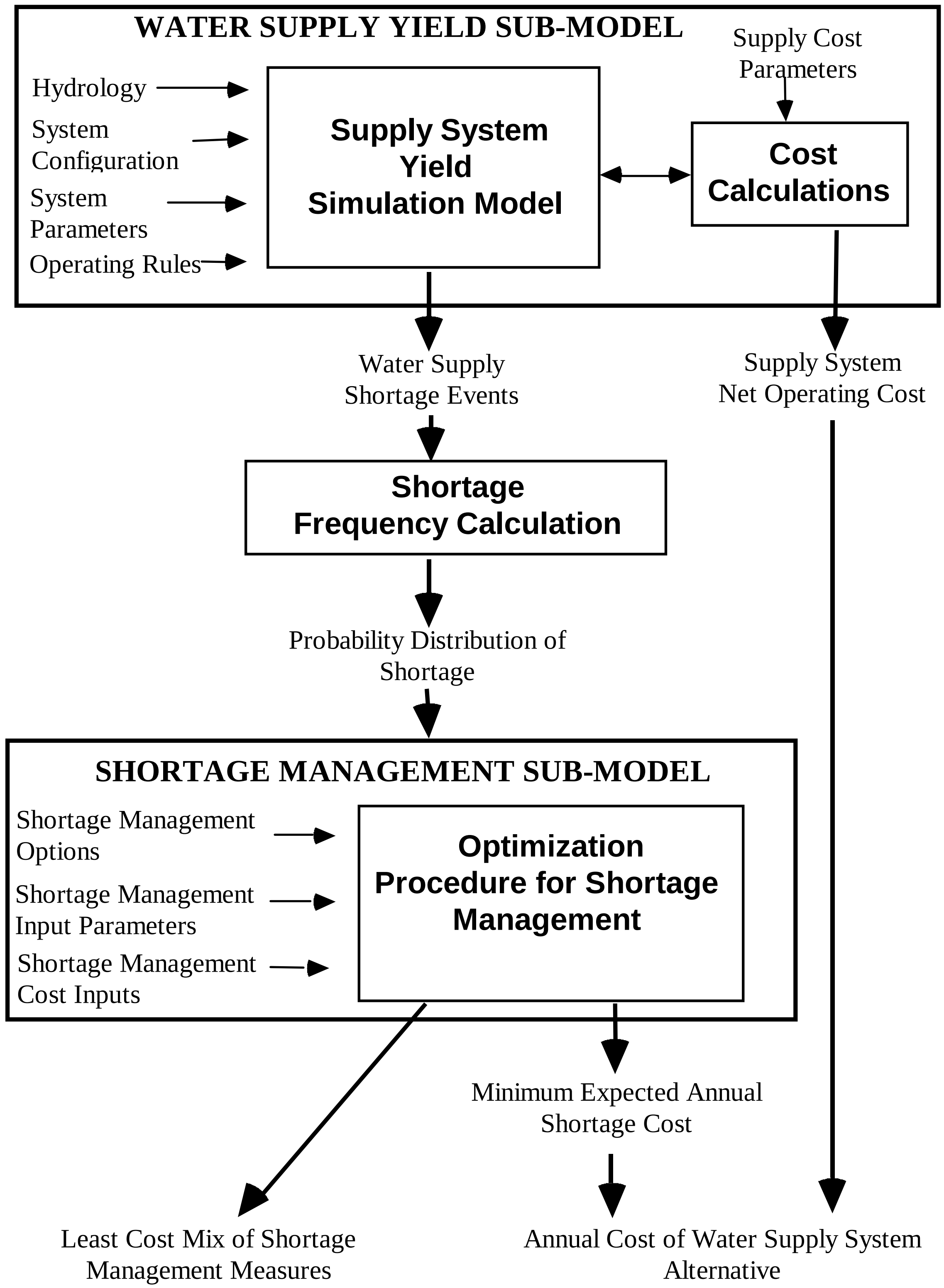


FIG. 1. Integrated Water Supply Planning Modeling Structure

shortages. This time series of shortage events is then reduced to a probability distribution of shortage through a plotting position formula (Lund et al. 1998). The shortage sub-model manages long-term and short-term demand and short-term supplemental supplies (water transfers and water reuse) to meet these probabilistic water shortages. Two-stage linear programming is used to identify the least-cost set of long- and short-term water conservation (water cutbacks) and water transfer measures, and water reuse, which accommodate the probability distribution of shortage (Wilchfort and Lund 1997). Two-stage linear programming provides a more flexible and accurate representation of shortage costs than simple piece-wise linear shortage penalties.

Final results from the integrated model include a minimum expected annual cost and a least-cost mix of shortage management measures (demand management and water transfer measures) for a given particular supply system alternative (system configuration and fixed operating rules). Expected value (risk neutrality) is used in this study to allow a rapid and rigorous assessment and comparison of probabilistic performance of alternatives and scenarios (Arrow and Lind 1970). Tradeoffs of overall expected cost versus the probability distribution of source yield can be examined.

**Water Supply Yield Sub-Model**

The configuration and operation of water sources in the supply system are represented in the yield sub-model. Uncertain hydrology is represented by a time series of stream flows for the simulation period. While historical stream flow records are most commonly used, synthetic stream flow data also could be used. Long- and intermediate-term supply-related options best handled with simulation techniques are incorporated in the yield sub-model. Adjustments needed when yield is less than 'full' demand are handled separately in the shortage management sub-model.

The yield-reliability model is fairly conventional, based on continuity and an operating rule, Equation 1.

(1) $$S_{t+1} = S_t + I_t - E_s(S_t) - R_s(S_t, I_t),$$

where $S_t$ is the storage at the beginning of time-step t, $I_t$ is the inflow at time t, $E_s(.)$ is evaporation during season s, and $R_s(.)$ is the reservoir release rule. Inputs to the yield sub-model are listed in Figure 1 and include representation of the supply system's physical configuration including any permanent water transfers, system operating rules, hydrologic data, input parameters, and variable operating costs for the supply system (pumping, hydropower, treatment, etc.).

Changes in system operating rules are yield-related decisions that can be investigated separately or jointly with other supply enhancement options (such as the use of permanent water transfers, or new storage infrastructure) by making changes to the simulation model. For example, the use of hedging in reservoir operations, changes in ground water pumping schedules, changes in the operation of conveyance structures, etc. can change supply system yield reliability. These strategies can be simulated in the yield sub-model and their effects captured as changes to the shortage probabilities and yield system operating costs. Results of each yield simulation include the net operating costs and a time series of water supply shortage events for the simulated period.

**Shortage Management Sub-Model**

The costs of shortages in urban supply are the costs of consumer and utility actions required to reduce demands to levels supplied. The objective of the shortage management sub-model is to select long-term and event decisions that minimize the expected cost of responding to the probability distribution of water shortages generated by the yield simulation sub-model. Details of its formulation and use for shortage management planning alone are presented elsewhere (Wilchfort and Lund 1997), but are summarized below.

Options included in the shortage management sub-model are categorized as demand related (e.g., conservation and cutbacks), water reuse, or short-term supply-related (e.g., water transfers) and are represented by linearizable decisions in the optimization problem. The objective function to minimize the expected annualized cost of shortage management, $Z$, is given by equation 2, with the first set of terms representing long-term shortage management costs and the second set of terms representing expected value costs for short-term management options:

$$\text{Min } Z = \sum_{i=1}^{n_1} (c_{1i} X_{1i}) + \sum_{s=1}^{n_s} \sum_{j=1}^{m} \sum_{k=1}^{n_2} p_{sj} (c_{2sjk} X_{2sjk}) , \qquad (2)$$

where,

$c_{1i}$ = unit cost of implementing long-term option $i$;

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

$m$ = number of shortage events;

$n_1$= number of long term options available;

$n_s$ = number of seasons;

$n_2$ = number of short-term options available;

$X_{1i}$ = level of implementation of long-term option $i$ (in units of implementation, e.g., units of capacity, toilets retrofitted, etc.);

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

$p_{sj}$ = probability of shortage level $j$ in season $s$.

First stage decisions, $X_{1i}$, are long-term (permanent) decisions that must be implemented well before a shortage to provide water or reduce use. These include water reuse, xeriscaping and water fixture retrofits (long-term conservation), and acquiring dry year water transfer options. Installing wastewater reclamation capacity is included because it can be modeled easily with optimization in the same way as long-term conservation. Second stage decisions, $X_{2sjk}$, are short-term operational decisions implemented selectively in response to a shortage level and having a probabilistic likelihood of use. Short-term options include consumer water cutbacks to reduce landscape watering and indoor use (short-term conservation to accept a one-time shortage event) and utility decisions to activate dry year transfer options and purchase spot market water. Costs of consumer cutback actions can be estimated from measures of lost consumer surplus or from contingent valuation studies such as Carson and Mitchell (1987) or CUWA (1994).

Interaction and tradeoffs between long- and short-term decisions are incorporated into the optimization through constraints on decision variables. For instance, a second-stage decision to activate dry year options in a shortage event is contingent on establishing the option contract in the first stage. The effectiveness of many short-term conservation efforts is reduced by adoption of related long-term conservation measures, such as potential lawn watering reductions being reduced if xeriscaping has already been implemented. This type of constraint reflects what is often called demand hardening. Other model constraints consist of physical limits on implementing long-term and short-term measures and the requirement to match demand to supply, after shortage management adjustments, in each shortage level having a non-zero probability of occurrence. Equations for these various constraints are discussed elsewhere (Wilchfort and Lund 1997; Lund 1995; Lund and Israel 1995a). This sub-model is better suited to droughts in regions with pronounced dry seasons and snowmelt, where warning of the onset and end of each drought season can be assumed (Wilchfort and Lund 1997).

User inputs include the variety of shortage management options (the decision variables) and their capacity limits, efficiency factors, and annualized unit costs. The shortage sub-model uses a shortage frequency distribution from the yield sub-model output ($p_{sj}$). Results from the shortage sub-model are the least-cost mix of long- and short-term shortage management options, their optimal quantities, and the expected (minimum) annualized cost of their implementation, for the given shortage frequency distribution.

**Integration of the Yield and Shortage Sub-Models**

The yield and shortage management models are run sequentially. The shortage frequency calculation procedure of Figure 1 converts the time series of water shortages from the yield sub-model into a discrete probability distribution of shortage for input as the second stage probabilistic events (index *m* in Equation 2) of the shortage sub-model optimization. Four steps are involved in this procedure.

First, the yield event for each season is converted into a percent shortage relative to the target 'full' demand and ranked in order of decreasing shortage. Next, the exceedence probability of each water shortage event is estimated based on its rank using the probability plotting position formula (r+1)/(n+2) (Laplace's rule of succession) where r is rank and n is the number of yield events (Lund et al. 1998; Jeffreys 1961). These event exceedence probabilities define the cumulative distribution of water shortages from the yield simulation. Estimates of the discrete probabilities (or frequencies) of incremental levels of shortage are computed from the cumulative distribution by linear interpolation and simple differentiation. The mid-point of the shortage interval is taken as the average magnitude for that shortage event. Discretization of shortage events is a matter of choice and can be important as will be seen in the application example.

Joint optimization of both shortage management and the yield system (capacity configuration and operating rules) is possible and would require embedding this modeling framework within a search algorithm for the non-linear configuration and operating rule decisions.

**Use of Results**

The total cost result from the integrated model is the expected cost of the supply reliability achieved considering hydrologic uncertainty, a given supply system alternative (i.e. system configuration and operating rules), and an optimized shortage management plan. The modeling process involves running the yield and shortage management sub-models for each supply system planning alternative. Alternatives can then be directly compared based on overall expected annual cost, summing net operating cost of yield system and expected cost of managing shortages. Other important non-economic performance information from the model can be compared, such as characteristics of each alternative's probability distribution of shortages (e.g., average shortage, probability of any shortage, probability of the worst shortage event, etc.) and levels of implementation of different shortage management options including consumer cutbacks.

## APPLICATION TO A MAJOR URBAN WATER SUPPLY SYSTEM

This section presents the application of our integrated model to a simplified representation of the East Bay Municipal Utility District (EBMUD) in California. EBMUD serves approximately 1.1 million people with an estimated demand of 215 mgd (million gallons per day) or about 240,000 ac-ft/yr (acre-feet per year). EBMUD is actively attempting to integrate various forms of water transfers, demand management, and yield enhancement options in planning their system. A summary of key features of the EBMUD application follows, with a complete description available in Lund et al. (1998).

### EBMUD Supply System

EBMUD's water supply system consists of two large storage reservoirs (Camanche and Pardee) on the Mokulemne River (mean runoff of 720,000 ac-ft/yr), three aqueducts conveying water from Pardee Reservoir to the service area, five small terminal reservoirs within the service area, and six treatment plants (EBMUD 1991). No ground water is used presently. In addition to surface water rights and contracts for 360,000 ac-ft/yr from the Mokulemne River, EBMUD has a contract for 150,000 ac-ft/yr of American River water from the U.S. Bureau of Reclamation. A simplified schematic of EBMUD's supply system appears in Figure 2. While expectation has been to divert American River water through the Folsom South Canal via an extension to their aqueducts, current EBMUD access to American River water is via the Sacramento River and diversion from the Sacramento-San Joaquin Delta. Legal conflicts from environmental concerns on the American River and in the Bay-Delta System currently restrict EBMUD's use of this water and construction of the canal extension. A disadvantage of Delta withdrawals is its much lower water quality compared to direct Mokulemne or American River withdrawals.

During the 1976-77 and 1988-92 droughts EBMUD experienced significant shortages and major cutbacks to customers. Conventional planning estimates of yield reliability for the present supply system and a forecasted 2020 demand of 280,000 ac-ft/yr, indicate that EBMUD will face water supply shortages in 1 out of every 3 years (34% probability of annual shortage) and shortages exceeding 25% of demand in nearly 1 out of every 10 years (EDAW Inc. 1992).

To manage supply deficits, EBMUD has relied on conventional reservoir operations, water conservation programs, and water rationing. Also, during the last drought emergency, EBMUD aggressively attempted to implement several innovative water transfers, though with little success (Lund et al. 1992). Nonetheless, in the context of long-term planning, several types of water transfers offer opportunities for improving EBMUD's water supply reliability when integrated with yield enhancement and demand management options. These transfer opportunities include: 1) integrating a permanent water transfer from the American River into the present Mokulemne supply system (based on their contract); 2) establishing dry year option contracts with senior

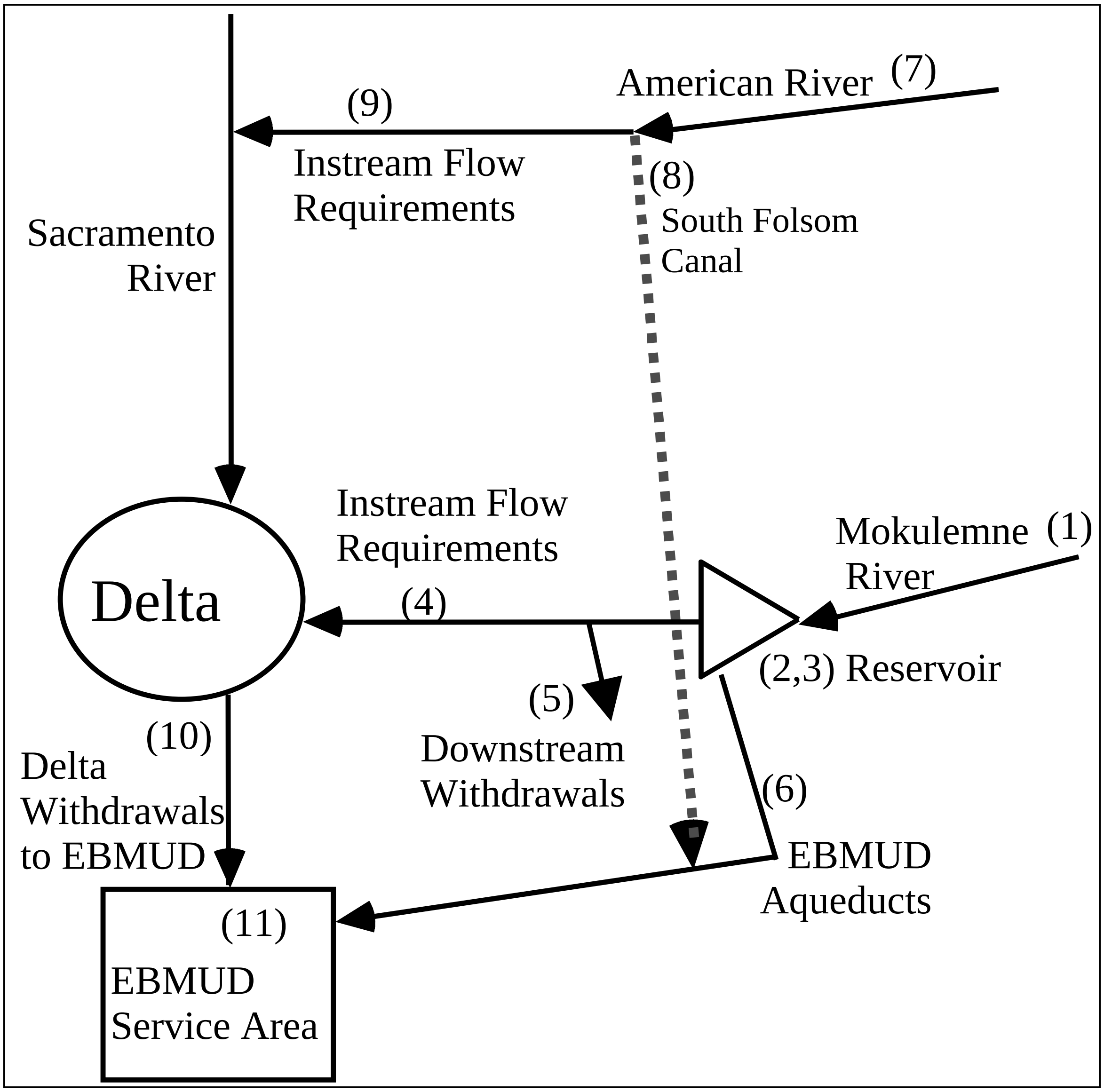


FIG. 2. Simplified Schematic of EBMUD Water Supply System and American River Alternatives

water-right holders to acquire water during system deficits; and 3) purchasing spot market water during shortage events.

EBMUD's American River water right is restricted in low flow years, and this stream's flow is highly correlated with the Mokulemne River's. Nonetheless, because their seasonal runoff peaks do not coincide and drought low flows are imperfectly correlated between the two basins, using American River water with a well-designed operating strategy, even under restrictions, improves EBMUD's water supply reliability. American River imports could be incorporated into EBMUD's present supply system by different physical configurations and operational strategies, e.g., the Folsom South Canal, ground water banking, access through an existing Delta diversion, and wheeling.

Water quality issues are important in the engineering of transfers for EBMUD. There are strong motivations to preserve the high quality of water entering the service area and significant operational limitations on treating lower quality Delta water with present treatment facilities. Given existing conveyance and treatment limitations, sources of water for short-term transfers, such as dry year options and spot market transfers, can be divided into two broad categories based on water quality: (1) high quality water from water rights holders on the Mokulemne River captured at Pardee Reservoir, and (2) low quality water captured at the Delta from other water sellers located in the Sacramento River System.

**Planning Alternatives Selected for Modeling**

Various supply and shortage management options (yield augmentation, conservation, water reuse, and water transfers) can be handled in this integrated modeling framework. For long-term yield enhancement, a permanent transfer of American River water to the EBMUD system through either the Delta ("Delta" alternative) or an extension of the Folsom South Canal ("Canal" alternative) will be evaluated against a Mokulemne-only base case ("BASE"). Scenarios for operating these two American River options in conjunction with the Mokulemne River supply in the yield simulation sub-model will be evaluated to see how reservoir and conveyance operating rules affect shortage management and overall costs. Finally, reservoir hedging rules are modified in conjunction with shortage management optimization to reduce overall expected cost of water supply reliability.

Long-term shortage management measures included in the shortage management sub-model are water reuse, water treatment capacity expansion (to allow use of more low quality water), xeriscaping, plumbing retrofits, and dry year option contracts. Short-term measures are activating dry year option contracts, low intensity lawn watering reductions, reduced indoor water use, more severe (higher cost) lawn watering reductions, and spot market water transfers. Spot market water transfer prices vary by season and increase with the severity of the shortage to reflect different supply and demand conditions. Two levels of water quality, high and low, are specified for dry year option and spot market water transfers, where high quality requires no increased treatment capacity.

**Model Setup for EBMUD Application**

The EBMUD integrated model application is composed of two seasons per year, one wet (November to March) and one dry (April to October). This choice of time step permits a simpler yet realistic simulation of river-reservoir operations with an annual draw down-refill cycle under California's hydrology. It also accounts for the seasonal timing of transfers for dry year option contracts, and allows for a smaller number of decision variables and constraints in the shortage management optimization.

As shown and numbered in Figure 2, the following components comprise the BASE supply system as modeled in the yield sub-model:

(1) 73 years (1921-1993) of Mokulemne River historical unimpaired stream flow;
(2) a reservoir located on the Mokulemne with 720,000 ac-ft of active storage representing the combined capacity of EBMUD's seven reservoirs;
(3) a modified standard linear operating rule for making reservoir releases with two hedging features: one for carryover storage from the wet to the dry season (triggered

by low forecasted dry season inflow), and the other for reducing the rate of dry season draw down (triggered by low projected end-of-period storage);

(4) instream flow requirements on the Mokulemne River downstream of the Reservoir of 105,000 ac-ft/yr (59% in the dry season);

(5) a single downstream withdrawal representing all other Mokulemne River users having higher priority entitlements for a total of 116,000 ac-ft/yr (92% in the dry season); and

(6) EBMUD withdrawals based on meeting 2020 demand of 280,000 ac-ft/yr (67% in the dry season).

Additional components needed to model the American River alternatives are:

(7) 73 years of American River historical unimpaired stream flow;

(8) a diversion point at the Folsom South Canal and its extension for the Canal alternative;

(9) minimum instream flow requirements in the American River, before EBMUD can divert water, of 473,000 ac-ft in the dry season and 400,000 ac-ft in the wet season (the 10% non-exceedence low flow by season);

(10) a Delta diversion for American River water rights; and

(11) treatment plant constraints restricting treatment of low quality Delta water to 35% of total EBMUD supply.

Instream flow requirements on the lower Mokulemne and American Rivers and Mokulemne River downstream withdrawals are important parameters in the yield simulation sub-model. Their values depend on uncertain institutional outcomes about such things as environmental regulations, legal decisions on water rights, and economic growth. The deterministic values listed above represent the most likely levels as indicated in technical documents (EDAW, Inc. 1992). The sensitivity of model results and planning decisions to uncertainty in these institutional parameters will be considered in the results section.

Reservoir operations in the yield sub-model are initially the same in all model runs, unless otherwise stated, with the three hedging parameters set at levels which aim to maintain end-of-year storage above 100,000 ac-ft for BASE case conditions. The effect of changing hedging operations on integrated system performance is examined in the second part of the results.

Marginal operating costs for the American River alternatives are estimated as $150/ac-ft of water diverted at the Delta for extra pumping and treatment, and $10/ac-ft of water conveyed by the Folsom South Canal extension for pumping costs, but no additional treatment. The Delta alternative requires no additional capital costs. The Canal alternative requires construction of the canal extension and related structures. Model results will be used to estimate the maximum willingness to pay (WTP) for the Canal by computing the difference between the costs of the Delta and Canal alternatives under their best operating policies.

The shortage frequency calculation procedure converts each season's shortage events from the two-season yield sub-model into a discrete probability distribution of shortage for each season. Six increments of 0%, 10%, 30%, 50%, 70% and 90% shortage were chosen.

In the shortage management sub-model, constraints on all options reflect levels suggested by technical reports (EBMUD 1991; EDAW, Inc. 1992). Outdoor and indoor conservation, through combined long- and short-term options can reduce demand up to 47% in the wet season and 60% in the dry season. Combined dry year options and spot market transfers of water are limited to 29,000 and 41,000 ac-ft in the wet and dry seasons respectively under existing treatment capacity. Additional volumes of low quality water transfers up to 29,000 ac-ft/dry and 21,000 ac-ft/wet season, require investments in additional treatment capacity. Cost coefficients for each option are listed in Table 1.

TABLE 1. Annualized Cost Coefficients for EBMUD Shortage Management Sub-Model

| Options | Cost ($/ac-ft) |
|---|---|
| *Long-Term Options (ac-ft/yr)* | |
| Additional water treatment capacity | 200 |
| Dry year option contract wet season | 19 |
| Dry year option contract dry season | 19 |
| Water reuse | 1500 |
| Xeriscaping | 150 |
| Indoor water fixture/plumbing retrofits | 30 |
| *Short-Term Options (ac-ft/event-season)* | |
| Activate dry year water transfer option (wet or dry season) | 80 |
| Spot market water transfer by shortage event | dry season ; wet season |
| 10% | 150 ; 80 |
| 30% | 300 ; 200 |
| 50% | 400 ; 300 |
| 70% | 500 ; 400 |
| 90% | 800 ; 600 |
| Reduced lawn watering - part I | 300 |
| Reduced lawn watering - part II | 700 |
| Reduced indoor water use | 400 |

The EBMUD integrated modeling application was programmed as an EXCEL spreadsheet workbook, using the built-in linear solver for the shortage sub-model optimization.

## MODELING RESULTS AND POLICY IMPLICATIONS

The first part of this section examines performance of the Canal and Delta alternatives for including American River water supplies. The second part looks at the effect of facility operating rules on the cost and effectiveness of integrated yield and shortage management activities. Sections assessing the economic value of expanding facilities and the costs of institutional uncertainties follow.

**Evaluating Alternatives for Improving Yield**

The integrated model was run for the BASE case and then modified and run for two operating policies for the Canal (C) and Delta (D) alternatives. Operating policy 1 (OP1) uses American River water as a secondary supply source for EBMUD demand, only when the EBMUD release from the Mokulemne Reservoir is insufficient. Operating policy 2 (OP2) increases storage in the reservoir by using American River water as the primary EBMUD supply whenever reservoir capacity is available.

Table 2 presents the probability distributions of seasonal shortage for each run. Overall expected costs for each system configuration and operating policy appear in the second column of Table 3. Given the preliminary yield and shortage management sub-models used in the analysis, these values are only illustrative. The BASE case cost includes only the expected value shortage management cost since it serves as the zero reference for net operating costs. The annual expected value cost for the Canal and Delta alternatives is the sum of net operating costs and shortage management costs. Capital cost of the Canal extension project is not included in overall cost results. Other modeling results from the yield and shortage sub-models are summarized in Table 3, illustrating the tradeoffs of yield reliability and expected annual costs for different system configurations.

TABLE 2. Shortage Probability Distributions from EBMUD Yield Sub-model for BASE Case and American River Alternatives

| | Discrete Probabilities of Shortage Events * | | | | | |
|---|---|---|---|---|---|---|
| | 0% | 10% | 30% | 50% | 70% | 90% |
| Run | *Dry Season* | | | | | |
| BASE | .9067 | .0083 | .0228 | .0154 | .0202 | .0267 |
| OP1-D | .9027 | .0182 | .0228 | .0103 | .0154 | .0267 |
| OP1-C | .9330 | .0083 | .0190 | .0063 | .0063 | .0267 |
| OP2-D | .9467 | .0083 | .0074 | .0059 | .0317 | 0 |
| OP2-C | .96 | .0083 | .0317 | 0 | 0 | 0 |
| | *Wet Season* | | | | | |
| BASE | .9467 | .0138 | .0034 | .0034 | .0034 | .0292 |
| OP1-D | .9467 | .0139 | .0036 | .0036 | .0036 | .0288 |
| OP1-C | .9600 | .0400 | 0 | 0 | 0 | 0 |
| OP2-D | .9733 | .0267 | 0 | 0 | 0 | 0 |
| OP2-C | .9733 | .0267 | 0 | 0 | 0 | 0 |

* = Shortage events are expressed as a percent of full seasonal EBMUD demand at 92,400 ac-ft and 187,600 ac-ft in the wet and dry seasons respectively.

TABLE 3. Expected Value Annual Costs, Shortage Management Plans, and Shortage Outcomes for EBMUD BASE Case and American River Alternatives (A= Yield sub-model result, B= Shortage sub-model result)

| | Expected Value Annual Cost [a] ($ millions) | | | Long Term Conservation | Dry Year Option Transfers (1000 ac-ft) | | Maximum Spot Market Transfer [b] | Probability of Shortage | | Avg. Seasonal Shortage (% Demand) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A+B** | **A** | **B** | **B** | **B** | | **B** | **A** | | **A** | |
| Run | Overall | Operating | Shortage | (1000 ac-ft/yr) | Dry | Wet | (1000 ac-ft) | Dry | Wet | Dry | Wet |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| BASE | 10.62 | 0 | 10.62 | 40 | 56.2 | 0 | 40.1 | .093 | .053 | 5.3% | 3.2% |
| OP1-D | 10.63 | 0.17 | 10.46 | 40 | 56.2 | 0 | 40.1 | .093 | .053 | 4.9% | 3.2% |
| OP1-C | 9.10 | 0.043 | 9.06 | 40 | 56.2 | 0 | 0 | .067 | .040 | 3.8% | 0.4% |
| OP2-D | 7.26 | 4.97 | 2.29 | 0 | 0 | 0 | 40.8 | .053 | .027 | 2.8% | 0.3% |
| OP2-C | 1.04 | 0.46 | 0.58 | 0 | 0 | 0 | 40.8 | .040 | .027 | 1.0% | 0.3% |

[a] = Overall expected value annual cost equals the sum of net supply operating cost (over BASE) and minimized shortage management cost only; costs for capital investment for canal extension structures, etc. are excluded.

[b] = This is the largest transfer of spot market water used in any single shortage event (i.e., among second stage decisions) in the shortage sub-model.

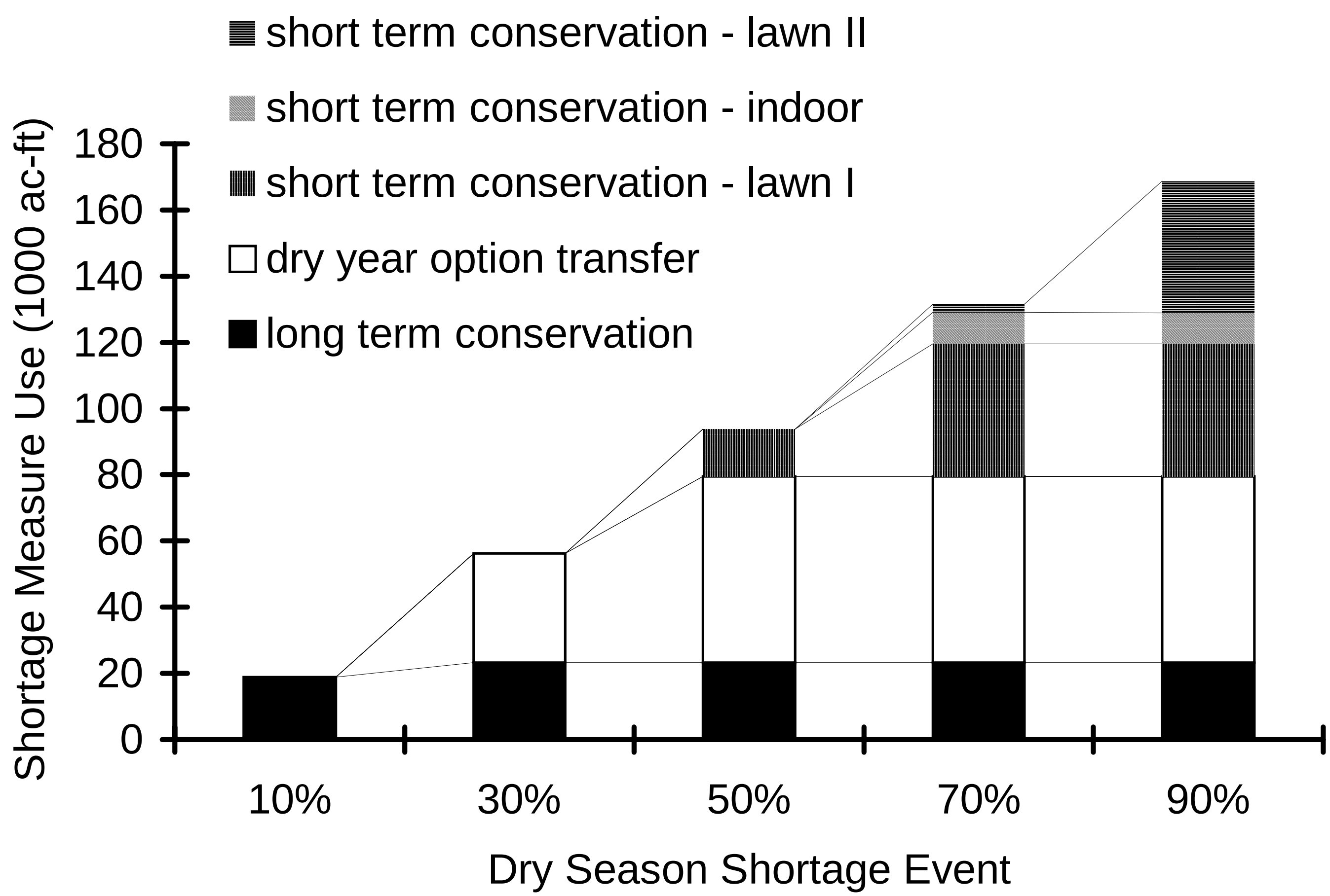


**FIG. 3. BASE Case Optimal Dry Season Shortage Management Plan**

*BASE Case Performance and Shortage Management*

The expected cost to manage shortages for the BASE case system configuration and operation is $10.62 million/yr. The probability of shortage occurring in the dry and wet seasons is 9.3% and 5.3% respectively (columns 9 and 10 of Table 3). Yield from the Mokulemne Reservoir is estimated as having nearly a 3% probability of a 90% shortage in either season (see Table 2), with an average deficit of 5.3% of demand (10,000 ac-ft) in the dry season and 3.2% of demand (3,000 ac-ft) in the wet season.

BASE case shortages are best managed with 40,000 ac-ft/yr of long-term conservation as plumbing retrofits, 56,200 ac-ft/yr of dry season dry year transfer options, and 26,300 ac-ft/yr (or 2,200 ac-ft/month) of additional treatment capacity to handle enough low quality water transfers (either dry year or spot market) for shortage events at or above the 50% level. Short-term conservation is used to supplement dry year water transfers in the 50%, 70% and 90% shortage events in the dry season, and spot market transfers in the 70% and 90% event in the wet season. Neither water reuse, which has the highest unit cost (see Table 1), nor wet season dry year transfer options are used. Figure 3 illustrates the optimal shortage management plan for each dry season shortage event.

More costly measures generally are added for larger shortage events. However, the least-cost order of dry year and spot market transfers differs between dry and wet seasons. Which water transfer type is less costly in a given situation depends on the expected value unit cost (unit price in an event multiplied by the event's probability) for each transfer type in each shortage event. In the BASE case wet season, using spot market water transfers in all events is cheaper than incurring the annual cost ($19/ac-ft) of holding a dry year option. Although these events' spot market price equals or exceeds the dry year transfer price (see Table 1), their probabilities are low enough (see Table 2) to keep their expected value cost below $19/ac-ft/yr. Conversely, in the dry season, shortages and their probabilities are high and spot market prices for these events ($150 to $800/ac-ft) are high enough to produce expected value unit costs greater than the combined annual option and expected activation costs of dry year transfers.

Use of different types of water transfers changes across seasons and shortage events as a consequence of subtle changes in the probability distribution of shortages. This effect demonstrates an important interaction of the shortage probability distribution, shaped by supply system decisions, with the price structure and availability of short-term water transfers.

*American River Alternatives*

Performance results for OP1 in Table 3 show that the addition of American River water via the Delta (OP1-D) does not improve the overall expected value cost ($10.63 million/yr) over the present EBMUD supply system (BASE case) because access at the Delta provides very little additional yield in times of reservoir shortfall. Minimum instream flows restrict the availability of American River water in dry years, and treatment limitations on Delta quality water further limit what EBMUD can use when this water is available. These small shortage management savings are nullified by the additional pumping and treatment costs of Delta water, indicating that the marginal cost of shortage accommodation is cheaper than relying on new Delta supplies under OP1. The similar probability distributions of shortage for the OP1 Delta alternative and BASE case in Table 2 result in the same least-cost shortage management plan.

Access to American River water via the Canal extension under OP1 (OP1-C) improves the overall expected value cost to $9.10 million/yr, reflecting improved yield reliability over the BASE case for both seasons (Table 3). Net operating costs are also low due to the high quality and low pumping cost of Canal water. Despite correlated hydrology and restricted access to the American River, the addition of American River supplies via the Canal reduces the overall expected cost.

As presented in Table 3 (OP1-C), long-term plumbing retrofit conservation of 40,000 ac-ft/yr exceeds the largest expected wet season shortage event (10%), and no other wet season options are needed. Additionally, long-term implementation of 56,200 ac-ft of dry season dry year transfer options and 26,300 ac-ft/yr of additional treatment capacity is needed for dry season shortages. Remaining increments of dry season shortage are managed with short-term conservation.

Long-term options such as conservation, additional treatment capacity, and water reuse, require permanent capital investments that create year-round capacity. As a consequence, in the OP1 Canal alternative, there is unused conservation and treatment capacity in the wet season due to implementation of long-term measures needed to handle much larger dry season shortage events. These inefficiencies in the shortage management plan are due to an imbalance in the expected size of wet and dry season shortages and suggest a potential solution in reservoir operations that spread shortages more evenly over seasons.

**Changing Facility Operating Policies**

Changing the operating policy for using American River water from OP1 (backup supply) to OP2 (primary supply) increases use of American River water to supply EBMUD demand. On average, under OP2, 33,200 ac-ft/yr and 46,400 ac-ft/yr of American River water are used in the Delta and Canal alternatives respectively, compared to 1,100 ac-ft/yr and 4,300 ac-ft/yr respectively under OP1. Net operating costs increase but yield reliability improves dramatically, producing large savings in shortage management costs for both alternatives (columns 3 and 4 in Table 3). OP2 results in a much lower total expected cost of $7.26 million/yr for the Delta alternative and $1.04 million/yr for the Canal alternative. The OP2 Delta alternative's large net operating cost ($4.97 million/yr for water treatment) offsets much of the savings in shortage management costs.

The largest probable shortage event in the dry season is reduced from 90% under OP1 to 70% and 30% under OP2, in the Delta and Canal alternatives respectively (Table 2). Consequently, no long-term shortage management measures are chosen under OP2 for either alternative. Because event probabilities are generally low, only spot market water transfers are used in both seasons, supplemented by short-term conservation in the dry season.

The Canal alternative under OP2 has significantly lower expected value cost than both the BASE case and the Delta alternative under either operating policy. The Delta alternative only reduces cost over the BASE case under OP2. Since only a few American River operating policies were examined, it is likely that other operations and configurations could further improve performance. Results from these two preliminary operating policies demonstrate the importance of integrating the analysis of supply system operating decisions for yield enhancement with long- and short-term shortage management decisions for identifying preferred alternatives.

**Willingness to Pay for the Canal Project**

The maximum annual willingness to pay (WTP) for construction of the Canal project linking the American and Mokulemne Rivers is the smallest expected cost for the Canal alternative subtracted from the next least costly alternative. Based on the illustrative results in Table 3, EBMUD's maximum WTP is $6.22 million/yr, calculated from the difference between the OP2 Canal cost and the OP2 Delta cost. In present value, EBMUD's WTP for the Canal project is $124 million, based on a 5% real discount rate and an infinite life-span. The difference in Canal and Delta annual costs under OP1 results in a present value WTP of only $30.3 million, demonstrating the importance of good operating policies for the value of the Canal project. A more complete analysis of maximum WTP would require modeling many different American River and reservoir operating policies.

**Sensitivity to Institutional Uncertainties**

Institutional uncertainties in yield simulation parameters such as future instream flow requirements and senior withdrawals are common yield-reliability concerns. Additionally, numerous institutional issues create uncertainty for the transaction and implementation of water transfers (Gray 1989; Lund et al. 1992; Lund 1993). Analysis was done to examine the sensitivity of modeling results to uncertainties in yield parameters and water transfer implementation. The results of this analysis are presented in Table 4 and discussed next.

The "Rosy" supply scenario assumes the lowest (i.e., most favorable to EBMUD) instream flow requirements (32,000 ac-ft/yr) and downstream withdrawals (91,000 ac-ft/yr) on the Mokulemne River, while the "Worst" scenario assumes the highest levels (131,000 and 116,000 ac-ft/yr respectively) that might reasonably occur. These two cases provide the bounds for BASE case performance, which thus far has been modeled assuming "most likely" parameter values. Under "Rosy" conditions, no shortages occur in the BASE case 73-year yield simulation and the small $0.1 million/yr expected shortage management cost is due to the small residual probability of the 10% shortage event from the plotting formula. Under the "Worst" conditions, decreased yield reliability raises expected shortage management costs to $12.99 million/yr. The probability of a 90% shortage increases to 7.3% and 3.3% in dry and wet seasons respectively, while annual probability of shortage is nearly 22%. Dry year options are purchased for both seasons, with spot market transfers added in the worst wet season shortage events. No other long-term options are added.

The institutional availability of at least one type of water transfer for shortage management is critical for reducing shortage costs in the BASE case. BASE case costs are only slightly greater when only one type of transfer is available, with removal of dry year transfers causing a greater cost increase. However, when no transfers are available, the average cost of shortage management climbs to $147.6 million/yr because of the need for 96,300 ac-ft/yr of water reuse and full use of all conservation in the 90% shortage events. The economic value of water purchased in dry years can be extremely large.

Increasing dry season instream flow requirements on the American River to 46% non-exceedence levels (1,200,000 ac-ft) decreases availability of EBMUD's water rights through the canal. This assumption has no effect on the Delta alternatives and a small effect on the cost of both the OP1

TABLE 4. Sensitivity of EBMUD Integrated Modeling Results to Uncertainty in Key Assumptions

| Run | Supply System Conditions | Shortage Management Conditions | Average Annual Cost ($ millions) |
|---|---|---|---|
| BASE | unchanged from base | unchanged from base | 10.62 |
| BASE | "Rosy" | unchanged | 0.10 |
| BASE | "Worst" | unchanged | 12.99 |
| BASE | unchanged | no dry year options | 11.51 |
| BASE | unchanged | no spot market transfers | 10.70 |
| BASE | unchanged | no dry year options and no spot market transfers | 147.60 |
| OP1-C | increased restriction on dry season American River water | unchanged | 9.46 * |
| OP2-C | increased restriction on dry season American River water | unchanged | 1.73 * |
| OP2-C | increased restriction on dry season American River water | no dry year options and no spot market transfers | 2.19 * |

"Rosy" = Most favorable assumptions to EBMUD for instream flow requirements and downstream withdrawals on the Mokulemne River are used in the Yield sub-model.
"Worst" = Highest levels of instream flow requirements and downstream withdrawals on the Mokulemne River are used in the Yield sub-model, creating the worst conditions for EBMUD operations.
* = Cost excludes capital investment for canal extension structures, etc.

and OP2 Canal alternatives, from increased short-term use of spot market transfers and conservation. No long-term options are needed in the OP2 Canal alternative as the magnitude of expected shortages increases only in the dry season to the 50% shortage event. When transfers are unavailable (with the OP2 Canal alternative under higher instream flow requirements), the magnitude of probable shortages are small enough to be managed completely by short-term conservation in place of spot market transfers at an increased expected shortage management cost of $1.90 million/yr, and a total expected cost of $2.19 million/yr.

The OP2 Canal alternative cost is not sensitive to uncertainty in either water transfer implementation or American River instream flow requirements. However, uncertainty in Mokulemne River instream flow requirements, downstream withdrawals, and water transfer implementation are very important for BASE case performance, and consequently, for estimating EBMUD's WTP for the Canal extension project. Under the "Rosy" supply scenario there is no need for American River water and WTP is zero. If water transfers are unavailable, under the most likely supply scenario, EBMUD's annual WTP grows to about $145 million/yr. These results demonstrate the economic vulnerabilities of different system configurations and operating policies to institutional uncertainties. Lund et al (1998) provide more detailed analysis of vulnerability based on probability distributions of institutional uncertainties.

## HEDGING FOR INTEGRATED YIELD AND SHORTAGE MANAGEMENT

Changes in the probability distributions of seasonal yield (shortage) have important implications for shortage management costs. By altering supply system operating rules, to modify yield reliability and shortages probabilities, supply and demand options can be jointly optimized for overall least-cost water supply reliability. So far we have examined this idea for American River operating policies only. Reservoir operations, held constant in the results so far presented, are an important technique to modify yield reliability. Hedging reservoir operating rules are commonly used to shift water in storage between seasons and years, to reduce the probability of extreme shortages by accepting more frequent small shortages (Hashimoto et al. 1982; Shih and Revelle 1994). This section demonstrates the use of this integrated modeling approach to identify a promising dry season hedging rule for reservoir operations in the Canal alternative under OP1.

### Hedging Rule Description

Figure 4 illustrates the dry season reservoir hedging rule used for the EBMUD application. Under a standard linear operating rule, in each period the release R (yield) from the reservoir depends on the quantity Q (the sum of water in storage plus anticipated inflow), and follows the solid line in Figure 4 (Lund and Guzman 1996; Maass et al. 1966). The target release is the sum of three dry season quantities: EBMUD's demand, lower Mokulemne River instream flow requirements, and downstream withdrawals. When Q is less than A (the target release volume), release falls below target and equals Q. Shortages occur, and reservoir storage is completely drained. When Q exceeds C (the sum of target plus reservoir capacity), the reservoir releases the target volume and spills all of Q in excess of capacity.

Hedging changes the initial slope of the standard rule by moving the point when shortages first occur (A) further out along the Q axis to B. The amount of hedging is represented as a proportion of the target. Hedged releases now follow the dotted line when Q is less than B. As hedging is increased, shortages occur earlier in the draw down of storage while larger amounts of water are held in storage for the next period. This simple form of hedging is used to explore the role of reservoir operating policies in improving the joint design of supply and shortage management systems.

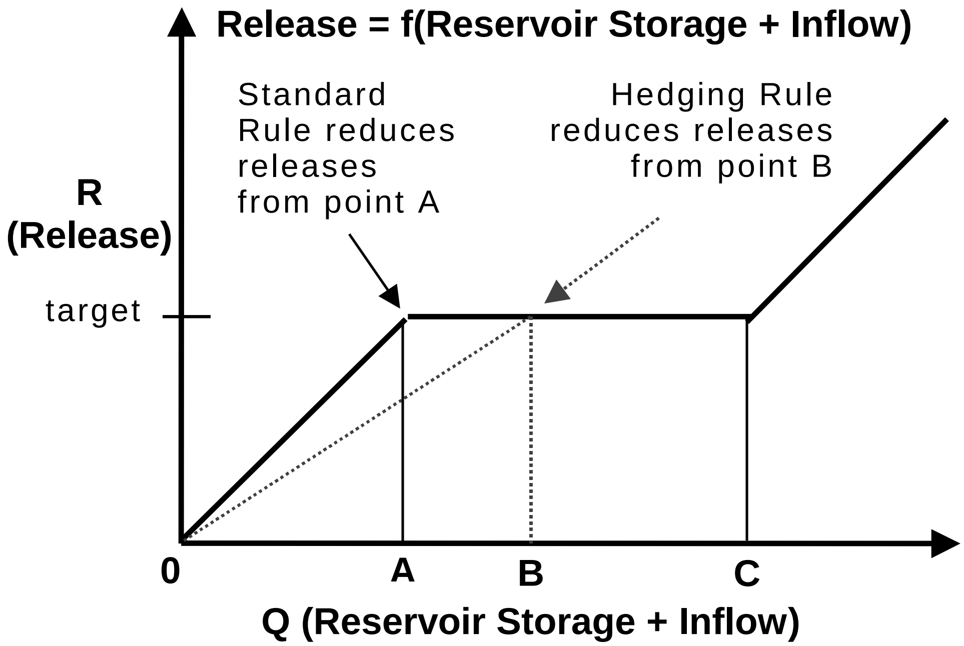


FIG. 4. Reservoir Operating Rule with Hedging

**Optimized Water Supply Reliability with Hedging**
The expected value cost of water supply reliability for the Canal alternative under OP1 in Table 3 is $9.10 million/yr, almost all of which is shortage management costs. In this and all other results in Tables 2, 3, and 4, dry season hedging was unchanged at 35% of the target. The OP1 Canal model was re-run with varying levels of dry season hedging to identify an improved hedging rule for this alternative. Changes in overall cost with increased dry season hedging appear in Figure 5 and reveal a discontinuous function with optimal hedging between 12% and 34%. The response of the integrated system to reservoir hedging is dramatic and illustrates the complex interdependencies between system operations and shortage management. These can be understood through the changes in shortage management induced by changes in seasonal shortage probabilities.

Average seasonal shortages also appear in Figure 5 to summarize changes in the shortage probability distributions. As dry season hedging increases, average shortages increase in the dry season and diminish in the wet season. Discontinuities in the shortage curves indicate the addition of the next (or the removal of the last) largest discrete shortage event to the probability distribution. In the wet season, the largest non-zero-probability shortage event progressively drops from 90% at 11% hedging to 10% at 34% hedging. Conversely, in the dry season the

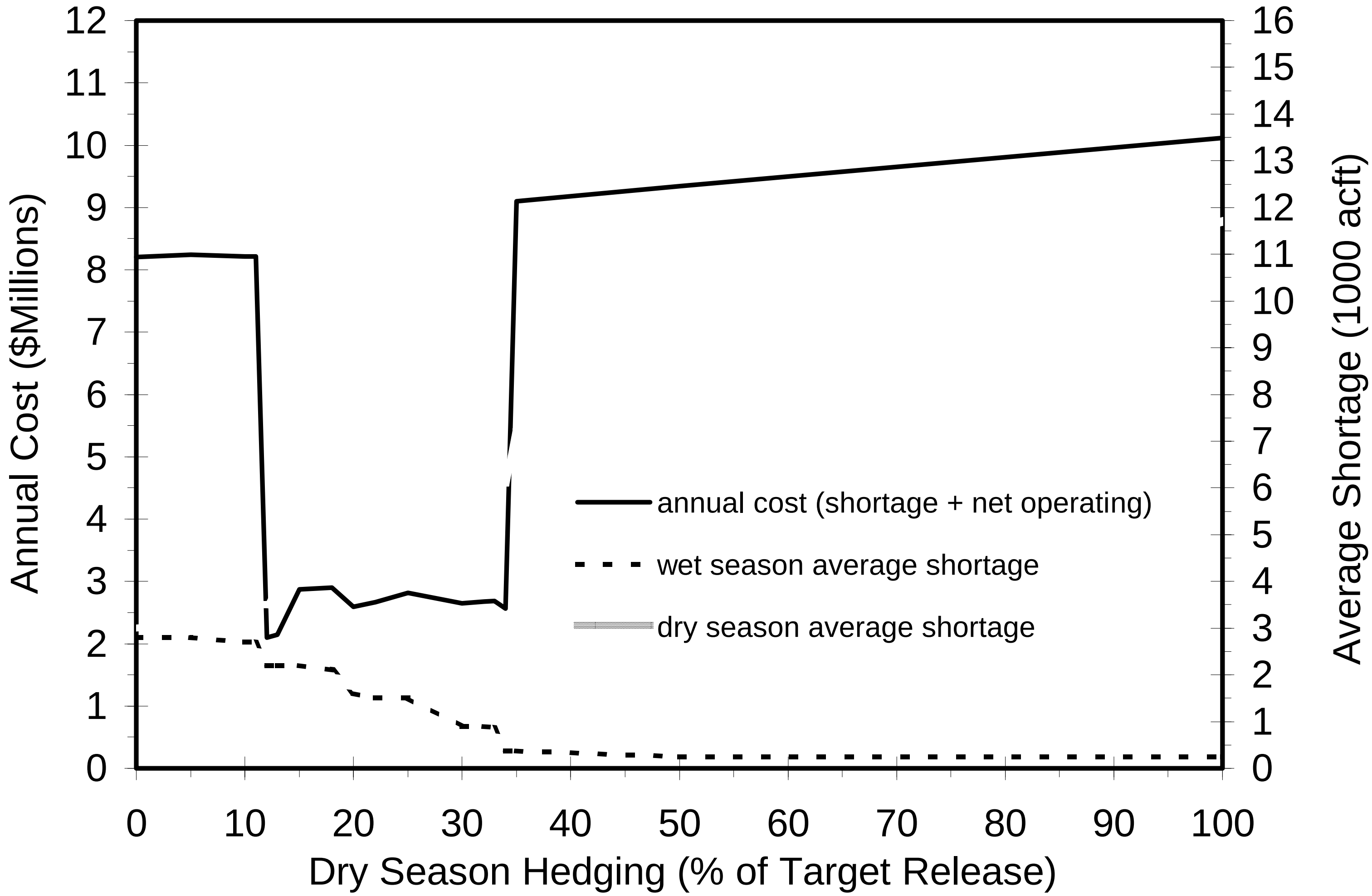


FIG. 5. Expected Value Cost and Average Seasonal Shortages with Increasing Reservoir Hedging in the Dry Season (American River CANAL Alternative under Operating Policy 1)

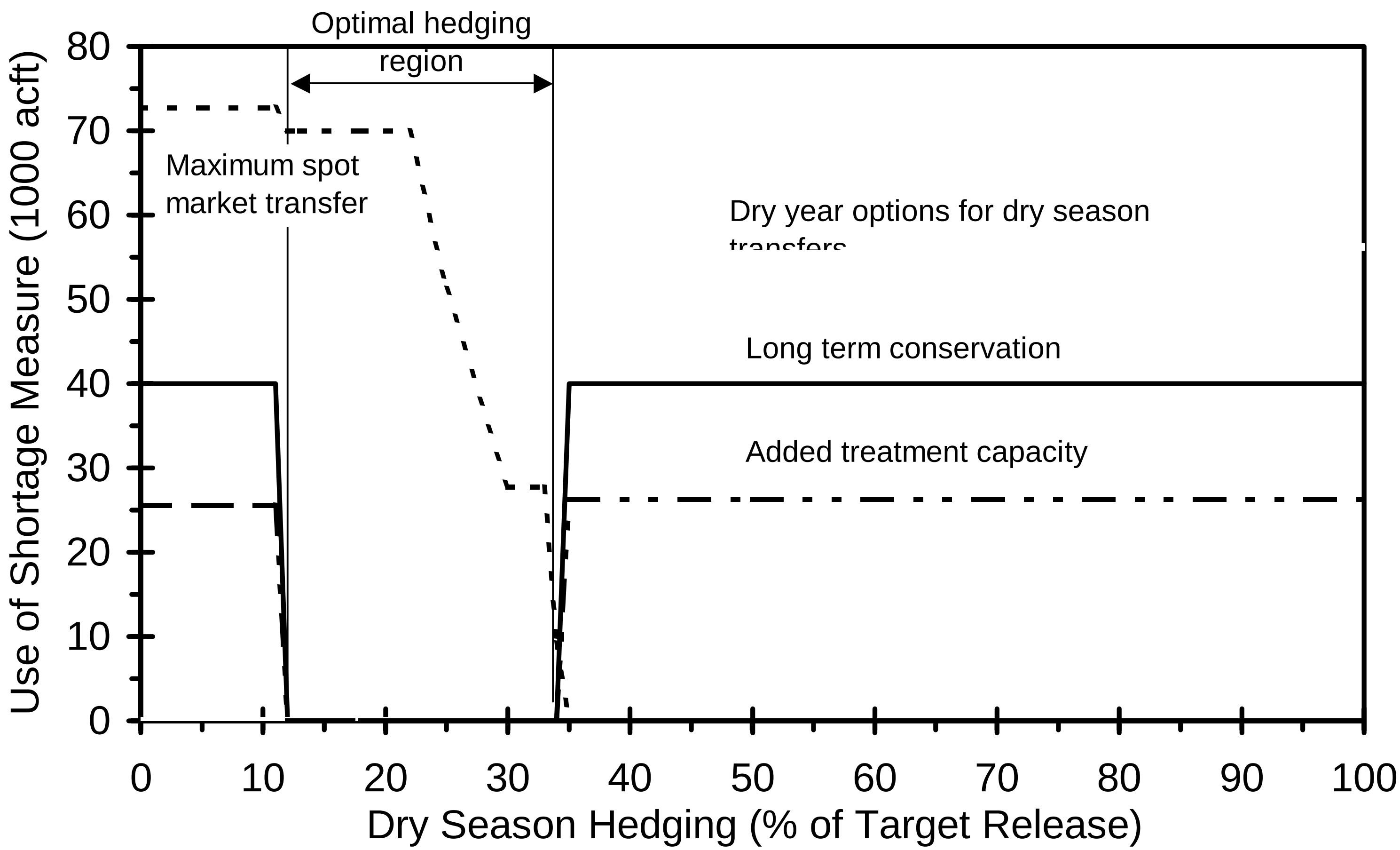


FIG. 6.  Optimal Use of Shortage Measures with Increasing Reservoir Hedging in the Dry Season (American River Canal Alternative under Operating Policy 1)

largest shortages increase from 50% at 13% hedging to 90% at 35% hedging. Minimizing the size and frequency of the largest shortage events is critical to reducing expected shortage costs.

The effect of hedging on optimal shortage management plans is shown in Figure 6. The least-cost hedging region is delineated along with the level of implementation of four critical shortage management options. Shortage management costs are greatly minimized when long-term conservation, additional water treatment capacity, and water reuse are avoided. This means that water transfer volumes remain within the existing treatment capacity limits (70,000 ac-ft/yr) in all shortage events. Within the optimal region, spot market transfers are used initially in both seasons, but as the probabilities of shortage events in the dry season increase, the use of spot market transfers is steadily replaced by dry year options, keeping the total amount of transfers constant and below 70,000 ac-ft/yr. With improved hedging, short-term conservation (consumer cutbacks) is sufficient to supplement transfers for managing shortages. It has lower expected costs than long-term conservation because remaining shortages after transfers are infrequent and small enough that consumer cutbacks are more economically efficient. And as long as shortages do not exceed 70% in either season, this less expensive shortage management plan remains feasible.

Outside the optimal hedging region costly shortage management options are required because the distribution of probabilistic shortages goes beyond the availability of inexpensive shortage management options. With too little dry season hedging, expensive long-term conservation and additional water treatment capacity are required to handle the 90% wet season shortage event. Too much dry season hedging increases the expected size and frequencies of dry season shortages up to the 90% event with no reduction in wet season shortage probabilities. These large dry season shortages require expensive long-term conservation and water treatment capacity and create cost inefficiencies from unused capacity in the wet season. Optimal hedging occurs when the seasonal distribution of expected shortages most closely matches the seasonal capacities of shortage options and water demands.

Hedging (and system operating rules generally) can effectively modify the magnitude and frequency of seasonal shortage events so that they more economically match seasonal capacity limits and other characteristics of demand and shortage management options. When excess long-term shortage management capacity exists in either season, from either permanent conservation, low quality water transfer treatment capacity, or water reuse capacity, cost efficiencies in overall water supply reliability can be achieved by redistributing supply system yield to shift shortages to this overly-reliable season. Each alternative in Table 3 is likely to have an optimal hedging rule that would reduce its expected costs. To improve integrated yield and shortage management, it is important to tune reservoir operations for each alternative.

## IMPLICATIONS FOR USE OF WATER TRANSFERS

This application illustrates three aspects of the integrated use of water transfers in least-cost urban water supply reliability planning, particularly in the Western United States where a prolonged and distinct dry season coincides with peak water demands. First, changes to reservoir operating rules, specifically hedging during the dry season to provide carryover storage into the next year, can directly influence the choice between spot market and dry year water transfers as the principal short-term supply option. By modifying the seasonal frequencies of shortages, hedging directly influences the least-cost selection of the type, magnitude, and season of use of temporary water transfers. In this application, under-hedging led to the need for large spot market transfers in rare extreme shortage events associated with multi-year droughts typical in the Western United States. Over-hedging, a more conservative approach, required setting up dry year options to facilitate frequent use of smaller short-term transfers. From an expected value analysis, however, under-hedging was more cost-efficient than non-optimal over-hedging in this application when short-term water transfers are an available shortage management option.

Second, when yield reliability involves a significant probability of very large shortage events, institutional uncertainty in the availability of short-term water transfers becomes critical for long-term shortage management. In particular, the example demonstrates that when transfers are unavailable as a short-term supply, shortage management costs increase significantly as more expensive and less flexible options are required. Furthermore, as demonstrated in the application, the economic benefits of or willingness-to-pay for new infrastructure in the Western United States can be highly sensitive to this availability of short-term water transfers for shortage management.

Finally, the interaction of the price structures of different water transfer types with the shortage event probabilities determines the optimal level of implementation of each type of transfer. With hedging, supply system yield can be operationally modified in response to changes in price structure or anticipated availability of each transfer type. Price structure, especially for spot market transfers, is highly uncertain, but important for hedging decisions. The integrated modeling framework presented in this paper provides an explicit way to assess the interactions of a changing spot market price structure with hedging.

## CONCLUSIONS

A new modeling framework is developed that integrates traditional yield simulation modeling with a cost-minimizing shortage management model. This framework is used to examine integrated resource planning decisions for urban water supply reliability from an economic and risk-based perspective. The present integrated model provides a risk analysis structure to identify effective operating policies and reservoir operating rules that reduce combined operating and shortage management costs for specific yield enhancement alternatives. Several comments and limitations on the proposed method are suggested by the case study demonstration.

The optimization of system operating rules in conjunction with shortage management is an essential part of least-cost planning for water supply reliability. Results investigating American River operating policies and changes in reservoir hedging illustrate the need to tune operation of the supply system to the cost and capacity characteristics of demand management, water transfers, and other shortage management options.

Institutional uncertainties affecting parameters in the yield simulation sub-model may be more important than hydrologic uncertainties in determining the magnitude and frequency of shortages. Their analysis and modeling should be integrated with hydrologic uncertainties in the yield simulation sub-model to assess the joint effects of these distinct sources of uncertainty for economic risk assessment and water supply reliability planning.

Discretization of shortage levels and extrapolation of probabilities beyond the largest simulated shortage for constructing the shortage probability distributions are two technical details of some importance for evaluating the performance of alternatives. Ideally, a finer discretization would reduce discontinuities in overall costs as yield from the simulation sub-model is modified. In this study, discretized shortage events were limited by the need to retain the shortage management linear program within the limits of spreadsheet optimizing software. How marginal probabilities are extrapolated beyond the largest simulated shortage event in the yield sub-model can have large consequences for cost performance of an alternative, especially if extrapolation causes shortage events large enough to require expensive long-term options in the shortage management plan.

This analysis was relatively easily and rapidly accomplished using spreadsheet software and required little in the way of new data. The availability of optimization algorithms within the spreadsheet software greatly facilitated the modeling. Software add-ins could further enhance the modeling capability and resolve some technical details.

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