SHORTAGE MANAGEMENT MODELING FOR URBAN WATER SUPPLY SYSTEMS

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ABSTRACT: Water shortages throughout the world have shaped the development of demand management and supply enhancement options to improve water supply reliability. A shortage management model based on two-stage linear programming is presented as a tool to integrate available water resources options while accounting for costs and hydrologic uncertainties. To illustrate the approach, the model is applied to a simplification of the East Bay Municipal Utility District (EBMUD) system. The model is expanded in several case studies to demonstrate its strengths in incorporating the effects of seasonal shortages and uncertainties relating to long-term and short-term management options. Conclusions regarding the effects of uncertainties on shortage management are presented. A special examination is made of conditions encouraging economical development of dual distribution system.

INTRODUCTION

Water shortages and threats of water shortages have induced the development of innovative demand management and supply enhancement measures. Demand management measures have relied on modifying consumption patterns and decreasing demand by means of education, low volume water fixtures, water rationing, tiered water pricing, and controlling landscaping. Supply enhancement measures have included new water supplies from new facilities reclamation and desalinization plants, water transfers, improving existing system operations, and increased use of groundwater.

A wide range of available demand management and supply enhancement measures can be considered in devising a management plan to increase supply system reliability and to respond to shortage events. Ideally, in developing demand management and supply enhancement practices, the effects of uncertainties associated with hydrology, water demands, environmental requirements and regulations, and availability of resources should be examined. Other factors that can significantly affect management decisions are the effects of seasonal shortages, limitations in imported water during drought events, the effects of system operation, and the quantities of waters supplied and demanded.

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

This paper describes the use of two stage linear programming to integrate long-term and short-term supply enhancement and demand management options for least-cost shortage management, considering yield reliability (Lund 1995; Lund and Israel 1995; Lund et al. 1995). The effects of hydrology uncertainty, availability of resources, water uses, and costs are incorporated into the model.

OPTIMIZATION MODELS FOR INTEGRATED WATER RESOURCES PLANNING

Management and operation of an urban water supply system have become complex tasks requiring careful planning. Optimization models have been developed to assist in this challenge and to better understand urban water supply system behavior.

Previous optimization models considered capacity enhancement and options to augment water supply based on physical and timing constraints. Butcher et al. (1969) used a dynamic programming model to determine the construction sequence of additional system capacity to meet increasing demand and account for the effects of interest rate, the rate of increasing demand, and the cost per unit supply available from each source. Morin and Esogbue (1971) modified the model presented by Butcher et al. by allowing a subset of available projects to be scheduled and developing a more general selection and sequencing model. Neither model accounted for variability in the existing water supply and the availability to regulate demand by means of conservation measures.

Other optimization models explored the ability to increase system reliability with systems operations. Palmer and Holmes (1988) developed an expert system to be used by water managers in determining reservoir operation under drought conditions based on results from historic drought events and inflows. Randall et al. (1990) developed a multiobjective program to study water supply system operation during droughts. The program was used to develop a revenue-reliability trade-off curve that could be used to operate the system. The trade off curve results indicated that significant increase in system reliability can be obtained with a relatively small decrease in revenues. Shih and ReVelle (1995) presented a mixed integer programming model to determine triggers, measured as reservoir storage volumes plus inflow, for rationing. 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.

As new water supply sources become scarce, increasingly controversial, and their marginal costs increase, water managers are using management options that curb or shape demand in anticipation of water shortages. Several optimization models reflect the trend of incorporating conservation and demand management into water supply system management. Lund (1987) used a sequential linear programming method to evaluate and schedule water conservation measures for avoiding or deferring capacity expansion to minimize costs. Rubenstein and Ortolano (1984) formulated a dynamic program to design demand management options to supplement limited available water sources. Their results showed that significant

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water savings can be attained by managing demand and that the program enabled the user to identify the trade-off between long-term and short-term water conservation measures.

Several demand forecasting models integrate the effects of conservation measures on demand and the overall water supply system. Accounting for conservation program performance in long-run demand forecasts is important particularly in recognizing the permanent and temporary elements of conservation (Weber 1993). Nieswiadomy (1992) analyzed water demand in the United States using data from the American Water Works Association (AWWA) augmented by monthly rainfall and temperature data from the National Oceanic and Atmospheric Administration (NOAA), and climatological and demographic data from the United States Department of Commerce. The impact of conservation programs was explicitly incorporated into the demand model. The results of the model indicated that in general, conservation practices were not effective in reducing water use, though education was an important factor in reducing water use in the west (Nieswiadomy 1992). Briassoulis used the ARIMA modeling framework to assess the effectiveness of water conservation measure in the greater Athens area in anticipation of shortages. Unlike Nieswiadomy's data for the United States, Briassoulis concluded that implementing conservation measures can significantly reduce consumption in Athens (Briassoulis 1994).

Uncertainties in environmental regulations, demand, and hydrological forecasts can greatly affect the ability to plan for a reliable urban water supply. It is desirable for optimization models to combine new options, new constraints, and uncertainties associated with water resources planning, as well as examine trade-offs between objectives.

Integrated resources planning (IRP), an approach commonly advocated for developing management strategies for long-term and short-term planning periods, integrates expansion, demand management, and uncertainties in developing water management strategies. IRP is a least-cost planning method designed to incorporate supply enhancement and demand management. IRP is used to develop planning scenarios and consider their environmental and economic impacts. The comprehensive nature of IRP allows planners to consider multiple objectives and uncertainties relating to environmental externalities, social impacts, and economic benefits, both locally and outside the planning region. IRP is well suited to considering alternatives without a monetary value by presenting trade-offs of competing interests. IRP methods are often sought to establish consensus among interest groups for dispute resolution over conflicts and litigation (Beecher 1995).

Optimization models for IRP are now being developed. Dziegielewski et al. (1992) developed the Drought Optimization Procedure, DROP, to identify the optimal components of a drought mitigation strategy. The DROP is based on a single drought event and its probability, and it is used to compare the costs of short term measures with and without implementing various long-term measures. The long-term alternative decision is based on balancing the incremental cost of the long-term adjustments with the incremental coping cost associated with implementing a drought contingency plan. In each analysis only one shortage event is considered repeatedly for the planning period (50 years); the procedure does not account for the wide variability in drought severity. Lund (1995) and Lund and Israel (1995) developed two stage and multiple stage optimization models to determine willingness to pay to avoid shortages that incorporate an entire shortage probability distribution. The optimization program considers both long-term and short-term conservation measures as well as water transfer options. These models are expanded in this work and applied to planning for urban water shortage management.

SHORTAGE MANAGEMENT MODEL METHODOLOGY

Two Stage Linear Programming

Here a two stage linear programming model is used to represent least-cost shortage management, given hydrologic uncertainty in supply system yield. The model integrates demand management options and supply enhancement measures for long-term and short-term durations. The first stage decisions in the model represent long-term measures such as conservation, dry year transfer contracts, additional water treatment, and water reuse. Long-term measures have a long life span, relatively fixed annualized cost, and usually must be implemented before shortages occur. The second stage decisions consist of short-term measures available to augment water supplies or reduce demands for particular shortage events. Short-term decisions are temporary responses to given shortage levels and their potential may vary with the decisions made in the first stage. The costs of short-term measures for each shortage level are weighed by the probability of the shortage.

Inputs to the optimization model include the different long-term and short-term measures available, their costs and effectiveness in either reducing demands or augmenting supplies. The combined demands may include urban use, withdrawals by senior right holders, and environmental uses. The model also requires a shortage or yield frequency distribution. The shortage exceedence probability distribution is based on a reservoir operation yield model. Usually, a simulation model is used based on seasonal historical inflow data, seasonal demands, a mathematical representation of the system configuration, and operating rules. The yield model provides a time series of shortages that are converted to a probability distribution of shortage events for use in two stage linear programming. This methodology is presented in Fig. 1. The model results provide the least cost combination of long-term and short-term measures, their expected level of use, and the combined annual cost associated with the shortage probability distribution.

Model Limitation

California and much of western North America experience droughts of long duration (many months to several years). The California climate combined with the East Bay Municipal Utility District's (EBMUD) controlled reservoir operation results in shortages long enough that the reaction time for triggering short-term measures is relatively unimportant. For many droughts in more humid regions, droughts are of short enough duration (a few weeks or months) that establishing the triggering rules for implementing short-term drought management measures can be the most important shortage management decisions. This aspect of shortage management is not addressed by our approach.

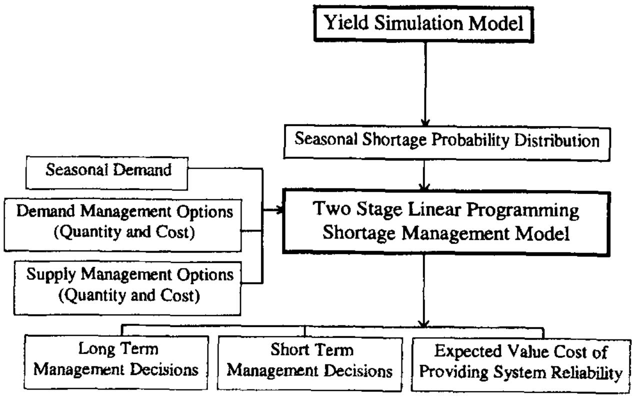

FIG. 1. Flow Diagram for Integrated Water Resources Planning

Model Formulation

Objective Function

The objective of the shortage management optimization model is to minimize the expected value cost of a combination of long-term and short-term alternatives required to meet demand for a predefined shortage or yield frequency distribution. The objective function has two components. The first component is the combined cost of all long-term measures selected in the first stage. The second component is the sum costs of all short-term measures implemented as a response to particular shortages weighed by each shortage probability. Eq. (1) is the mathematical representation of the objective function.

$$\min Z = \sum_{i=1}^{m} c_i L_i + \sum_{s=1}^{y} \sum_{e=1}^{r} p_e \sum_{j=1}^{n} c_{j,s} S_{j,e,s} \qquad (1)$$

where Z = total cost of responding to shortage probability distribution (in \$1,000s); L_i = annual long-term measure quantity (m^3/yr), $\forall i$; $S_{j,e,s}$ = seasonal short-term measure quantity (m^3/season), $\forall j, e, s$; p_e = shortage event probability $\forall e$; c_i = unit cost of long-term measure i (\$/m^3), $\forall i$; $c_{j,s}$ = unit cost of short-term measure j for season s (\$/m^3), $\forall j, s$; s = season (of y seasons); i = long-term measures (of m measures); j = short-term measures (of n measures); and e = shortage event (of r events).

Decision Variables

The model decision variables are the long-term (L_i) and short-term ($S_{j,e,s}$) alternatives 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. Long-term decisions have units of m^3/yr. Short-term decisions include drought conservation measures, activating dry year transfer options, and purchasing spot market water. 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 m^3 per season and event. A more detailed description of decision alternatives appears in the next section.

Model Constraints

The principal model constraints are limits on the long-term and short-term measures and the requirement of satisfying the demands at each storage level for each season. The sum of long-term measures converted to seasonal water volumes and short-term measures also cannot exceed seasonal shortages [(2)]. Long-term and short-term measures also cannot exceed specified limits [see (3) and (4), respectively]. Limits of conservation measures are based on demand and their effectiveness. Xeriscaping is a function of outdoor use and water fixture retrofit is a function of indoor use. Nonnegativity constraints apply to all long-term and short-term measures [(5) and (6)].

$$\sum_{i=1}^{n} f_{i,s} L_i + \sum_{j=1}^{m} S_{j,e,s} \geq SH_{s,e}, \ \forall s, e \qquad (2)$$

$$L_i \leq L_{i,\max}, \ \forall i; \quad S_{j,e,s} \leq S_{j,s,\max}, \ \forall j, e, s \qquad (3, 4)$$

$$S_{j,e,s} \geq 0, \ \forall j, e, s; \quad L_i \geq 0, \ \forall i \qquad (5, 6)$$

where $SH_{s,e}$ = shortage, the shortage volume for seasons s and event e (m^3/season); and $f_{i,s}$ = distribution factor for long-term measure i in seasons (dimensionless)

$$\sum_{s=1}^{y} f_{i,s} = 1, \ \forall i$$

More specific constraints apply to the relationship between long-term and short-term measures. Short-term conservation efforts often are limited by the long-term conservation measures adopted. This constraint type reflects "demand hardening"; as more conservation measures are permanently placed, the effectiveness of short-term conservation measures decreases and their relative costs increase (Lund 1995).

As an example, for our case study, lawn watering reduction in response to a shortage, a short-term conservation measure, depends on the level of long-term Xeriscaping attained [(7)]. Lawn watering reduction can be divided into two segments to reflect the severity of implementing large water reductions. Lawn watering reduction I (measure lw1) is first implemented and lawn water reduction II (measure lw2) is implemented at a much higher cost as needed [(8)].

Installing water displacement devices to temporarily reduce water demand depends on the reduction due to the long-term water fixture retrofitting decision [(9)]. The demand hardening factor (h_i) represents the reduction in the effectiveness of short-term water conservation as more permanent water fixture retrofitting measures are implemented.

$$S_{lw,e,s} \leq (L_{xe,\max} - L_{xe}) f_{xe,s}, \quad \forall s, e \qquad (7)$$

$$S_{lw1,e,s} + S_{lw2,e,s} \leq S_{lw,e,s}, \quad \forall s, e \qquad (8)$$

$$S_{wd,e,s} \leq (L_{rt,\max} - h_{rt} L_{rt}) f_{rt,s}, \quad \forall s, e \qquad (9)$$

where $S_{lw,e,s}$ = lawn watering reduction limit for season s and event e (m^3/season); $S_{lw1,e,s}$ = lawn watering reduction part I for season s and event e (m^3/season); $S_{lw2,e,s}$ = lawn watering reduction part II for season s and event e (m^3/season); $S_{wd,e,s}$ = water displacement device for season s and event e (m^3/season); L_{xe} = Xeriscaping annual water savings (m^3/yr); L_{rt} = fixture retrofitting annual water savings (m^3/yr); h_{rt} = demand hardening factor for long-term retrofitting (dimensionless); f_{xe} = Xeriscaping seasonal factor (dimensionless); and f_{rt} = fixture retrofitting seasonal factor (dimensionless).

Water transfers often are limited by the treatment capacity of the existing water system. Water treatment capacity can be expanded as a long-term measure to increase the quantity of water that can be contracted as a dry year transfer option or purchased from spot markets [(10)]. For each shortage level, the amount of dry year option activated depends on the long-term decision of the dry year option contract [(11)]. The sum of the spot market purchased and the dry year option activated must not exceed the total transfer limit, which might vary with a particular shortage event [(12)].

$$S_{tt,e,s} \leq (\mathrm{CAP} + L_{\mathrm{CAP}}) f_{\mathrm{CAP},s}, \quad \forall s, e \qquad (10)$$

$$S_{ta,e,s} \leq L_{tc} f_{tc,s}, \quad \forall s, e \qquad (11)$$

$$S_{ta,e,s} + S_{sm,e,s} \leq S_{tt,e,s}, \quad \forall s, e \qquad (12)$$

where CAP = available capacity for transferred water treatment (m^3/yr); $f_{i,s}$ = distribution factor for long-term measure i in seasons (dimensionless); $S_{tt,e,s}$ = total transfers (dry year option and spot market) for season s and event e (m^3/season); $S_{ta,e,s}$ = activated dry year option for season s and event e (m^3/season); $S_{sm,e,s}$ = spot market purchased for season s and event e (m^3/season); L_{CAP} = additional water treatment capacity (m^3/yr); and L_{tc} = annual dry year option contract (m^3/yr).

LONG-TERM AND SHORT-TERM MEASURES

Long-term and short-term measures include both demand management and supply enhancement. The following options are included in the model.

Conservation

Water conservation practices are used to reduce water demand, moderate peak consumption to delay or avoid capital expenditures of water system expansion, and reduce the effects of water consumption on the environment. Common water conservation methods include efficient irrigation, Xeriscaping, and water fixture retrofits. Water agencies encourage conservation by enacting various forms of rationing such as fixed allotments to customers, percent reduction in supply, adoption of tiered pricing to control consumption, and rotation of service to customers (Lund and Reed 1995). Education that emphasizes the public benefit of conservation and persistently informs of the consequences of serious water shortages has been shown to have an important effect on the implementation of conservation measures (Cameron and Wright 1990). Conservation measures can be permanently incorporated into the supply system (water fixture retrofits and Xeriscaping) or be adopted as a short-term measure in response to a particular shortage event (reduced lawn watering). Short-term conservation programs tend to become less effective in mitigating emergency shortages and more expensive as permanent conservation practices are integrated into the water supply system in anticipation of future shortages (Weber 1993). The total cost of implementing conservation measures includes the cost of implementing the conservation measure as well as the foregone revenue by the water supplier (Mann and Clark 1993).

Water Reuse

Reused water can be added to the supply system as either a new source of water supply or for pollution control. Reused water has been used for agricultural and landscaping irrigation, industrial process and cooling water, complying with environmental instream flow requirements, ground-water recharge, and direct consumptive use. The reuse 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. Reusing water for landscaping applications generally requires only secondary treatment and disinfection, while reusing water for potable purposes requires much more extensive treatment. In addition to primary and secondary treatment, potable reuse requires treatment processes such as recarbonation, multimedia filtration, selective ion-exchange, carbon adsorption, reverse osmosis, and disinfection. In general, water reuse is more feasible and cost effective for nonpotable purposes than for human consumption (Asano and Madancy 1984).

In evaluating the cost of reuse as a water supply source, the cost of the required added treatment, the conveyance system, and operation and maintenance should be considered. Generally, the majority of cost associated with wastewater reclamation is attributed to the cost of distribution (approximately $300/AF) to which treatment, operation, and maintenance costs must be added. The deferred costs of wastewater effluent discharge permits, an external benefit, should be incorporated in water reuse cost analysis (Asano and Mills 1990).

Water Transfers

Water transfers can be used to augment water supply during shortage conditions that are due to droughts, high demands, and interruption of normal supply due to natural disasters. Water transfers can be used to meet demand, increase reliability, improve quality, and satisfy environmental constraints. Various water transfer methods can be integrated into a regional water supply system (Lund and Israel 1995).

Permanent transfers account for the permanent acquisition of water rights by a water agency to supplement the existing water supply. Contingent transfers or dry year options are long-term alternatives in which a contract is made between an agricultural senior water rights holder and a water agency to be activated during shortage events. Spot market transfers are short-term transfers, usually completed within a year, and can be used either to augment the water supply during a shortage event or to increase system reliability in wet years. Water banks are a constrained form of spot market. Water is purchased from agricultural users and sold to urban suppliers at fixed prices. The difference between the buying and selling prices accounts for the bank's technical and administrative costs.

The cost of water transfers varies with market conditions. The total cost of water transfers includes the purchase cost, conveyance modification costs, treatment cost, transaction costs, and costs associated with third party losses such as economic losses to community and increased ground-water pumping. The amount of water actually transferred can vary greatly from the amount contracted due to conveyance losses because of evaporation, seepage, and natural accretion, and due to the uncertainty associated with the amount of water a farmer actually has the rights to sell (Lund and Israel 1995).

EXAMPLE CASE STUDY

East Bay Municipal Utility District

A simplified representation of the East Bay Municipal Utility District (EBMUD) system is used to illustrate the application of the shortage management model. The EBMUD system serves over one million people in Alameda and Contra Costa Counties, California. Most of the water serving these counties is supplied from the Mokelumne River. The Pardee and Camanche reservoirs and local storage reservoirs in the service area, with a combined capacity of 888E6 m^3 (720 TAF), serve the EBMUD. Future EBMUD service area water demands in 2020 are expected to total 358E6 m^3 (290 TAF/yr). The ability to meet future demands may become limited due to decreasing availability of water supply sources as a result of increased consumption by senior water rights holders, increasing instream requirements to protect fish, wildlife, and riparian habitat, and limited new water sources. The ability to supply adequate water also is limited due to increasingly stringent water quality standards. Both the availability of water and the quality of sources are therefore important for future water allocation.

A time series of the stream flow record of the Mokelumne River between 1921 and 1993 was used in a yield simulation model of the EBMUD system to produce shortage probability distributions (Lund et al. 1995). The shortage probability distribution, based on shortage results from the yield model, is used as an input in the shortage management model.

Incorporating Demand Management and Supply Enhancement Options

For this study, management options were somewhat simplified from what they should be for an actual study of a water supply system. Long-term measures considered in the model are conservation, dry year transfer options, water treatment capacity expansion, and water reuse. Long-term conservation efforts include Xeriscaping and installing low water consumption fixtures. Xeriscaping and water fixture retrofitting are assumed potentially to decrease EBMUD water consumption by 25% and 20%, respectively. Dry year transfer options and water reuse are assumed to be able to provide additional water supply that amounts to approximately 50% of the EBMUD system's overall demand.

Short-term measures include conservation, activating dry year options, and purchasing spot market water. Conservation measures include reducing lawn watering and installing water displacement devices in toilets. The effectiveness of these con-

TABLE 1. Limits and Costs of Alternatives

Measures (1)	Basis for quantity limit (2)	Cost [\$/10^3 m^3 (\$/AF)] (3)
(*a*) Long Term (Annual)		
Conservation—Xeriscaping	Function of outdoor use	122 (150)
Conservation—water fixture	Function of indoor use	24 (30)
Transfers limits	Function of treatment capacity and reclaimed water	—
Dry year option wet season	Function of transfer limit and availability	16 (20)
Dry year option dry season	Function of transfer limit and availability	16 (20)
Limited reuse	Function of treatment capacity	1,220 (1,500)
Existing treatment capacity	Function of existing system layout	—
Treatment capacity expansion	Function of feasibility	162 (200)
(*b*) Short Term (Seasonal)		
Conservation—lawn watering, I	Function of implemented Xeriscaping	243 (300)
Conservation—lawn watering, II	Function of implemented Xeriscaping and lawn water level I	568 (700)
Conservation—water displacement device	Function of implemented water fixture and demand hardening	325 (400)
Active dry year option	Function of available dry year option contract	97 (120)
Spot market	Function of transfer limit and availability	Varies with event

TABLE 2. Base Case Shortage Management Model Results

LONG-TERM ANNUAL DECISIONS 10^6 m^3 (TAF)

Conservation		Additional treatment capacity (3)	Dry Year Option		Potable reuse (6)	Annualized cost (\$1,000) (7)
Xeriscaping (1)	Water fixture (2)		Dry season (4)	Wet season (5)		
0	74 (60)	21 (17)	88 (72)	0	0	6,633

TABLE 3. Base Case Shortage Management Model Results

Short-Term Seasonal Decisions

Event (1)	Probability (2)	Shortage (%) (3)	Shortage [10^6 m^3 (TAF)] (4)	Short-term measures (5)	EV cost (\$1,000) (6)
1 wet season	0.933	0	0	None	0
2 wet season	0.017	20	23 (18)	None	0
3 wet season	0.01	40	46 (37)	Spot market	34
4 wet season	0.004	60	68 (55)	Spot market	43
5 wet season	0.004	80	91 (74)	Spot market, conservation	82
6 wet season	0.031	100	114 (92)	Spot market, conservation	1,191
1 dry season	0.947	0	0	None	0
2 dry season	0.007	20	46 (38)	None	0
3 dry season	0.007	40	93 (75)	Dry year option	29
4 dry season	0.005	60	139 (113)	Dry year option, conservation	44
5 dry season	0.005	80	185 (150)	Dry year option, conservation	107
6 dry season	0.03	100	231 (188)	Dry year option, conservation	1,307

Note: Total cost, including amount from Table 2, column (7), \$1,000/yr: 9,470.

servation measures will depend greatly on the implementation of long-term conservation measures. As more long-term conservation measures are implemented, the effectiveness of short-term conservation measures decreases. The activation of dry year options will be limited by the amount contracted as a long term measure. Buying spot market water depends on the available water treatment capacity and the quantity of the dry year options activated for specific shortage levels. The limits and costs of the long-term and short-term alternatives considered are summarized in Table 1.

The base case incorporates seasonal water demands and shortages. The dry season extends from April through October and the wet season extends from November through March. These seasons correspond roughly to high and low urban water demand seasons respectively, as well as to central California's hydrology. A seasonal factor is applied to the long-term measures to reflect their water savings contribution during the two seasons. Seasonal factors are proposed to the seasonal water demand. 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 at each season and sixty-six constraints reflect the alternative's limits.

Results of Base Case

Based on a simplified yield simulation model of the EBMUD system (Lund et al. 1995), a shortage exceedence probability distribution was composed and discretized to six shortage levels. The maximum shortages observed for the wet season and dry season were 114E6 m^3 (92 TAF) and 219E6 m^3 (177 TAF), respectively, based on 7 yr of simulation. The total number of shortages observed in the simulation was five, three in the wet season and two in the dry season (this small sample of shortages poses obvious problems for estimating yield reliability). The following results are contingent upon this yield reliability scenario.

The model results summarized in Tables 2 and 3 suggest that the existing water treatment capacity was inadequate and should be expanded by 21E6 m^3/yr (17 TAF/yr) to allow for additional purchases of short-term spot market water. Additionally, long-term conservation by water fixture retrofitting should be implemented to decrease annual water demand by 74 m^3 (60 TAF). Long-term water reuse was not adopted as an additional water source. As a response to shortages, short-term conservation included lawn watering reduction as well as some installation of water displacement devices for extreme shortage levels. The total expected value of perfect water supply cost of the assumed shortage probability distribution was \$9.5 million/yr.

BASE CASE VARIATIONS

The base case is expanded to examine three variations of this shortage management problem. These examples illustrate the importance of considering seasonal shortages, spot market limitations, and water quality in shortage management decisions to increase supply system reliability.

Seasonal versus Annual Yield Models

Annual and seasonal yield simulation models can produce significantly different shortage exceedence probability distributions. The difference in the distributions can be attributed to the rougher averaging and lumping of the annual simulation model. Thus, the annual system model will tend to experience less severe shortages and will tend to recover faster than a seasonal yield simulation model. The differences between annual and two-season time step simulation models are reflected in Fig. 2, end of year storage, indicating the differences in the extent of storage depletion and the length of time required for the system to recover under both scenarios for a simplified EBMUD system (Lund et al. 1995). 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 27–31.

The difference in probability distribution can affect the results of the shortage management optimization model. A comparison of an annual model and a seasonal model indicates that different decisions and consequences of ignoring the yield

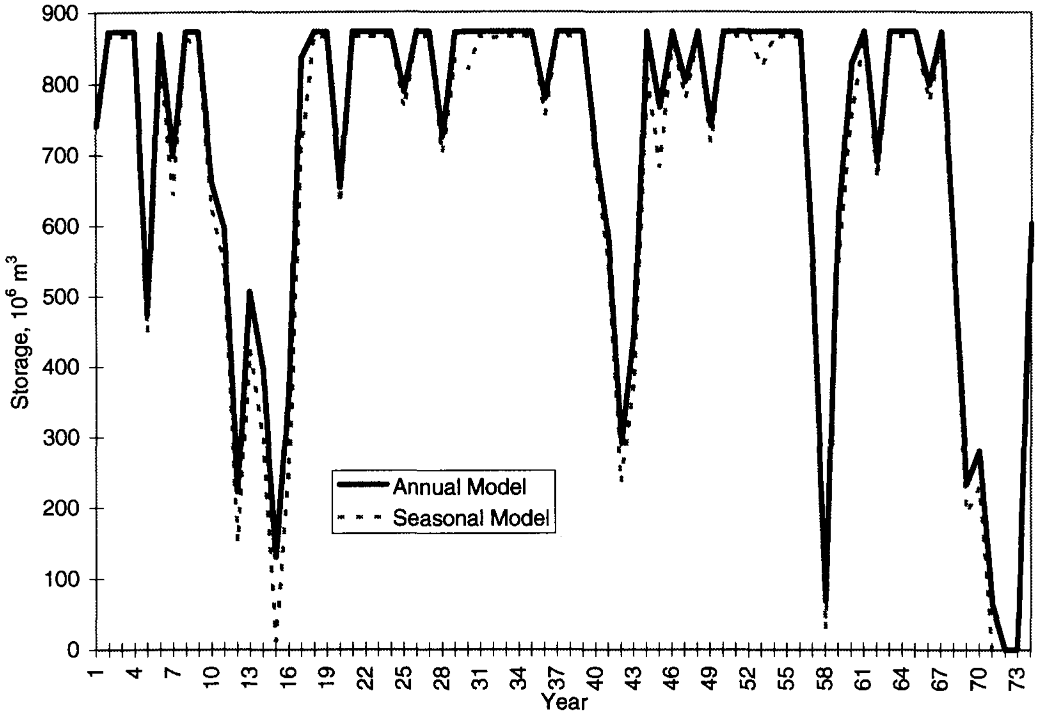

FIG. 2. End of Year Storage—Annual versus Seasonal Simulations

TABLE 4. Summary of Shortages Magnitude and Frequency, 10^6 m^3 (TAF)

Description (1)	Annual model (2)	Seasonal Model	
		Wet season (3)	Dry season (4)
Maximum shortage	263 (213)	114 (92)	219 (177)
Average shortage	12 (10)	5 (4)	1 (8)
Number of events	2	3	2

effects of seasonal operations. Shortage magnitudes and frequencies for the annual and seasonal models are summarized in Table 4. The average shortage based on the annual model was 12E6 m^3 (9,744 AF), while the average annual shortage based on the seasonal model is 15E6 m^3 (11,795 AF) (combined seasons). The seasonal model results included a 100% shortage absent in the annual model results. The less severe shortage probability distribution results in a significantly lower expected value cost of managing shortage, $3.8 million/yr for the annual model, versus $9.5 million/yr for the more realistic seasonal yield and shortage-management models.

More significant is the difference in management and planning decisions for the two formulations of the simulation model. Due to the higher probabilities of extreme shortages in the seasonal model, long-term conservation is instituted, water treatment capacity is enhanced, and dry year transfers are contracted. Spot market purchases, dry year transfers, and additional temporary conservation measures are implemented as necessary at particular shortage levels. For the annual yield model, results of the shortage management model indicate no use of dry year transfers. Instead, limited long-term conservation measures are instituted and short-term conservation and spot market purchases are invoked during emergency shortages as needed. Results of the shortage management model based on annual time steps are summarized in Tables 5 and 6.

This example demonstrates the importance of seasonality in shaping the shortage distributions from a yield simulation, and its consequences for the design of least-cost shortage management policies.

TABLE 5. Annual Shortage Management Model Results

LONG-TERM ANNUAL DECISIONS 10^6 m^3 (TAF)						
Conservation		Additional treatment capacity (3)	Dry Year Option		Potable reuse (6)	Annualized cost ($1,000) (7)
Xeriscaping (1)	Water fixture (2)		Dry season (4)	Wet season (5)		
0	5 (4)	0	0	0	0	132

TABLE 6. Annual Shortage Management Model Results

Short-Term Seasonal Decisions					
Event (1)	Probability (2)	Shortage (%) (3)	Shortage [10^6 m^3 (TAF)] (4)	Short-term measures (5)	EV cost ($1,000) (6)
1	0.947	0	0	None	0
2	0.007	20	69 (56)	Spot market	29
3	0.007	40	138 (112)	Spot market, conservation	163
4	0.007	60	207 (168)	Spot market, conservation	370
5	0.033	80	276 (224)	Spot market, conservation	3,133
6	0	100	0	None	0

Note: Total cost ($1,000/yr) including amount from Table 5, column (7): 3,827.

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 is activated. During drought conditions, potential water sellers will be susceptible to water shortages as well and therefore purchasing spot market water may be limited by water availability rather than treatment capacity. The base case study is reevaluated for a range of spot market limits during water shortage events and assumes that spot market contracts are independent of dry year option contracts.

The long-term decisions and expected value cost based on

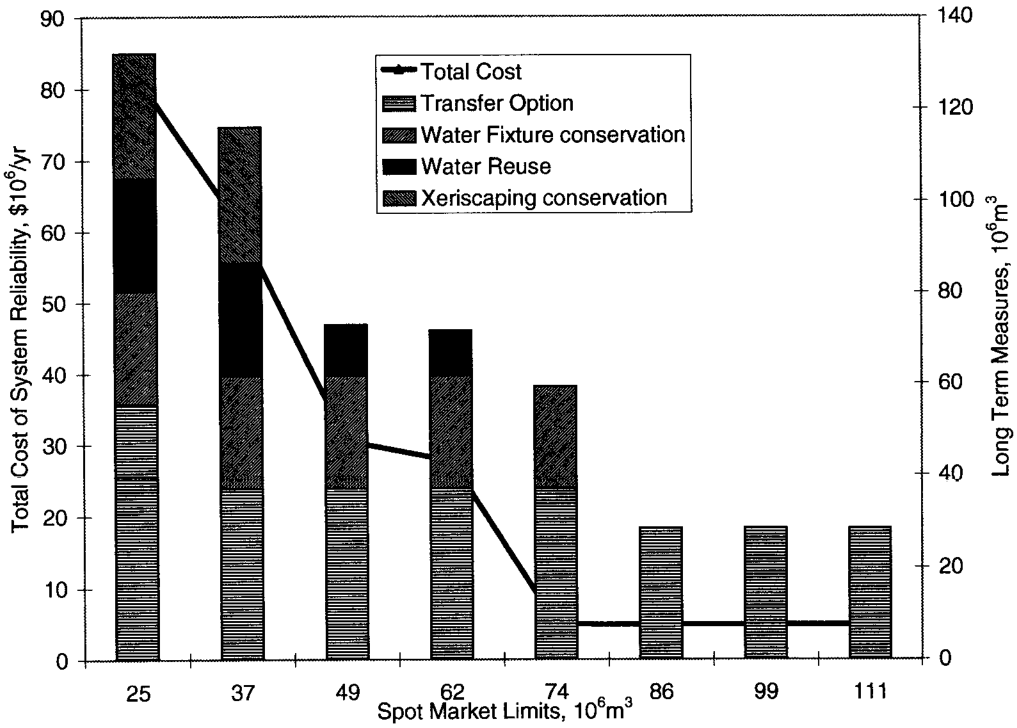

FIG. 3. Effects of Spot Market Limits

spot market limits are shown graphically in Fig. 3. The results of this evaluation 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 the transfer option, spot market limits below 86E6 m^3 (70 TAF) require the installation of low consumption water fixtures; spot market limits below 74E6 m^3 (60 TAF) force the use of highly treated reused water; and spot market limits below 49E6 m^3 (40 TAF) lead to conservation by way of Xeriscaping. The availability of spot market water during shortages for this case study is important if limited to less than 86E6 m^3 (70 TAF), since the costs increase substantially for a substitute conservation measures.

Several Water Qualities

The base case assumes a single distribution system and the use of high quality water for all uses. This example is expanded to incorporate two water qualities: low quality and high quality. The low quality water demand is based on selected landscaping and golf course water uses. The amount of low quality water demand will vary greatly between dry and wet seasons. Weather changes and droughts directly affect low quality water demand. Low quality water can be applied only if a separate distribution system is available. Having a separate distribution system allows use of water of low quality from sources such as reused water, dry year options, and spot market purchases. Low quality water demand can be reduced with conservation efforts such as Xeriscaping and lawn watering reduction.

High quality water demand is a function of residential, commercial, and industrial uses. High quality water can be augmented with dry year options and buying spot market water. 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 high drinking water standards and the additional costs associated with installing a separate distribution system.

To incorporate varying water qualities into the shortage management model, an additional dimension of quality, q, is added to all decision variables. The quality dimension results in an additional 25 decision variables and 37 constraints for this problem. Eq. (13) represents the revised objective function. Eqs. (14)–(22) are the revised constraints equations. A new constraint is added to reflect the capacity limit of the separate distribution system [(23)]. The capacity limit of a separate distribution system for a different water quality supply is a function of the annual demand for that water quality and the long-term measures implemented to reduce this water quality demand. For the example of two water qualities, low quality and high quality, the limit of separate distribution system for the low quality will be based on outdoor use less the decrease in demand due to Xeriscaping.

$$\min Z = \sum_{q=1}^{l} \left(\sum_{i=1}^{m} c_q L_{i,q} + \sum_{s=1}^{y} \sum_{e=1}^{r} p_e \sum_{j=1}^{n} c_{j,e,s} S_{j,e,s,q} \right) \tag{13}$$

$$\sum_{i=1}^{n} L_{i,q} f_{i,s} + \sum_{j=1}^{m} S_{j,e,s,q} \geq SH_{s,e,q}, \ \forall s, e, q \tag{14}$$

$$L_{i,q} \leq L_{i,q,\max}, \ \forall i, q; \quad S_{j,e,s,q} \leq S_{j,s,q,\max}, \ \forall j, e, s, q \tag{15, 16}$$

$$S_{j,e,s,q} \geq 0, \ \forall j, e, s, q; \quad L_{i,q} \geq 0, \ \forall i, q \tag{17, 18}$$

$$S_{lw,e,s,q} \leq (L_{xe,q,\max} - L_{xe,q}) f_{xe,s}, \ \forall s, e \tag{19}$$

$$S_{lw1,e,s,q} \leq S_{lw1,s,q,\max}, \ \forall s, e \tag{20}$$

$$S_{lw1,e,s,q} + S_{lw2,e,s,q} \leq S_{lw,e,s,q}, \ \forall s, e \tag{21}$$

$$S_{wd,e,s,q} \leq (L_{rl,q,\max} - h_{rl} L_{rl,q}) f_{rl,s}, \ \forall s, e \tag{22}$$

$$L_{ds,q} f_s \leq D_{\text{Tot}}, g_{s,q} - f_s \sum_{i=1}^{n} L_{i,q}, \ \forall q, s \tag{23}$$

where $L_{ds,q}$ = annual distribution system capacity for water quality q (m^3/yr); D_{Tot} = annual demand (m^3/yr); f_s = seasonal factor (dimensionless); and $g_{s,q}$ = fraction of seasonal demand attributed to water quality q (dimensionless).

For this problem, the model results based on two water qualities were identical to the results obtained for the base case. It is therefore not economical for this system to consider separate water qualities in developing a shortage management plan. This conclusion could be reversed for a different urban water system with different costs, limits, and effectiveness of the long-term and short-term measures used in the shortage management model. In some cases, wastewater disposal costs or constraints might further motivate use of a separate low quality distribution system.

SENSITIVITY ANALYSIS

The results presented in the two water qualities case are specific to the values used in this example analysis. Sensitivity analysis can be used to assess the effect of uncertainties on management decisions, the acceptable limits of errors and uncertainty, the degree of importance of uncertainties, and the need to understand and quantify the uncertainties associated with the decision variables. The two water quality case is used to study the effects of options availability, options cost, and increasing total demand. A summary of comparisons between the two water qualities case and the base case is presented in Table 7. The difference between the expected value cost of the base case (high quality only) model and the two qualities model represents the value of implementing a separate distribution system, buying low quality water, and avoiding high treatment costs of water and wastewater.

Option Availability

Existing treatment facility layout and land availability may constrain the ability to expand treatment capacity which in turn will limit the use of water transfers (spot market purchase or dry year option contracts). The shortage management model can be used to demonstrate the effect of decreasing treatment availability on the measures implemented and the expected value shortage management cost. Limiting treatment capacity expansion to below 12E6 m^3 (10 TAF) encourages the separation of water qualities and installing a separate distribution system. A separate distribution system replaces the expensive reused water option of the base case and allows low quality spot market purchases and dry year option contracts.

In areas where low use water fixtures have been installed, conservation measure to reduce high quality water demand will become very limited (both long term retrofitting and short term displacement device). Reducing the effectiveness of water fixture from 32% of indoor use (base model assumption) to 20% of indoor use also makes provision of a dual water distribution system economical. Implementing the separate distribution systems allows the purchase of low quality spot market and low water quality dry year options.

Option Cost

As drinking water quality requirements become more stringent, treatment costs will increase and the allocation of water based on quality could potentially become cost effective. A 50% increase in water treatment cost makes a separate system for low quality water conveyance economical. Having dual distribution capacity allows direct use of low quality water and avoids expensive reductions in high quality demands.

TABLE 7. Effect of Water Quality on Shortage Management Costs

Case (1)	Total Cost: Seasonal model ($1,000/yr) (2)	Total Cost: Two-qualities model ($1,000/yr) (3)	Separate distribution system [10^6 m^3/yr (TAF/yr)] (4)	Cost reduction for optimized dual system (%) (5)
Base case	9,500	9,500	0	0
Water treatment capacity limited to 10 TAF	89,000	10,700	11 (9)	88
Water fixture limited to 21% of indoor use	97,300	16,900	4 (3)	83
Increase water treatment cost by 70%	11,800	11,600	21 (17)	2
Increase annual urban demand by 50%	110,400	25,300	26 (21)	77

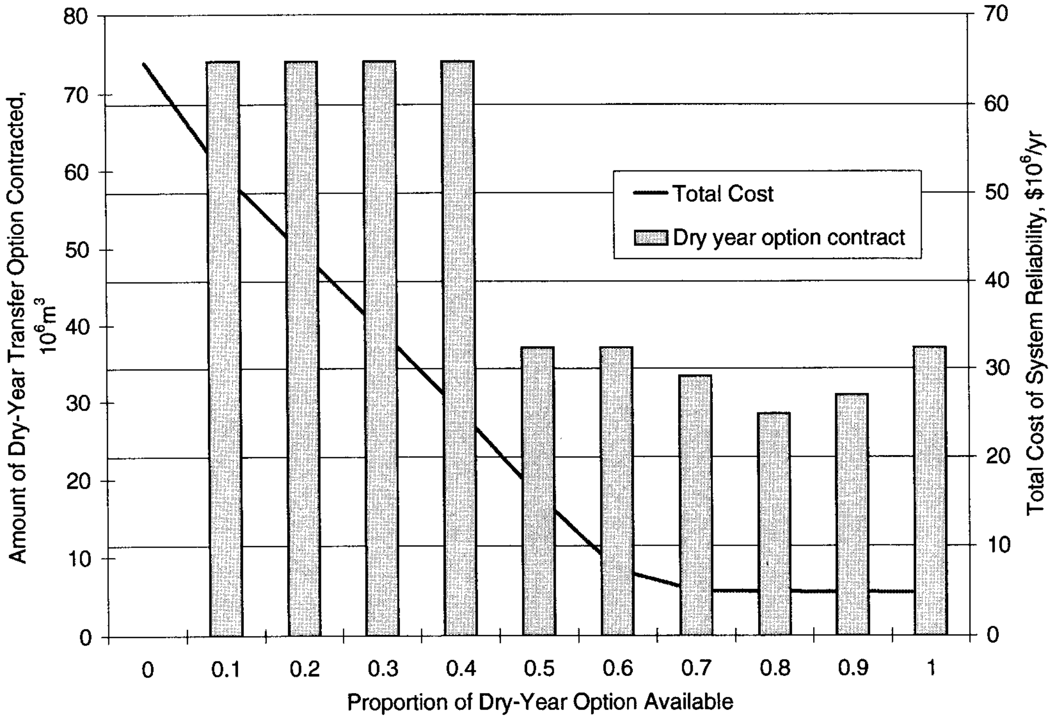

FIG. 4. Effect of Different Proportions of Dry Year Option Transfer Available

Increasing Demand

With population growth, annual water demand is expected to increase. Comparison of the base case and the two water quality case indicates that with total demand increasing by more than 30%, long-term measures will change by increasing water supply either through potable reused water (base case) or by providing an additional distribution system to promote low quality reuse. The results of the two cases show that if demand increases enough to encourage water reuse, management based on the two water qualities model and installation of separate distribution system will become more cost effective. The difference in expected value cost represents the difference between advanced water treatment (potable reused water) and the costs of separate distribution systems and costs of low quality water. The effect of accounting for water qualities on expected value cost for increasing demands is demonstrated in Fig. 4.

CONCLUSIONS

The shortage management model, based on two stage linear programming, is potentially valuable for identifying promising combinations of long-term and short-term measures to manage demand and enhance available supply given a shortage exceedence probability distribution and a desire to minimize shortage costs. The model is also valuable for understanding the effects of uncertainties relating to cost, availability, and effectiveness of measures used to improve system reliability. This shortage-management modeling and optimization approach appears to be applicable and useful for a wide variety of urban water supply reliability problems. In addition, the following conclusions can be made regarding particular measures for the example presented:

- Limitations on spot market and water transfers during droughts encourage long-term conservation measures such as Xeriscaping and water fixture retrofit.
- 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), as demand hardening reduces short-term conservation availability, as environment regulations on wastewater disposal become more stringent, and/or as water demands increase.
- Distinguishing among water qualities does not improve shortage management costs as long as a high quality water supply is available and conservation efforts are feasible.
- Small increases in demand do not change the character of long-term and short-term decisions but rather affect the amount and cost of options selected.
- The two-stage optimization model is useful for integrated assessment of operation, demand management, and supply enhancement to improve water supply planning and management in light of uncertainties in hydrology and environmental externalities
- The two-stage optimization model is useful for understanding the effects of cost and availability of long-term and short-term measures on water supply reliability, management choices, and shortage management costs.

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