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OPTIMAL RESPONSE TO PERIODIC SHORTAGE: ENGINEERING/ECONOMIC ANALYSIS FOR A LARGE URBAN WATER DISTRICT

by

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1. Introduction

The problem addressed by this study is how a large urban water district can best respond to a drought or the prospect of a drought. Specifically, what is the least-cost combination of alternatives to meet periodic shortages? A solution to this problem may involve structural approaches (such as developing new local storage capacity), a mix of structural and nonstructural (such as conjunctive use combined with water exchanges or sales), or purely nonstructural approaches (such as changes in water pricing). The application is to the East Bay Municipal Utility District (EBMUD), which includes portions of Alameda and Contra Costa counties on the east side of San Francisco Bay, but the concepts and methods (and some of the findings) will be relevant to other districts.

In order to compare the costs of various combinations of options, a computer program has been constructed to model operation of the EBMUD system under a wide variety of environmental and management scenarios. Separate cost estimates for construction and operation of the supply-side options are developed with engineering data from EBMUD and others. Costs of water use reduction are inferred from a synthetic demand curve for water. The next section provides a description of the EBMUD Operations Model and an illustrative application. Section 3 describes supply-side cost estimation procedures and presents cost estimates, in terms of dollars per acre-foot (af) of water provided in drought years, for key reservoir options under consideration. Section 4 applies the same approach to a range of conjunctive use/water marketing options. Finally, section 5 looks at the cost (measured by losses in consumer surplus) of achieving a demand reduction though price increases within EBMUD.

2. The EBMUD System and Operations Model

2.1. The EBMUD System

The main features of the EBMUD system are two large reservoirs on the upper Mokelumne River, approximately 80 miles to the northeast of the service district, three aqueducts to bring water to the district, five local or terminal reservoirs, and six local treatment plants. These facilities are shown in Figures 2.1 and 2.2. Of the two reservoirs on the River, just Pardee, the upper, smaller of the two, with a capacity of 211 thousand acre-feet (kaf), is currently connected to the aqueducts. The larger (430 kaf) Camanche Reservoir is used for supplying senior water rights (mainly agricultural users in the reservoir area), stream flow regulation, and flood control.

Of the local reservoirs, only three are large enough to matter: Briones, at 60 kaf; San Pablo, at just under 40 kaf; and Upper San Leandro, at just over 40 kaf. The two small reservoirs together contribute about 15 kaf, for a total local storage capacity of 155 kaf. These reservoirs serve a district of about 350 thousand households, or 1.1 million people. Before the current drought, annual consumption had reached a maximum of about 240 kaf, which is equivalent to an average over the year of 220 million gallons per day (mgd). EBMUD is entitled to a substantially larger amount of Mokelumne water, about 360 kaf or 325 mgd.

The issue that motivates this study is whether the district needs an addition to terminal storage, both to help it get through periods of shortage, and to protect against sudden outage due to disruption of the aqueducts at their most vulnerable point, where they traverse the Delta, by a natural disaster such as an earthquake or flood. EBMUD began an in-house planning process to address this issue in early 1987, and solicited public input over the next couple of years. Findings and recommendations are given in a Final EIR (EBMUD, 1989). The main recommendation is for construction of a large, new local reservoir, preferably in Buckhorn Canyon, just to the east of the existing Upper San Leandro Reservoir. The proposed Buckhorn Reservoir would have a capacity of 145 kaf, making it almost as large as all of the existing local reservoirs combined. A variant of this plan would involve cooperation with the adjacent Contra Costa Water District (CCWD) in construction of a new reservoir, Los Vaqueros, to serve both districts. As it appears CCWD intends to go ahead with Los Vaqueros in any event, the issue for EBMUD is whether to join in an expanded effort.

EBMUD argues that the new reservoir, preferably Buckhorn, would best meet the objectives of averting both drought-related shortages and sudden disruptions. As we show in Appendix A to this paper, we believe the problem of disruption can and should be handled separately. The paper then focuses on an analysis of reservoir and nonreservoir alternatives for meeting periodic shortages.

2.2. Structure of the Model

The computer program is a mass balance model, allocating water flowing down the Mokelumne River to downstream releases, storage, transport, or consumptive use (see Figures 2.3 and 2.4). In each run of the model, a static (constant average use) EBMUD system is subjected to a sequence of variable runoff patterns. Shortage patterns (frequency and severity) can then be estimated for each planning scenario. The model is highly parameterized, allowing examination of a wide variety of physical and operational scenarios.

The model is designed to run on Quattro Pro, a spreadsheet similar to Lotus 123, and is divided into three separate files for convenience and flexibility: flows, parameters, and model.

2.2.1. Flow File

This file contains assumed inflows to Pardee Reservoir by month, based on U.S. Geological Survey records from October, 1927 through September, 1989. Clearly, past flow patterns will not recur in the future. However, use of the historical patterns provides a reasonable starting point for estimating the frequency of shortages under various assumptions. Synthetically generated flow patterns could also be used. For example, if the changes in precipitation patterns resulting from global warming can be estimated, synthetic flows could be generated to indicate how a given system would perform under the new conditions.

2.2.2. *Parameter File*

Physical Parameters

- Seepage losses in the Mokelumne River

  Significant quantities of water are lost by seepage to the bed of the Mokelumne River as it flows from Camanche Reservoir to the Delta. Illegal diversion may also take place. Inasmuch as EBMUD is responsible for satisfying the water rights of downstream users such as the Woodbridge Irrigation District (WID), near the Delta, water above and beyond the rights of downstream users must be released into the river to compensate for seepage losses and illegal diversion in transit. Such losses range from 40 to 120 kaf per year. No analytical relationship has been found between river flows and seepage. The model was calibrated using crude correlations between seepage losses and river flows during the 1976-77 drought. The rationale was that seepage losses are particularly crucial in dry years. This approach is conservative in that river losses are probably lower as a percentage of flows in wetter years.

- Evaporation from storage

  The rate of evaporation from storage can be altered. The normal assumption is that three feet evaporate per year from Pardee and Camanche Reservoirs. As reservoir levels and surface areas drop, the model reduces evaporation. Local storage does not include evaporation because local rainfall equals evaporation in dry years and exceeds it in wet years. Local rainfall is not otherwise accounted for in the model.

- EBMUD normal water use

  Average demand and seasonal variation in demand are parameters. Demand is assumed to be sinusoidal about the average with a peak in summer.

Structural Parameters

- Size of existing storage reservoirs

  Some question exists over how much of the bottom storage in existing reservoirs could be extracted during a shortage. Also, EBMUD is considering raising Pardee Reservoir. The model allows the impact of various assumptions to be studied.

- New storage reservoirs

  EBMUD has considered several new local storage options including Buckhorn and Los Vaqueros Reservoirs. The model allows these reservoirs to be integrated into the system. Inasmuch as Los Vaqueros may be filled with water somewhat lower in quality than EBMUD's traditional supplies, the model allows Los Vaqueros to be operated differently such that it is only utilized under more extreme conditions.

- Capacity of conveyance facilities

  The speed with which EBMUD can replenish local storage depends on the capacity of the Mokelumne Aqueduct, the three pipelines connecting EBMUD to Pardee Reservoir. The model can examine the impacts of increasing this capacity.

- Water treatment capacity/Limiting Los Vaqueros supply component

  The model assumes that Los Vaqueros supplies (if present) are blended at a high enough dilution that the water quality impacts are negligible. The model also assumes that the water is run directly through EBMUD's main filter plants (to avoid contamination of terminal storage). Thus, Los Vaqueros use patterns depend on both the dilution pattern and the amount of filter treatment capacity in the system. Both can be altered in the model.

- Existence of new secure delta pipeline

  EBMUD has minimum local storage targets to protect against drought and loss of the Delta pipelines (see below). The construction of an earthquake-proof pipeline across the Delta would allow EBMUD's storage reserve requirements to be reduced and would thus impact EBMUD operational patterns.

Operational Parameters

- Maximum acceptable demand reductions in drought

  It is EBMUD policy that customers should never experience shortages greater than a specified level. This can be altered, in the model, to examine the impacts of various levels. The model will not permit a shortage greater than the specified level and will, instead, allow storages to drop below specified minimums, if necessary.

- Storage levels

  EBMUD has operational criteria which seek to maintain minimum flow levels in local terminal reservoirs to protect against drought, loss of pipelines as they cross the Delta, and loss of pipelines as they cross the fault lines in the East Bay hills. A number of parameters allow these criteria to be altered in size and priority.

  A critical parameter is the October carryover target (i.e., the amount of total storage to be carried into the next water year). The model attempts to meet this target through reductions in demand and purchase of additional supplies (if available). If the carryover target cannot be met, the October storage is allowed to drop below the target. The October carryover target can be computed in two ways in the model. It may be simply proportional to demand or may be determined by a function of demand, maximum allowable demand reductions, downstream flow requirements, and the minimum predicted inflows into the system for the next year. The former is used for most model runs in this study; the latter will allow greater precision in later studies. Current EBMUD practice appears to call for a target carryover of about 1.2 times annual demand or use.

Also important is a switch which allows the Delta seismic security reserve storages to be breached in time of drought. The local seismic minimums cannot be breached, however.

Minimum storages can also be specified for Pardee and Camanche Reservoirs (for environmental protection).

- Flood control requirements

Flood control requirements are very complex and have had to be simplified for purposes of the model. The simplifications are conservative in that upstream reservoir capacity which helps satisfy these requirements has been ignored. While these requirements have not been altered for any of the runs in this study, the hypothetical construction of a downstream flood bypass could allow reductions in flood control requirements at Pardee and Camanche.

- Releases for downstream water rights holders and for environmental purposes

EBMUD is responsible for meeting downstream water rights. These rights are extremely complex, varying according to the amount of runoff and other factors. In one case, EBMUD has a contract with downstream water users to release water at certain times. That contract was recently revoked by EBMUD. As noted above, EBMUD must also make up for any losses incurred during transit down the river to the water right holder.

EBMUD is also responsible for releasing water to meet the environmental needs of the river itself. Currently, required releases are minimal. However, much higher flows may be required in the future. Again, seepage losses will need to be made up by EBMUD.

Water rights, instream flows, and seepage losses can all be varied.

- Water transfer/conjunctive use programs

  One option to increase water supplies during drought is to reduce releases from Camanche Reservoir for downstream water rights holders, in turn allowing EBMUD to keep more water in Pardee Reservoir for transmission through the Mokelumne Aqueducts. This could be done by purchase or as part of a conjunctive use program in which reduced surface water deliveries are compensated by pumping extra groundwater.

  On the other hand, releases downstream cannot be reduced below the minimum specified for environmental purposes. The model has a switch which allows a transfer/conjunctive use program to be activated. In dry years (a parameterized criterion), flows are reduced in the river to environmental minimums, effectively increasing the storage in the EBMUD system.

2.2.3. Model File

The working file takes information from the flow and parameter files and operates the system on a month-by-month basis: distributing and releasing water, calling for demand reductions in time of drought, and so on. The output from this file is a detailed record of hypothetical operations over the period chosen.

Each month begins with a set of initial values for the system:

- Storage levels in the reservoirs.
- Drought shortage levels (if applicable).
- Target levels for the terminal reservoirs. In normal times terminal reservoirs are kept nearly full. In times of drought, levels are allowed to drop, subject to security minimums.

Inflows into the system are drawn from the flows file while demand is drawn from the parameter file. Demand will be reduced if drought reductions are in effect. Aqueduct flows from Pardee are drawn so that demand and target terminal storage levels are met if possible. If withdrawals or deposits are being made to or from Los Vaqueros, aqueduct flows also compensate for this. The new terminal storage and Los Vaqueros storage levels can now be computed.

Next, releases from Camanche for downstream commitments, flood control, or other purposes (e.g., spillage) are computed. Finally, Pardee releases are computed. Now, new Camanche and Pardee storage levels can be computed.

The month of April is treated separately in the model. This is when basic decisions are made about how the system will be operated over the next year. April is chosen because, by April 1, most of the winter's precipitation has already fallen and the snow pack has been assessed. Thus, the runoff for that water year is known with a fair degree of certainty. In April, predictions are made about the storage levels in EBMUD reservoirs which will exist on October 1. If storage levels will be adequate, then the system operates normally. If October 1 storage falls below acceptable drought carryover minimums, then a drought response will be necessary. The model requires conservation from the customers as needed to ensure that the October 1 carryover level is met—until the maximum acceptable conservation level is reached. Thereafter, storage is allowed to fall below acceptable carryover minimums.

Terminal storage has a priority over storage in Pardee and Camanche Reservoirs. Thus, predictions for Pardee October levels must show that the reservoir would drop below minimums before terminal storage is allowed to drop. This priority system maximizes water available to the District (since even a drained Pardee will fill in most winters.) Such a priority also maximizes local storage levels, allowing security levels to be maintained as often as possible.

2.3. Some Illustrative Results

Model runs considered various permutations of the following parameters:

- EBMUD demand level.

  Runs were made assuming demand levels of 210, 240, 270, and 300 mgd. Before the current drought, which has reduced consumption, the highest (annual average) demand was 220 mgd. EBMUD planning contemplates a range of demands from 240 mgd to 300 mgd by the year 2020.

- Maximum allowable drought shortages.

  The maximum shortages allowed were either 39 percent or 25 percent, corresponding to EBMUD policy and planning.

- The amount of new terminal storage.

  The amount of terminal storage added was 0, 50, 100, and 145 kaf (capacity of the proposed Buckhorn Reservoir).

- Downstream environmental flow requirements.

  Current flow requirements are minimal. The California Department of Fish and Game (DFG) is now negotiating higher flow levels with EBMUD. A draft Fisheries Management Plan (DFG, 1991) proposes significant increases in flows. The increased flows were utilized for a series of runs.

- A water market/conjunctive use program.

This program is discussed above. A set of runs was made assuming that EBMUD would purchase water in dry years from downstream water users to allow reduced releases from Camanche Reservoir.

For any given runoff pattern, we would expect EBMUD supplies to be negatively impacted by higher average demands and instream flow requirements and positively impacted by greater amounts of terminal storage and the creation of a water market/conjunctive use program. The model runs bear this out. Assuming a repetition of the runoff patterns from 1927 to 1989, EBMUD would be particularly vulnerable to shortages during roughly four periods: 1932-34, 1962, 1976-77, and 1988-present.

Given the current system, drought impacts vary sharply with demand level. With a demand level of 300 mgd, shortages of 20 percent or more would be experienced approximately 7 years out of 60. At the other extreme, with demand reduced to 180 mgd (approximately the current level of use), the system would not have experienced shortages during the period of record.

The addition of terminal storage shifts these impacts downward. For example, with a normal year demand of 300 mgd, 50 kaf of additional terminal storage would reduce the number of years of shortages greater than 20 percent from 7 to 5; 100 kaf would reduce the number to 4; while 145 kaf would reduce the number to 3. To give another example relevant to present circumstances, the addition of 145 kaf of additional terminal storage would have allowed EBMUD to pass through both the 1976-77 and present droughts without imposing shortages on its customers. Of course, the cost of averting shortages in this way can be very high, as discussed in the next section.

Another set of runs was made to examine the impact of reducing the EBMUD target storage levels for October 1. In essence, reducing this target would mean that EBMUD was willing to allow storage levels to drop lower during drought. Intuitively, such a change in operating procedure should reduce the frequency of moderate shortages, while increasing the risk of major shortages. With a demand of 240 mgd and a target carryover storage of 161 kaf (about half the normal level), EBMUD would not have experienced any shortages over the historical record. Even at a demand of 300 mgd with a carryover target storage of 202 kaf (again, half the normal level), EBMUD would have only experienced a single shortage episode over the 62 years of record—a 25 percent reduction in 1977. Although the possibility of major shortages must be acknowledged, this analysis indicates that a relaxation in carryover storage requirements may be worth consideration, particularly if EBMUD has confidence in its ability to purchase additional supplies during severe drought.

Runs were also made to examine the impact on drought shortages of building an earthquakeproof aqueduct across the Delta. The effect is minimal. The reason is that EBMUD practice (and the standard model assumption) is to let terminal storage drop below earthquake-security minimums during severe drought under the assumption that the conjunction of severe drought with a major earthquake is very unlikely. Thus, while an improved aqueduct would give EBMUD greater protection in the event of an earthquake, it provides minimal improvement during periods of drought.

A series of runs was made to examine the possible impacts of a water marketing/conjunctive use program. In such a program, EBMUD would reduce releases from Camanche Reservoir into the Mokelumne River (but not below environmental minimum flows) during dry years. However, as downstream water rights are already fairly limited in dry years, and environmental regulations will still require releases, water purchase or conjunctive use agreements with downstream water rights holders are not sufficient, by themselves, to assure adequate supplies during prolonged droughts.

Finally, runs were made to examine the impacts of increasing the minimum flow standards in the Mokelumne River below Camanche Reservoir. The standards used in the model were those proposed by the DFG. The proposed releases are markedly higher than currently required. The impacts on EBMUD are significant, with a greatly increased frequency and severity of shortage. The model also shows that these impacts could be greatly reduced through increased terminal storage, reduced base demand, and/or dry-year market transfers.

We close this description of the model with a caveat. Its predictive power should not be overstated. The period of record is relatively short (62 years), future weather patterns may be statistically different and, of course, the operation of EBMUD is both more complex and less consistent than implied by the rigid relationships of a model that necessarily abstracts and simplifies.

3. Cost Estimation of Reservoir Options

3.1. Cost Concepts

Before a systematic economic analysis to quantify the costs of proposed reservoir projects is undertaken, a brief explanation of cost concepts is necessary. This study will focus mainly on financial, or market-based costs, but will also briefly consider nonmarket costs such as those arising from environmental impacts. The monetization of these nonmarket costs is beyond the scope of the study. However, relative magnitudes will be indicated where relevant.

To determine the effective unit cost of water supplied by the proposed projects, we use three variants: (1) unit cost calculated over the defined planning horizon, (2) unit cost calculated over the approximated lifetime of reservoir projects, and (3) unit cost of a perpetuity (a project that provides benefits "forever"). The concept most often employed in the comparison of different possible capital expenditures is that of economic equivalent unit cost over a defined planning horizon. This is the standard method employed by the California Department of Water Resources (DWR); see for example (DWR, 1990). EBMUD has defined its planning horizon to be

30 years. However, reservoir projects under consideration have expected lifetimes of between 50 and 100 years. Since EBMUD presents some data for an 80-year operation period, this time span will be used as an approximation of the lifetime of various projects.

The economic equivalent unit cost of a project is the ratio of the equivalent annual cost to the annual "water supply accomplishments" for the project under consideration. Since the objective of the project is to create a standby water supply capable of alleviating hardships during drought, rather than a yearly or even daily on-line supply, the water supply accomplishments are defined to be the water actually delivered in drought years that otherwise would be unavailable.

In practice, it is conventional to evaluate costs treating the zero project year as the year water deliveries begin or, in this case, the year water deliveries are possible if a drought occurred. Negative years and thus a present value factor greater than one are assigned to the planning and construction period. In this manner, the years of actual operation are labeled 1 to 30 and 1 to 80 for the planning horizon and lifetime calculations, respectively. The results are mathematically equivalent to designating the start of planning as the 0 year and then incorporating 30 or 80 years of operation after initial operating conditions are achieved.

The present value factor is $(1 + r)^{-n}$, where r is the real discount rate and n is the year under consideration. The present value cost allocation for each year is the product of the cost and the present value factor associated with that year. In the final analysis the sum of the present value of the costs for each year, or equivalently the total present value cost, of the project is multiplied by the capital recovery factor to arrive at the equivalent annual cost. The formula used in subsequent calculations is derived in Appendix B.

The water supply accomplishments of each project are evaluated using the 62-year hydrological record available for the Mokelumne River watershed. Since, as just noted, the measure of accomplishments is based on an intermittent use of additional water made available by the project during a drought, and the planning horizon is defined to be 30 years, a yearly average of the water supply accomplishments of the project based on the full hydrological record will be employed. Economic equivalent unit water cost is the equivalent annual cost divided by the average annual project yield.

3.2. Reservoir Options

In the present analysis of reservoir options, we restrict our attention to Buckhorn and Los Vaqueros, the principal proposals in EBMUD's *Final EIR* (1989). Consideration of these two will elucidate the impact of reservoir construction on the ability to deliver water to customers and the effective cost of the water delivered. However, if the earthquake-security and drought problems are decoupled (as we show in Appendix A), nonterminal reservoir options can also be considered as drought solutions. Thus, a third reservoir option which appears to have some merit, namely the extension of the Pardee Reservoir dam, could also be included. We refrain from doing so as reliable cost figures are not yet available.

The water supply accomplishments of additional reservoir storage are calculated using the computer model of the EBMUD system described in the preceding section. Figure 3.1 is an example of one run of the model. The bars extending down from the top of the graph indicate an occurrence of a water shortage below the nominal demand level, and the oscillating line across the middle of the graph represents the total amount of water in storage at any time over the 62-year hydrological data set. The assumptions of the model which most directly influence the water supply accomplishments of the proposed options are: (1) the specified acceptable supply shortage—25 percent in this run—in time of drought and (2) the target reservoir system inventory carryover predicted on April 1 and specified for October 1 in any year of 1.2 times the annual demand level. Priorities interact in an interesting way, as noted in the preceding section. Water is delivered to the customers at the full demand level as long as the carryover target is not violated. If this level of deliveries will result in a violation of the carryover target, deliveries are curtailed with the maximum reduction being the specified acceptable shortage. If the maximum reduction will still not keep the total reservoir storage above the target carryover, then this criterion is violated with the reservoir storage system being drawn down below 1.2 times annual demand.

The adherence to these criteria results in predicted total water supply shortages over the course of a 62-year hydrological cycle for a range of demand levels for the current reservoir system (zero additional storage) and for an augmented reservoir system with 50, 100, or 145 kaf of additional capacity as presented in Table 3.1. Note that the total shortages are greater with the 39 percent acceptable reduction. The resultant total water supply accomplishments of various reservoir options are derived from the difference between the shortage in the base case (zero additional storage) and the shortage with the specified capacity enhancement. Water supply accomplishments tend to be greater for the 39 percent acceptable reduction policy because the averted shortages are greater. At the 210 mgd demand level, any of the additional storage capacities results in no shortages; in particular, the 1977 shortage is avoided. However, at the 240 demand level, the 1977 shortage still occurs with an additional 50 kaf of storage, is ameliorated somewhat with 100 kaf of additional storage with 39 percent acceptable reductions, and is completely eliminated with 145 kaf of additional storage. At the 270 mgd demand level, additional storage eliminates most of the shortages other than that of 1977; this shortage still occurs because the reservoir system enters the year 1977 with a lower inventory than it would under a lower demand. If the water supply accomplishments are annualized over the course of the 62-year hydrological record, we obtain the figures shown in Table 3.2.

The costs for the various reservoir options are derived from estimates in the EBMUD *Final EIR* (1989) and supporting documents. Table 3.3 lists the capital costs, initial filling costs, and estimated annual operating expenses which include refilling costs for Buckhorn and Los Vaqueros Reservoirs of specified capacity dedicated to EBMUD. To establish a baseline figure, treatment costs for Los Vaqueros are not included. If Los Vaqueros is fully integrated into the EBMUD system, then it may be possible to effectively mix 10 percent Los Vaqueros water with EBMUD's current delivery system and not violate current health standards. If Los Vaqueros is wholly or partially filled with surplus Sierra water—a likely possibility—then this is, in turn, the more likely. Additionally, CCWD will have excess capacity at treatment plants dedicated to Los Vaqueros. As CCWD demand grows, summer excess capacity is likely to disappear, but winter excess capacity will remain. Finally, the proposed modular design of CCWD's treatment plant allows for construction of additional capacity dedicated to EBMUD. These possibilities for incorporating Los Vaqueros into the EBMUD and CCWD systems suggest that EBMUD's estimate of Los Vaqueros treatment costs is excessive.

For the planning horizon and approximate lifetime equivalent unit cost calculations, a three-year construction period followed by one year for initial filling of the reservoir is assumed. To establish a lower bound on unit water costs, in the perpetuity calculation, the construction time and filling time are neglected and it is assumed that benefits derive from the projects immediately.

The resulting unit costs for the range of reservoir options under consideration are presented in Table 3.4. For a 39 percent acceptable reduction, an 80-year lifetime, a 4 percent real interest rate, and 210 mgd demand (the demand level in the table closest to the historic high of 220 mgd), the cost per af for a 145 kaf reservoir at

Buckhorn Canyon is $8,265.83. Of course, the cost is lower at higher demand levels; at 300 mgd, for example, it falls to just $1,195.12. As we shall see, this range is far higher than those calculated for some of the alternatives for meeting periodic shortages. One apparent anomaly is the high cost of water at the 240 mgd demand level; however, this can be explained by the same argument presented above in describing the water supply accomplishments. At the 240 mgd demand level, additional storage will slightly or not at all alleviate the 1977 shortage; whereas, at higher demand levels, the 1977 shortage is not alleviated but other shortages not occurring at the 240 mgd are alleviated and, at lower demand levels, the 1977 shortage is totally eliminated.

Assuming EBMUD's estimates are correct, it is clear that Los Vaqueros water would be more expensive than Buckhorn water for the reservoir capacity options investigated, presumably because the terrain at Buckhorn—a relatively narrow canyon—is better suited to dam construction. On the other hand, given that a smaller Los Vaqueros will be built even without EBMUD's participation, the environmental impacts associated with EBMUD's participation in Los Vaqueros are likely to be far less than those resulting from construction at Buckhorn. Also significant are the high costs of dam extensions if a smaller capacity Buckhorn reservoir is initially constructed. If weather patterns of the recent past change significantly, the option of maintaining the Buckhorn site for a full-size reservoir, i.e., not constructing a smaller reservoir now, may be quite valuable.

The most striking feature of this analysis, the very high cost of water per af under any of the options considered, points to the difficulty and expense of attempting to solve an intermittent problem (drought) with a permanent increment to storage. As will be shown in later sections, intermittent solutions to intermittent problems can be much more cost effective. In other words, if we only need the extra water occasionally, it may be cheaper to rent than to buy.

3.3. Effect of Increased In-Stream Flows

During the current drought, heightened concerns have developed over the level of flow in the Mokelumne River. As noted earlier, the DFG has made recommendations for flows in the river to protect in-stream uses. The adoption of these recommendations would have a very significant impact on EBMUD's operation of Pardee and Camanche Reservoirs and on its ability to deliver high quality Sierra water to its customers. EBMUD and DFG are currently involved in negotiations to determine future flow rates. The following analysis assumes that the DFG's recommendations are adopted. The incorporation of these increased flow requirements into the computer model results in a very substantial increase in the frequency and severity of shortages incurred. Moreover, reservoir levels can get drawn down to nearly zero. Although this is not realistic, for purposes of this study, we adhere to the operation criteria indicated previously. In severe shortages the criteria would presumably be altered to provide some measure of security, but the alteration is likely to be specific to the particular situation of the drought incurred and is therefore not modeled here.

The total supply shortages and water supply accomplishments that would result over the course of the 62-year hydrological record, if the flow recommendations are adopted, are presented in Table 3.5. Given the reservoir costs developed in the previous section and the water supply accomplishments under enhanced flow conditions, unit water costs are calculated and presented in Table 3.6. Looking at the same configuration as we did for current flow requirements, the cost per af is $1.500.69. Not surprisingly, since shortages are now much more frequent, these costs represent a significant decrease over the previous case. However, as just noted, the calculation is probably unrealistic, since the implied drawdown of the reservoirs would presumably lead to a change in the operational criteria assumed in the model.

4. Cost Estimation of Conjunctive Use/Water Exchange Options

Conjunctive use options, by which we mean those involving use of both ground and surface water, combined with water exchanges or water marketing, address the intermittent nature of the drought problem. Since nearby irrigation districts, most importantly WID, and also some riparian users, have both groundwater reserves and surface water entitlements, the idea is to work out an agreement in which one or more of these agencies or individuals pump additional groundwater in dry years, thereby freeing some of their surface entitlements. EBMUD might then purchase the surface water. Alternatively, EBMUD might pay the costs of pumping groundwater and also subsidize groundwater recharge during normal or wet years.

Three possible programs are investigated in this section. The list is not all-inclusive of the variants of conjunctive use options, but a plausible range of possibilities is considered. Assessments are based on current instream flow requirements, but we consider also the implications of more stringent requirements.

The first two options specifically address the issue of groundwater depletion in San Joaquin County, in particular groundwater depletion in the vicinity of the Mokelumne River (Brown and Caldwell, 1985). In both options, water right holders downstream from Camanche Reservoir reduce their use of surface water in dry years and make up the deficit by pumping groundwater. EBMUD covers the cost of acquisition of groundwater for farmers. The two options explored here diverge only in the proposed EBMUD investment in the acquisition of water for the farmers. In the first, existing wells are utilized and EBMUD subsidizes the energy cost of pumping the water to the surface. In the second, EBMUD subsidizes in addition the cost of constructing new wells and annual maintenance. In either case, in wet years EBMUD provides excess water to the downstream agricultural users to supplant existing groundwater use and/or to enhance groundwater recharge. The third option is direct water purchases by EBMUD from downstream water right holders (or others) in dry years.

In all of the options, both parties to the agreement are better off after the agreement is in place. In all, as we shall show, EBMUD obtains water that it can deliver to its customers during droughts at far lower cost than is possible from the reservoir options. In the first two options, the downstream right holders receive the same amount of water. The only difference is that groundwater is substituted for surface water. Additionally, the local groundwater aquifer is enhanced, reducing future pumping costs. In the third option, the farmers receive a payment for the water which they are willing to accept; farmers will only be willing to accept a payment which fully compensates them for the expected profit that will be lost if they forgo the use of some quantity of water. The local groundwater aquifer could also be enhanced in this option, if farmers choose to leave some land fallow in dry years. However, if farmers replace the transferred surface water with groundwater, the aquifer will deteriorate at a greater rate. Therefore, for the third option to be viable given the groundwater deficit problem in San Joaquin county, some land must be left fallow in dry years.

The computer model is employed to assess these options with an additional operational criterion which supersedes all others to determine the years in which water transfers occur. The water transfer decision criterion is based on the predicted October 1 reservoir system carryover as calculated on April 1 and is triggered by the level of Camanche Reservoir. The system goal is to keep Pardee Reservoir full. If it is predicted that Camanche will become too low and thus water will have to be drawn from Pardee, then the water transfer is instituted. The volume of the transfer is calculated to be the maximum possible up to the point where in-stream flow requirements will be violated. This maximum volume derives from the quantity of downstream water rights which, in turn, are based on the type of year (wet or dry) that actually does occur. The transfer volumes represent the difference between the releases that would be necessary to satisfy downstream water rights and the releases necessary only to satisfy flow requirements. These transfer volumes assume 40 percent transit losses resulting from seepage and illegal diversions. Some surface water may still be available to farmers depending on the nature of the flow requirements. In particular, if flow requirements are higher between Camanche Reservoir and agricultural diversion locations than they are further downstream, the difference may still be diverted for agricultural use. After a transfer occurs, the criteria are the same as before: incur a shortage and then allow the carryover to fall below 1.2 times annual demand.

With this configuration, an example of the model output is given in Figure 4.1. The dark bars extending up from the bottom of the graph indicate the volume of water transfer that occurs for the given year. The total supply shortage and water supply accomplishments over the 62-year hydrological record for the conjunctive use program are presented in Table 4.1. In Table 4.2 the reduction in releases resulting from the transfer program and the actual water transfers (60 percent of release reduction) are shown. Note, in comparing Tables 4.1 and 4.2, that the total reduction in releases is greater than the total water supply accomplishments. This disparity occurs because the transfers are instituted as of April 1 based on predictions of carryover volume for October 1. Therefore, the total reduction in releases may not translate directly into water supply accomplishments if, for example, runoff or rainfall after April 1 is greater than predicted. At this stage of development, the model does not incorporate daily adjustments that would be available under real operations.

As in the discussion of reservoir options, we see an apparent anomaly at a demand level of 240 mgd. Total water supply accomplishments of zero result at this level because the conjunctive use program does not ameliorate the 1977 drought. By contrast, at the 210 mgd demand level, the 1977 shortage is completely eliminated. This results from the ordered nature of the criteria and the system storage projections on April 1 for October 1. At the 240 mgd demand level, before the institution of a conjunctive use program, a supply shortage occurs and the carryover target is violated. With a conjunctive use program in place, a transfer occurs, a supply shortage again occurs, and the carryover target is again violated. Thus, in both cases the complete 39 percent supply shortage occurs but, with the institution of a conjunctive use program, the drawdown of the reservoir system below the carryover target is less severe, which enhances water supply security for the next year. At the 210 mgd demand level, the institution of a water transfer affects the carryover prediction and, therefore, a supply reduction is not instituted.

To complete the calculation of the unit cost of water, the costs associated with each transfer mechanism must be determined. In the first option where existing wells are used and EBMUD subsidizes the pumping costs, the following assumptions are made: (1) the approximate average depth to groundwater in the area concerned is 65 feet (derived from Brown and Caldwell, 1985); (2) the average well pump energy consumption is 1.75 kilowatt hours (kwh) per af per foot raised (Brown and Caldwell, 1985, supporting data); (3) the average cost of energy is $0.0633125 per kwh (average summer price based on Pacific Gas and Electric (PG&E) agricultural rate schedule AG-5B, a reasonable assumption reflecting the unknown excess capacity of existing wells); and (4) planning and administrative costs of 15 percent are added (following standard engineering/economic cost accounting practice).

Resulting unit costs based on these assumptions and calculated over a 30-year planning horizon are presented in Table 4.3. Since expected costs and benefits are utilized and it is assumed that a shortage can occur in any given year with equal probability based on historical averages, the unit costs of water are independent of the discount rate for the first option. The striking result is that unit costs are far lower—by as much as two to three orders of magnitude—than corresponding reservoir costs.

For a 39 percent acceptable reduction, a 4 percent real interest rate, and 210 mgd demand, the cost per af under the first option is just $5.73.

For the second option, five additional assumptions are necessary: (1) the cost of construction of a well, including pump rated at 2,000 gallons per minute (GPM), is $25,000 (based on inquiries of local drillers and pump distributors); (2) each pump undergoes a major overhaul every five years costing $2,500 (based on inquiries of pump distributors); (3) if each pump is operated an average of approximately 18 hours per day for 6 months of the year, then 33 wells are required to extract the maximum transfer capacity; (4) the cost of energy is $0.03907 (based on summer off-peak rate from PG&E agricultural rate schedule AG-5B, the off-peak rate is utilized because a preliminary calculation revealed that a greater number of pumps operating in only off-peak hours is less expensive than fewer pumps operating continuously); and (5) annual operation and maintenance costs per well are, net of energy and overhaul costs, $1,000 per well. Resulting unit costs of water based on these additional cost assumptions for the second conjunctive use option are also presented in Table 4.3. Neither option has been optimized with respect to well sizing and operational parameters. Some flexibility exists, such as the opportunity to operate wells for 12 additional hours each weekend at summer off-peak rates. In reality, an intermediate option, where wells are jointly financed and used, is more likely to evolve because, in the second option, the new wells are only used in dry years. Again, however, the costs are strikingly lower—by one to two orders of magnitude—than for the reservoirs. For the low (210 mgd) demand scenario, the cost per af is $105.75.

The third option, as noted above, is direct water purchases by EBMUD from the downstream right holders. How large a payment might they require in order to be willing to give up the water? We have just seen that one alternative to the use of the foregone surface water, namely, pumping additional groundwater, would entail costs ranging (approximately) from $5 per af to $105, depending on what one assumes about the need for new wells. If these cost estimates are reasonable, then an offer of not less than $105 per af ought to be sufficient to induce substantial sales. In this case the farmer has the option of taking the money and using it to simply replace the surface water with groundwater. Of course, farmers (or districts) without access to groundwater might require a larger payment. They, and for that matter some farmers having access to groundwater, might let at least a portion of their land lie fallow for a year. Others might switch to less water intensive crops, and still others might adopt water saving irrigation methods. These adjustments, which do not involve additional pumping of groundwater, may in fact be socially preferred, as they would not aggravate the overdraft problem.

Here we need to mention a recent and significant institutional innovation. In 1991 a State Water Bank was created, for the purpose of facilitating transfers from those districts with water to sell to those who wanted to buy. The Bank set the prices: $125 per af to sellers, and $175 per af to buyers. It is interesting to note that the price to sellers was calculated to "yield a net income to the farmer similar to what the farmer would have earned from farming plus an additional amount to encourage the farmer to enter into a contract with a new and untried Water Bank" (DWR, 1992, p. 5). The price to buyers did not include conveyance costs (the energy costs of pumping the water from the Delta for State Water Project contractors, and the energy costs plus a facilities fee for noncontractors). That is, buyers would have to pay $175 per af plus conveyance costs. Assuming the Bank is continued beyond 1991, and the price schedule remains the same, the downstream right holders on the Mokelumne River could sell water for $125 per af. Similarly, EBMUD could buy water for $175. Conveyance costs would presumably be low, as EBMUD has a pumping station at the western edge of the Delta, where the aqueducts emerge. However, an alternative marketing arrangement might be made between EBMUD and the downstream right holders directly, i.e. without the intermediation of the Bank. A direct transfer at any price between $125 and $175 plus conveyance costs would, in theory, leave both buyer and seller better off. The opportunity for a mutually beneficial transaction will exist so long as there is a difference between the buying and selling prices set by the Bank, since the transfer is accomplished simply and costlessly by leaving additional water in Pardee Reservoir.

However the conjunctive use/water transfer arrangement works, it is evident that the much lower unit costs of water obtained in this fashion result both from the intermittent nature of the arrangement and the disparity in cost between, on the one hand, pumping groundwater and, on the other, building and maintaining surface reservoirs for the first two options, and the disparity in the (marginal) value of water to farmers and to urban users for the third option.

We suggested earlier that EBMUD could contribute to groundwater recharge in normal or wet years at very low cost. In most years, as evidenced by the number of transfer years indicated in Table 4.2, the Mokelumne watershed provides excess water. As calculated below for the more conservative case of increased instream flows, an average of over 200 kaf per year of water is not appropriated in two-thirds of the years in the hydrological record. EBMUD has rights to approximately half of this water or 100 kaf. This excess water creates the opportunity to supplant existing groundwater use in wet years and also for spreading operations to further augment groundwater recharge. Existing conveyance facilities would be used to deliver water to supplant groundwater use within irrigation districts. These facilities are currently used below their capacity. Two low-cost options for spreading are also apparent. Irrigation district canals are empty five to six months per year. The first option would open and fill these canals in wet years. The rather large canal seepage losses would effectively augment current recharge rates. The second option includes the first but proceeds one step further; water is diverted from the canals into some portion of the approximately 54 percent of the fields that are not orchard or vineyard (EBMUD, 1990). This further spreading could greatly enhance recharge and perhaps provide winter waterfowl habitat as well. The costs associated with these spreading options have not been estimated and are, therefore, not included in our cost calculations. However, these costs are not expected to be large since existing conveyance facilities are utilized. There would perhaps be labor effort, which would carry an out-of-pocket cost, though the true opportunity cost of the farmers' time during the winter might be close to zero. Of perhaps greater importance are the institutional barriers that must be overcome before commencement of water exchange and water spreading activity. EBMUD's current water right allows for the diversion of up to 364 kaf per year for beneficial use within its service area; the water exchanges and spreading operations would not be inside EBMUD's current service area. Additionally, acquisition of water that is not currently appropriated in very wet years may present difficulties if flow requirements are increased.

As discussed earlier, DFG has recommended increased flow requirements for the Mokelumne River. The effect of the proposed requirements under the conjunctive use options, and the resulting water supply accomplishments, are shown in Table 4.4. Note that the total volume of shortages over the 62-year hydrological record is vastly increased above the level for the same options with existing flow requirements. In Table 4.5 the reduction in releases, implied water transfers, and the number of years in which transfers or surpluses occur for the 62-year record are presented. Additionally, the average annual surplus of the Mokelumne watershed, for years in which releases occur with no specific use identified except maintaining flood-safety margins, is shown in Table 4.5. Finally, the unit costs of water supplied for the conjunctive use options under these enhanced in-stream flow requirements are presented in Table 4.6. Note that, for option 2, the costs are lower than the comparable costs under current flow requirements. For example, the cost per af in the most expensive scenario, involving option 2 under low demand, falls from $105.75 to just $42.28. The lower costs presumably result from the spreading of well construction costs over the larger volumes of water transfers called for in the enhanced flow regime.

Again, as with the comparison of unit costs for reservoir and conjunctive use options under existing flow requirements, the cost of supplying water with higher in-stream flow requirements is far lower for the conjunctive use options than the comparable reservoir options, although the disparity is reduced. These findings suggest that a conjunctive use/water exchange or water marketing scheme would be the least-cost drought contingency measure. We believe that this is true but only in part. Recall that upstream water rights are limited in dry years so that not all of a projected EBMUD shortage can be made up by the kinds of transfers discussed in this section. In a sufficiently dry year, the main user of Camanche Reservoir water, the Woodbridge Irrigation District, could get as little as 30 kaf—less than half of its normal consumption and about half of what EBMUD would require to make up a 25 percent shortage. Water transfers might, of course, be sufficient if purchases could be made, in addition, from other water districts, through a mechanism such as the 1991 State Water Bank.

5. Consumer Surplus Loss Due to a Price-Induced Reduction in Water Consumption

5.1. Introduction

Thus far, we have considered a variety of techniques to supplement water supplies during periods of drought. One important alternative available to water district managers is to reduce demand to appropriate levels through pricing policy. In this case, although the actual expenditures on projects which physically increase water supplies are absent, reduction of water demand through increased prices is not without cost. When water consumption is successfully reduced by increased prices, water users suffer a reduction in welfare as measured by consumer surplus loss. This consumer surplus loss can be used as the measure of the costs incurred from reducing water consumption through higher prices. Further, these costs can be used to compare price-induced demand reduction with other available options.

In order to ascertain the effect on EBMUD water users of a reduction in water use, it is necessary to know how consumers react to changes in water prices. While no definitive study has yet been done for the East Bay, there have been a variety of studies conducted concerning residential demand for water in other regions. These studies attempt to theoretically model water demand and then statistically estimate the relative impacts of the determinants of the quantity of water consumed. While there is still considerable debate as to the theoretically correct water demand model, a number of empirical studies have been published focusing on various aspects of modeling water demand.

Section 5.2 outlines the calculations necessary to compute the loss in consumer surplus due to a water use reduction of 25 percent in EBMUD. In section 5.3, the best of the available studies are described, evaluated, and used to suggest bounds on an estimate of the loss in consumer surplus due to the price-induced reduction in consumption. Finally, the results are compiled, summarized, and compared to those obtained in earlier sections.

5.2. Cost of Reduced Water Consumption

In this section, the base statistics for water use by EBMUD customers are described, along with an introduction to the notion of consumer surplus and how it is calculated. In short, this section describes the calculations used in arriving at the final estimates of costs.

5.2.1. Water Use in the EBMUD

All cost calculations done here are made for water use in the EBMUD for the year 1987, the most recent "normal" year. At that time, population within the district consisted of 1.1 million residents occupying 350,000 households. Daily water consumption was 220 million gallons. Since water demand studies are almost invariably conducted using monthly water demand data accounting for population in terms of households, a transformation is necessary to make these base numbers amenable to the studies to be used. Using the figure of 30.417 average days per month, average monthly water consumption per household in the EBMUD was 19,119.2571 gallons.

The studies often vary concerning the unit of measure for water consumption. This means it is necessary to compensate for these differences in order to use the results of these studies for comparison in the setting of East Bay water use. Some studies use units of thousand gallons while others use units of hundred cubic feet (ccf). This means that a transformation is necessary to normalize EBMUD quantities and prices to those used in each of the studies considered here. The necessary transformation for water use measured in thousand gallons is obvious; the transformation for ccf is made using one af of water as the basis for the transformation. One af of water is equivalent to 325,850 gallons and is also equivalent to 435.6 ccf.[1] Thus, in units adapted for the studies used, average monthly water consumption for 1987 was 19.119 thousand gallons or 25.5585 ccf. The proposed 25 percent reduction in water consumption results in a target of 14.3393 thousand gallons or 19.1688 ccf for the new level of consumption.

In connection with the two units of measure for consumption, two complementary measures of water prices must also be accounted for in the studies. For the EBMUD, the marginal price for water in 1987 was $290 per af. Using the same transformation as described above, we get a marginal price of $0.8899 per thousand gallons or $0.6658 per ccf.[2]

5.2.2. Consumer Surplus Loss

To understand the economic concept of consumer surplus, consider the graph in Figure 5.1. The demand curve is the set of points describing the maximum amount consumers are willing to spend for a quantity of the good. Now consider the consumer purchasing at Q^1 when price is P^0. Clearly this consumer was willing to pay more than she had to pay given the equilibrium price. In other words, she received benefit from the good in excess of what she paid for it. This additional benefit, the difference between willingness to pay and the price, derived by consumers purchasing a good at the market-equilibrium price, is called consumer surplus. If we consider all the consumers of this good then, graphically, consumer surplus is defined as the area under the market-demand curve and above the equilibrium price level. Given this definition, with an increase in prices, it is clear that there will be a resulting consumer surplus loss as this area is diminished, all other demand factors the same. As can be seen in Figure 5.1, when price rises from P^0 to P^1, quantity demanded falls from Q^0 to Q^1. The area representing lost consumer surplus is the area (A + B). Mathematically, this area is calculated for the general demand function as

$$\text{(1)} \qquad \text{CS loss} = \int_{P_0}^{P_1} Q(P)\, dp.$$

where Q(P) is the demand function and CS is consumer surplus. In the case of a linear demand curve[3], the calculation of consumer surplus can be done with simple geometry. The consumer surplus loss is area contained in the appropriate rectangle and triangle. This area is calculated as

$$\text{CS loss} = Q^1\left(P^1 - P^0\right) + \frac{1}{2}\left(Q^0 - Q^1\right)\left(P^1 - P^0\right) \tag{2}$$

$$= \left(P^1 - P^0\right)\left(Q^1 + \frac{1}{2}\left(Q^0 - Q^1\right)\right)$$

where, in the context of this analysis, Q^0 is the initial level of consumption in 1987 measured in thousand gallon or ccf units and Q^1 is the target level of water consumption, 25 percent lower than the 1987 consumption level. The only remaining information needed to estimate the consumer surplus loss is the size of the increase in water price necessary to effect the targeted 25 percent decrease in quantity demanded. For that we turn to the several published water demand studies.

5.3. Water Demand Studies

The key to understanding the degree to which prices must change to generate a 25 percent cutback in water consumption is the price elasticity of demand for water in the EBMUD. However, since no definitive study of water demand has been done for the district, we utilize a variety of studies which have been conducted in other regions. Using these studies is a second-best approach, since they are not studies of water demand of EBMUD water users. Further, due to the lack of consensus as to the most appropriate method for modeling water demand or performing statistical estimates, these studies use a variety of differing techniques. As a result, the studies are described and assessed in terms of the modeling and statistical techniques as well as in terms of their applicability to water demand in the EBMUD. Then, the respective estimates of consumer responsiveness to prices are used to develop an approximate range of potential consumer surplus losses which would be incurred by reducing water consumption by 25 percent.

5.3.1. Theoretical Models and Statistical Techniques

One of the most basic theoretical questions among researchers is, to what measure of price do consumers respond?[4] The controversy is grounded in the contention that, due to monthly or bi-monthly billings based on often complicated block-rate pricing structures, consumers may not clearly know the price of the water that they consume. One possible price specification is average price—total bill divided by quantity. In other words, consumers can read their total water consumption and charges from their billing statement and then act accordingly.

Another possible price specification is marginal price. The idea that consumers respond to marginal price (the price of the next unit consumed) appeals to economists since consumer theory relies on marginal prices in explaining demand. Even if consumer responsiveness to prices is based on marginal price, the issue of water demand is further complicated by the block-rate pricing structure employed by water districts. This complicates the analysis because the price consumers face is not independent of their choice of quantity. In other words, the consumer can affect the marginal price paid by consuming in different blocks. To account for this complexity, the Taylor-Nordin (see Taylor, 1975, and Nordin, 1976) price specification includes both the marginal price of water (the price of water in the block determined by quantity consumed) and a variable accounting for the difference between what was paid and what would have been paid if the marginal price were constant over all quantities. Because the Taylor-Nordin price specification has received relatively wide acceptance, no studies from before the Taylor-Nordin publications are included. The acceptance of the Taylor-Nordin price specification does not mean that it is not without flaw, however. For example, by definition, the coefficient of the difference variable should be equal to the negative of the income coefficient; in empirical studies it is rarely equal.

Once the desired price specification is chosen (for this report, the Taylor-Nordin specification), it is necessary to choose an estimation technique. Because water is priced using some form of a block-rate structure, the price paid for water is not independent of consumers' purchases. Due to the potential lack of independence between price and quantity consumed, coefficients estimated by the ordinary least squares (OLS) technique may be biased. To deal with this, some studies use instrumental variables or systems of equations techniques, while others resort to more clever specifications, and still others simply ignore the problem. The way in which the various studies address this problem is important in assessing the validity of the estimates.

Many studies are conducted using survey data from individual households within water districts. This avoids the surprisingly difficult problem of aggregation of water consumption data, but it may also make the results less illuminating as to the cost of reducing aggregate water consumption for an entire water district. For studies which employ aggregate data, it is important to consider how the aggregation of price data was conducted and how population is justified.

Finally, since responsiveness to price depends fundamentally on how long consumers have to adjust water use technology, the notion of long-run versus short-run price elasticities and the attendant consumer surplus loss is important. Studies using cross-section data are able to account for long-term adjustments in the water using capital stock between sections of the data. This is because observed differences in the price variable correspond to consumers in different regions facing different prices to which, over time, they have adjusted. Conversely, studies employing time-series data are able to account for the period-to-period partial adjustment in consumption in response to changing prices. Some studies use both types of data, but not all report long-run and short-run responses. It seems that, to understand the cost of drought through price-induced cutbacks in consumption, short-run responsiveness to prices would provide the most appropriate measure of consumer surplus loss. However, given the length of the current drought, long-run elasticities may be relevant as well. Whenever possible, estimated consumer surplus losses will report whether the estimate is for the long or short run.

5.3.2. The Studies

Each study is briefly summarized and its estimated water demand equation reported. Because the specification of each demand curve is so different and because this analysis focuses only on consumer surplus loss, only the price terms of each equation will be included. Based on the coefficients of each study, an estimate of consumer surplus loss associated with a 25 percent reduction in water consumption is calculated.

Using time-series data from Tucson, Arizona, for the period 1974 to 1980, Agthe *et al.* (1986) estimate both long-run and short-run price elasticities. During this time, Tucson used an increasing block-rate pricing schedule. The data used are aggregated and consumption is measured in ccf per household each month. The authors use the notion of the stock of water consuming capital goods and the utilization rate to estimate long-run and short-run elasticities, respectively. Since data on water consuming capital stock are unavailable, time is used as a proxy. The demand equations are estimated with a simultaneous equations technique to correct for simultaneity bias.

(3) Long run $Q_i = 11.42 - 34.57\, P_i - 2.45\, D_i + \ldots$

(4) Short run $Q_i = 47.17 - 20.16\, P_i - 1.36\, D_i + \ldots$

where D is the Taylor-Nordin difference variable. For this first study, the steps in calculating the consumer surplus loss will be carefully outlined. Hereafter, the estimated loss will simply be stated and the emphasis will be on the characteristics of the study. The consumer surplus loss is calculated as described in section 5.2.2. In applying equation (2) to this demand curve, we use the initial consumption level of $Q^0 = 25.5585$ ccf per household per month. A 25 percent reduction in Q^0 implies that the targeted consumption level $Q^1 = 19.1668$ ccf per household per month. Also, as is shown in section 5.2.1, the initial EBMUD price $P^0 = \$0.6657$ per ccf. The question remaining is what level of price, P^1, results in the targeted level of consumption, Q^1. This is where the demand equation is used. From the demand equation, we can solve for the price level which gives the desired consumption level assuming no change in the difference variable or in the non-price variables. We have, for the long-run model,

$$Q^1 = 11.42 - 34.57\ P^1 + \ldots.$$

Since the price change is the only source of change in the model, it must be the case that

$$Q^1 - Q^0 = \Delta Q = -34.57\ (P^1 - P^0) = -34.57\ \Delta P.$$

Thus,

$$\Delta P = \Delta Q/(-34.57) = -6.3917/(-34.57) = 0.1849$$

and

$$P^1 = 0.1849 + P^0 = 0.8507.$$

Now we can apply equation (2) using the values Q^0, Q^1, P^0, and P^1, as derived above. The result is that, for the long-run model, the consumer surplus loss is \$4.14 per household per month which translates into **\$17,388,000** of annual consumer surplus loss for the EBMUD. For the short-run model, similar calculations result in \$7.09 monthly consumer surplus loss per household or **\$29,778,000** per year for the district as a whole.

Billings and Day (1989) use the same set of time-series cross-section data from Tucson except that consumption is reported in thousand gallon units. It is not clear from the paper how population is controlled but, since the same data are used, it is likely that they are monthly observations of household consumption. The authors estimate two models differing in the specification of price. One is an average price model where consumers respond to the variable defined by the total water bill divided by quantity consumed. The other is the marginal price model described in some detail in section 5.3.1. It is not expressly stated, but it appears that OLS was used to estimate the relationships. Only elasticities are reported in the model, making the calculation of consumer surplus loss slightly different. The models are

(5) Average Price Model $Q_i = \beta_0 + \beta_1 AP_i + \dots$

with $\varepsilon_{AP} = -0.70$ and

(6) Marginal Price Model $Q_i = \beta_0 + \beta_1 P_i + \beta_2 D_i + \dots$

with $\varepsilon_P = -0.52$ and $\varepsilon_D = -0.21$, where ε_x denotes the price elasticity of demand for water with respect to the x variable. Calculation of consumer surplus can be done noting that the elasticity of demand is the percentage change in demand associated with a one percent change in price. We know that the desired percentage change in demand is 25 percent. This gives

$$\varepsilon_P = \frac{\%\Delta Q}{\%\Delta P} = \frac{-.25}{\%\Delta P} \tag{7}$$

and, equivalently,

(8) $$\%\Delta P = \frac{-.25}{\varepsilon_P}.$$

For the average price model, this implies that $\%\Delta P = .3571$ which gives a P^1 of \$1.2077 per thousand gallons. Computing the consumer surplus loss as before gives a welfare cost of **\$22,344,000** annually for the water district. Applying the same analysis to the marginal price model gives a consumer surplus loss of **\$30,072,000** for the district each year.

Note that the surplus loss for the marginal price model is very close to the loss calculated for the short-run model of Agthe *et al.* (1986): \$30 million *vs.* \$29.8 million. We would expect this, given that both use the same data set. In fact, we would expect the results to be identical, except that Agthe *et al.* use a simultaneous equation technique, and it appears that Billings and Day (1989) use OLS, which biases the estimated price coefficient downward (Henson, 1984). The bias presumably accounts for the difference in surplus losses: A weaker price effect means that price must be raised further to accomplish the desired reduction in consumption, thereby increasing the loss in consumer surplus.

Billings (1982) compares estimates of a new equation with a more conventional technique for which results were published in 1980 (Billings and Agthe). In the 1980 paper, the authors estimate the demand relationship with OLS using the Taylor-Nordin price specification. The data are from Tucson over the period January, 1974, to September, 1977. The only difference is the use of cents per ccf rather than dollars per ccf. The appropriate adjustment is made for the welfare cost estimates of each set of equations. Household observations are obtained and analyzed. The results and welfare-cost estimates resulting from this paper are given below.

(9) $$Q_i = -14.2 - 0.331\ P_i - 1.96\ D_i + \ldots$$

The welfare loss associated with the linear model can be calculated as described in section 5.3.1 and results in consumer surplus loss of **$18,144,000** for the entire water district. The authors include a log model in their analysis, which corresponds to a Cobb-Douglas demand function. For such a demand function, data are required to calculate the consumer surplus losses which are unavailable for this study.

Billings (1982) proposes a different specification and then estimates the relationships with the same data as the 1980 study. The proposed estimator is developed to eliminate the bias that occurs when estimating with aggregate data in which measurement error may exist for Q. The estimator begins from the definition of total revenue and the estimation of that relationship,

$$\text{Total Revenue} = TR = PQ = \alpha + \beta Q + e. \tag{10}$$

Since, by definition,

$$\frac{dTR}{dQ} = P = \beta \tag{11}$$

then β can be interpreted as the marginal price to the consumer. Similarly, α can be seen as the difference variable. Estimation of the equations of the linear and double-log specifications of this relationship were performed. The results are

$$Q_i = -17.8 - 0.425\, P_i - 1.19\, D_i + \ldots . \tag{12}$$

The linear model provides an estimated annual consumer surplus loss of **$14,112,000** for EBMUD.

Moncur (1987) compares the effectiveness of pricing as a water conservation tool to the effectiveness of non-price conservation tools used during two droughts in Honolulu, Hawaii. The data are survey responses from individual households conducted over the 42 bi-monthly billing periods ending at the close of 1981. Honolulu used a constant rate block-pricing scheme.[5] The demand curve is estimated using the Fuller and Battesse (1974) method which accounts for both time-series and cross-sectional differences. Moncur reports both long-run and short-run price elasticities for the appropriate models. The model reported here is the fifth in his paper. It includes a lagged consumption term which is intended to account for long-term changes in water consumption capital stock. Consumption is measured in thousand gallons per household. The model is

$$Q_i = 12.502 + 0.234\, Q_{i-6} - 20.361\, P_i + \ldots \tag{14}$$

and the reported long-run elasticity is -0.345; its short-run counterpart is -0.265. Using these elasticities, we find a long-term consumer surplus loss of **$45,318,000** and a short-term loss of **$58,968,000.**

Nieswiadomy and Molina (1989) use data on 101 households in Denton, Texas, for the summer months of 1976 through 1985. During the years 1976-1980, consumers faced a decreasing block-rate schedule; while in the years 1981-1985, they faced an increasing block-rate schedule. Since it is unlikely that the EBMUD would resort to declining block prices during a drought, the equations estimated for this period are excluded. The authors correct the simultaneity problems using two methods: an instrumental variables technique introduced by Terza (1986) and two-stage least squares (2SLS). The estimates did not differ much, so the equation estimated by 2SLS is included since that technique is more generally known. Consumption is measured in thousand gallon units. There is no mention of short-term and long-term elasticities. The estimated coefficient of the difference variable is positive and statistically significant.

(15) 2SLS Model $Q_i = -3.40 - 18.48\ P_i + 1.07\ D_i + \ldots$

The price response in this model results in a consumer surplus loss of **$18,186,000.**

Schefter and David (1985) estimate the demand function using cross-section data for 1979 for 131 communities in Wisconsin. As opposed to most demand studies, average marginal price and average difference variable are used rather than the marginal price and difference variable of the average consumer. The data appear to be for increasing block rates. All estimations were performed with OLS; simultaneity problems are not addressed. The data are based on thousand gallon units of consumption. There is no mention of short-run and long-run elasticities. Since information about the distribution of consumers within the block structures was unavailable, five equations were estimated to allow analysis of the sensitivity of the estimation to varying assumptions on the distribution of consumers. The estimates of all equations using the notion of average marginal price and difference variable are very similar. The equation given below assumes that consumers are normally distributed across the blocks and the variance parameter is the same for all of the communities included in the study. It is interesting to note that of all the studies using a difference variable in the price specification analyzed here, only the equations in this paper have an estimated coefficient that appears very close to the negative of the coefficient of income.

(17) $Q_i = 25.8 - 4.97\ P_i - 0.00174\ D_i + 00172\ I$

where I is income. With this model, the estimated consumer surplus loss resulting from a price-induced 25 percent cutback in water consumption is **$67,578,000** per year for the district.

The final study (Weber, 1989) is noteworthy because it uses data from EBMUD to estimate water demand. The data cover the period January, 1981, to

December, 1987, and are both time-series and cross-section in nature. The sections are represented by various "pressure zones," corresponding to elevations, in the district. These zones vary in terms of income, lot size and, most importantly, price (a surcharge based on the elevation of the zone). This provides the author with an opportunity to consider the long-run elasticity of demand. The technique used to estimate the pooled time-series cross-section data is not described, but we believe it is OLS. It is stated that EBMUD uses a single-unit water rate, which we take to mean no rising or falling block rates. In this case OLS is appropriate, as the simultaneity problem does not arise. However, it appears that rising block rates were in effect for a substantial part of the study period.[6] As noted earlier, this means that OLS estimates will be biased downward.

Since this study is focused specifically on water demand in the EBMUD, it could be argued that it, alone, should be sufficient in determining the welfare cost associated with increasing prices to reduce consumption in the EBMUD. However, there are difficulties with the study that in our judgment makes it worthwhile to include the results of the studies already described. One we have just noted is that results may be biased by use of OLS. A second is that, in the period that the data cover, there is little or no variation in the price of water. The result is, as the author shows in estimating the time-series data only, the price variable is not significant in explaining water consumption. Most variation in water consumption is attributable to changes in weather variables. While this may be true when the price of water does not vary, it is not very helpful in determining how much water prices must change to induce a 25 percent reduction in consumption. Adding the cross-section data provides some variation in price at any time but still not over time. Estimation of the pooled time-series cross-section model provides the author with an estimated elasticity of demand of

$$\varepsilon_p = -0.202.$$

Using equation (3) with this elasticity, the annual consumer surplus loss is estimated to be **$77,616,000**. The very low estimated elasticity of demand explains why this measure of consumer surplus loss is greater than for any other study. This leaves two possible conclusions: (1) EBMUD customers do not respond as readily to changes in prices as water customers in other areas or (2) the lack of variability in price over the study period, plus the use of OLS in the presence of rising block rates, bias the estimated elasticity toward zero.

5. 4. Summary: Caveats and Comparison to Cost Estimates

To confidently compute and compare the estimates of consumer surplus loss, it is important to take into consideration the applicability and quality of the studies on which the estimates are based. For example, a demand curve estimated for rural water users may not be applicable to water demand by EBMUD customers. There are similar concerns associated with whether the data were aggregate or household-level. Theoretical issues, such as price specification and the estimation procedure followed, are important. Although the Taylor-Nordin (marginal price/difference variable) price specification seems to be well accepted, it is not universally used. The issue of the independence of price and consumption is still debated, leaving a question as to whether a systems of equations estimation technique is necessary. It is also informative to know whether a welfare-loss estimate is a long-run or short-run estimate or if the authors made any reference to the timing concept. A summary of the papers included here may be found in Table 5.1. Information on the topics just mentioned is included along with the yearly consumer surplus loss estimates associated with each of the studies analyzed. The estimates range from $14,112,000 to as high as $77,616,000 of consumer welfare loss if EBMUD were to induce a 25 percent cutback in water consumption from 1987 levels by raising prices. These consumer surplus losses may appear not comparable to the out-of-pocket costs of supply-side drought management techniques. In contrast to actual outlays, consumer surplus is the monetary measure of the aggregate benefit to consumers due to paying less than they were actually willing to pay. But note that the consumer surplus loss represents a real loss to water consumers as the price they have to pay approaches the price they are willing to pay. Since this loss is a monetary measure, it is, in fact, comparable to costs of the various supply-side techniques.

To facilitate comparison of the costs of a price-induced cutback in water consumption to the other costs, the consumer surplus losses reported above are transformed to the cost per af of reduced water consumption. Intuitively, there is little difference between this measure and the cost per af of additional water supplies. A reduction in water consumption during periods of drought leaves more water in the system from which water districts draw their supplies. This results in a *de facto* expansion in available water stocks. To convert the costs reported above to a "per af" basis, we must convert the projected 25 percent reduction in water consumption to af. Using the standard described in footnote 1, we find that, for EBMUD in 1987, this is a reduction in consumption of 60 kaf[7] Resulting consumer surplus loss per af, ranging from a low of $229 per af to a high of $1,260 per af, is shown in Table 5.2.

The range is, for the most part, below that for the reservoir options but above that for conjunctive use. This suggests that conjunctive use, combined with water exchange or water marketing, as described in the preceding section, would be the least-cost alternative for dealing with a temporary shortage. But recall, again, that in a dry year, and in the absence of a mechanism like the 1991 State Water Bank, there would not be enough water available to meet the projected EBMUD shortage. A conjunctive use scheme might then be tried first, with the remaining shortfall made up by price-induced conservation. Note that the associated consumer surplus loss (in total and per af) would be much less than reported just above, since only a part of the shortage would need to be made up. We suggested earlier that perhaps 30 kaf might be forthcoming from a water exchange/marketing arrangement with the Woodbridge Irrigation District and other downstream Mokelumne River right holders. Since this represents approximately half of the 25 percent shortage that we have been assuming, only the remaining half of the shortage would need to be made up by means of a price increase. The resulting consumer surplus loss per af would then be just half of the amounts reported in Table 5.2, or $115-$630 per af.

Consumer surplus loss can also be reduced if it is measured in a different way. One might argue that part of the loss represented in Figure 5.1, namely the rectangle labeled "A," is not really a welfare loss, since this extra payment by consumers is received as income by the seller. Thus, only the triangle labeled "B" in the figure is a true welfare loss: a benefit formerly captured by consumers, now by no one. It seems to us that the appropriate measure of welfare loss depends on what is done with the amount "A." If is to be redistributed to consumers, or perhaps others in the community, it is not "lost." If, on the other hand, it is not redistributed in some fashion, then it stands as part of the consumer surplus loss. Without resolving this question, we present estimates of consumer surplus loss calculated as just the triangle, "B," in Table 5.2. These estimates range from a low of $33 per af to a high of $180 per af, making them quite comparable to the costs of the conjunctive-use/transfer options, even assuming that all of the projected shortage is made up by price-induced conservation.

6. Summary and Conclusions

The problem posed at the outset of this paper was, how can a large urban water district best respond to a drought? What is the least-cost combination of alternatives to meet periodic shortages? We hypothesized that an answer might involve what we called nonstructural, or demand-side approaches, as well as the conventional approach of adding to storage capacity by building new reservoirs. The hypothesis was tested in application to the East Bay Municipal Utility District (EBMUD), a large district serving 1.1 million people on the east side of San Francisco Bay.

Our findings by and large confirm the hypothesis. The cost per acre-foot (af) of water delivered was estimated for a range of capacities for each of the new reservoir options identified in the EBMUD planning process, Buckhorn and Los Vaqueros. Buckhorn, which EBMUD would build and use by itself, appears to be somewhat cheaper than Los Vaqueros, which would be a joint project with the Contra Costa Water District (CCWD). Our more detailed cost calculations therefore were carried out for Buckhorn. Summarizing the sensitivity analyses for variants of the Buckhorn project, we found a range of costs running from about $1,000 per af to about $12,000 per af. The low cost is for a reservoir having a capacity of 145 thousand acre-feet (kaf), EBMUD's preferred alternative, demand at the top of the range of estimates, namely 300 million gallons per day (mgd), and a management regime that would, in the absence of the new reservoir, accept a shortage of up to 39 percent of normal deliveries (one of EBMUD's planning alternatives). The high cost is for a reservoir having the same capacity, demand at the low end of the range of estimates (210 mgd), and an acceptable shortage of 25 percent (EBMUD's other planning alternative). Our best estimate would be somewhere in the middle of this range, between $4,000 and $8,000 per af. It is worth noting (though that is all we do in the present study) that Los Vaqueros, though somewhat more expensive, would be preferred on environmental grounds. This is because CCWD will almost certainly proceed here regardless of EBMUD participation, so that development of the Buckhorn site would mean two impacts instead of one.

A prime alternative to reservoir construction we identified was a combination of conjunctive use and water transfer. One variant of the approach would have EBMUD pay the costs of increased groundwater pumping by downstream (from the EBMUD dams) water right holders in dry years, and perhaps also undertake low-cost groundwater recharge activities in wet years, in exchange for the right holders' not taking some or all of their surface water entitlements, which would be left behind the dams for EBMUD use. Another variant would have EBMUD simply pay for this water, leaving to the sellers the decision on how to adjust to reduced surface water supplies. We calculated that the costs of increased groundwater pumping would range from $5 per af to $105, depending on whether new wells are required. The higher figure might also represent the sale price of the surface water, since the sellers would have the option of taking the payment and using it to replace the surface water with groundwater. The cost saving, as compared to the reservoir alternatives, is dramatic. It can be explained by the intermittent nature of the conjunctive use/transfer, the disparity in cost between pumping groundwater and building a surface reservoir, and the disparity in the (marginal) value of water to farmers and urban users.

One difficulty with the conjunctive use/transfer approach is that it would probably not yield enough water, by itself, to compensate fully for projected EBMUD shortages. The next most promising alternative appears to be participation in the new State Water Bank, if this continues in operation. Founded in 1991, the Bank bought water for $125 per af and sold it for $175 plus conveyance costs. In fact, assuming the Bank continues, the downstream right holders would have the option of selling to it, rather than to EBMUD directly. A mutually beneficial exchange might then involve EBMUD paying the right holders some amount greater than the $125 they could get from the Bank, but less than the $175 plus conveyance costs it would have to pay the Bank for water.

Finally, we considered a purely demand-side approach: raising prices, within EBMUD, to achieve a cutback in consumption dictated by drought. The loss in consumer surplus associated with a price increase required to achieve a 25 percent cutback falls within a range of approximately $33-$1,260 per af, depending on the demand elasticity and on how consumer surplus is calculated. Even this is well below the range of reservoir cost estimates. Moreover, the cost would be reduced if at least some water were available through conjunctive use or purchase. For example, if the conjunctive use/transfer option could yield half the amount required, which we believe it could, and there were no other purchase options, such as through the State Water Bank, the cost of making up the remaining shortfall by increasing the internal EBMUD price would be just half that indicated above.

Appendix A

The Separability of the Earthquake and Drought Problems

EBMUD's proposed solution for both the earthquake and drought problems is the construction of Buckhorn Reservoir with a capacity of 145 kaf. EBMUD's analysis, based on a policy of a maximum acceptable shortage of 39 percent during a drought, suggests the need for additional storage of 55 kaf by the year 2020 for the drought problem alone. In fact, no new storage would be needed until the year 2000. In essence, then, the additional 90 kaf of storage is a one-time solution to the earthquake-security problem—one time in the sense that, once a severe earthquake occurs, an option exists to build a secure aqueduct at that time or build another aqueduct that will fail in the event of another severe earthquake. If the secure aqueduct option is preferred to the "disposable" aqueduct option in the future, the additional storage becomes superfluous to the solution of the earthquake problem (though additional storage could provide some benefits during a drought).

From an a priori present value perspective of costs, it is possible that a disposable aqueduct may be desirable. However, if a replacement secure aqueduct is the desired course of action after a future earthquake, there is a positive probability that the severe earthquake could occur before the completion of Buckhorn Reservoir. Essentially, it is possible that the excess capacity necessary for earthquake security will become unnecessary if a severe earthquake occurs before the reservoir can be filled. Then a decision has to be made whether to complete Buckhorn as a reservoir dedicated to solving only the drought problem. Therefore, in addition to minimizing the expected present value of the cost of solving the two problems, planners must also be aware of the positive risk of committing to an option, such as Buckhorn Reservoir, which may become economically unsound before it is completed and in operation. The other options do not suffer from this problem.

Consider three general aqueduct options as illustrated in Figure A.1, where Figure A.1a represents the existing configuration: (1) Utilize existing aqueducts, and build two secure aqueducts after a severe earthquake (Figure A.1b). (2) Build a secure pipeline now (Figure A.1c, No. 4), and repair/build a secure pipeline after a severe earthquake (Figure A.1b, No. 3). (3) Build secure pipeline No. 4, and retrobuild No. 3 into a secure pipeline (Figure A.1d, Nos. 4 and 3). Clearly, these options are listed in order of increasing expected present value of cost. However, when drought alleviation activities are included (restricting our attention to just reservoir options for the moment), the order changes.

Before including the drought activities, a brief explanation of the determination of costs is necessary. Reservoir costs are derived for an 80-year lifetime. The construction and filling costs are not spread out over four years (three construction years and one initial fill year), as in the reservoir section of the main text. There, this distinction is meaningful, because water supply benefits cannot accrue until four years after construction begins. In this case, the benefits of earthquake security are also not realized until the reservoir has been filled, but only the relative costs of different means of solving the earthquake-security problem are examined. The only apparent implication of the lag is that, if a 145 kaf reservoir is selected to solve both the drought and earthquake problems, then there is a positive probability that a severe earthquake could occur before completion of the reservoir as discussed above. Aqueduct costs were obtained from EBMUD for both dredged and tunneled river crossings and are presented in Table A.1. The present value expected cost of aqueduct replacement is based on the assumption of a uniform probability of a severe earthquake of 1/83 per year (based on a recurrence interval of 83 years for high ground shaking—EBMUD, 1989—and an assumption of uniformity). These present value expected costs are also shown in Table A.1.

The choice of option 1 is also essentially a choice of a 145 kaf Buckhorn Reservoir to provide water during the first earthquake outage that prompts the building of secure pipelines. The choice of option 2 would also require additional water availability for drought but not for earthquake security. Again, restricting our analysis to only reservoir options, a 55 kaf Buckhorn Reservoir would be the least-cost reservoir for option 2. Finally, option 3 also has an associated 55 kaf Buckhorn Reservoir. Note that this option would only be chosen if the restriction of flow in option 2 (i.e., having only pipeline No. 4 available for some time) results in expected economic costs greater than the difference between options 2 and 3. Reservoir costs are shown in Table A.2. A variation of option 2 could also be considered in which pipeline No. 3 is retrofitted now (Figure A.1e) and No. 4 is built after failure of No. 1 and No. 2 in an earthquake (resulting in Figure A.1b). This option is only viable if No. 1 and No. 2 can provide adequate flow while No. 3 is being retrofitted.

The costs for each package of drought and earthquake-security measures are presented in Table A.3. (Additional benefits, such as reduced pumping costs for options 2 and 3 are not included.) Note that option 2 is less costly than option 1 (which is EBMUD's proposed solution) and option 3 is comparable in cost to option 1. This analysis implies that the security problem should be addressed separately as an optimal aqueduct replacement problem. Additionally, it is shown in the main body of the text that other alternatives can alleviate a drought more cheaply than a reservoir, even a scaled-down version of Buckhorn.

Appendix B

Mathematically, if the total present value cost (PVC) is to be repaid in equal annual cost increments (c) at the end of each of n years, then c is determined as follows.

$$
\begin{aligned}
\mathrm{PVC} &= \sum_{k=1}^{n} \frac{c}{(1+r)^{k}} \\
&= \frac{c}{1+r} \sum_{k=0}^{n-1} \frac{1}{(1+r)^{k}} \\
&= \frac{c}{1+r} \left[\sum_{k=0}^{\infty} \frac{1}{(1+r)^{k}} - \sum_{k=n}^{\infty} \frac{1}{(1+r)^{k}} \right] \\
&= \frac{c}{1+r} \left[\sum_{k=0}^{\infty} \frac{1}{(1+r)^{k}} \right] \left[1 - \frac{1}{(1+r)^{n}} \right] \\
&= \frac{c}{1+r} \left[\frac{1}{1 - \frac{1}{1+r}} \right] \left[\frac{(1+r)^{n} - 1}{(1+r)^{n}} \right] \\
&= \frac{c}{1+r} \left[\frac{1+r}{r} \right] \left[\frac{(1+r)^{n} - 1}{(1+r)^{n}} \right] \\
&= \frac{c}{r} \left[\frac{(1+r)^{n} - 1}{(1+r)^{n}} \right].
\end{aligned}
$$

Thus,

$$
c = r \left[\frac{(1+r)^{n}}{(1+r)^{n} - 1} \right] \mathrm{PVC}
$$

and, therefore, the capital recovery factor is

$$r\left[\frac{(1+r)^n}{(1+r)^n - 1}\right]$$

where n is the defined planning horizon or approximated lifetime.

Footnotes

[*] We are grateful to Robert Deacon and Michael Hanemann for helpful comments on an earlier draft.

[1] One af of water is equivalent to 43,560 square feet, one foot deep. This gives 1 af = 435.6 ccf = 325,850 gallons and a conversion factor of 1 ccf = 748.05 gallons.

[2] Price = \$290 per af = \$290/334,583.3 gallons. This gives price = \$0.8667 per 1,000 gallons. Similarly, \$290 per af = \$290/435.6 ccf implies that the price is \$0.6657 per ccf.

[3] All of the studies included in this analysis estimate linear-demand curves.

[4] In fact, some researchers maintain that the question of whether residents respond at all to water prices has not been resolved.

[5] In the first 18 months of the study, consumers faced a declining block-rate schedule. However, few of the consumers ever had quantities large enough to be in the second block. Thus, we can effectively assume a uniform block-rate schedule throughout the study.

[6] A jump of 25 percent to 33 percent in the rate occurred at a low level of household consumption, making it likely that most households were affected from May, 1979, through July, 1985.

[7] We saw that 1 af = 325,850 gallons. The 25 percent reduction corresponds to 20,075,220,000 gallons annually. Using the conversion factor above, we find that water consumption is to be reduced 20,075,220,000/325,850 = 61,609 af.

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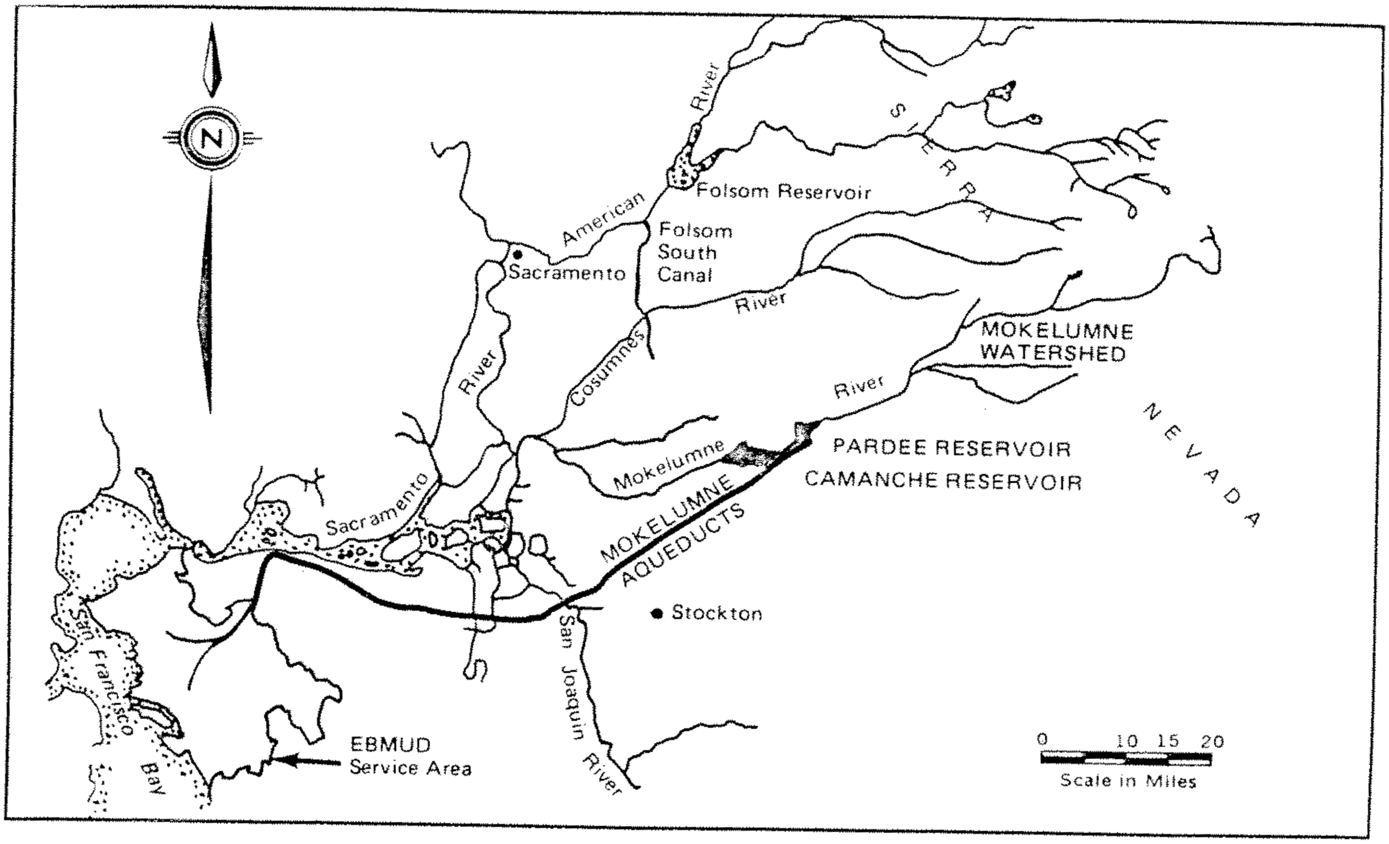


Figure 2.1. EBMUD Water Supply System.

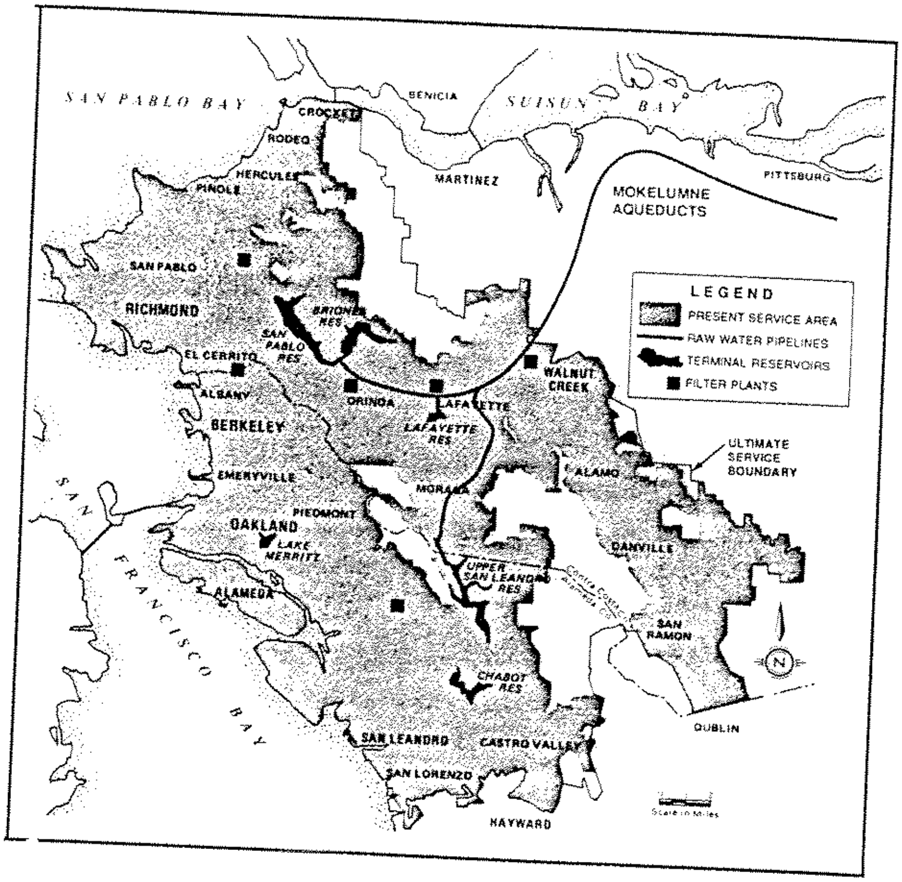


Figure 2.2. EBMUD Service Area and Terminal Reservoirs.

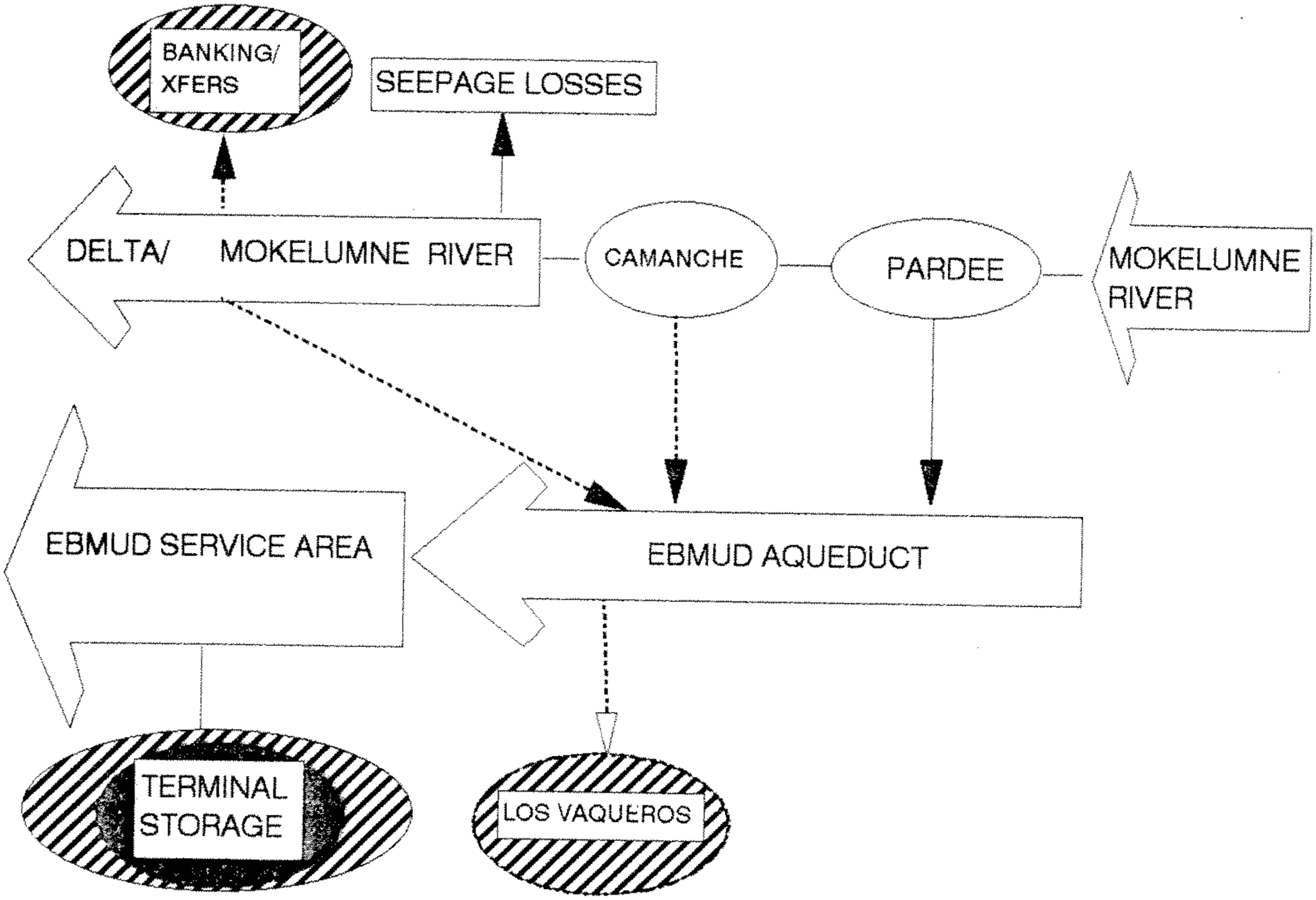


Figure 2.3. EBMUD Planning Options.

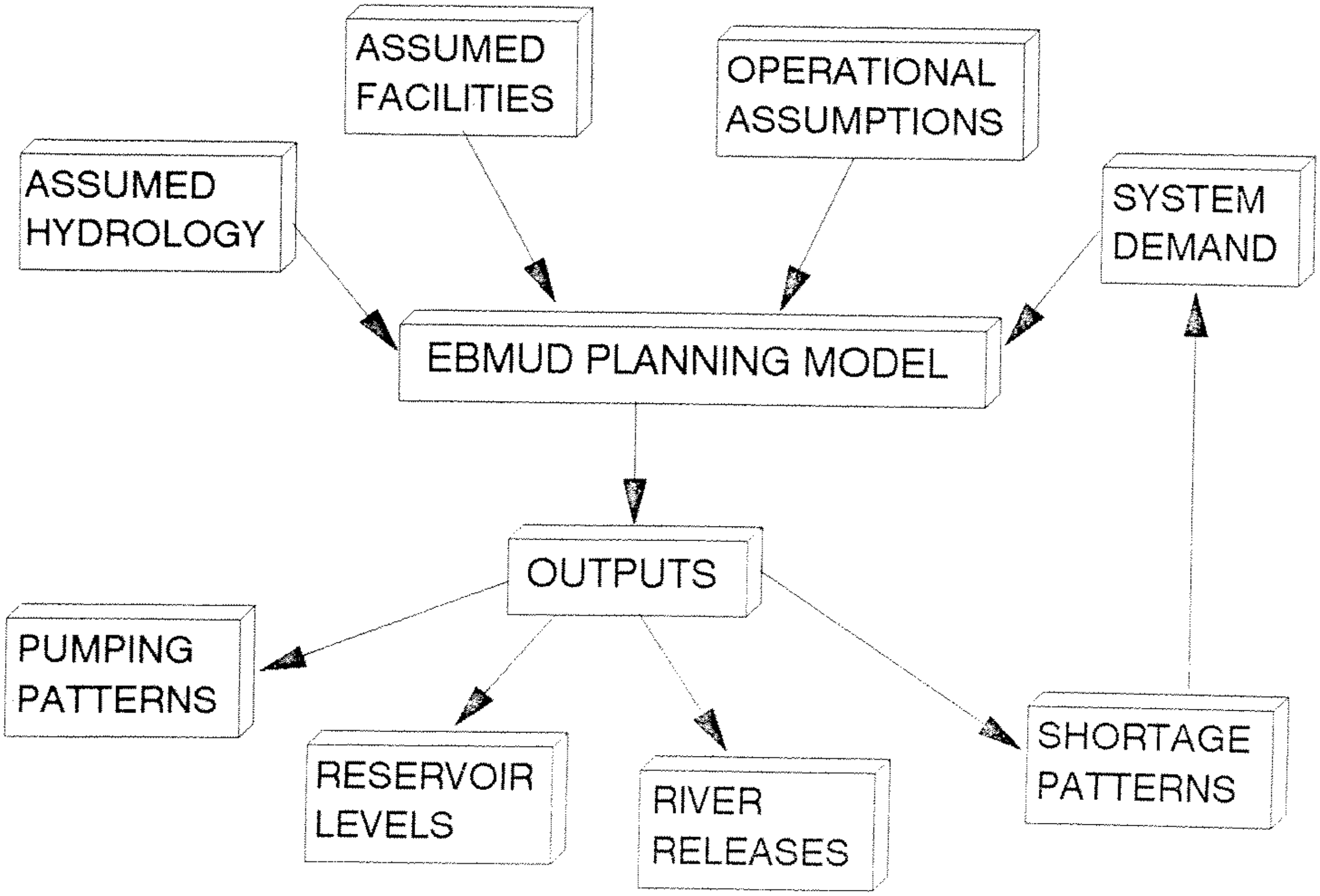


Figure 2.4. EBMUD Planning Model.

TABLE 3.1

Total Supply Reductions and Total Water Supply Accomplishments Under Various Reservoir Options

Demand level	Additional storage	Acceptable percent supply reduction			
		39 percent		25 percent	
		Total supply shortage	Total water supply accomplishment	Total supply shortage	Total water supply accomplishment
mgd	kaf				
300	0	788.6		517.6	
	50	627.6	161.0	478.0	39.6
	100	488.5	300.1	404.3	113.3
	145	332.8	455.8	238.8	278.8
270	0	377.9		251.0	
	50	232.1	145.8	75.7	175.3
	100	118.0	259.9	75.7	175.3
	145	118.0	259.9	75.7	175.3
240	0	104.9		67.3	
	50	104.9	0.0	67.3	0.0
	100	67.3	37.6	67.3	0.0
	145	0.0	104.9	0.0	67.3
210	0	65.9		58.8	
	50	0.0	65.9	0.0	58.8
	100	0.0	65.9	0.0	58.8
	145	0.0	65.9	0.0	58.8

TABLE 3.2

Average Annual Water Supply Accomplishment (af)

Demand level (mgd)	Additional storage	39 percent	25 percent
300	50	2,597	639
	100	4,840	1,827
	145	7,352	4,497
270	50	2,352	2,827
	100	4,192	2,827
	145	4,192	2,827
240	50	0	0
	100	606	0
	145	1,691	1,085
210	50	1,063	948
	100	1,063	948
	145	1,063	948

TABLE 3.3

Capital Costs, Initial Filling Costs, and Estimated Annual Operating and Maintenance Expenses: Various Reservoir Options

Buckhorn Reservoir

Capacity	Capital costs	Initial fill costs	Estimated annual operating and maintenance costs
kaf		million dollars	
50	83	7	.418
100	133	12	.627
145	160	18	.794

Los Vaqueros Reservoir

Dedicated EBMUD capacity	Capital costs	Initial fill costs
kaf	million dollars	
50	124	4
100	159	8
145	187	11

TABLE 3.4

Buckhorn Reservoir: Unit Cost of Water Supplied (dollars per af)

		Acceptable supply reduction											
		39 percent						25 percent					
		Method of calculation											
Demand level (mgd)	Additional storage (kaf)	Perpetuity		80-year lifetime		30-year planning horizon		Perpetuity		80-year lifetime		30-year planning horizon	
		Discount rate											
		3%	4%	3%	4%	3%	4%	3%	4%	3%	4%	3%	4%
300	50	1,185.32	1,540.38	1,373.21	1,719.81	2,028.82	2,316.90	4,819.16	6,262.53	5,580.99	6,989.53	8,245.19	9,415.84
	100	1,016.46	1,332.23	1,177.22	1,476.63	1,743.82	1,992.62	2,692.32	3,502.24	3,118.62	3,911.86	4,619.63	4,657.02
	145	824.31	1,071.88	953.77	1,195.12	1,411.19	1,611.53	1,487.42	1,831.84	1,559.29	1,953.86	2,307.11	2,634.64
270	50	1,308.89	1,700.97	1,516.25	1,898.95	2,240.15	2,558.21	1,201.55	1,478.87	1,261.47	1,579.88	1,863.76	2,128.36
	100	1,173.68	1,526.75	1,359.19	1,704.90	2,013.38	2,300.63	1,920.60	2,366.20	2,015.46	2,528.08	2,985.54	3,411.44
	145	1,445.63	1,879.80	1,672.74	2,096.04	2,474.97	2,826.33	2,365.62	2,913.38	2,480.40	3,108.08	3,670.02	4,190.96
240	50	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	100	8,112.79	10,553.39	9,402.03	11,793.35	13,927.35	15,914.50	∞	∞	∞	∞	∞	∞
	145	3,581.69	4,657.43	4,146.78	5,196.06	6,135.53	7,006.43	6,161.92	7,588.60	6,462.77	8,098.27	9,562.49	10,919.68
210	50	2,895.85	3,763.22	3,354.89	4,201.64	4,956.61	5,660.46	3,582.15	4,408.98	3,761.86	4,711.27	5,557.88	6,346.92
	100	4,628.85	6,021.15	5,360.12	6,723.35	7,939.96	9,072.85	5,725.86	7,054.36	6,010.34	7,538.86	8,903.13	10,173.12
	145	5,701.38	7,413.54	6,596.64	8,265.83	9,760.31	11,146.02	8,906.13	8,685.68	7,396.86	9,268.44	10,944.30	12,497.71

TABLE 3.5

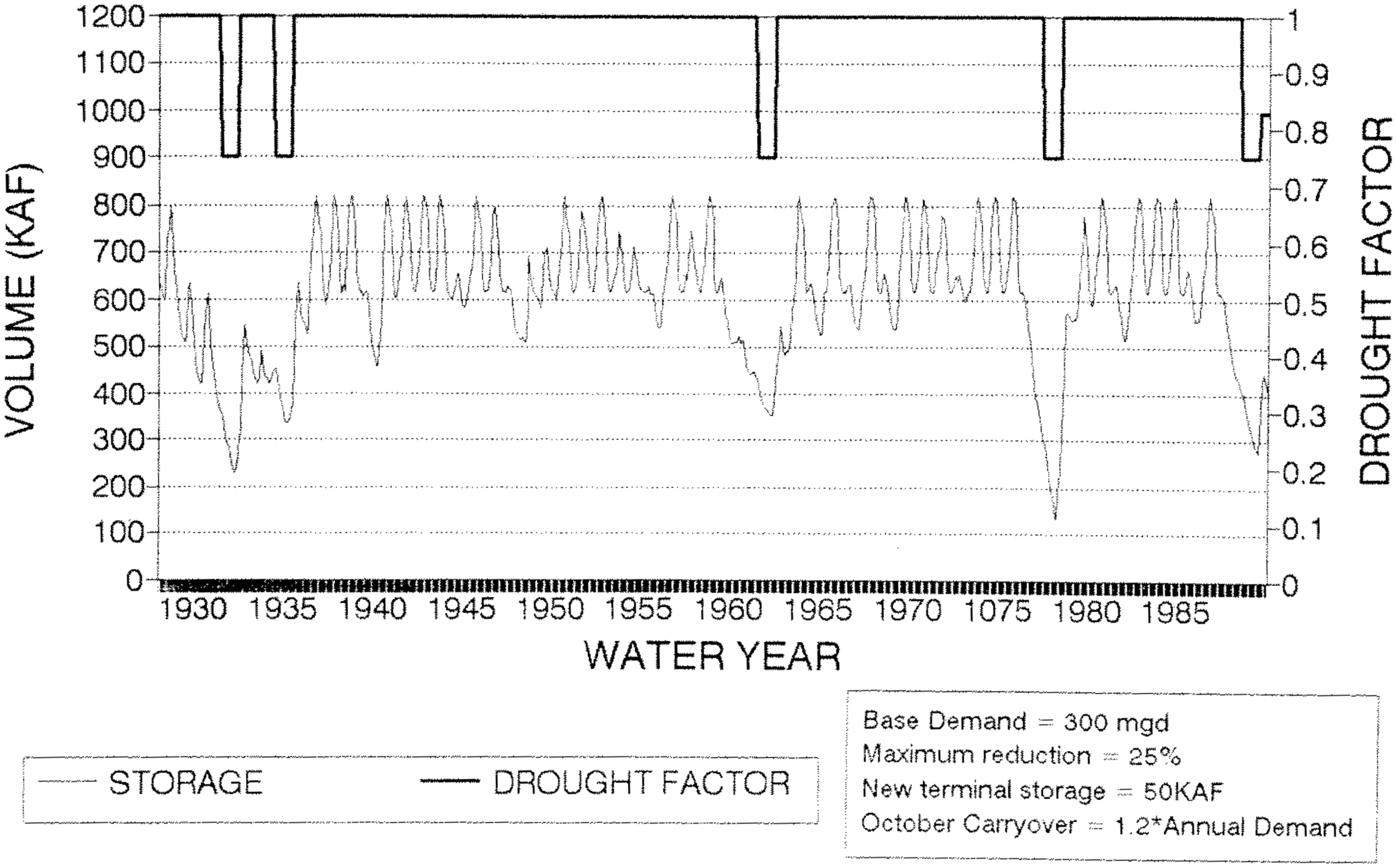
Total Supply Reductions and Water Supply Accomplishments Under Department of Fish and Game Flow Recommendations and 39 Percent Acceptable Supply Reduction Policy

Demand level	Additional storage	Total supply shortage	Total water supply accomplishment	Average annual water supply accomplishment
mgd		kaf		af
300	0	2,933.3		
	145	1,811.7	1,121.6	18,090
270	0	1,715.1		
	145	1,210.0	505.0	8,145
240	0	1,049.4		
	145	700.3	349.1	5,631
210	0	642.6		
	145	279.6	363.0	5,855

TABLE 3.6

Unit Cost of Water Supplied for 145 kaf Buckhorn Reservoir Under Department of Fish and Game Flow Recommendation With a 39 Percent Acceptable Supply Reduction Policy (dollars per acre-foot)

Demand level (mgd)	Method of calculation					
	Perpetuity		80-year lifetime		30-year planning horizon	
	Discount rate					
	3%	4%	3%	4%	3%	4%
300	334.99	435.59	387.63	485.71	573.53	654.95
270	744.00	967.45	860.91	1,078.77	1,273.79	1,454.63
240	1,076.25	1,399.49	1,245.27	1,560.39	1,842.49	2,104.07
210	1,035.04	1,345.90	1,197.64	1,500.69	1,772.00	2,023.56



Base Demand = 300 mgd
Maximum reduction = 25%
New terminal storage = 50KAF
October Carryover = 1.2*Annual Demand

Figure 3.1. EBMUD Demand and Storage.

TABLE 4.1

Total Supply Reductions and Water Supply Accomplishments of a Conjunctive Use Option and 39 Percent Acceptable Supply Reduction Policy

Demand level	Water transfers	Total supply shortage	Total water supply accomplishments
mgd	yes or no	kaf	
300	n	788.6	
	y	585.5	203.1
270	n	377.9	
	y	300.2	77.7
240	n	104.9	
	y	104.9	0.0
210	n	65.9	
	y	0.0	65.9

TABLE 4.2

Total Reductions in Releases and Total Water Transfers

Demand level	Number of years out of 62 water transfer to EBMUD	Total reduction in releases	Total water transfer to EBMUD (60 percent or total reductions)
mgd		kaf	
300	7	322	193.2
270	4	180	108.0
240	4	180	108.0
210	2	76	45.6

TABLE 4.3

Unit Cost of Water Supplied for Conjunctive Use Options Based On 39 Percent Acceptable Supply Reduction Policy Calculated for 30-Year Planning Horizon (dollars per af)

Demand level (mgd)	Option 1		Option 2	
	Pumping energy costs		All well costs	
			Discount rate	
	3%	4%	3%	4%
300	7.88	7.88	36.07	38.03
270	11.51	11.51	88.68	93.79
240	∞	∞	∞	∞
210	5.73	5.73	99.72	105.75

TABLE 4.4

Total Supply Reductions and Water Supply Accomplishments of a Conjunctive Use Option With Enhanced In-Stream Flows and 39 Percent Acceptable Supply Reduction Policy

Demand level	Water transfers	Total supply shortage	Total water supply accomplishments
mgd	yes or no	kaf	
300	n	2933.3	
	y	2065.7	867.6
270	n	1715.1	
	y	1275.7	439.4
240	n	1049.4	
	y	764.0	285.4
210	n	642.6	
	y	468.2	174.4

TABLE 4.5

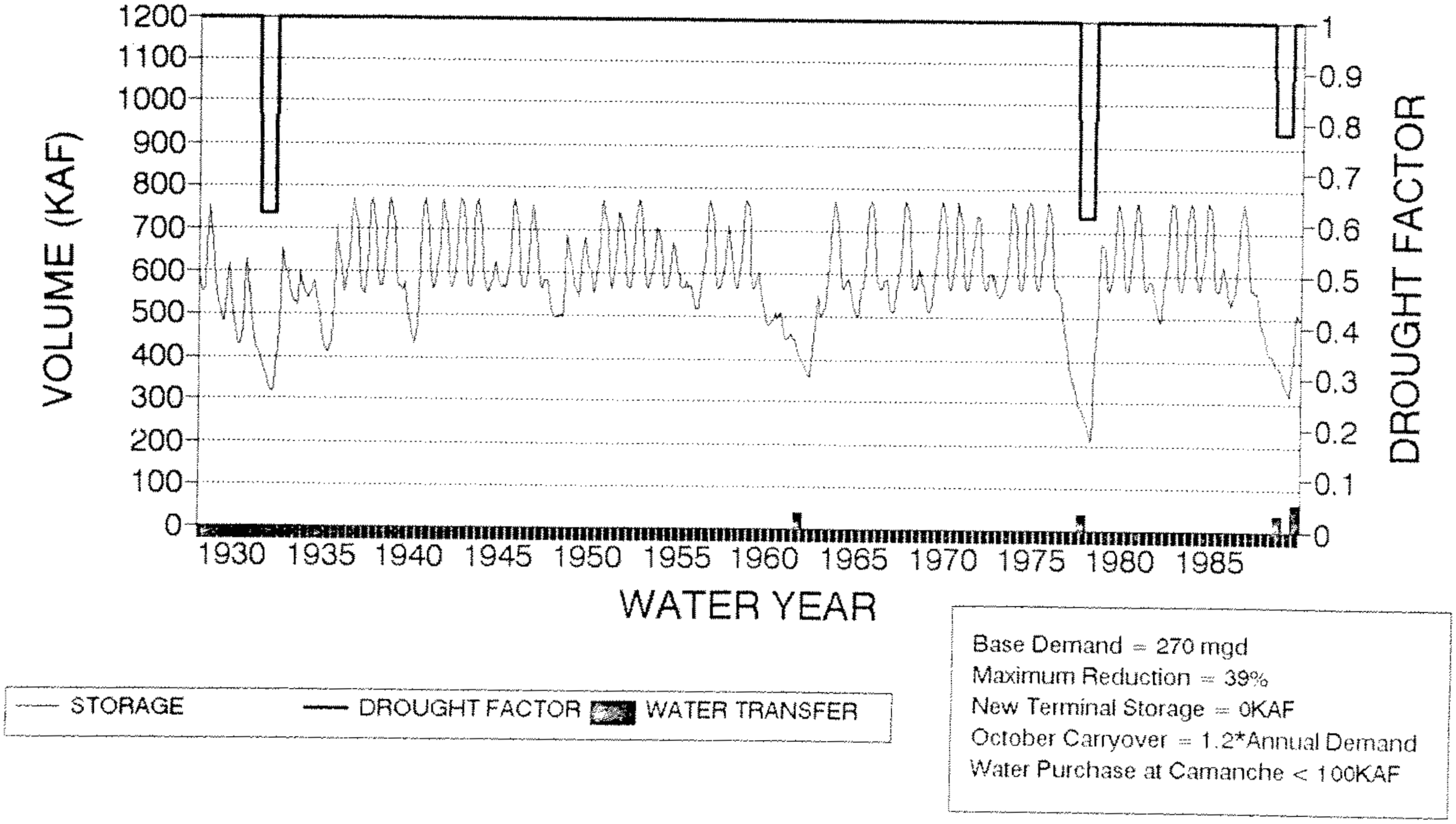
Total Reductions in Releases, Total Water Transfers, and Average Annual Watershed Surplus With Enhanced In-Stream Flows

Demand level mgd	Number of years out of 62 water transfer to EBMUD	Total reduction in releases kaf	Total water transfer to EBMUD (60 percent of total releases) kaf	Number of years out of 62 water surplus	Average annual watershed surplus kaf
300	27	1,080	648.0	36	224.8
270	17	634	380.4	37	244.8
240	11	424	254.4	38	266.7
210	7	208	124.8	39	288.2

TABLE 4.6

Unit Cost of Water Supplied for Conjunctive Use Options Based on 39 Percent Acceptable Supply Reduction Policy With Enhanced In-Stream Flows, Calculated for 30-Year Planning Horizon
(dollars per af)

	Option 1		Option 2	
	Pumping energy costs		All well costs	
	Discount rate			
Demand level (mgd)	3%	4%	3%	4%
300	6.19	6.19	11.12	11.58
270	7.17	7.17	18.85	19.75
240	7.38	7.38	26.76	28.16
210	5.93	5.93	40.00	42.28



Base Demand = 270 mgd
Maximum Reduction = 39%
New Terminal Storage = 0KAF
October Carryover = 1.2*Annual Demand
Water Purchase at Camanche < 100KAF

Figure 4.1. EBMUD Demand, Storage, Transfers.

TABLE 5.1

Summary of Characteristics and Consumer Surplus Losses

Authors	Price specif.	Estimate tech.	Data aggreg.	S-R/L-R	Consumer surplus loss
Agthe *et al.*	Taylor-Nordin	Simult. eqn.	district	long-run	$17,388,000
	T-N	Sim. eqn.	district	short-run	$29,778,000
Billings Day	Ave. price	OLS	district	mixed*	$22,344,000
	Taylor-Nordin	OLS	district	mixed*	$30,072,000
Billings Agthe	Taylor-Nordin	OLS	household	short-run*	$18,144,000
Billings	T-N	OLS	household	short-run*	$14,112,000
Moncur	Mar. price	Fuller-Battese	household	long-run	$45,318,000
	Mar. price	F-B	household	short-run	$58,968,000
Nieswiadomy Molina	Taylor-Nordin	2SLS	household	short-run*	$18,186,000
Schefter David	Taylor-Nordin	OLS	district (corrected by distrib.)	long-run*	$67,578,000
Weber	Marginal price	Pooled TS-CS; OLS	district	long-run	$77,616,000

*Not stated by the author but determined by the nature (time series or cross section) of the data.

TABLE 5.2

Consumer Surplus Welfare Loss

Authors	Rectangle plus triangle Loss per af	Triangle Loss per af
Agthe *et al.*		
L-R	$282.23	$40.22
S-R	$483.34	$68.85
Billings Day		
A-P	$362.67	$51.81
M-P	$488.11	$69.54
Billings Agthe	$294.50	$42.27
Billings	$229.06	$32.72
Moncur		
L-R	$735.57	$104.98
S-R	$957.13	$137.03
Nieswiadomy Molina	$295.18	$42.27
Schefter David	$1,096.89	$156.80
Weber	$1,259.82	$179.97

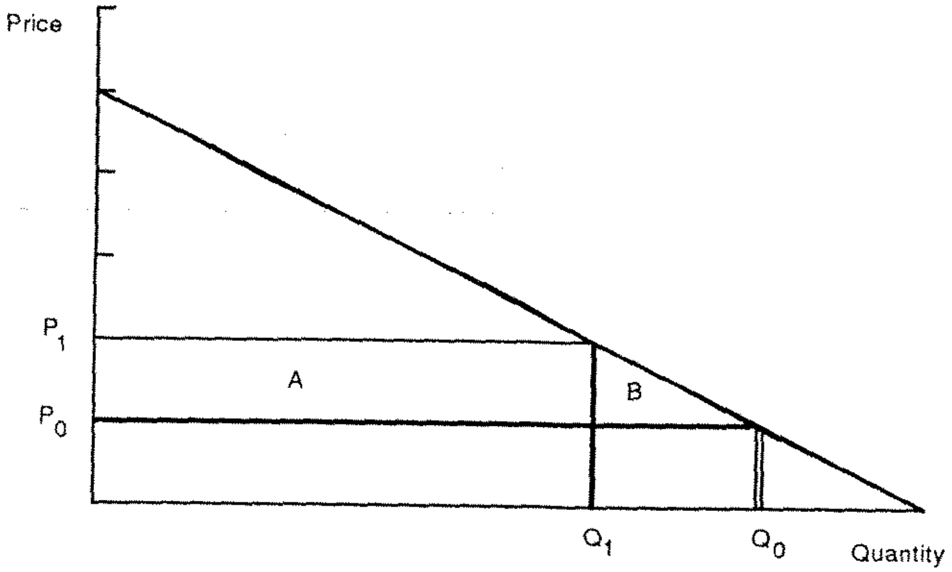


Figure 5.1. Consumer Surplus Losses.

TABLE A.1

Current and Expected Present Value (After a Severe Earthquake) Costs for Aqueduct Construction ($ million)

	Current aqueduct construction costs	Expected present value cost for construction of aqueducts after a severe earthquake	
		Discount rate	
		3%	4%
Retrobuild No. 3	51.0	18.72	14.77
Build No. 4			
Dredged	90.0	33.04	26.06
Tunneled	102.0	37.44	29.54

TABLE A.2

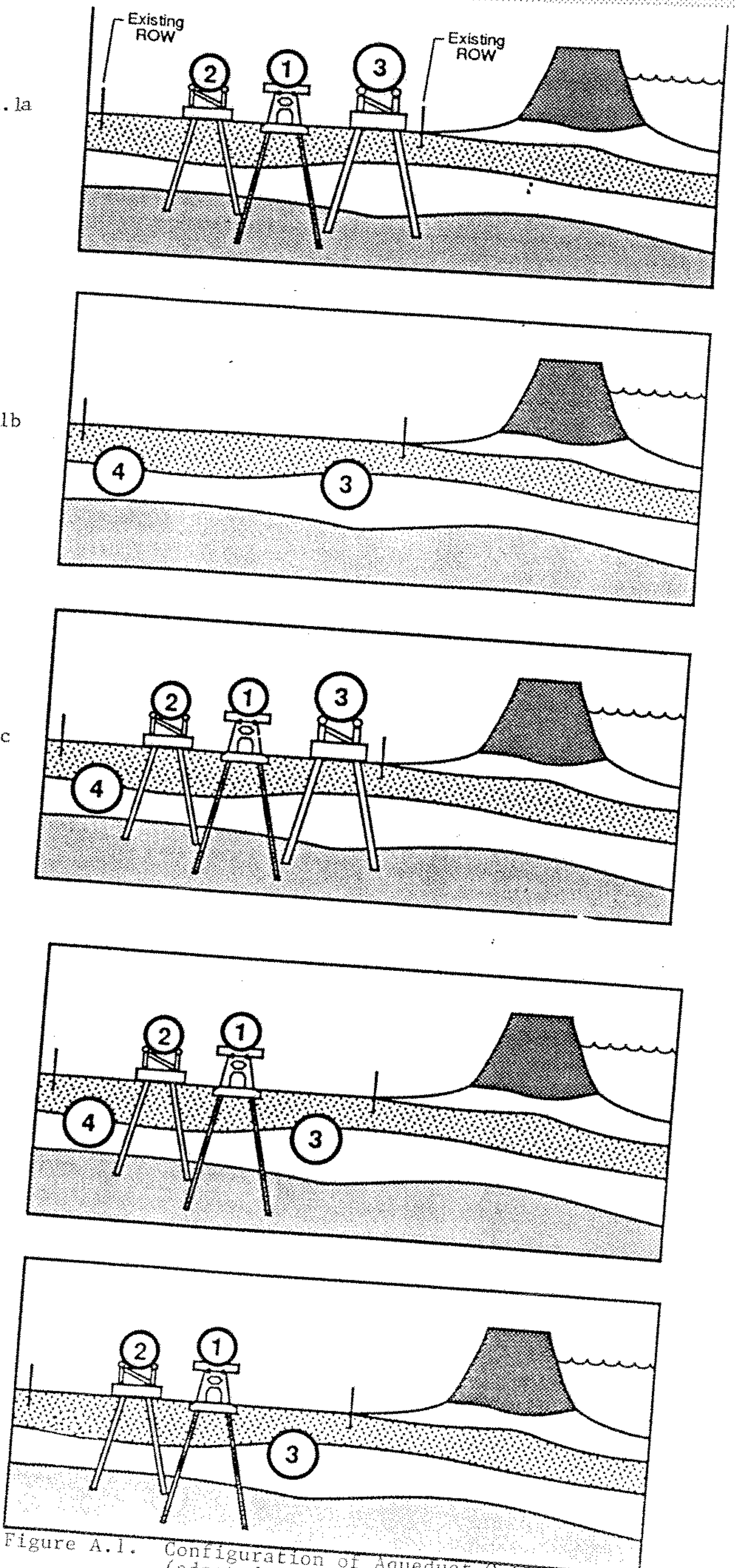
Capital and Operation and Maintenance Costs for Buckhorn Reservoir of Specified Capacity ($ million)

Capacity (kaf)	Total cost Discount rate 3%	 4%
145	202.0	197.0
55	102.6	100.0

TABLE A.3

Total Cost for Each Package of Drought and Earthquake Security Measures
($ million)

	River crossing type			
	Dredged		Tunneled	
	Discount rate			
	3%	4%	3%	4%
Option 1	253.76	237.83	258.16	241.31
Option 2	211.32	204.77	223.32	216.77
Option 3	243.60	241.00	255.60	253.00



A.1a

A.1b

A.1c

A.1d

A.1e

Figure A.1. Configuration of Aqueduct Options (adapted from EBMUD)