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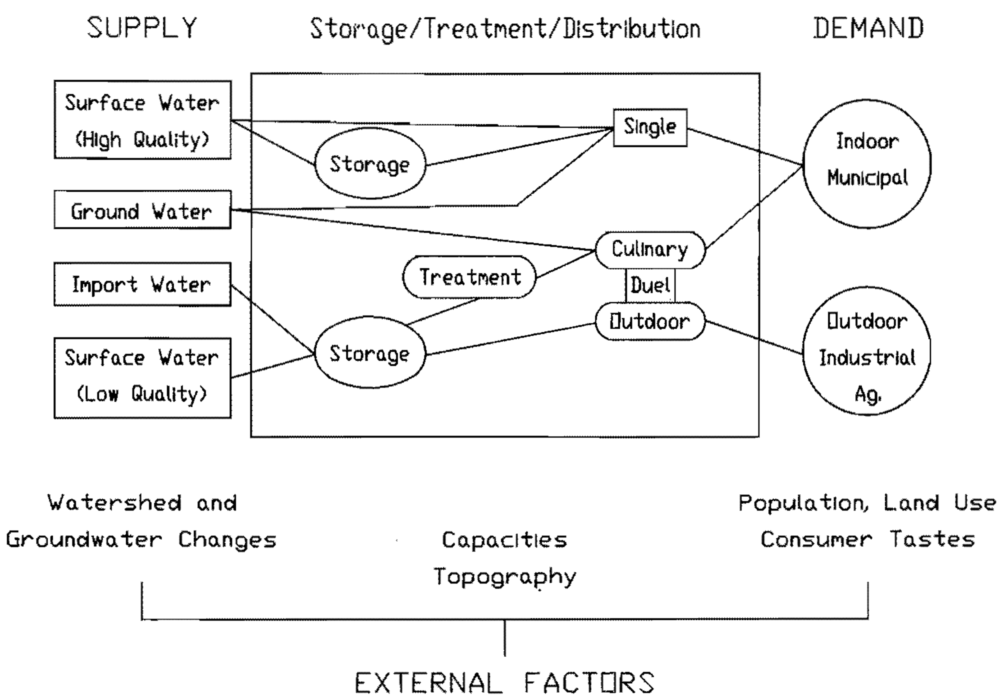

Utah Water Research Laboratory
Utah State University
Logan, Utah 84322-8200

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WATER RESOURCES PLANNING SERIES
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ECONOMIC EVALUATION OF CONSERVATION CONCEPTS FOR MUNICIPAL WATER SUPPLY SYSTEMS

by

Trevor C. Hughes, Rangesan Narayanan, Mac McKee,

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ABSTRACT

Five concepts for conservation of municipal water supply are analyzed from an economic efficiency perspective. They include: 1) seasonal pricing (for reduction of peak period water use), 2) dual water systems (separate high quality drinking water and untreated outdoor irrigation systems), 3) imported water transmission facility capacity optimization, 4) flow restricting devices, and 5) short-term rationing concepts.

Optimization models, including generalized model generators, were developed for analysis of the first three concepts and demonstrated by applications to cities in Utah. The flow restricting device and short-term rationing concept analyses applied approaches taken from the literature to example sites in Utah. The final chapter is a comparison of results and summary of conditions which favor each approach to conservation.

Conclusions include: Seasonal pricing was demonstrated to reduce peak period water use but is not justified in Salt Lake City because the added cost of metering exceeds the additional benefits. Dual water systems are potentially an important concept for matching various qualities of water with appropriate uses and producing net economic benefits. Determination of capacity of an imported water facility is dominated more by the decision maker's attitude toward risk than by pricing policy. Flow restricting devices produce economic benefits only if the change in quality of service is ignored. Price elasticity is much lower during a drought than during normal conditions.

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Chapter I	-	Bruce Bishop and Mac McKee
Chapter II	-	Rangesan Narayanan
Chapter III	-	Robert LeConte and Trevor Hughes
Chapter IV	-	Mac McKee
Chapter V	-	Trevor Hughes
Chapter VI	-	Rangesan Narayanan and Trevor Hughes
Chapter VII	-	Trevor Hughes
Appendix A	-	Sumani Al-Hassan

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CHAPTER I

INTRODUCTION

Water Conservation and Water Management

The Motivation to Conserve

A variety of reasons have been offered for explaining why water should be conserved. The reasons range from the traditional utilitarian viewpoints--e.g., water should be conserved so that the economic yield per unit of water use can be increased--to the preservationists attitude--e.g., water should be conserved in order to maintain in-stream flows for protection of ecological resources.

The desire to "conserve" is often motivated by drought situations (i.e., rare hydrologic events of low water availability coupled with water prices set too low), or by perceived shortages by any of a number of water use interests of society. In many cases, however, water shortages are symptomatic of larger, more complex problems affecting water use. Pricing policies, enlistment policies, major property rights, and institutional and legal structure are likely to contribute to the efficient allocation and use of water. For example, decisions about the quantity of water to be made available for various uses cannot be made without also considering water use impacts on water quality and on other resource uses, such as energy development.

Water Conservation and Its Meaning

Water use in the west has historically emphasized "development" of water resources for economically productive purposes. This is changing as opportunities for large-scale water projects become more expensive and environmental opposition to them mounts. The emphasis for water resources development is now shifting toward the avoidance of waste (Weatherford et al. 1982). This implies "conservation," which is a politically attractive word when applied to water use. However, as Weatherford et al. (1982) have pointed out, there are several diverse and conflicting definitions of the term, each of which enjoys considerable intellectual and political support.

The "Zero-Price" Concept

The more traditional definition of water conservation, especially in the western states, links conservation with development and use. Under the zero-price concept, water that is not used (especially for traditional utilitarian purposes) is wasted. Public policy should be directed toward development of the means to apply water to the land and other productive activities so that benefits of its use can be brought to society. The primary emphasis is on full development and use, not on efficiency in the economic sense. This gives rise to what Weatherford et al. (1982) call the "water is different" syndrome, i.e., the belief that, since water is basic to life it should be treated differently--in particular, it should not be priced since it is the key to economic growth. Reasons for this "water is different" philosophy include:

a. Water is a mobile resource and thus used in transit rather than by possession. The expenditure is not for water as a commodity but for a capacity (storage or transmission) that causes water of desired quality to flow along a desired path in a desired time frame. The cost of doing so is highly variable, spatially and temporally, and causes the marginal delivery cost to fluctuate over wide ranges. Charging institutions and monitoring hardware do not have sufficient flexibility to achieve marginal cost pricing and must respond in an averaging sort of way. One example is your finding that seasonal pricing really does not pay.

b. Water is assigned to users by law rather than possessed by the developer that can acquire it at least cost. Trades are reviewed for legality. This adds a great deal of bureaucracy to buying and selling. The bureaucracy is geared to average conditions whereas the needs for conservation is greatest during droughts.

c. Once marginal cost pricing is abandoned for reasons in "a," people have been able to use political pressure to obtain water use at little cost and have since grown over time to expect it as a free good. Conservation contradicts this expectancy.

The "Infinite-Price" Concept

Some adopt the attitude that "conservation" is the preservation and protection of a resource from its more typical utilitarian uses. This attitude holds that natural resources, including water, should be conserved for aesthetic, ecological, and environmental purposes. Effectively, by preserving water in its natural state to the exclusion of other uses, an infinite price is placed on the development and use of water.

The "Hydrologic Efficiency" Concept

The concept of "hydrologic efficiency" seeks to eliminate all avoidable losses resulting from processes or practices that cause water to be used in nonproductive ways (e.g., evaporation and transpiration into the atmosphere, drainage into the ocean, pollution, loss to geologic formations from which it cannot be recovered, etc.). Efficient, and therefore "conservative" use of water means extracting the maximum productivity from each drop.

The "Economic Efficiency" Concept

The "economic efficiency" concept holds that water should be developed and used following policies guided by the tenants of welfare economic principles. Water is neither a free good nor a mystically priceless commodity. Water is a resource that, like any other, should be developed or preserved depending upon the resulting benefits and costs to society. Greater technical ("hydrologic") efficiency should be sought only when it is economically efficient for society or for the individual users to do so. Following rules of economic efficiency, conservation may be accomplished by pricing water at its marginal value in the market, wherein it is made possible for water to be transferred to its highest-valued uses, including preservation as a use. The fundamental axiom of this viewpoint is that water users are not likely to conserve unless the price of water reflects its scarcity value--water is wasted because it is not appropriately priced.

Economic Efficiency and Water Management

The definition of water conservation used in the research reported here is that of the economic efficiency concept. Water should be used (or preserved) for whatever purposes that maximize the net benefits to society, where all benefit and cost streams are appropriately discounted. In those cases where the allocation of water has not been in a fashion which was most beneficial to society (whether for purposes of development or preservation), this has happened not because of our pursuance of economic efficiency but because of a lack of it.

Many problems exist in our ability to determine the best means to allocate and manage water: our techniques of benefit and cost estimation are imperfect; we lack efficiently functioning water markets, and the common property nature of the resource produces inefficiencies in allocation and use. However, the principle of economic efficiency is sound and, in theory, can be used to direct the search for the most socially beneficial manner in which to use water resources. As a consequence, the analyses of water conservation approaches reported in this document are all based on the fundamentals of economic efficiency.

Framework and Approach for Analysis of Water Conservation

Implementing water resource conservation measures based on economic efficiency involves the application of strategies aimed at managing the physical system and also modifying the social and economic conditions supplying and using water. The physical system consists of supply sources and facilities for transmission, treatment, and distribution of water to points of use. In managing this system, conservation is only one of several concerns. Other important considerations include system capacity to meet average and peak demands, reliability, water quality consistent with user requirements and to protect public health, cost of operation and maintenance, and so on. The future development and configuration of the physical system is influenced by various external factors such as type and availability of new sources, population growth and densities, land use patterns and, most importantly, consumer or user variables affecting demand. Some of these factors may be controllable in developing an efficient water system. Management intervention for water conservation then may be thought of as those options for modifying both the physical system and external factors including water user demand. Figure 1-1 illustrates these general relationships in the water supply and use system.

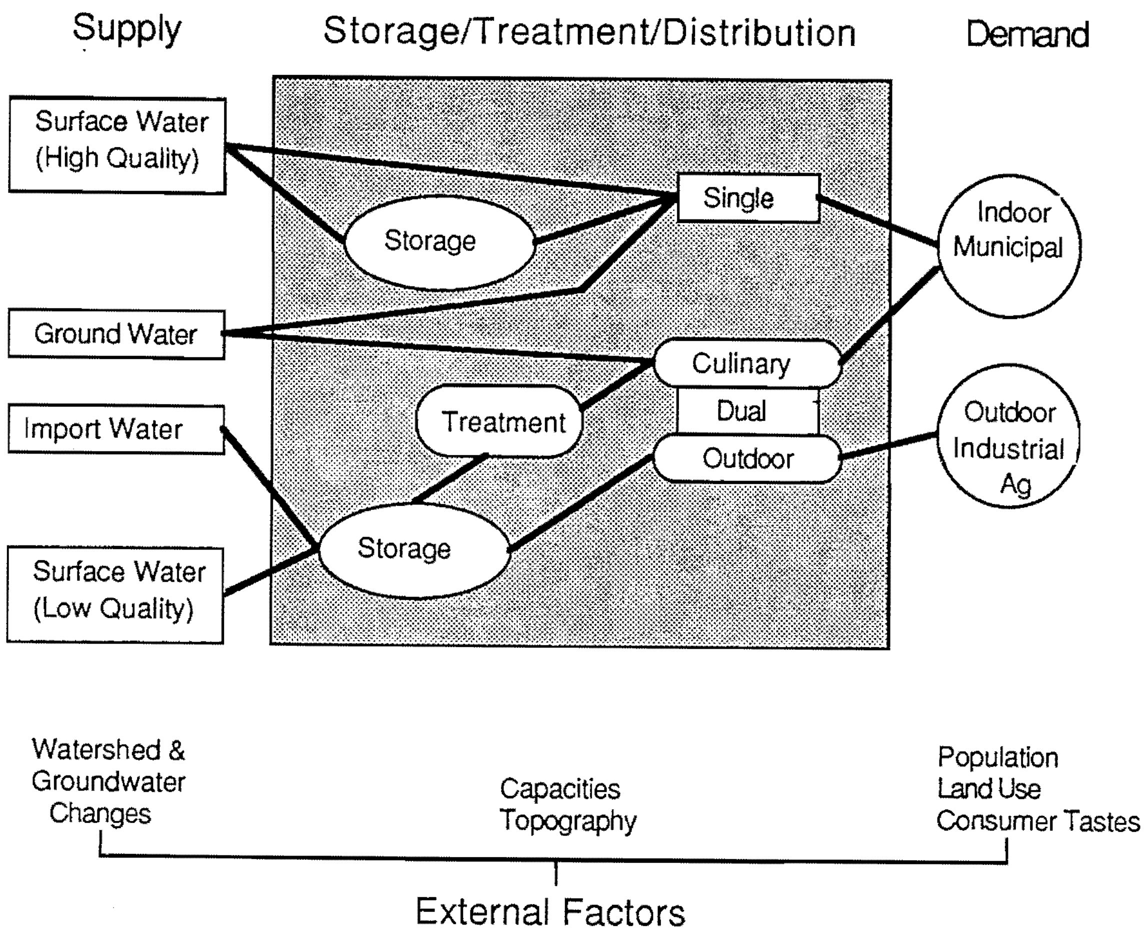


Figure 1-1. Schematic of water supply and demand system.

Physical System

From the perspective of water conservation, water sources must be considered in terms of both quantity and quality as related to the cost of supply. The water supply for a municipal system will typically include a variety of surface and groundwater sources, and perhaps imported water as well. Efficient use of multiple sources necessitates the conjunctive use of available supplies, such that the cost of supplying various quantities of water at differing quality levels can be minimized.

Delivering water supplies to meet user demand involves a system of transmission, storage, treatment, and distribution facilities. Depending on the quality of sources, treatment may be required to meet the water quality standard set for municipal or culinary uses. Generally, a goal of matching the quality of water sources with quality requirements of users would help promote conservation, but the economic efficiency of providing systems to accomplish this must be evaluated. If a single distribution system for municipal supply is used, then all water--whether used for culinary purposes or for outdoor watering or industrial use--must be treated to culinary water standards. The use of dual systems, that is separate systems for high quality culinary water and for lower quality outdoor and industrial water uses, offers an option for conserving high quality water sources and avoiding high treatment costs for low quality sources that could satisfy industrial and outdoor uses with low quality requirements.

The physical characteristics of water supply sources, storage, treatment, and distribution facilities impose constraints on the system in terms of availability, capacity, and flow. The sizing of storage and equalizing reservoir capacity, and the capacities of treatment plants and distribution lines affect both quantity and cost of the supply. Design and construction of future physical facilities to meet water conservation and economic efficiency objectives would, therefore, include consideration of the following kinds of issues:

1. Combinations of sources and transmission capabilities to be developed or expanded, including analysis of conjunctive use and management of surface and groundwater sources and the use of imported sources.

2. Treatment levels and capacity expansion of treatment plants in relation to sources and supply, distribution, and user quality standards.

3. Dual water distribution systems to separate supplies according to use with appropriate quality levels, treatment, and distribution system capacities to meet indoor and outdoor uses.

4. Physical conservation devices at the user level, such as water saving devices in showers, toilets, and other plumbing fixtures, that reduce the consumption of water.

External Factors Impacting Water Use Efficiency

External factors are a key consideration in the implementation of water conservation practices. Population growth and densities and land use, particularly conversion of agricultural land to urban and industrial uses, will affect decisions on water supply source reallocation or development, and the capacity expansion of various physical facilities. On the user side, price, income, lot size, and other variables that are determinants of consumer demand may change or be subject to manipulation over time. Models (for analysis of configurations of sources, treatment facilities, distribution systems, and capacity expansion) need to be able to evaluate the consequences of variations in these external conditions and the potential effects of policies directed at conservation and economic efficiency of water use in the following areas:

1. Physical system (sources, transmission, treatment facilities, distribution, capacity expansion)

   a. Population and industrial growth rates
   b. Land use (e.g., agricultural to urban land conversion)

2. Consumer demand functions

   a. Municipal
   b. Industrial
   c. Agricultural

Water Conservation Intervention

Overlaying the physical system of water distribution and use are management options for water conservation. The options and points of intervention in the physical system are identified in Figure 1-2. Management decisions may be taken on either the supply side, including treatment and distribution facilities needed to bring water to points of use, or the demand side. Both involve the nature and technology of use.

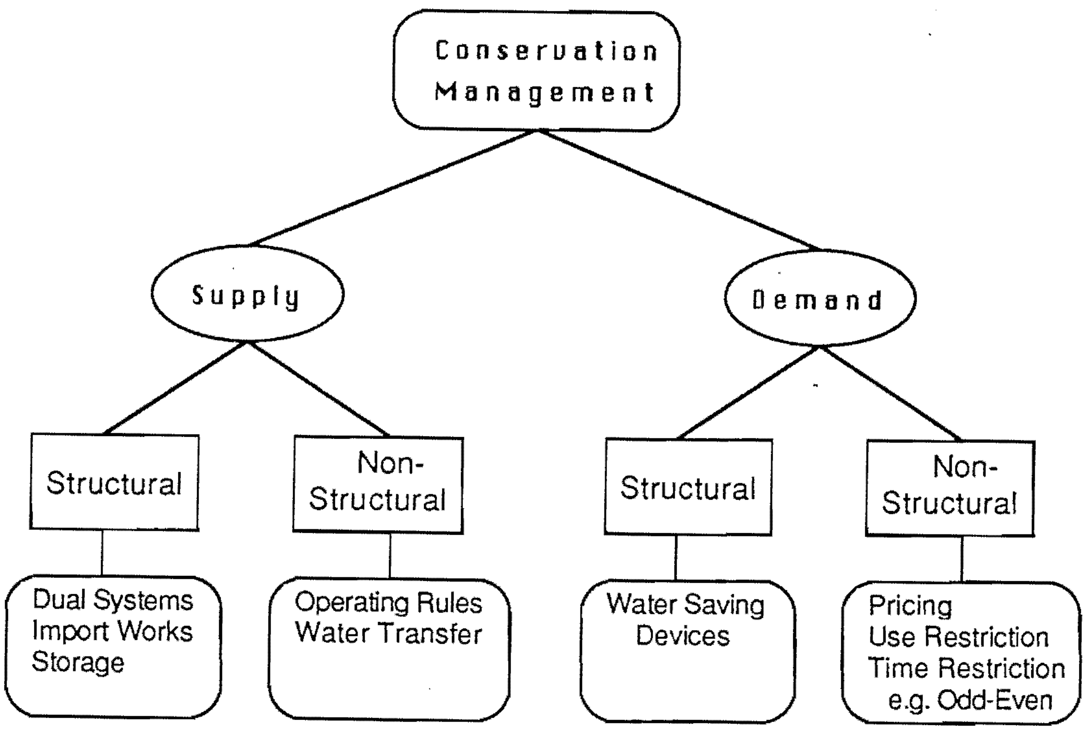


Figure 1-2. Overview of conservation management options.

1. Supply management

   a. Structural options such as dual systems and import facilities
   b. Nonstructural such as operating rules and water market transfers

2. Demand management

   a. Structural options such as user water saving devices

b. Nonstructural such as pricing, mandatory use restrictions, and time of use restrictions

The various structural and nonstructural management options to alter supply and demand conditions could be implemented singly or in combination with others. The question of which management alternatives should be selected should be evaluated in terms of the economic efficiency of the measures. The following chapters develop and discuss the economic efficiency models for evaluating conservation strategies using:

- pricing strategies
- dual supply/distribution systems
- conjunctive use of water or import of water
- conservation devices at demand points
- short-term alternatives

The optimization models presented in this study serve as analytical tools for evaluating various management options.

Format of Report

Chapters II through VI discuss each of these five concepts as an essentially stand-alone topic. Readers interested in particular topics may go directly to the chapter of interest. Chapter VII was written with two objectives in mind: 1) summarize very briefly the research approach and the results of each conservation concept; and, 2) synthesize these separate concepts where possible by comparing results and identifying common ground such as conditions which favor, as well as detract from, successful use of each conservation approach.

CHAPTER II

AN EVALUATION OF THE ECONOMIC FEASIBILITY OF SEASONAL WATER PRICING

Introduction

Substantial changes in municipal water demands are observed between various seasons of the year. Hughes (1980) found that the peak monthly demand is about two and a half times the average monthly demand. The availability of water also fluctuates during various months of the year. Seasonal price variations can be used to reduce the storage required to accommodate seasonal variations in demand with cyclical fluctuations in water supply. The problem of finding the necessary price changes and the determination of longrun system capacity is known as the peakload pricing problem.

Interest in this topic originally came about as some French economists in the early forties were seeking solutions to electricity pricing. Now a general solution to this problem and various modifications and extensions have been provided in studies by Steiner (1957), Hirshleifer (1958), Williamson (1966), Pressman (1970), and Penzar (1976).

Most of the studies in peakload pricing have been generally with respect to pricing of electricity. In the area of water resources, Hanke and Davis (1971, 1973) and Hanke (1982) provided the conceptual framework for municipal water pricing and capacity determination under seasonal pricing as well as annual uniform pricing. Riley and Scherer (1979) provide a theoretical discussion of an approach to pricing and capacity determination under cyclical demand and supply with storage. The purpose of this chapter is to extend the analyses of these authors and illustrate a methodology for practical application. First, a rigorous comparison of annual uniform pricing and seasonal pricing with a two-period model will be presented. Second, comparative static analysis based on linear approximation of water demands will be provided. Third, an application using a case study area will be demonstrated using nonlinear and nonlinear integer programming techniques.

Seasonal Pricing

Consider a municipal system faced with two demand curves for water, D_1 in the winter season and D_2 in the summer season. Let S_1 and S_2 be the marginal cost of supplying water in the winter and summer respectively (for simplicity they are assumed to be constant). It will be assumed that between seasons the cross elasticity of demand for water is zero. Economic efficiency would dictate that the price in the winter P_1 be set where D_1 and S_1 intersect. The optimal prices and quantities (Q_1 for winter and Q_2 for summer) are shown in Figure 2-1.

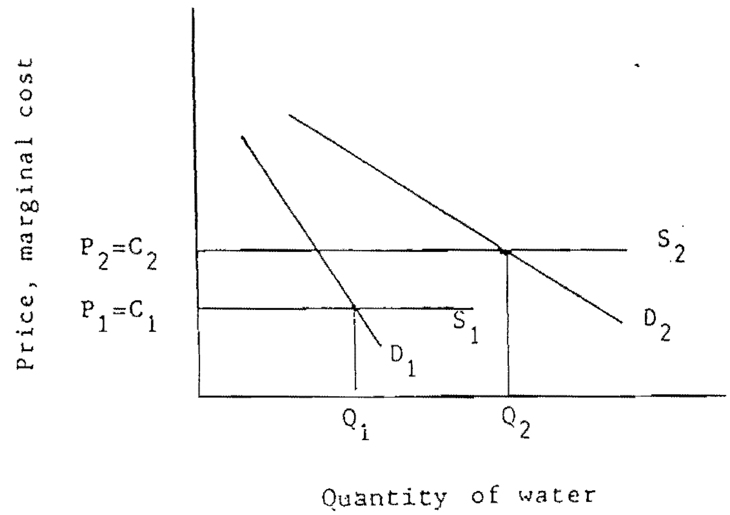


Figure 2-1. Seasonal pricing.

The reasons for the shortrun supplies S_1 and S_2 to be different in the two seasons require further explanation. Unlike other produced goods, the availability of water in the streams is important. For example, water may be supplied from Stream A in the winter at the lower cost C_1 to meet the entire demand. In the summer, Stream A might dry up, and it may be necessary to supply water from Stream B to meet the summer demand at a higher cost C_2. Also, the existing water right structure might allow different quantities to be diverted at different periods of the year. For example, the municipality may have 100 percent rights to flows in Stream A during winter and 100 percent of the rights to flows in Stream B in the summer and no rights from these streams during other periods. This will lead to the supply curves S_1 and S_2. Another example would be limited high quality water at P_1 which must be supplemented by more expensively treated poor quality water during season 2.

If the demands in both seasons can be met at the same constant cost, then prices in the two seasons will be set equal to this cost. Uniform prices will prevail throughout the year. Also, if storage is available in the system, then the price difference between the two seasons could be reduced further. One can easily extend the pricing analysis under limited storage with an associated marginal storage cost or determine the longrun optimal storage capacity also with an associated incremental capacity cost of storage. In the analysis of seasonal pricing with or without storage, it is implicitly assumed that water meters are read for all consumers prior to price changes. The extra cost associated with meter reading, billing and other administrative costs associated with seasonal pricing must be taken into account as pointed out by Hanke (1982). For a quarterly metering schedule in Salt Lake City, Utah, the costs of metering, billing, and administration are about 7 percent of the total annual cost.

Annual Uniform Prices

Most of the municipalities do not change prices over seasons. This is perhaps due to the additional costs that are incurred in metering and billing. If the prices are to be held constant between seasons, a unique optimal price exists that maximizes the conventional welfare criterion. This optimal uniform annual price could be derived by maximizing the sum of the consumers' and producers' surplus in the two time periods. Let P_1 (Q_1) and P_2 (Q_2) be the demands in winter and summer and C_1 and C_2 be the cost functions. Forming the Lagrangian,

$$L = \int_0^{Q_1} P_1(X_1)dX_1 + \int_0^{Q_2} P_2(X_2)dX_2 - C_1(Q_1) - C_2(Q_2) - \lambda(P_1 - P_2)$$

the saddle point $(Q_1^*, Q_2^*, \lambda^*)$ must satisfy

$$\lambda^* = \frac{P - C_1'(Q_1^*)}{P_1'} = - \frac{P - C_2'(Q_2^*)}{P_2'}$$

and $P_1 = P_2 = P$ where P_1', P_2', C_1', and C_2' are first derivatives with respect to their arguments. If Q_1 increases by 1 unit, the consumers' surplus changes by $P-C_1'$. However, the price changes by P_1'. Therefore, the change in consumers' surplus per unit change in price is $(P-C_1')/P_1'$ for the winter season. This should be equal to $-(P-C_2')/P_2'$ for the summer season. If these are not equal, the price could be changed so that consumers' surplus could be increased. It follows from the first order condition that the optimal price will be between the marginal costs C_1' and C_2' for the two seasons. Figure 2-2 shows these concepts graphically.

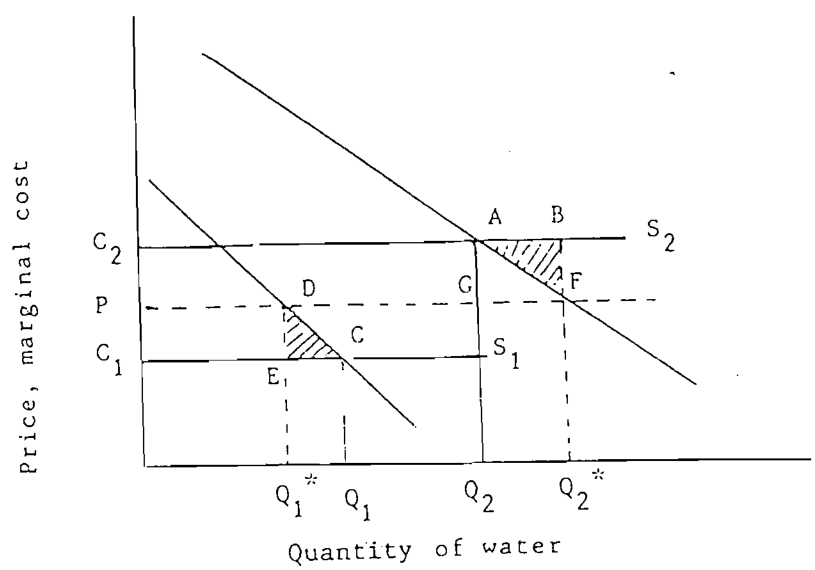


Figure 2-2. Uniform pricing.

Under the assumption of linear demand functions, the following propositions with respect to uniform price P could be easily demonstrated. First, a change in the intercepts of the price axis of the demands have no effect on the price P. However, an increase in any one of the intercepts will increase the optimal quantity corresponding to that period. Second, an increase in the marginal cost in any period will increase the optimal price P. Third, an increase in the absolute value of the slope of a demand curve corresponding to a season will decrease or increase the optimal price depending upon whether the marginal cost for that season is less than or greater than the marginal cost for the other season.

The sum of the shaded areas in Figure 2-2 (equal to half of the square of the differences in marginal costs divided by the sum of the absolute value of the slopes of the demands) represents the welfare loss associated with annual uniform pricing. If this welfare cost is less than the additional metering, billing, and other administrative costs, uniform pricing should be preferred in the shortrun. Otherwise seasonal pricing should be implemented.

System Capacity Determination

System capacity refers to the water treatment plants, transmission and distribution systems and associated pipe sizes and pump capacities that would determine the maximum amount of water that could be supplied in a given season. Under seasonal pricing, it is generally established that in an off-peak period, the price should be set to marginal costs, while in the peak period, the price should, in addition to the marginal cost, include the additional capacity cost. Modification of this condition is necessary for systems with storage (at a given level) and for those systems where storage level is considered a variable (Riley and Scherer 1979). In the case of uniform pricing, the necessary conditions derived in the previous section must be modified so that the relevant marginal cost during peak season must include the marginal capacity cost. That is, if the second season is the peak season, the necessary conditions is given by

$$\lambda^* = \frac{P - C_1'}{P_1'} = - \frac{P - C_2' - k}{P_2'}$$

where k is the marginal capacity cost. From the comparison of seasonal and uniform pricing schemes, it is evident that the required capacity is greater for uniform pricing. Long-term losses resulting from excess capacity under uniform pricing (assuming metering costs are negligible) could be calculated if information on demand growth is available.

Metering Costs

The cost of metering and billing customers is the key to preforming a correct cost-benefit analysis. If these costs are prohibitively 'high' the uniform pricing is preferred. On the other hand, if the costs are 'negligible,' then seasonal pricing is efficient. Neither of these two extremes is a realistic assumption. Given the additional cost of metering, one can balance the incremental welfare gain by price changes in a season to the increased metering costs in that period. If this can be done, then one can choose in a multi-season case, in which of the periods it is worthwhile to change prices and hence incur metering costs and in which of the periods it is better to keep uniform prices. In essence, an optimal metering schedule along with seasonal pricing over an annual cycle could then be obtained as part of the solution. In addition, the solution endogenously identifies the seasons and the corresponding prices. In order to examine the feasibility of seasonal pricing and identify the optimal prices, an optimization model is developed for a multi-source model with reservoirs.

The cost of metering discussed here is not the capital cost of installing meters, but rather the variable cost of labor for reading meters and processing bills more times per year.

A Multi-Source Pricing Model

A nonlinear programming model is developed to determine the optimal allocation of water sources, reservoir operation with respect to storage and releases and water prices for three different schemes. These are (a) seasonal pricing (ignoring metering costs), (b) optimum annual uniform pricing (assuming high metering costs), and (c) optimal seasonal pricing over an annual cycle with additional metering cost taken explicitly into account. These three analyses were carried out with water demand for the base year (1975) and with projected water demands for two future years (1990 and 2010).

(a) Seasonal Pricing Model

Let $P_t(Q_t)$ be the inverse demand function for season t. The gross benefits is given by the area under the demand curve for all seasons.

$$GB = \sum_t \int_0^{Q_t} P_t(\hat{Q}_t)\, d\hat{Q}_t \tag{2-1}$$

Assuming constant marginal cost of supply for each of the water source j equal to C_j, the total water supply cost is given by

$$C = \sum_j C_j\, T_j \tag{2-2}$$

where T_j is the total water supplied from the jth source over a year. The net benefit is then given by

$$NB = \sum_t \int_0^{Q_t} P_t(\hat{Q}_t)\, d\hat{Q}_t - \sum_j C_j\, T_j \tag{2-3}$$

Let Z_{jt} be the quantity of water supplied from the jth source during season t. For any given time t, it must be true that the sum of water from all sources must be greater than the quantity demanded Q_t. That is,

$$\sum_j Z_{jt} - Q_t \geq 0 \qquad \text{for all } t \qquad (2\text{-}4)$$

Similarly, the sum of Z_{jt} for a source j over all seasons must be equal to the total annual water supplied T_j. Therefore,

$$\sum_t Z_{jt} - T_j = 0 \qquad \text{for all } j \qquad (2\text{-}5)$$

Let R designate the set of surface sources for which storage is available. Let S_{jt} and R_{jt} denote the level of storage and the quantity of water released at time t for source j that belongs to the set R. The mass-balance for the reservoirs can be written as

$$S_{jt} - S_{jt-1} + R_{jt} = I_{jt} \qquad j \in R, \text{ for all } t \qquad (2\text{-}6)$$

where I_{jt} is the reservoir inflow. The storage at anytime, however, must be restricted to be less than the reservoir capacity S_j. This is done through the following constraints,

$$S_{jt} \leq S_j^* \qquad j \in R, \text{ for all } t \qquad (2\text{-}7)$$

The water supplied to the municipal system Z_{jt} from the reservoir must be less than or equal to the release R_{jt}. That is

$$Z_{jt} - R_{jt} \leq 0 \qquad j \in R, \text{ for all } t \qquad (2\text{-}8)$$

For those streams that are directly used by the municipal system (with no storage facilities), the quantity supplied Z_{jt} must be less than inflows:

$$Z_{jt} \leq I_{jt} \qquad j \notin R, \text{ for all } t \qquad (2\text{-}9)$$

In addition, all variables are required to be nonnegative. Maximizing (2-3) subject to (2-4) through (2-9) is a nonlinear programming problem. If the objective function (2-3) is concave, a global optimum solution could be found through standard optimization techniques. The optimal decision variables Z_{jt}, T_j, S_{jt}, R_{jt}, and Q_t indicate water allocation by source over seasons and reservoir operating policies. When Q_t is substituted in the inverse demand function, seasonal prices P_t could be determined. By replacing the demand functions $P_t(Q_t)$ corresponding to base year by projected demands for future years, changes in seasonal pricing corresponding to future years could be obtained.

(b) Uniform Pricing Model

The only modification that is necessary to determine optimal uniform annual prices is to impose an additional set of constraints that states either $P_t(Q_t)/P_{t+1})(Q_{t+1}) = 1$ for all t or $P_t(Q_t)-P_{t+1}(Q_{t+1}) = 0$ for all t. However, this is a nonlinear constraint in general. If the inverse demand functions are taken as linear functions or constant elasticity demand functions, these constraints could be written as linear constraints of the form

$$K_{t+1}Q_t - K_t(Q_{t+1}) = b_t \qquad \text{for all } t \qquad (2\text{-}10)$$

where K_t and b_t depend upon the parameters of the demand functions. Maximizing (2-3) subject to (2-4) through (2-10), one can obtain optimum annual uniform price.

(c) Optimal Seasonal Pricing Model

To take into account the metering cost, let n define the number of times the system is metered and let M be the cost of metering. The objective function is then

$$NB = \sum_t \int_0^{Q_t} P_t(\hat{Q}_t)\, d\hat{Q}_t - \sum_j C_j T_j - Mn \qquad (2\text{-}11)$$

where Mn is the total metering and billing costs. The variable n must be an integer and should be less than or equal to the number of seasons. To see how n must be decided, first modify Equation (2-10) as follows:

$$K_{t+1}Q_t - K_tQ_{t+1} + D_t^+ - D_t^- = b_t \qquad \text{for all } t \qquad (2\text{-}12)$$

Add the following set of constraints:

$$R\, I_t - D_t^+ \geq 0 \qquad \text{for all } t \qquad (2\text{-}13)$$

$$R\, I_t - D_t^- \geq 0 \qquad \text{for all } t \qquad (2\text{-}14)$$

$$\sum_t I_t - n = 0 \qquad (2\text{-}15)$$

where R is a large positive number and I_t are integer variables 0 or 1. If D_t^+ and D_t^- are both zero or equal, Equation (2-12) is the same as (2-10) and uniform pricing holds. In this case, n will be zero and all I_t will be zero. If D^+ or D^- are both different from zero and are unequal, then I_t is forced to be different from zero and must take a value of 1. By Equation (2-15) n increases by 1 and the metering costs are subtracted from the objective (2-11). Therefore, I_t indicates whether or not water consumption in season t needs to be metered. The quantity $D_t^+ - D_t^-$ indicates the deviation of prices from season t to season t + 1, and n indicates the total number of times the system is metered annually. Solution of this problem involves maximizing (2-11) subject to (2-4) through (2-9) and (2-12) through (2-15) along with integer constraints on variables I_t. This is a nonlinear integer programming problem. So long as the net benefit is a concave function, in principle, the application of branch and bound techniques must yield a global optimum solution without having to exhaustively search the decision space. Although no computer program is currently available for this concave Integer Program, the branch and bound technique was manually implemented to solve this problem. The model developed in this section is used for demonstrating the feasibility of seasonal pricing for Salt Lake City, Utah.

Model Application for Salt Lake City

Salt Lake City, located in the northern part of Salt Lake County, had an estimated population of about 300,000 in the base year (Figure 2-3). The total number of municipal connections served by the Salt Lake City Water Department (SLCWD) was about 74,200. The city has primary rights to most of the high quality streams originating in the Wasatch Mountains in the east. The six major streams from which water is supplied are City, Emigration, Parleys, Mill, Big Cottonwood, and Little Cottonwood Creeks. The water right structure is quite complicated with respect to the time, quantity, and priority. Approximations in terms of percentages of average monthly flows seemed to capture water use from these streams fairly well. Parleys and Bit Cottonwood Creeks have reservoirs with estimated capacities of 1043 and 538 million gallons, respectively. Presently, the major import source is the Deer Creek Reservoir on the Provo River. In addition, groundwater from both pumped and artesian wells are used to supplement the surface sources. At this time, the city charges 25/100 cubic feet throughout the year over and above a monthly fixed fee depending on the size of the connection.

Average monthly water availability for each of the six streams and the artesian wells were obtained from a 30-year record. The import water from Deer Creek Reservoir is constrained by the capacity of the aqueduct and is brought to Salt Lake City along with water from Little Cottonwood. However, monthly pumping rates were allowed to vary within capacity limitations imposed by the pumps.

The unit costs of each source was estimated considering treatment costs and transmission and distribution costs. Estimated average monthly water availabilities and unit costs by source are given in Table 2-1. The demand information was derived from a monthly time-series model by Hansen and Narayanan (1981). These estimated monthly demand functions which are in log-linear form were evaluated at mean monthly temperature and rainfall quantities. Statistical test of the hypothesis that the price elasticities are the same for all months of the year could not be rejected. The water demand functions of the form $Q_t = A_t P_t^{-\eta}$ was used in this study where the price elasticity is $\eta = 0.469$, the price P_t is in \$/100 cub ft and the quantity Q_t is in gallons per connections per day. The coefficients A_t where t represents each of the 12 months of the year starting from January to December are 283 for November through March, 366 for April, 521 for May, 693 for June, 877 for July, 757 for August, 572 for September, and 383 for October. The demands were rescaled so that the quantities were in MG per month and the prices were in \$/MG. The cost of additional one-time metering and billing was estimated by Salt Lake City Water Department personnel to be \$60,000. Presently, Salt Lake City has a quarterly metering schedule

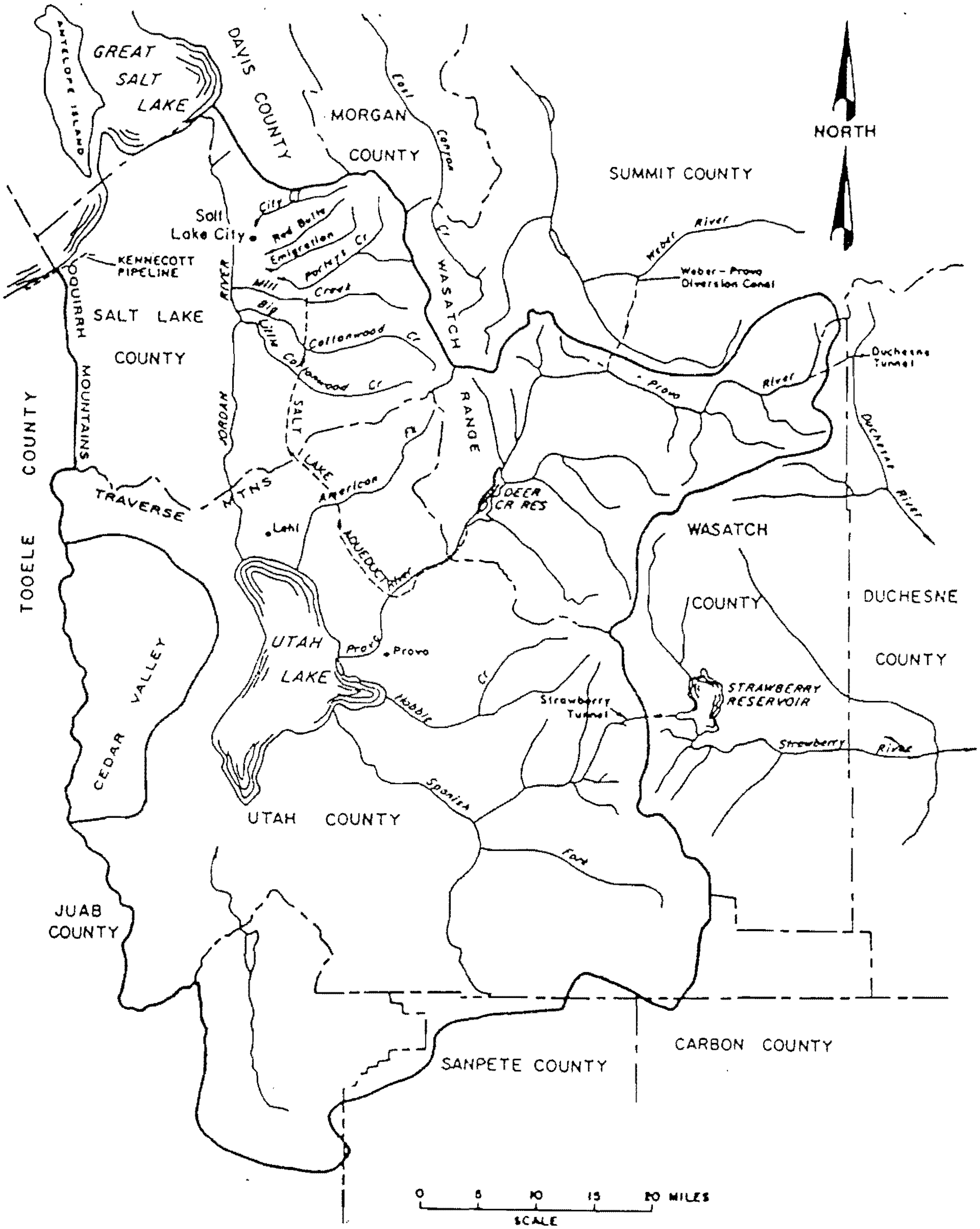


Figure 2-3. Case study area.

Table 2-1. Estimated water availabilities (MG) and costs by source ($/MG).

Sources	1 Jan	2 Feb	3 Mar	4 Apr	5 May	6 June	7 July	8 Aug	9 Sep	10 Oct	11 Nov	12 Dec	Unit Cost $/MG
City Creek	130	130	195	325	423	391	325	228	162	130	130	195	249
Emigration	0	32	65	195	195	97	32	32	32	32	0	0	188
Parleys	-	195	195	258	1075	1727	879	423	260	228	228	195	226
Mill Creek	65	65	130	325	293	162	130	97	97	97	65	65	188
Big Cottonwood	32	32	456	1108	3161	3193	1205	586	423	456	391	358	204
Little Cottonwood	130	130	162	423	1792	2998	1010	358	228	195	162	162	186
Deer Creek	464	413	369	257	670	941	1584	2089	1335	1054	535	474	303
Pump Wells	-	-	-	-	-	-	-	-	-	-	-	-	242
Artesian Wells	48	113	93	47	116	201	222	243	180	81	93	0	188

which is performed on a rotational basis. The three analyses outlined in the previous section (seasonal pricing, uniform pricing, and seasonal pricing with metering costs) were conducted for three time periods and the solutions were obtained using the nonlinear optimization program MINOS.

Model Results

The allocation of water from different sources by month, the reservoir operating policies and the appropriate prices for the case of seasonal pricing (with no metering costs) for years 1975, 1990, and 2010 are shown in Tables 2-2 through 2-4. Surface water availabilities start increasing in April and continue through June. Demands are relatively low in these months and hence prices are lower too. In the months of June through September, demands are high, peaking in July, and the price rises in these months. In October, demand starts going down while relatively abundant surface supplies are available and therefore the price drops. From November through March the demands are low and so are the surface supplies. Consequently more expensive ground and import water use is required and the prices are held relatively high. Prices vary over an annual cycle from \$204/MG to \$303/MG.

In the case of optimum annual uniform pricing, the detailed results are shown in Tables 2-5 through 2-7 for years 1975, 1990, and 2010. To keep the prices uniform, the quantity of water supplied in high demand months is greater than under seasonal pricing. In 1975, the recommended uniform price is \$253/MG. The prices increase to \$270/MG in 1990 and to \$271/MG in 2010. If metering costs were indeed negligible, uniform pricing results in a welfare loss of \$21,000 in 1975, \$56,000 in 1990, and \$61,000 in 2010. The welfare cost of annual uniform pricing is obtained by subtracting the value of the objective function for uniform pricing from that of the seasonal pricing solutions for a given year. The water supply costs for these two pricing schemes are shown in Table 2-8. From the results, it is clear that no conclusion can be drawn on total cost with respect to the two pricing schemes. In 1975, the cost of water is about \$200,000 less in the case of uniform pricing than under seasonal pricing. In 1990 and 2010, the total cost of water supply is lower for the case of seasonal pricing by \$50,000 and \$20,000, respectively.

To find the optimal seasonal pricing scheme, metering costs must be included in the objective. The estimated metering cost is \$60,000 for one time metering of all customers served by Salt Lake City. This is lower than the potential gains from seasonal pricing for year 1975 (which is only \$21,000) and for year 1990 (which is only \$56,000). In fact it is only slightly less than the potential gains from seasonal pricing for year 2010 (which is equal to \$61,000). Therefore, the solution to the optimal seasonal pricing scheme is the same as annual uniform pricing. This result is perhaps consistent with the availability of storage and the added flexibility due to significant groundwater sources in Salt Lake City. These factors decrease the price differential between seasons and hence decrease the potential welfare gains from seasonal pricing.

Table 2-2. Water allocation (MG) and seasonal prices ($/MG) for 1975.

Sources	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
	Months												
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	391	0	0	0	0	684	0	638	1619	613	638	4584
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	285	0	774	968	487	252	1205	586	961	0	309	358	6190
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	0	0	0	0	0	0	0	0	0	0	0	0	0
Pump Wells	761	419	0	0	0	0	788	2253	476	0	0	0	4700
Artesian Wells	48	114	93	47	117	202	223	243	180	81	94	0	1442
Storage:													
Parleys	195	0	0	1043	163	1043	782	1043	632	860	443	0	
Big Cottonwood	285	317	0	139	0	538	538	538	0	456	538	538	
Release:													
Parleys	0	391	358	32	2607	0	684	0	638	0	613	638	
Big Cottonwood	285	0	774	968	3300	2655	1205	586	961	0	309	358	
Total (MG)	1420	1282	1420	1960	2884	3712	4400	3798	2777	2025	1374	1420	
Prices ($/MG)	255	255	255	205	205	205	255	255	255	228	255	255	

Table 2-3. Water allocation (MG) and seasonal prices ($/MG) for 1990.

Sources	Months												Total
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	391	73	0	0	0	423	260	1271	1943	0	619	4982
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	0	0	521	1108	950	848	1205	586	961	0	847	358	7387
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	0	413	0	0	0	0	0	1174	0	0	0	474	1174
Pump Wells	1140	503	345	0	0	0	1338	1067	26	0	165	112	4700
Artesian Wells	48	114	93	47	117	202	223	243	180	81	94	0	1442
Storage:													
Parleys	195	0	0	1043	163	1043	1043	1043	0	228	423	0	
Big Cottonwood	32	65	0	0	0	538	538	538	0	456	0	0	
Release:													
Parleys	0	391	358	32	2607	0	423	260	271	0	0	619	
Big Cottonwood	0	0	521	1108	3161	2655	1205	586	961	0	847	358	
Total (MG)	1513	1366	1513	2173	3347	4308	4689	4048	2960	2349	1464	1513	
Prices ($/MG)	303	303	303	226	204	204	303	303	303	226	303	303	

Table 2-4. Water allocation (MG) and seasonal prices ($/MG) for 2010.

Sources	Months												
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	753	310	32	0	0	423	1303	228	2235	0	256	5543
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	325	325	456	1108	1365	1382	1205	586	961	0	658	547	8337
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	464	278	369	0	0	0	82	0	1336	0	536	474	3539
Pump Wells	831	0	229	0	0	0	1837	1700	100	0	0	0	4700
Artesian Wells	48	114	93	47	117	202	223	243	180	81	94	0	1442
Storage:													
Parleys	558	0	0	1043	163	1043	1043	0	0	228	423	362	
Big Cottonwood	0	0	0	0	0	538	538	538	0	456	189	0	
Release:													
Parleys	0	753	358	32	2607	0	423	1303	228	0	0	256	
Big Cottonwood	32	32	456	1108	3161	2655	1205	586	961	0	658	547	
Total (MG)	1701	1536	1701	2442	3762	4842	5271	4550	3327	2641	1646	1701	
Prices ($/MG)	303	303	303	226	204	204	303	303	303	226	303	303	

Table 2-5. Water allocation (MG) and uniform prices ($/MG) for 1975.

Sources	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
	Months												
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	391	0	0	0	0	684	0	638	1516	613	638	4481
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	285	0	774	785	217	0	1205	586	961	0	309	358	5484
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	0	0	0	0	0	0	0	0	0	0	0	0	0
Pump Wells	761	419	0	0	0	0	788	2253	476	0	0	0	4700
Artesian Wells	48	114	93	47	117	101	223	243	180	81	94	0	1347
Storage:													
Parleys	195	0	0	1043	163	1043	782	1043	632	860	443	0	
Big Cottonwood	285	317	0	322	0	538	538	538	0	456	538	538	
Release:													
Parleys	0	391	358	32	2607	0	684	0	638	0	613	638	
Big Cottonwood	285	0	774	785	3483	2655	1205	586	961	0	309	358	
Total (MG)	1420	1282	1420	1777	2614	3365	4400	3798	2777	1922	1374	1420	
Prices ($/MG)	253	253	253	253	253	253	253	253	253	253	253	253	

Table 2-6. Water allocation (MG) and uniform prices ($/MG) for 1990.

Sources	Months												Total
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	391	0	0	0	0	423	260	1271	1755	0	619	4721
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	0	0	521	1007	543	325	1205	586	961	0	857	358	6357
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	464	413	38	0	0	0	0	2089	143	0	0	0	2232
Pump Wells	1224	579	430	0	0	0	1598	377	46	0	246	196	4700
Artesian Wells	48	114	93	47	117	202	223	243	180	81	94	0	1442
Storage:													
Parleys	195	0	0	1043	163	1043	1043	1043	0	228	423	0	
Big Cottonwood	325	651	0	100	0	538	538	538	0	456	0	0	
Release:													
Parleys	0	391	358	32	2607	0	423	260	1271	0	0	619	
Big Cottonwood	0	0	521	1007	3262	2655	1205	586	961	0	847	358	
Total (MG)	1597	1442	1597	1999	2940	3785	4950	4272	3124	2161	1545	1597	
Prices ($/MG)	270	270	270	270	270	270	270	270	270	270	270	270	

Table 2-7. Water allocation (MG) and uniform prices ($/MG) for 2010.

Sources	Months												Total
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	576	109	32	0	0	423	1303	228	2018	0	433	5125
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	32	32	456	1108	900	784	1205	586	961	0	745	460	7274
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	464	413	369	0	0	0	1084	0	1336	0	536	474	4676
Pump Wells	921	123	319	0	0	0	1115	1942	276	0	0	0	4700
Artesian Wells	48	114	93	47	117	202	223	243	180	81	94	0	1442
Storage:													
Parleys	380	0	0	1043	163	1043	1043	0	0	228	423	185	
Big Cottonwood	0	0	0	0	0	538	538	538	0	456	101	0	
Release:													
Parleys	0	576	358	32	2607	0	423	1303	228	0	0	433	
Big Cottonwood	32	32	456	1108	3161	2655	1205	586	961	0	745	460	
Total (MG)	1791	1617	1791	2241	3297	4244	5550	4791	3503	2424	1733	1791	
Prices ($/MG)	271	271	271	271	271	271	271	271	271	271	271	271	

Table 2-8. Total water supply cost/year in million dollars.

Year	Pricing Scheme	
	Seasonal Pricing	Uniform Pricing
1975	5.962	5.776
1990	6.654	6.704
2010	6.704	7.724

If the cost of metering is reduced, then optimal seasonal pricing might be different from uniform pricing. To investigate this question, the metering cost was reduced to $20,000 and the solution was obtained using the nonlinear integer programming approach by manually implementing the branch and bound technique. The objective function value decreased by $53,000 compared to seasonal pricing case. The solution indicated that July through March, the price should be maintained at $295/MG and for April through June, price should be reduced to $209/MG. This will entail metering once at the end of June and again once at the end of March. Details of the solution are presented in Table 2-9. A welfare cost comparison of the three analyses is provided in Table 2-10. The first column corresponds to seasonal pricing. While the welfare costs are zero in this case, the metering costs should be added to compute the total resource cost to society. In the second column, welfare costs of optimum uniform pricing are shown. Meters are assumed to be read once a year so a one-time metering cost is added to compute the total resource cost. The third column shows the results for welfare cost and metering cost under optimal seasonal pricing for year 2010, where the model selects both the prices and the seasons. The total resource cost is the lowest in this case. The results indicate that in year 2010, the optimal seasonal pricing involves a welfare gain of $28,000 over uniform pricing and $67,000 over seasonal pricing schemes.

Conclusions

The application of an optimal seasonal pricing model to Salt Lake City suggests that at present metering costs an annual uniform price of $253/MG is optimal in 1975. It must increase as demand grows over time to $270/MG in 1990 (a 37 percent increase is assumed) and to $271/MG in year 2010 (a 76 percent demand growth is assumed). The current uniform prices are higher than the recommended rate. It appears that the monthly connection fee (fixed charge) is perhaps subsidizing the operating costs. Unless substantial reduction in metering costs are accomplished due to technological changes such as computerized metering information and processing of customer bills to less than about $0.15 per connection for one-time metering, uniform prices are optimal. However, current prices must be reduced (while increasing the connection fee) to the price levels recommended in this study. Development of additional storage and supplies from the Central Utah Project will lead to reinforcing the conclusions of this study.

Table 2-9. Water allocation (MG) and optimal seasonal prices ($/MG) for 2010.

	Months												
Sources	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
City Creek	130	130	195	0	0	0	326	228	163	0	130	195	1497
Emigration	0	33	65	195	195	97	33	33	33	33	0	0	717
Parleys	0	519	358	71	0	0	423	716	0	1923	904	401	5318
Mill Creek	65	65	130	326	293	163	130	97	97	97	65	65	1593
Big Cottonwood	0	0	521	1108	1324	1330	1205	586	961	0	309	896	8243
Little Cottonwood	130	130	163	424	1792	2998	1010	358	228	195	163	163	7754
Deer Creek	0	118	0	0	0	0	1585	2089	0	0	0	0	3792
Pump Wells	1348	445	558	0	0	0	397	252	1703	0	0	0	4700
Artesian Wells	48	114	93	47	117	202	223	243	180	81	94	0	1442
Storage:													
Parleys	323	0	0	1004	163	1043	1043	586	814	1043	334	128	
Big Cottonwood	32	65	0	0	0	538	538	538	0	456	538	0	
Release:													
Parleys	0	519	358	71	2568	0	423	716	0	0	904	401	
Big Cottonwood	0	0	521	1108	3161	2655	1205	586	961	0	309	896	
Total (MG)	1721	1554	1721	2529	3721	4790	5333	4603	3366	2329	1665	1721	
Prices ($/MG)	295	295	295	209	209	209	295	295	295	295	295	295	

Table 2-10. Welfare cost comparison ($/year).

Year	1 Seasonal Pricing			2 Uniform Pricing[b]			3 Optimal Seasonal Pricing		
	Welfare Loss	Metering Cost[a]	Total	Welfare Loss	Metering Cost[a]	Total	Welfare Loss	Metering Cost[a]	Total
1975	0	80,000	80,000	21,000	20,000	41,000	-	-	-
1990	0	120,000	120,000	56,000	20,000	76,000	-	-	-
2010	0	120,000	120,000	61,000	20,000	81,000	13,000	40,000	53,000

[a]Metering cost is assumed to be $20,000.

[b]Assumed to require one metering per year.

CHAPTER III

DUAL WATER SYSTEMS

Introduction

Cities in several western states (and particularly in Utah) have a history of serving outdoor residential water demands from a system of canals and ditches. Although an open ditch system as a supplement to a municipal treated water system is in some sense a dual system, the phrase dual system will be defined here as a pressure pipeline system delivering nonpotable water for irrigation of residential lots. Although this language is misleading (the word dual should more correctly encompass both the potable and nonpotable components), the misnomer will be continued here. The potable component of delivery systems will be referred to variously as the culinary or drinking or treated water system while the word dual will imply the untreated delivery system.

There is a small amount of literature on multiple water systems, however, almost none on the specific type of dual system which is common in the western U.S. For example, Deb (1978) has researched cost of multiple water systems where two or more qualities of water may be used inside a residence for flushing toilets versus washing versus drinking. The American Water Works Association is attempting to develop standards for dual water systems. Their draft manual (AWWA 1982) recommended such safeguards as treatment equal to drinking standards from a bacterial standpoint, backflow prevention devices and metered connections--none of which are followed in Utah. Many of the AWWA concerns are because the fact that the typical source for dual systems in many states is reclaimed sewage effluent rather than irrigation water direct from mountain watersheds as is normally the case in Utah.

The dual system concept has become somewhat controversial because of possible health hazards (such as cross-connections to the drinking water system). It is not our objective here to address these health aspects nor argue for or against dual systems, but rather to analyze the economic dimensions of this concept. The objectives are:

1. Develop a conceptual framework for benefit-cost analysis of dual systems, both in the static and dynamic (investment timing) sense.

2. Develop generalized computer software for rapid application of these concepts at particular sites, by water resource planners.

Since dual water systems are almost always unmetered (at individual service points), the marginal price is zero and more total water is used than if residential demand is served from a single system. This may appear to make a dual system an unlikely concept for inducing water conservation. However, dual systems do in fact "conserve" in two ways:

1. Naturally high quality water is allocated to uses with high quality requirements (a fraction of the population can be supplied with drinking water from naturally safe sources).

2. The total cost of meeting water demands may be reduced; thereby increasing social welfare. Both of these results fit the economic definition of water conservation given previously (improved management of the water resource).

Dual water supply systems exist in many western states: Idaho, Washington, California, Montana, Wyoming, Colorado, and Utah. Hughes (1985) found that dual supply systems result in a 2 to 24 percent saving in total water cost for the Wasatch Front cities of Utah, sampled in his study. Utah has more and larger scale dual systems than other states. The Weber River Basin in northern Utah has at least 20 dual systems that have been operating mostly since the 1960s and which serve more than 39,000 families (Hughes 1985). The population growth along the Wasatch Front is causing a rapid shift in land uses from agricultural to residential. Table 3-1 illustrates the changes in irrigated acreages in some specific Utah counties from 1978 to 1982. The trend depicted in that table is expected to continue for the next few decades. This shift is making water used previously for irrigation available for municipal uses. Assuming that an irrigation company already has water rights and a pressure distribution or an open ditch system to serve to irrigated agriculture, a favorable situation exists for conversion to residential dual system.

This chapter will be divided into three major sections: 1) the benefit-cost analysis framework and related models for the static problem (a single point in time) will be presented, 2) the dynamic (investment) timing problem analysis and related models will be conceptualized, and 3) applications to both hypothetical and real systems will be demonstrated and analyzed.

Table 3-1. Irrigated acreages for various Utah counties (acres).

County	1978	1982	Diff	% Variation
Box Elder	127036	107030	-20006	-15.7
Cache	87117	78129	-8988	-10.3
Davis	31693	24314	-7379	-23.3
Duschesne	107873	89095	-18778	-17.4
Morgan	8248	7973	-275	-3.3
Salt Lake	22852	17399	-5453	-23.9
Summit	28588	26432	-2156	-7.5
Utah	90728	86874	-3854	-4.2
Wasatch	17666	18452	786	4.4
Weber	35776	32763	-3013	-8.4
Total for Utah	1168621	1082328	-86293	-7.3

Benefit-Cost Analysis Concept

Assume for simplicity that water demand for outdoor, indoor, and combined uses are linear as shown in Figures 3-1 and 3-2. In these figures, D_O represents the outdoor demand function, D_I represents demand for indoor use, and D_T is the total, or combined, demand during a particular season. The area between the total and the indoor demand curves and above the marginal cost curve (area A) represents the benefits to the society from outdoor use of water priced at P_T when no dual supply system exists. The expected total demand is Q_T which is the sum of outdoor demand Q_O and indoor demand Q_I. If, however, we consider a city with a dual system, the total treated water will be Q_I' priced at P_I (Figure 3-1) and the quantity of water demanded for outdoor use will be Q_O' since raw water systems are normally unmetered (Figure 3-2). Note that Q_O' should always be greater than Q_O and therefore a dual water system will in general result in higher total water use than a single system. This assumes that the quality of the raw water will not influence the consumer behavior, in other words that the outdoor demand curve remains unchanged. Area C less area D in Figure 3-2 would represent the net benefits to the society brought up by the outdoor use of water with a dual water supply system in operation. One could expect the operating cost of dual systems to be less than that of culinary systems because of reducing treatment and costs. As a consequence the net benefits associated with outdoor use of water when a dual supply system is in operation should be greater than outdoor benefits when a dual system exists. The question of interest is whether the extra benefits exceed the cost of building and operating the dual supply system. The criterion of economic feasibility (CF) is:

$$CF = NB_O' - NB_O - Cd$$

where

CF	=	net benefits to the society when using a dual supply system
NB_O'	=	sum of consumer's and producer's surplus from outdoor use of water with a dual supply system (Figure 3-2)
NB_O	=	sum of consumer's and producer's surplus from outdoor use of water without a dual supply system (Figure 3-1)
Cd	=	capital and O&M costs of dual supply system

Delaying capital investment in the expansion of water treatment facilities is a benefit generated by the installation of a dual water supply system, but this is included as part of the CF function as defined above.

If $CF > 0$, then the dual supply system increases the total welfare to society, and should be built. If $CF < 0$, it would cost more for society to build and operate a dual supply system than to stay with a single system; the dual supply system should not be implemented.

The following section looks at different approaches that could be used to obtain combined, indoor, and outdoor demand curves.

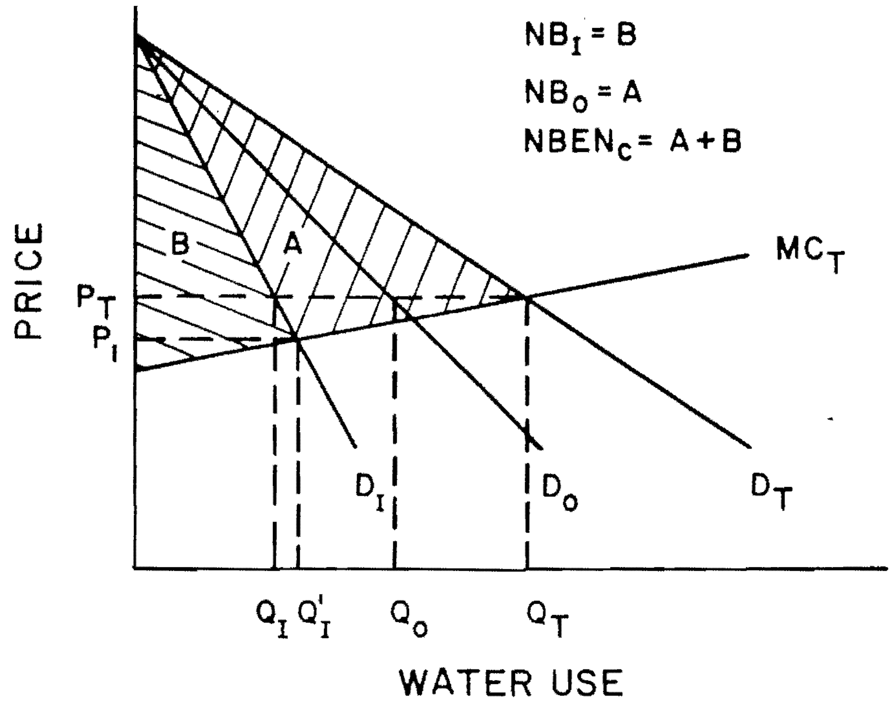


Figure 3-1. Net benefits associated with outdoor use of water without dual water supply system.

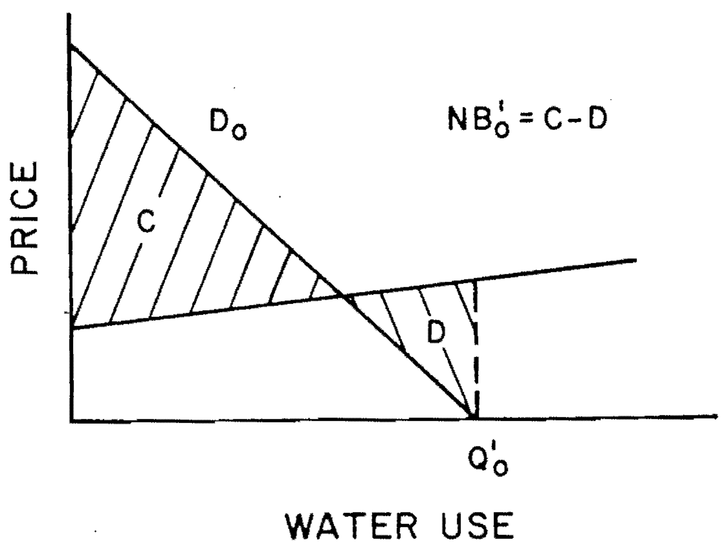


Figure 3-2. Net benefits associated with outdoor use of water with dual water supply system.

Demand Functions

Municipal water use is a function of numerous factors. The water resources literature abounds in discussions concerning the importance of each and many attempts have been made to develop models that try to explain the large variability in water use by expressing demand as a function mainly of economic and climatologic parameters. Most multiple regression models identify price as being an important determinant (Hughes 1980). Other factors susceptible to influence the municipal use of water are temperature and precipitation (Hansen and Narayanan 1981, Howe and Linaweaver 1967), percentage of daylight hours (Hansen and Narayanan 1981), lot size, size of household, and appraised value of house (Howe and Linaweaver 1967). Municipal water use commonly is modeled as a deterministic function of other variables. Linear and log-linear models have been extensively developed. The general form of these models is:

$$Q = a + b_1x_1 + b_2x_2 + ... + e$$

for the linear model, and

$$\ln Q = a + b_1 \ln x_1 + b_2 \ln x_2 + ... + e$$

for the log-linear model, where

Q = average water demand
x_i = explanatory variable
b_i = regression coefficient
e = error term

Municipal water use models usually are seasonal or monthly models. Using seasonal and monthly models presents the advantage of better representing the fluctuations in demand for water throughout the year, which becomes important for efficient capital investment in water supply projects. Seasonal variations in water demand can be quite substantial. For example, water use in Salt Lake City during a typical year is shown in Figure 3-3. The peak use rate is 309 cfs during summer compared to 87 cfs during the nonirrigation season. Hughes (1980) found that the peak monthly demand is about two and a half times the average monthly demand. Since dual water supply systems operate during the irrigation season and that municipal water exhibits dramatic changes inside a year, a careful and accurate benefit-cost analysis of dual water supply systems at least requires the use of seasonal, if not monthly demand curves.

Generally, price schedules and water demand are available so that total (indoor and outdoor) monthly municipal demand curves can be estimated fairly accurately. For those cities which have a dual supply system indoor water use is metered and thus the monthly indoor demand curves can be estimated with precision. These demand curves then could be used to estimate indoor water demand for surrounding municipalities. Another approach in obtaining monthly indoor demand curves is to assume that the indoor use remains relatively constant from one month to another. Thus monthly demand curves can be indirectly estimated from

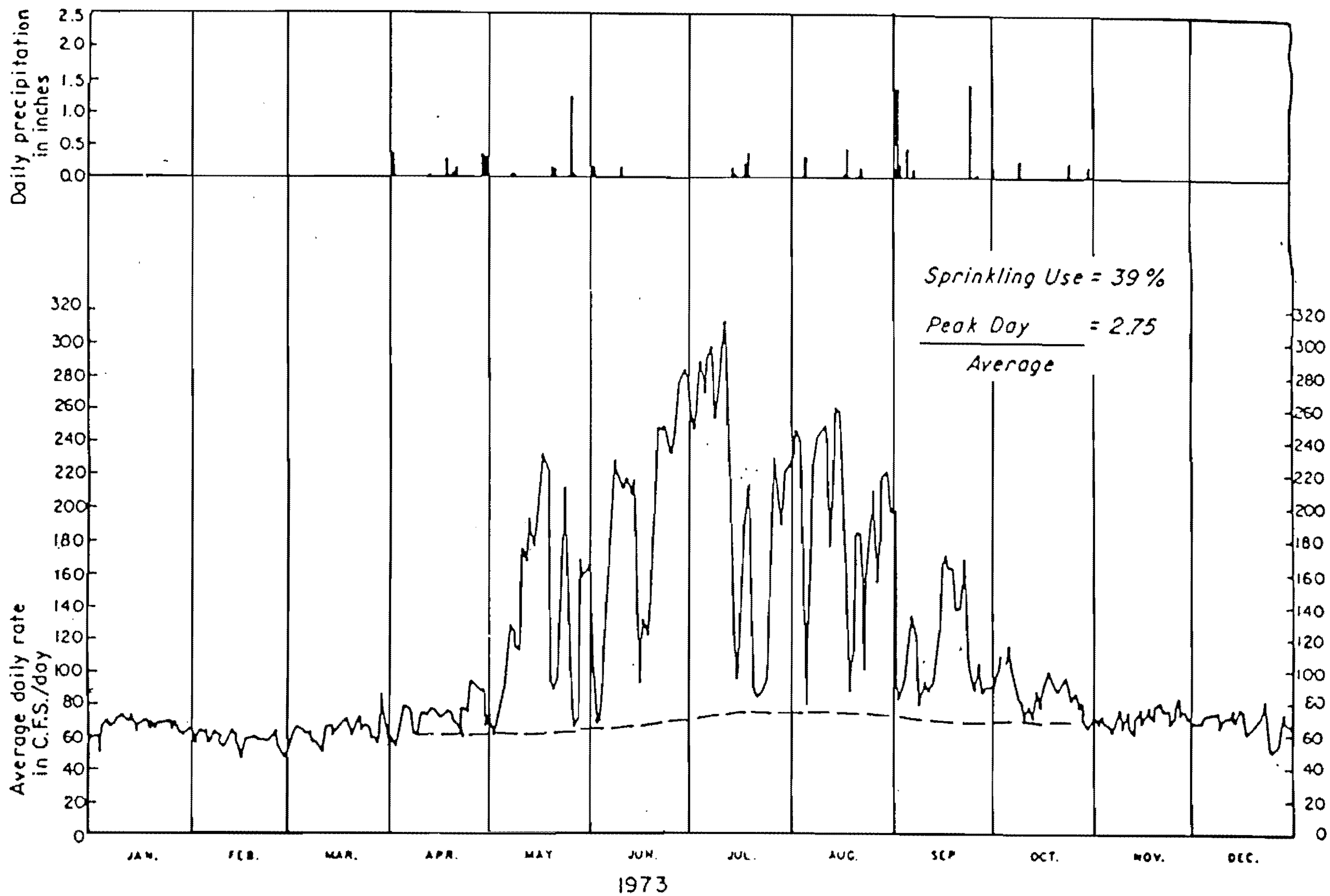


Figure 3-3. Total delivery to conduits by Salt Lake City Water Department (after Kirkpatrick 1976).

the winter demand patterns. Finally, models already developed can be used to estimate monthly demand curves. Those models are often site specific and must be used with circumspection for municipalities that are remote from those used as a basis to derive the models. Examples of monthly demand models are found in Hansen (1981). He developed monthly time series models of municipal water demand for Salt Lake City and the Granger-Hunter district, Utah. On the other hand, Howe and Linaweaver (1967) and later Howe (1982) derived water demand functions applicable over large regions in the United States.

Outdoor demand functions must be determined indirectly because water in dual supply systems has a marginal price of zero since it is unmetered. A recognized technique consists in disaggregating the total demand curve into an outdoor and an indoor component by horizontally subtracting the indoor demand curve from the total, or combined, demand curve. Howe and Linaweaver (1967), in their study of sprinkling demand, utilized this concept of disaggregation to separate the domestic from the sprinkling use of water. This technique ignores the fact that people may be influenced in their consumption by the quality of the raw water being delivered. The magnitude as well as the direction of this influence are not known, but are considered to be minor. A second approach for obtaining outdoor demand functions is the utilization of regression models. Howe and Linaweaver (1967) and Howe (1982) developed such models applicable over large regions in the United States.

Cost of Dual Systems

Cost Model Methodology

To evaluate economic feasibility of a dual distribution system, one must obtain estimates of both capital and operating costs of such a system. Specific features of a dual water system, in addition to the network itself, may include pumping stations, equalizing reservoirs, and pressure reducers. A typical representation of the dual water distribution system components is illustrated in Figure 3-4. Note that the network as presented in this figure is of branched, or nonlooped, type. Examination of detailed construction drawings of several dual systems showed that some systems were constructed according to the same design standards as is customary for municipal culinary systems (4"-6" minimum diameter pipes and looped systems). These design standards have the advantage of 1) isolating an area with a break or leak and continuing service from a different path during repairs, 2) delivering fire flows, and 3) preventing stagnant water in dead end lines. Looped networks are certainly justified for reliability and health reasons where drinking is the product being delivered; however, in the case of dual water distribution systems, there seems to be little justification for using 4 to 6" minimum diameter pipes and looped systems since dead end lines present no problems in terms of stagnation, fire protection is not intended, and taking larger sections out for service maintenance causes no troubles since irrigation can be delayed for days. Furthermore, the economic feasibility of dual supply systems would clearly improve for branched relative to looped systems and the following model assumes the former. The reference year for computing costs is 1985.

Accurate cost estimates for dual water systems require 1) the knowledge of the configuration of the distribution network (network layout, dimensions of the area to be covered by the network) and 2) the pipe sizes in the networks. Unfortunately, the network configuration is highly dependent on numerous factors: the street network, the topography of the terrain, the area to be covered, and the configuration of major transmission and connecting lines for individual blocks. In order to come up with a general relationship that still would give reliable results, a standardized network must be selected. Such a network is presented in the following section. Pipe sizes will depend on a maximum flowrate to be delivered by each pipe. The U.S. Bureau of Reclamation design criteria for pressure irrigation systems in Utah will be used for sizing pipe. This standard reflects the fact that not every lot is expected to demand water at the same time (and the function is therefore nonlinear). A best fit representation of the USBR standard is:

$$Q_d = 0.09735*A**0.7933 \quad \text{for } A < 50$$
$$= A/25 \quad \text{for } A > 50$$

where

Q_d = design flow, cfs
A = area to irrigate, acres

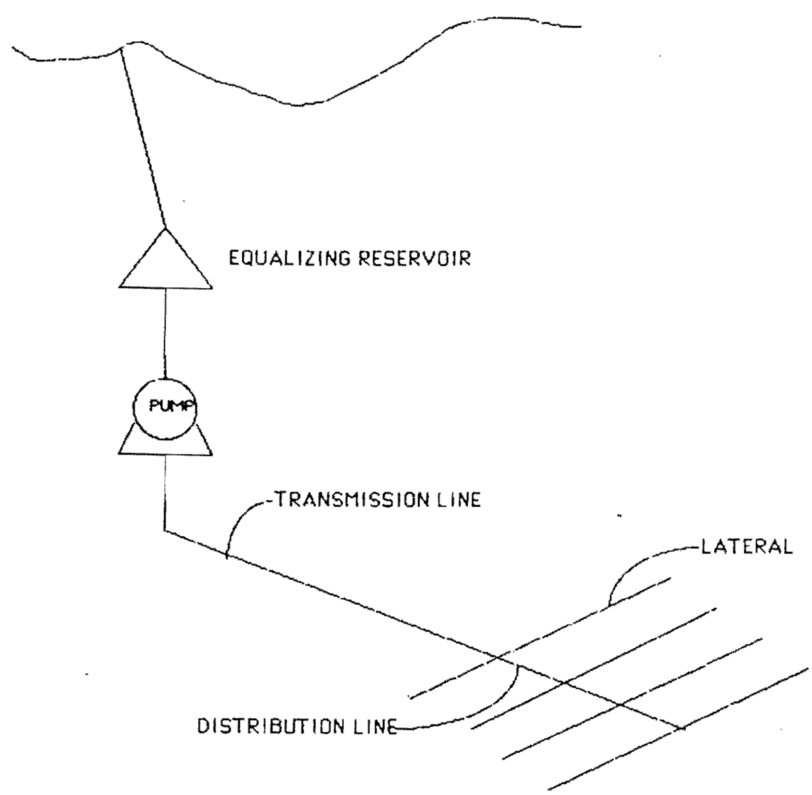


Figure 3-4. Representation of a dual system.

Standardized Configuration of a Dual Water System

The street network is one of the most decisive factors when selecting the configuration of a dual system. Two possible schemes investigated are shown in Figures 3-5A and B. Hydraulic analyses revealed that both networks perform equally well in achieving adequate pressures for a given irrigation area. Cost analyses showed that the cost of building and operating either network is about the same. Since there seems to be no net advantages in selecting one configuration from the other, the network type shown in Figures 3-5A was chosen for investigation.

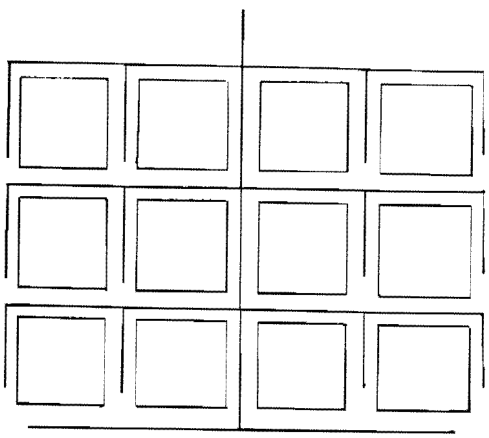


Figure 3-5A. Standardized network - scheme 1.

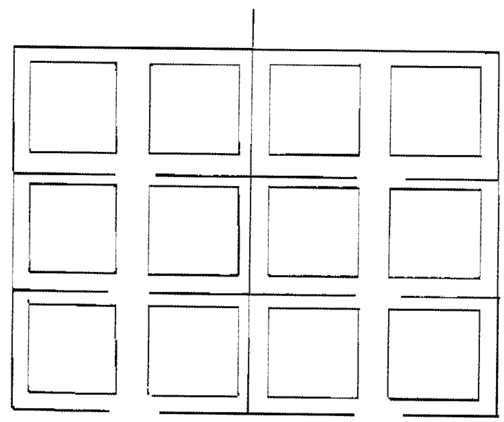


Figure 3-5B. Standardized network - scheme 2.

The standardized dual water supply system can be subdivided into three basic components:

1. The transmission system. This system carries the water from the source to the network. Pumps and reservoirs may be needed for a proper operation of the system.

2. The distribution line. This pipeline takes water from the transmission system and delivers it to the different laterals comprising the network.

3. The laterals. The laterals carry water from the distribution line to the lots.

In order to give more versatility in the cost estimation of the dual water system, the transmission lines are analyzed separately from the remaining networks. Also in order to accommodate odd shapes of the areas to be served, the laterals and distribution lines are analyzed independently. Hydraulic-cost models were developed in order to obtain reasonable estimates of the cost of laterals, distribution lines, and transmission systems. The models are the subject of the next section.

Hydraulic-Cost Models

Lateral and distribution lines. The objective function of the optimization model is the minimization of the cost (capital and O&M) of a lateral or a distribution line. Physical constraints include a minimum pressure requirement at nodes of consumption and a maximum velocity requirement inside the pipes. A representation of a lateral is shown in Figure 3-6. The subscript "j" refers to a line number and the subscript "i" identifies a particular pipe diameter. As an example, L_{31} would represent the length of an 8-inch diameter pipe (described by the subscript 3) in line number 1. Any set of pipes between two adjacent nodes defines a line. Nodes are either points of consumptions or junction of two or more lines. Adopting the above nomenclature, the mathematical formulation of the hydraulic-cost model becomes:

$$\text{MIN } (1+VALV)\left(\sum_{j}\sum_{i} C_i L_{ij}\right)CRF + (1+VALV)\sum_{j}\sum_{i} K_1 D_i^{a_1} L_{ij}$$

S.T.

$$\sum L_{ij} = TL_j$$

$$\sum_{PATH} \Delta h_j \leq \Delta H$$

$$\Delta h_j = \left[\frac{F\, Q_{dj}}{C_h}\right]^{1.852} \sum_i \left[\frac{L_{ij}}{D_i^{4.87}}\right]$$

$$V_{ij} \leq VMAX$$

where

- VALV = fraction of the cost due to valves
- L_{ij} = length of pipe "i" in line "j"
- C_i = unit cost for the pipe "i"
- D_i = diameter of the pipe "i"
- TL_j = total length of line "j"
- h_j = head loss inside line "j"
- Q_{dj} = flow inside line "j"
- V_{ij} = velocity inside pipe "i" in line "j"
- CRF = capital recovery factor
- ΔH = maximum head loss between the inlet of the lateral or distribution line and a node of water consumption
- C_h = Hazen-Williams roughness coefficient
- F = unit adjustment factor. = 2.3136 if D_i is in feet and Q_{dj} is in cfs
- VMAX = maximum velocity inside a pipe
- K1, a1 = parameters

The variables are the different lengths of pipes inside each line. Thus the objective function as well as its constraints are all linear in

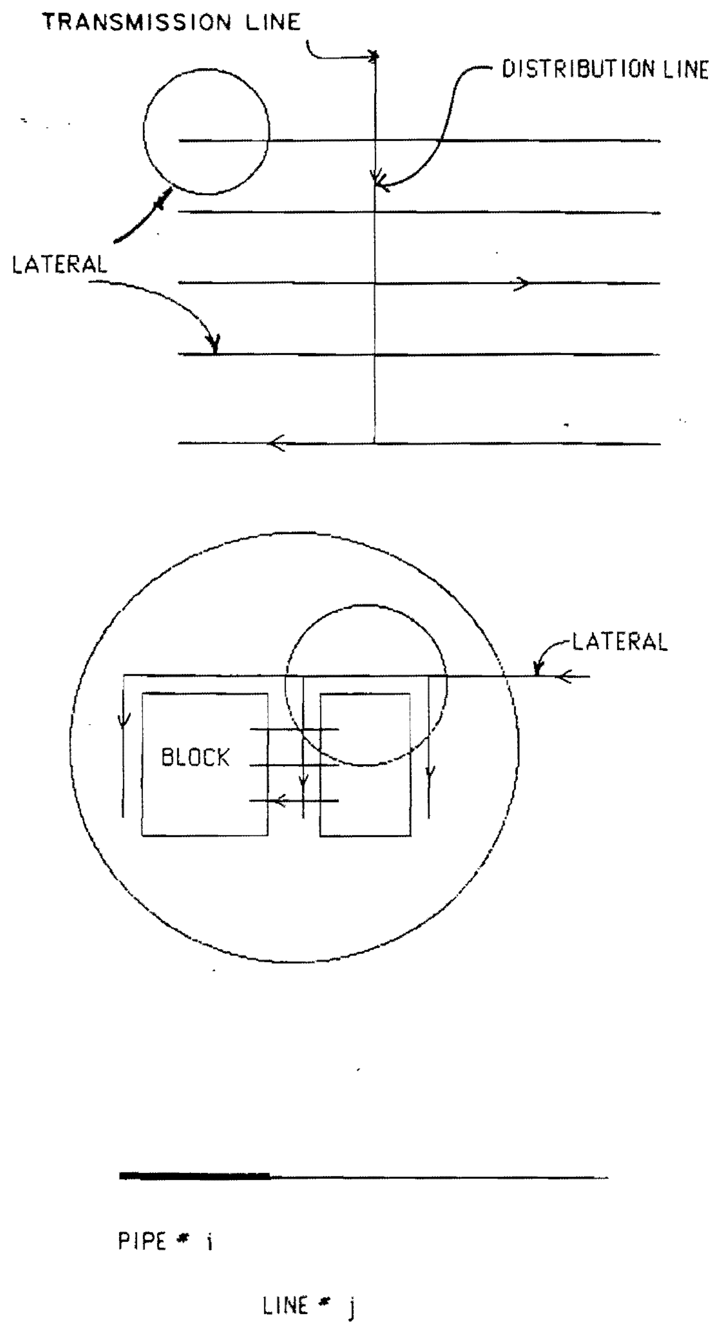


Figure 3-6. Representation of a lateral.

terms of L_{ij}. Linear programming techniques can be used to solve the model.

The first term of the objective function represents the capital costs of the lateral or the distribution line. The second term represents the O&M costs. The structure of the O&M function is similar to the one proposed by Deb (1978), with the exception here that costs due to valves are added. The inclusion of the costs associated to valves will not affect the optimal design of the lateral or the distribution line, but will have a definite impact on the overall cost of those components.

The transmission system. This model is similar to the model outlined in the previous section with the exception that costs related to pumps must be added. A general expression for the capital costs of pumps is:

$$CP = K_2\, H^{a_2}\, Q_p^{a_3}$$

where

K_2 = parameter
a_2, a_3 = exponents < 1
H = total head
Q_p = flowrate in pump

The flowrate in the pump corresponds to the average rate on the maximum day (not the peak instantaneous demand) and is a fraction of the design flow rate:

$$Q_p = b_1\, Q_d$$

The flow inside each line of the transmission system is known since the design flows are known. The remaining unknown in the pump cost equation is the total head H. However, since a_2 is smaller than 1 the function is concave. Minimization of a concave function can lead to a local minimum solution. This difficulty was avoided, however, by linearizing the function:

$$CP = K_2(m{*}H + b)Q_p^{a_3}$$

A general expression for the pump operating costs is:

$$OP = K_3\, HQ_a$$

where

Q_a = average flowrate of the system
K_3 = parameter depending on such factors as the pump efficiency, the cost of energy, and the number of hours/day the pump is in operation

The average flowrate of the system can be represented by the dual water use (≈ 3 AF/AC/year in Utah) and is a fraction of the design flowrate:

$Q_a = b_2 Q_d$

Because Q_s (and thus Q_a) is known in a branched system, the expression for the pump operating costs is linear in terms of H. However, because the linearized capital cost function for pumps now contains a constant term (K_2 b $Q_p^{a_3}$), the use of mixed integer programming techniques is required. The mathematical formulation of the model is:

$$\text{MIN } (1+\text{VALV}) \left(\sum_j \sum_i C_i L_{ij}\right)\text{CRF} + (1+\text{VALV}) \sum_j \sum_i K_1 D_i^{a_1} L_{ij}$$

$$+ \left[\sum_j K_2 (m\ H_j + bI_j) Q_{pj}^{a_3}\right]\text{CRF} + \sum_j K_3 Q_{aj} H_j$$

S.T.

$$\sum_i L_{ij} = TL_j$$

$$\sum_{\text{PATH}} \Delta h_j \le \Delta H$$

$$\Delta h_j = \left[\frac{F\ Q_{dj}}{C_h}\right]^{1.852} \sum_i \left[\frac{L_{ij}}{D_i^{4.87}}\right] - H_j$$

$$V_{ij} \le \text{VMAX}$$

$$H_j \le MI_j$$

$$I_j = 0,1$$

where

M = maximum anticipated value for pumping heads
I_j = integer variable

If pumping is not required in line "j," then $H_j = 0$ and I_j is set to zero. If pumping is required, then $H_j > 0$ and I_j is forced to take the value of one.

Reservoir costs are not added to the model because the presence of a reservoir does not influence the design of the transmission system and depending on the situation reservoirs may not be required.

Regression analysis. Having developed a detailed hydraulic cost model the question now arises--could an adequate but simpler representation of system costs be developed by regression analysis on the parameters in the detailed model?

Since each transmission conduit length is site specific, no attempt was made to correlate the costs of the transmission lines to the total area to be served by the dual supply systems and/or other physical parameters. However, regression functions were derived between the cost of laterals and distribution lines and physical parameters such as the area to be served by those components and average block size. The relationships were obtained by first solving the model detailed in the previous section for numerous combinations of areas to be served and block sizes, and then by regressing the costs on the physical parameters. The blocks were assumed square in dimensions, and the average width of a street was fixed at 60 feet. Results of the analysis are shown in Tables 3-2 and 3-3 for the laterals and the distribution lines, respectively. Costs are adjusted to the base year 1985. Unit cost for pipes were taken from bidding schedules in Utah. Average pipe costs are shown in Table 3-4.

Validation of the regression functions. The cost of a nonlooped water supply system for Haights Creek, Utah, was computed from the bidding schedule and also using the cost relationships. A schematic representation of the dual supply system taken for the analysis is shown in Figure 3-7 and analysis results are presented in Table 3-5. They suggest that the cost relationships and the standardized network are reliable tools for the computation of the overall cost of a dual supply system without having to make the design of the system.

Benefit-Cost Optimization Static Model

The multi-source pricing model developed in Chapter II was used to find the total and indoor water net benefits necessary to assess the economic feasibility of dual water supply systems. The nonlinear programming model also determines the optimal allocation of water sources, reservoir operation with respect to storage and releases and water prices for a uniform pricing scheme. The computation of the outdoor water net benefits when a dual supply system is in operation is a straightforward procedure not requiring an optimization model. Since the raw water is priced at zero, the procedure simply consists in calculating the area under the demand curve between $\hat{Q}_t = 0$ and $\hat{Q}_t = Q_t$, where Q_t corresponds to the water demand for a zero-priced water. The area under the marginal cost curve is assumed to be zero. This assumption is realistic since no treatment costs are usually associated with raw water and the operation and maintenance costs of the dual supply system (pumping costs, network maintenance) are being considered in the cost analysis described previously. The structure of the optimization model has been detailed in Chapter II.

The optimization model was nonlinear, so the nonlinear package MINOS (Murtagh and Saunders 1977) was used in the analyses. MINOS requires parameter and linear constraints to be entered in standard MPS format. Because of the tremendous task of entering all the constraints of the model in MPS format, a matrix generator was developed. The detailed description of the matrix generator may be found in LeConte (in progress).

Investment Timing Model

The evaluation of dual water supply systems as outlined previously, assumes that the aggregated demands for water (the horizontal summation

Table 3-2. Regression cost functions for laterals.

CAPITAL COST = 735 $AREA^{1.15}$ $BLOCK^{-0.246}$	$R^2 = 0.995$
CAPITAL COST = -5650 + 960 AREA	$R^2 = 0.976$
O&M COST = 1/100 CAP. COST = 7.35 $AREA^{1.15}$ $BLOCK^{-0.246}$	
O&M COST = 1/100 CAP. COST = 56.5 + 9.6 AREA	

Table 3-3. Regression cost functions for distribution lines.

CAPITAL COST = 0.510 $TAREA^{0.584}$ $LENGTH^{1.01}$	$R^2 = 0.998$
CAPITAL COST = -137230 + 49.9 TAREA + 66.2 LENGTH	$R^2 = 0.961$
O&M COST = 1/100 CAP COST = 0.00510 $TAREA^{0.584}$ $LENGTH^{1.01}$	
O&M COST = 1/100 CAP COST = -1372 + 0.5 TAREA + 0.66 LENGTH	

- Prices adjusted to 1985
- Pipe costs are taken from Table 3-4.

AREA:	total area served by a lateral, including streets, in acres
TAREA:	total area served by a distribution line, including streets, in acres
BLOCK:	average block area, in acres
LENGTH:	length of the distribution line, in feet

Table 3-4. Average pipe costs adjusted to base year 1985.

ϕ	Cost ($/foot)	Remarks
1"	2.50	Flexible tubing, installation costs included
1 1/2"	2.80	Flexible tubing, installation costs included
2"	2.50	Installation costs included
3"	2.79	Installation costs included
4"	3.19	Installation costs included
6"	4.05	Installation costs included
8"	5.20	Installation costs included
10"	7.15	Installation costs included
12"	9.45	Installation costs included
14"	12.38	Installation costs included
16"	15.00	Installation costs included
18"	18.00	Installation costs included
20"	20.20	Installation costs included
24"	27.11	Installation costs included
30"	38.20	Installation costs included
36"	47.98	Installation costs included

Regression equation $c = 0.276\ \phi^{1.4389}$ $r^2 = 0.996$

(valid between ϕ = 6" and ϕ = 36")

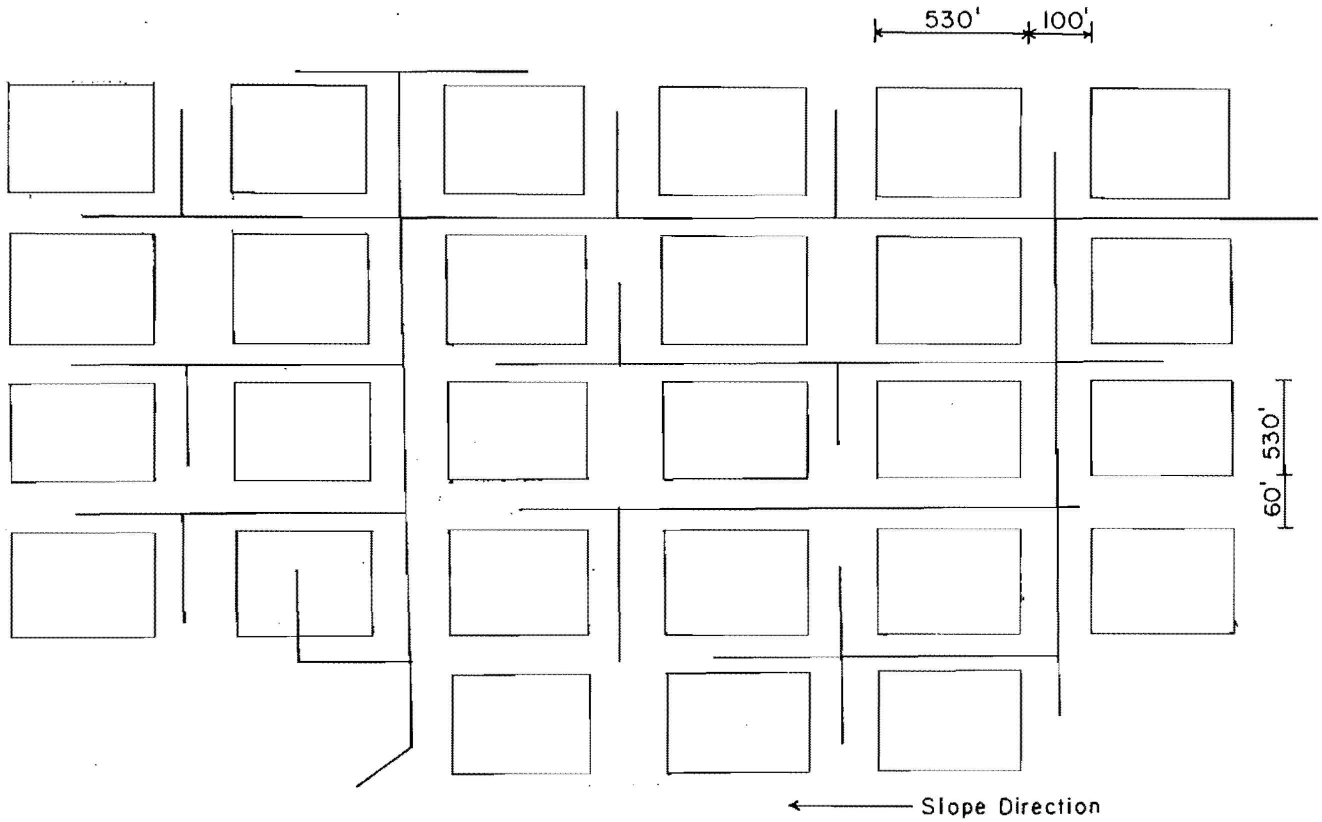


Figure 3-7. Haights Creek dual supply system.

Table 3-5. Comparison of costs - Haights Creek.

Area to irrigate: 130 acres (excluding streets)

Estimated population: 3000

	Bid schedule	Cost function	% difference
Capital cost: pipes	$165,314	$152,979	7.5
Capital cost: paving[a]	$ 99,600	$103,825	-4.2

[a]Paving costs of $3/foot is assumed.

of individual demands for both outdoor and combined water) are constant from year to year. In this section the analysis will be extended to include the investment time problem where demand is increasing over time (the total population to be served is growing). The most common scenario of interest is the evaluation of dual water supply systems in rapidly urbanizing areas, where land use is changing from agricultural to residential and where water previously used for crop irrigation now becomes available for watering lawns and gardens. Since the time frame becomes part of the economic analysis, the basic problem now is determining what time to invest in a dual water supply system which will maximize the welfare to society.

In urbanizing areas it is likely that dual water distribution systems will expand as the city grows, the rate related to the population growth rate of the city. It is unrealistic to assume that a dual water supply system for a population of 20,000 would be constructed when the existing population of the city is only 5,000 and when it might take 20 years to reach the maximum capacity of the system.

Since the area to be served by a dual water supply system increases with time, so will the total benefits from water consumption and the costs required to maintain and operate the system. Capital investment also is a dynamic process, as initial capital is required to "start" the system, followed by future investments necessary to meet the growing demand.

Let $TBEN_D$ be the total net benefits from water consumption (both indoor and outdoor) when a dual water supply system is being built in year t^* and subsequently expanded until the maximum surface area to be irrigated is attained. The maximum size of the irrigated zone depends on such factors as the topography of the terrain, the presence of natural obstacles (rivers, lakes) the existence of water rights, etc. Note that although the dual water supply system does not expand after the maximum surface area is reached, benefits are still generated. Let t_F be the year when the expansion of the dual water supply system ceases. The mathematical expression of the total net benefits $TBEN_D$, assuming t^* being less than t_f is:

$$TBEN_D = \sum_{t=o}^{t^*} \frac{NBEN_C(t)}{(1+\gamma)^t} + \sum_{t=t^*}^{t_f} \frac{NBEN_D(t)}{(1+\gamma)^t} + \sum_{t=tf}^{\infty} \frac{NBEN_D|_{tf}}{(1+\gamma)^t} - \sum_{t=t^*}^{t_f} \frac{O\&M(t)}{(1+\gamma)^t}$$

$$- \sum_{t=t_f}^{\infty} \frac{O\&M|_{tf}}{(1+\gamma)^t} - \frac{CAP(t^*)}{(1+\gamma)^{t^*}} \qquad (3\text{-}1)$$

where:

$NBEN_C(t)$ = Annual sum of the consumers' and producer's surpluses from water use when no dual water supply system is in place.

$NBEN_D(t)$ = Annual sum of the consumers' and producer's surpluses from water use when a dual water supply system is in operation.

$O\&M(t)$ = Annual costs necessary to maintain and operate the dual water system.

$CAP(t^*)$ = Capital costs necessary to build and subsequently expand the dual water supply system, discounted at t^*.

γ = Discount rate.

The first term in Equation (3-1) represents the total benefits before the construction of a dual water supply system, discounted to $t = o$. Figure 3-1 shows how $NBEN_C(t)$ can be obtained from information on water demand curves and marginal cost curves. Since the population to be served by a dual water supply system grows with time so will $NBEN_C(t)$. The second and third terms of Equation (3-1) account for the benefits once a dual water supply system is in operation during the expansion period (from t^* to t_f) and during the static period (from t_f to infinity), respectively. In practice, the upper time limit to compute benefits does not extend to infinity. However, its selection is justified on the basis that the exact knowledge of the upper limit is unknown and as the planning period increases, the discounted benefits become negligible. $NBEN_D$ can be broken down into two components: benefits benefits from indoor use of water (NB_I), and benefits from outdoor use (NB_O'). Those benefits are schematically represented in Figures 3-1 and 3-2. Note that the marginal cost curve for the outdoor water does not include the annual costs required to maintain and operate the dual water supply system, which are directly inserted into Equation (3-1). However, the marginal cost curve does include costs to treat the outdoor water, if any. The annual O&M costs include maintenance of the different components of a dual water supply system (network, transmission pipes, pumping stations, equalizing reservoirs) and the energy cost for pumping, if any. Finally, the capital costs consist of all costs needed for building and expanding the dual water distribution system. Included are the costs to build and expand the network, costs for the transmission pipes, pumping stations, equalizing reservoirs, and paving costs. The capital costs discounted at t^* are calculated as follows:

$$CAP(t^*) = ICAP(t^*) + \sum_{t=t^*}^{t_f} \frac{\Delta CAP(t)}{(1+\gamma)^{t-t^*}} \qquad (3\text{-}2)$$

where:

$ICAP(t^*)$ = Initial investment required to build a dual water supply system at $t = t^*$.

$\Delta CAP(t)$ = Capital cost required to expand the dual water supply system.

The evaluation of the capital and O&M costs for the different components of the dual water supply system is thoroughly explained in the cost model section.

So far, an expression to evaluate the total net benefits from water use has been obtained in the case where a dual water supply system is constructed. In order to decide on the economic viability of the dual water supply system alternative, those benefits must be compared to the total net benefits without a dual system. Let $TBEN_C$ be those benefits. They are calculated as follows:

$$TBEN_C = \sum_{t=o}^{t_f} \frac{NBEN_C(t)}{(1+\gamma)^t} + \sum_{t=t_f}^{\infty} \frac{NBEN_C|t_f}{(1+\gamma)^t} \qquad (3\text{-}3)$$

The dual water supply system alternative should be implemented if:

$$CF = TBEN_D - TBEN_C > 0 \qquad (3\text{-}4)$$

The feasibility criterion CF is a function of t^*, the time to start investing in a dual water supply system. Since CF varies with t^*, the goal here is to get the value of t^* that will maximize the feasibility criterion:

$$\max_{t^*} CF = TBEN_D - TBEN_C \qquad (3\text{-}5)$$

Substituting $TBEN_D$ and $TBEN_C$ by their respective expressions yields:

$$MAX - \sum_{t=t^*}^{t_f} \frac{NBEN_C(t)}{(1+\gamma)^t} - \sum_{t=t_f}^{\infty} \frac{NBEN_C|t_f}{(1+\gamma)^t} + \sum_{t=t^*}^{t_f} \frac{NBEN_D(t)}{(1+\gamma)^t} + \sum_{t=t_f}^{\infty} \frac{NBEN_D|t_f}{(1+\gamma)^t}$$

$$- \sum_{t=t^*}^{t_f} \frac{O\&M(t)}{(1+\gamma)^t} - \sum_{t=t_f}^{\infty} \frac{O\&M|t_f}{(1+\gamma)^t} - \frac{CAP(t^*)}{(1+\gamma)^{t^*}} \qquad (3\text{-}6)$$

In Equation (3-6) time is being considered as a discrete variable. The optimization procedure can be simplified by considering time as a continuous variable as follows:

$$MAX = -\int_{t^*}^{t_f} \frac{NBEN_C(t)}{(1+\gamma)^t} dt - \int_{t_f}^{\infty} \frac{NBEN_C|_{tf}}{(1+\gamma)^t} dt + \int_{t^*}^{t_f} \frac{NBEN_D(t)}{(1+\gamma)^t} dt +$$

$$+ \int_{t_f}^{\infty} \frac{NBEN_D|_{tf}}{(1+\gamma)^t} dt - \int_{t^*}^{t_f} \frac{O\&M(t)}{(1+\gamma)^t} dt - \int_{t_f}^{\infty} \frac{O\&M|_{tf}}{(1+\gamma)^t} dt - \frac{CAP(t^*)}{(1+\gamma)^{t^*}}$$

(3-7)

Also, noting that $(1 + \gamma)^{-t}$ can be replaced by $e^{-\gamma t}$, the objective function is:

$$MAX = -\int_{t^*}^{t_f} NBEN_C(t)e^{-\gamma t}dt - NBEN_C|_{t_f} \int_{t_f} e^{-\gamma t}dt + \int_{t^*}^{t_f} NBEN_D(t)e^{-\gamma t} dt$$

$$+ NBEN_D|_{t_f} \int_{t_f}^{\infty} e^{-\gamma t} dt - \int_{t_f}^{t_f} O\&M(t)e^{-\gamma t}dt - O\&M|_{t_f} \int_{t_f}^{\infty} e^{-\gamma t}dt$$

$$- CAP(t^*)e^{-\gamma t^*} \qquad (3-8)$$

The following expressions are suggested to describe the variations of the benefit and cost terms with time:

$$NBEN_C(t) = NBEN_C^o e^{\alpha t} \qquad (3-9)$$

$$NBEN_D(t) - O\&M(t) = NBEN_D^o e^{gt} \qquad (3-10)$$

$$CAP(t^*) = CAP^o e^{\beta t^*} \qquad (3-11)$$

The exponents α, g, and β in Equations (3-9), (3-10), and (3-11) respectively may be viewed as growth rates for the different benefits and costs involved in the analysis. Substituting in the objective function (3-8) gives:

$$MAX = NBEN_C^o \int_{t^*}^{t_f} e^{(\alpha-\gamma)t} dt - NBEN_C^o e^{\alpha t_f} \int_{t_f}^{\infty} e^{-\gamma t}dt$$

$$+ \; NBEN_D^o \int_{t^*}^{t_f} e^{(g-\gamma)} dt \; + \; NBEN_D^o \, e^{gt_f} \int_{t_f}^{\infty} e^{-\gamma t} dt \; - \; CAP^o \, e^{(\beta-\gamma)t^*} \qquad (3\text{-}12)$$

After solving the integrals, the objective function is:

$$MAX = \frac{NBEN_C^o}{\alpha-\gamma} \left[e^{(\alpha-\gamma)t^*} - e^{(\alpha-\gamma)t_f} \right] - \frac{NBEN_C^o e^{(\alpha-\gamma)t_f}}{\gamma}$$

$$\frac{NBEN_D^o}{g-\gamma} \left[e^{(g-\gamma)t_f} - e^{(g-\gamma)t^*} \right] + \frac{NBEN_D^o e^{(g-\gamma)t_f}}{\gamma} - CAP^o e^{(\beta-\gamma)t^*} \qquad (3\text{-}13)$$

The optimal time to start investing in a dual water supply system is obtained by differentiating Equation (3-13) with respect to t^* and equating to zero and solving for t^*:

$$\frac{d(OBJF)}{dt^*} = NBEN_C^o e^{(\alpha-\gamma)t^*} - NBEN_D^o e^{(g-\gamma)t^*} - (\beta-\gamma) CAP^o e^{(\beta-\gamma)t^*} = 0$$

(3-14)

Equation (3-14) does not have an analytical solution in general and must be solved using numerical procedures. The Newton-Raphson method to find roots of equations is particularly well suited here since Equation (3-14) contains only one root and its derivative is continuous for all t^*.

In some particular cases, it is possible to obtain an analytical solution to Equation (3-14). For example, if the exponents α and g are set equal, then the solution of Equation (3-14) is:

$$t^* = \frac{1}{\phi-\beta} \ln \left[\frac{(\beta-\gamma) CAP^o}{NBEN_C^o - NBEN_D^o} \right] \qquad (3\text{-}15)$$

with $\phi = \alpha = g$

In many situations it is likely that α and g will be almost identical, enabling the use of Equation (3-15) to solve for t^*. The rationale underlying this assumption is that indoor, outdoor, and combined benefits from water consumption will naturally tend to follow similar growth rates. Finally, it must be stressed that the solutions to Equations (3-14) and (3-15) may not correspond to a maximum of the objective function. A minimum or a saddle point can be reached. The shape of the objective function, and consequently the occurrence of a maximum, a minimum, or a saddle point, will be conditioned by the values of the different coefficients and exponents comprising Equation (3-14).

This model has been programmed in FORTRAN language. The model was applied to both a hypothetical setting and also to a real world application. Discussion of both applications follows.

The Hypothetical Example

All costs pertaining to the construction and operation and maintenance of the dual water distribution system were adjusted to the year 1985. The discount rate used is 7%, however sensitivity to discount rate was also analyzed. The monthly linear water demand curves used in the analysis were developed from exponential-type demand curves for Salt Lake City (Hansen and Narayanan 1981) using linear regression analyses. Prior to linearization, the demand curves were updated to the year 1985 and adjusted for the City of West Jordan, Utah, a likely candidate for implementation of dual systems. Details of the adjustment are presented in the section on the West Jordan model application. The approximations hold as long as the price for water remains within 0.1 and 0.3 \$/100 ft^3, the usual price range in many culinary water systems in Utah. Table 3-6 shows the exponential demand curves and their corresponding linear approximations. The demand curves for Salt Lake City were developed assuming four people/connection (see Chapter II). The area served by the dual water supply system has a population of 5000 at time 0. The assumed population growth rate is constant at 5%, which is representative of a fast growing city. As an example, a city experiencing a growth rate of 5% will see its population double every 15 years. It is further assumed that the maximum, or final, area under study covers a surface of 1900 acres, or 3.0 square miles, including streets. Street widths are fixed at 60 feet, and blocks have dimensions of 600 ft x 600 ft. With an assumed constant population density of 10,000 people/sq. mi., the maximum number of people to be served is 3.0 x 10000 = 30000. It will take 37 years for the city to attain this population. Four independent pipe networks will be built in order to meet the maximum irrigation demand. Economies of scale could be realized by building and expanding a single network, however, this appears to be unrealistic since water users would be reluctant to pay for a network with a very large capacity to accommodate expansions in a remote future. Table 3-7 shows the physical characteristics of each pipe network. Figure 3-8 illustrates the general layout of the hypothetical site under study for implementing a dual water supply system. It is assumed here that the topography of the terrain and the location of the source of irrigation water favor a gravity-fed system, hence no pumping is required. The culinary water network takes its water from a single source and the unit cost of the source is assumed to be \$250/MG. The source can accommodate the rising demand in all years. Finally, it is assumed that water rights don't have to be purchased. Also a supplementary cost for irrigation water delivery is added. This is to cover extra expenses such as annual billing, administrative costs, etc. The added cost is fixed at \$5/lot/year. A four person/lot density is taken for this example, which gives an average lot area of 10,000 square ft or 0.22 acre.

Cost functions. The capital and O&M costs for each of the four networks (laterals and distribution lines) were computed according to the regression cost functions. The fraction of the costs accounted for

Table 3-6. Demand curves used in the hypothetical example.

Month	Linear approximation $Q = a+bP$ a	b	r^2
Jan	939.3	-1578.1	0.96
Feb	939.3	-1578.1	0.96
Mar	939.3	-1578.1	0.96
Apr	1214.8	-2040.9	0.96
May	1729.2	-2905.2	0.96
June	2300.1	-3864.3	0.96
July	2910.8	-4890.3	0.96
Aug	2512.5	-4221.2	0.96
Sept	1898.5	-3189.6	0.96
Oct	1271.2	-2135.7	0.96
Nov	939.3	-1578.1	0.96
Dec	939.3	-1578.1	0.96

Note: Q is in gal/conn/day
P is in $/100ft^3$

Table 3-7. Physical characteristics of pipe networks.

Characteristic	Network #1	Network #2	Network #3	Network #4
Area served	300 acres	500 acres	500 acres	600 acres
Average length	4300 feet	4300 feet	4300 feet	4300 feet
Average width	3000 feet	5000 feet	5000 feet	6000 feet
Average land slope	0%	0%	0%	0%
Minimum pressure	30 psi	30 psi	30 psi	30 psi
Population served	5000	7500	7500	10000

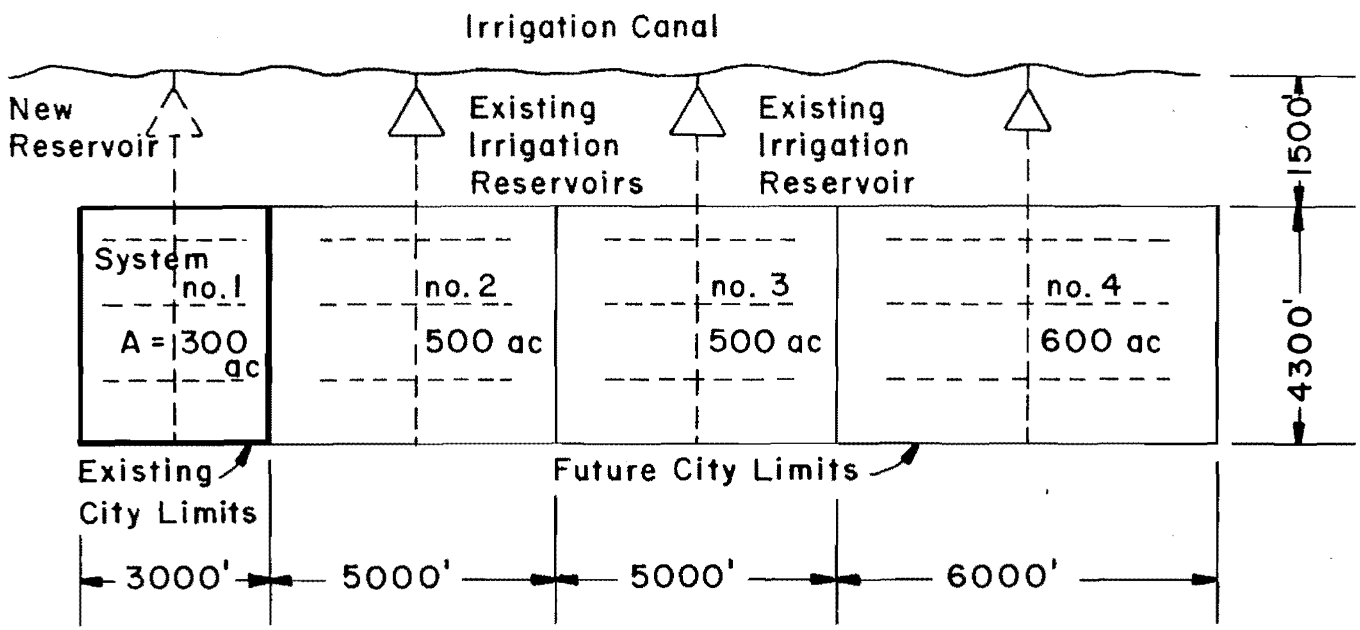


Figure 3-8. General layout of the hypothetical site.

by the valves and fittings was estimated at 11% from information taken in bidding schedules. The cost of the transmission network was computed using the hydraulic cost model previously developed. The unit costs for the pipes used in the calculations are shown in Table 3-4. The capital and O&M costs of the equalizing reservoir were computed from Equations (3-16) - (3-18) adjusted to the base year 1985:

$$CAP.COST_{res} = 30000\ STOR^{0.54} + CLAND \qquad (3\text{-}16)$$

$$STOR = 0.035\ IRRG \qquad (3\text{-}17)$$

$$O\&M\ COST_{res} = 0.01\ CAP.COST_{res} \qquad (3\text{-}18)$$

where

STOR = storage capacity of reservoir, in AC-FT
IRRIG = irrigated area, in AC
CLAND = cost of land purchase, in $

Equations (3-16) and (3-18) were obtained from Deb (1978). Equation (3-17) has been derived based on the following USBR standards:

- reservoir should hold a 12-hour demand on maximum day
- maximum day = 1.3 times maximum month (July) average/31
- July demand = 0.84 AF/AC for the Weber Basin

Paving costs were computed assuming a unit cost of paving of $5/foot. This value was obtained by averaging costs taken in bidding schedules after adjusting to the base year 1985. Table 3-8 shows the capital and O&M costs pertaining to each of the four dual water distribution systems considered in the analysis.

Table 3-8. Capital and O&M costs of dual water systems.

	Capital Costs ($)			
	System #1	System #2	System #3	System #4
Network	307000	492000	492000	628000
Reservoir	90000	0[a]	0[a]	0[a]
Transmission pipe	27000	40000	40000	40000
Paving[b]	250000	450000	450000	550000
	O&M Costs ($/year)			
Network	3070	4920	4920	6280
Reservoir	900	0	0	0
Transmission pipe	270	400	400	400

[a]Existing irrigation reservoirs.
[b]Potential paving costs, i.e., assuming all pipes under paved areas.

A general expression for the relationship between the total capital costs required to build the dual water supply system and the starting year for its construction and subsequent expansions was derived using the cost information contained in Table 3-8. The expression is:

$$CAP(t^*) = 0.1278E7\ e^{0.03136t^*} \qquad r^2 = 0.997 \qquad (3\text{-}19)$$

Equation (3-19) was derived first by obtaining an equation similar to the structure of Equation (3-2) and then by performing a regression analysis between t^* and the capital costs. The underlying assumptions are:

1. Capital costs to expand the system are incurred every year following t^*.

2. A one-time cost is assumed in the case of reservoirs, transmission pipelines, and pumping stations.

3. There are no paving costs associated with the expansion of a dual water supply system (pipes precede paving as new subdivisions are added).

The first assumption may be violated, however, the exact sequence of capacity expansions of a dual water supply system is not known, the problem being site specific. A continuous expansion of the system appears to be a reasonable approach.

From Equations (3-11) and (3-19) CAP^o and β are equal to 0.1278E7 and 0.03136, respectively.

Benefit functions. The annual benefits from water consumption with and without a dual water supply system $NBEN_C(t)$ and $NBEN_D(t)$ were computed for different populations using the linear demand functions shown in Table 3-6 and taking \$250/MG as the unit cost of the only source of culinary water. The marginal price for the untreated, or irrigation water was taken to zero (unmetered). The population to be served can be related to time via the initial population and the population growth rate. Consequently, it is possible to develop benefit time relationships to be used in the investment timing model. The annual benefits $NBEN_C$ and $NBEN_D$ are shown in Table 3-9 for different time periods. The relationship between $NBEN_C(t)$ and time is:

$$NBEN_C(t) = 0.1322E6\ e^{0.04873t} \qquad r^2 = 0.999 \qquad (3\text{-}20)$$

Note that the benefit growth rate is approximately equal to the population growth rate. This is because the benefits remain constant per lot during the entire period of analysis and that the number of people per lot is assumed to be the same everywhere over the irrigated area. Likewise, the relationship between $NBEN_D(t)$ - O&M(t) and time, where O&M(t) is the total operation and maintenance cost of the dual water supply system at time t including the added cost for water delivery taken at \$5/lot/year,

Table 3-9. Annual benefits from water consumption.

Year	Population	Annual Benefits ($) Without Dual Water System	With Dual Water System
0	5000	1.32E5	1.86E5
5	6400	1.68E5	2.38E5
10	8100	2.15E5	3.01E5
15	10400	2.75E5	3.86E5
20	13300	3.50E5	4.94E5
25	16900	4.47E5	6.28E5
30	21600	5.70E5	8.03E5
35	27600	7.29E5	1.03E6

$$NBEN_D(t) - O\&M(t) = 0.1745E6\ e^{0.04902t} \qquad r^2 = 0.999 \qquad (3\text{-}21)$$

From Equations (3-9) and (3-20), and (3-10) and (3-21), the values for $NBEN_C^0$, α, $NBEN_D^0$, g are 0.1322E6, 0.04873, 0.1745E6 and 0.04902, respectively.

<u>Hypothetical example results</u>. The investment timing model was run for the hypothetical setting and conditions set forth in the preceding subsection. Table 3-10 shows the results of the simulation with and without the analytical solution. Note the similarity of the results between the numerical and analytical approaches. This closeness was expected since the exponents α and g in Equations (3-20) and (3-21) are almost identical. From the results, the "best" time to initiate the dual water supply alternative is during year 8, with a city population of approximately 7400. A corresponding increase in the total welfare to the society of $143,000 or $10,010 annually is generated by adopting the dual water supply system alternative. Figure 3-9 shows the concave nature of the objective function. Benefits increase as the period to start building the dual water supply system is pushed back from year 0 to year 8, then decrease afterwards as the savings incurred by delaying the investments in capital are outweighed by the costs necessary to distribute and treat culinary water that will be used as irrigation water. Year 34 marks the period when building a dual water supply system is no longer economically efficient.

The sensitivity of the model to various parameters was also assessed. The following parameters were investigated for this purpose: population growth rate, discount rate, unit cost of culinary water source, pumping head, proximity of the irrigation water source, acquisition of water rights, and added costs to distribute irrigation water.

Table 3-10. Results of the simulation

	Analytical Solution	Solution Obtained Numerically
Optimal time (year)	7.7	8.2
Net benefits ($)	0.1234E6	0.1428E6

a) Population growth rate. Figures 3-10 and 3-11 show the effect of varying the population growth rate on the optimal time to start investing in a dual water supply system and on the corresponding maximum net benefits, respectively. A very sharp decrease in the optimal time is noted as the population growth rate increases from 2 to 4 percent. Thereafter, the optimal time continues to decrease but at a much slower rate. Note that in the case of a fast growing city the "best" time approaches zero. Figure 3-10 shows that the maximum net benefits steadily increase with the population growth rate. The sensitivity analysis appears to confirm the intuitive conclusion that dual water systems are a particularly viable alternative in fast growing cities.

b) Discount rate. The results of the sensitivity analysis are presented in Figures 3-12 and 3-13. As expected, the effect of an increase in the discount rate is to hold the investments (optimal time to invest is pushed back) and to lower the maximum net benefits. Figure 3-12 reveals that as long as the discount rate is at or below 6%, the "best" time to build the system is now. Figure 3-13 shows that at a discount rate of 7.5% or more the dual water system alternative is not recommended. Assuming that the hypothetical example is representative of applications in Utah, the economic feasibility of the dual water system alternative is probable since financing of such systems is usually subsidized by state water development loan programs.

c) Unit cost of source of culinary water. Figures 3-14 and 3-15 show the results of sensitivity to water supply marginal cost. As one might expect, an increase in the unit cost of treating and delivering culinary water has a positive impact on the viability of the dual water system measure. The results suggest that a city which has a naturally high quality source of surface water is not a potential candidate for implementation of a dual water system. Conversely, a city which must pay substantial amounts to treat and/or carry water is likely to draw benefits by building a dual water supply system. Thus, cities with low water quality culinary sources or those which have to import high quality water are likely candidates for dual water supply systems.

d) Pumping head. The sensitivity of the optimal time to invest and the corresponding maximum net benefits on variations of the pumping

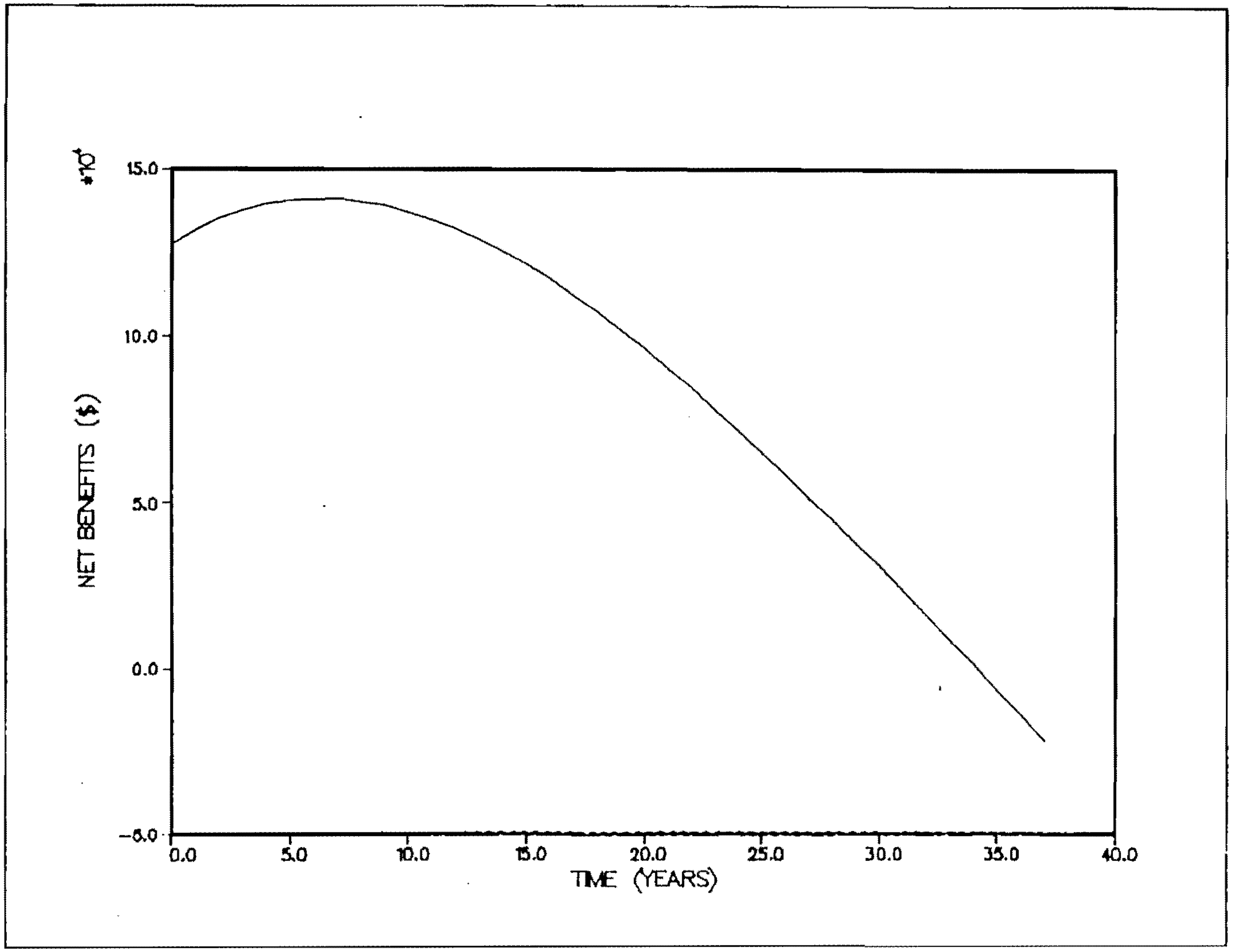


Figure 3-9. Stream of benefits for the hypothetical example.

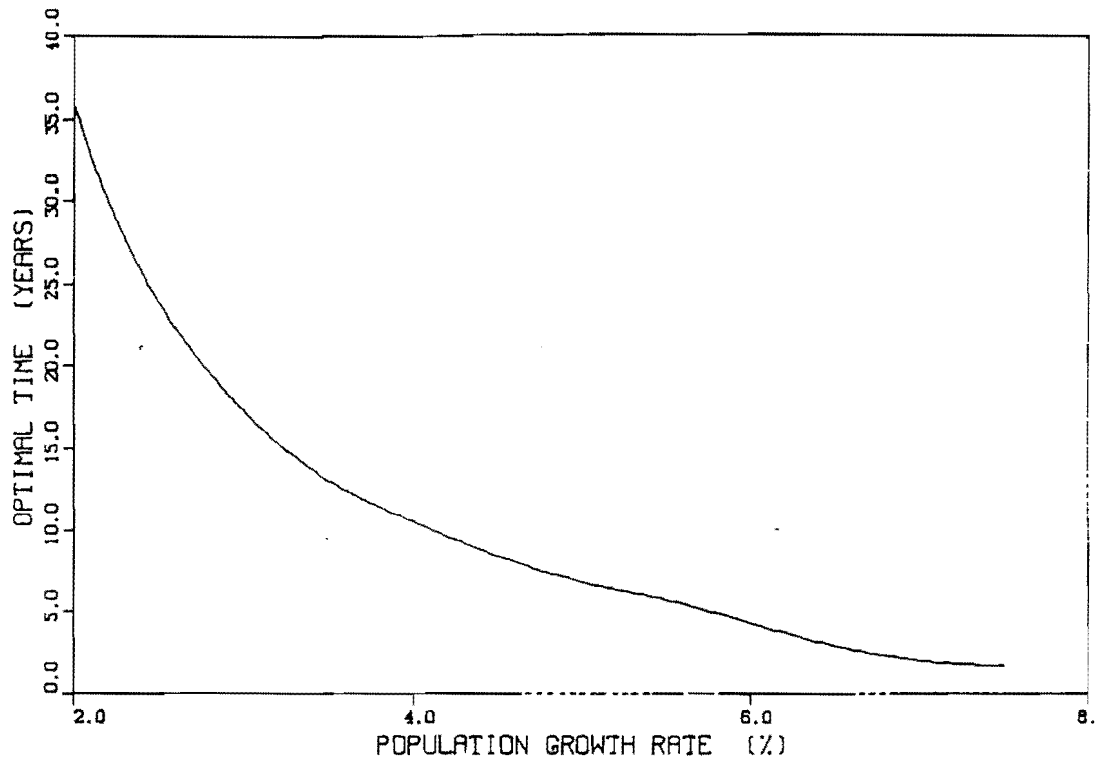


Figure 3-10. Variation of optimal time to start building a dual supply system with the population growth rate.

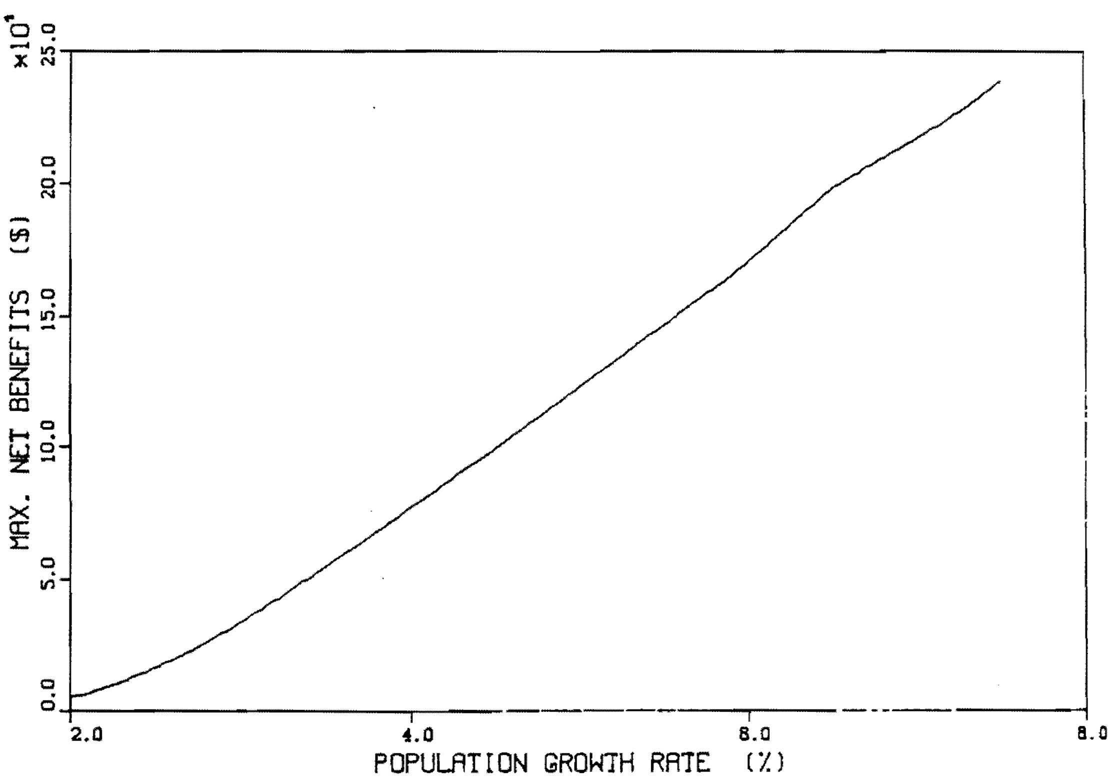


Figure 3-11. Variation of maximum net benefits with the population growth rate.

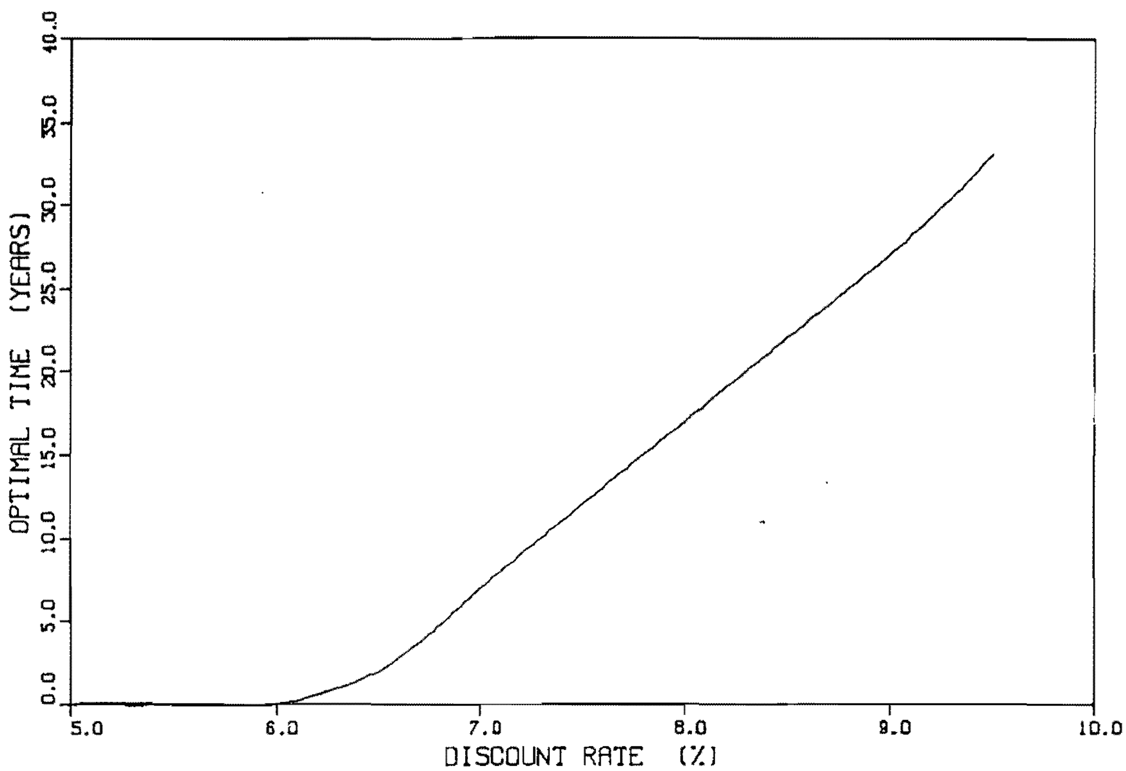


Figure 3-12. Variation of optimal time to start building a dual supply system with the discount rate.

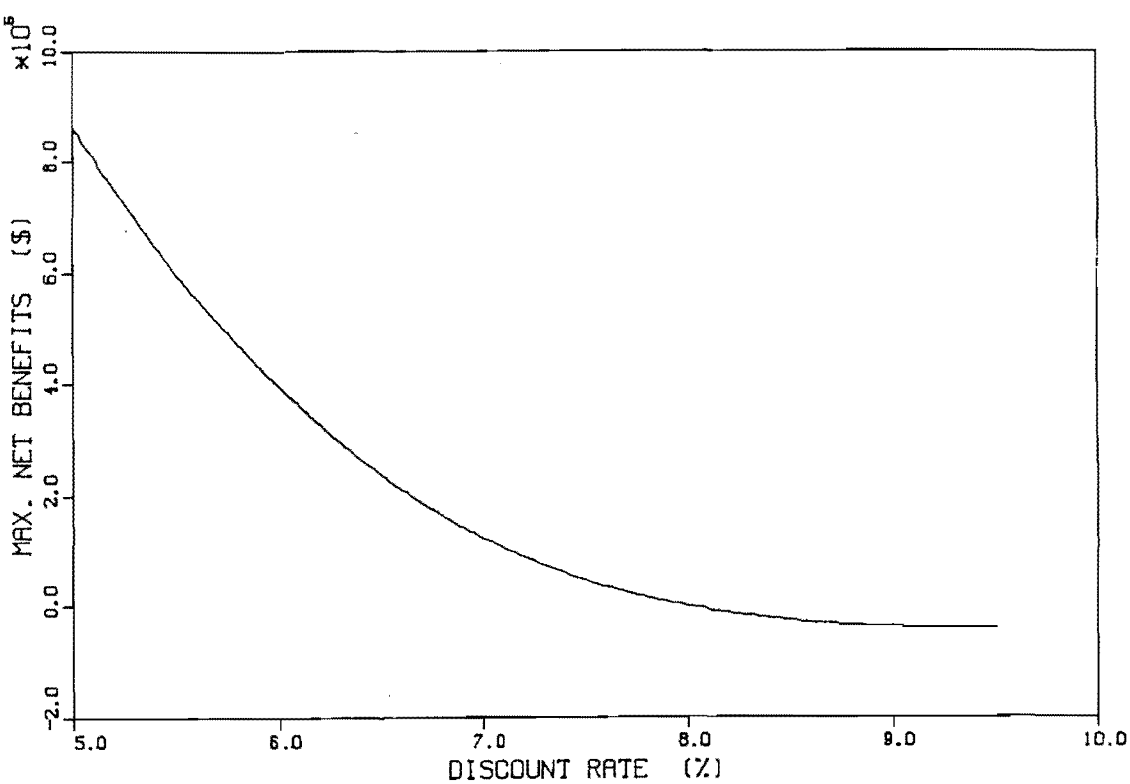


Figure 3-13. Variation of maximum net benefits with the discount rate.

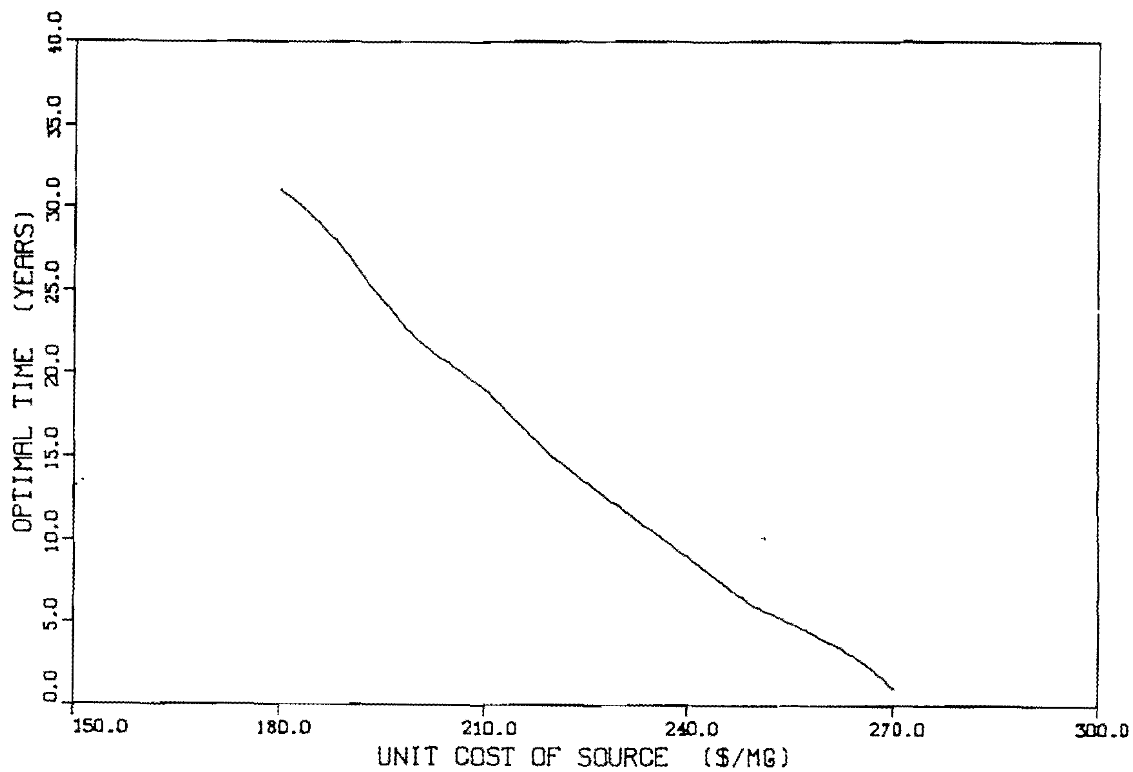


Figure 3-14. Variation of optimal time to start building a dual supply system with unit cost of culinary water source.

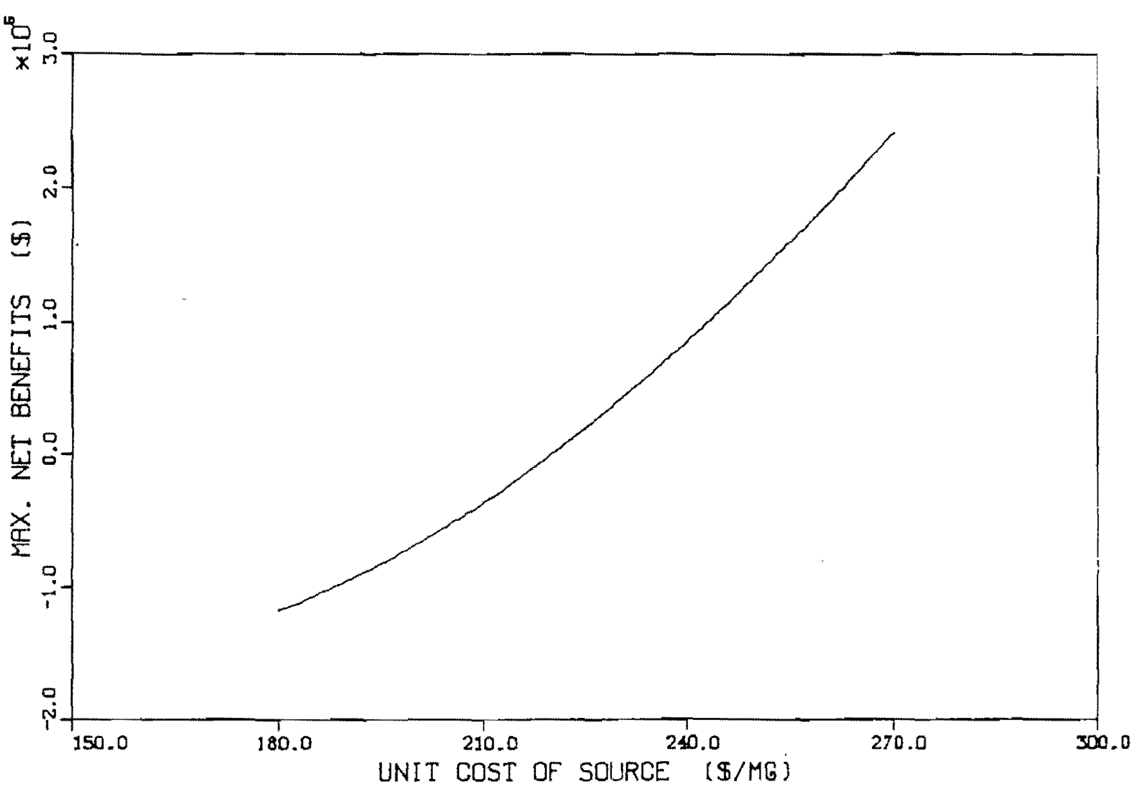


Figure 3-15. Variation of maximum net benefits with unit cost of culinary water source.

head are presented in Figures 3-16 and 3-17, respectively. As the pumping head increases the optimal time to start investing is pushed back. The effect is not significant. The reason is that capital and O&M costs of pumping are relatively small for the range of heads examined here as compared to the capital costs of the dual water system and the benefits generated from water consumption. For example, capital cost for pumps and pumping stations to serve 30,000 people is $106,000 for a 90-foot head compared to capital costs of $1.9 million for the network only. The O&M costs are $24,000/year compared to benefits in the order of $1,000,000/year. The capital and O&M costs for pumps and pumping stations were computed from the following relationships (Deb 1978):

$$CAP.COST_{pumps} = K_1 Q^{0.453} H^{0.642} \qquad (3\text{-}23)$$

$$O\&M_{pumps} = K_2 QH \qquad (3\text{-}24)$$

where K_1 and K_2 are function of parameters such as the cost of energy and the mechanical efficiency of the pumps.

e) Proximity of the source of irrigation water. Figures 3-18 and 3-19 display the influence of the proximity of the source of irrigation water on the viability of the dual water system alternative. As expected, dual systems are not feasible if the source of irrigation water is too remote from the irrigation site. In this particular example, the dual water system alternative starts to generate negative benefits as the distance exceeds 4000 feet.

f) Water rights acquisition. Figures 3-20 and 3-21 show the results of the sensitivity study. The water right costs were computed as losses in farm productivity based on crop values. For example, alfalfa typically is evaluated at $70/acre/year. Results of the analysis suggest that the existence of water rights is critical to the profitability of the dual water system alternative. In this particular example, water rights costs of $30/acre/year or more cause the dual water system to be economically infeasible. Areas already having water rights are the most likely candidates for the dual water supply system alternative, reinforcing the premise that dual water systems should be looked at as a viable water conservation measure in growing cities where land use changes from agricultural to residential and where water rights come with the land.

g) Added cost for water delivery. Those added costs usually would be included as a fixed charge to the consumer and would be used to cover any extra expenses pertaining to the operation of the dual water system. A useful unit is $/lot/year. The sensitivity analysis is presented in Figures 3-22 and 3-23. The total number of lots was obtained by dividing the total population by the assumed number of people/lot. The results suggest that the model is very sensitive to those costs.

Finally, note that $5/LF paving costs seem extremely high relative to other system costs. A unit cost of paving less than $5/foot should

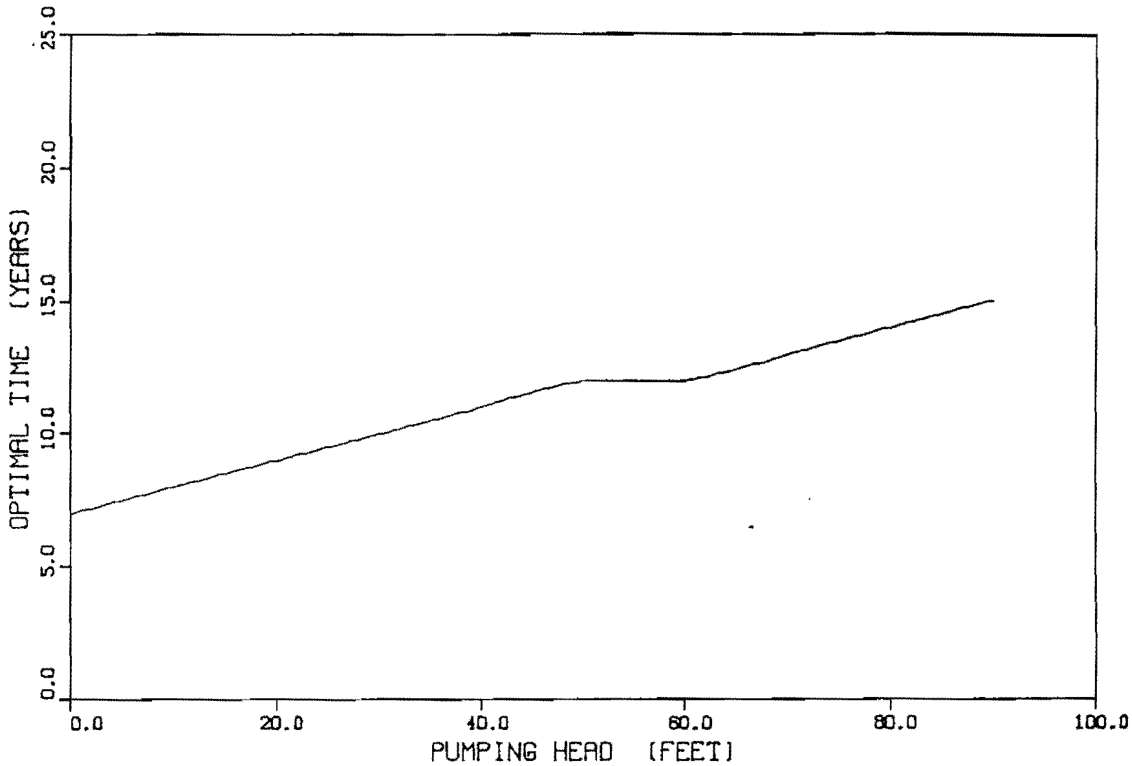


Figure 3-16. Variation of optimal time to strrt building a dual supply system with the pumping head.

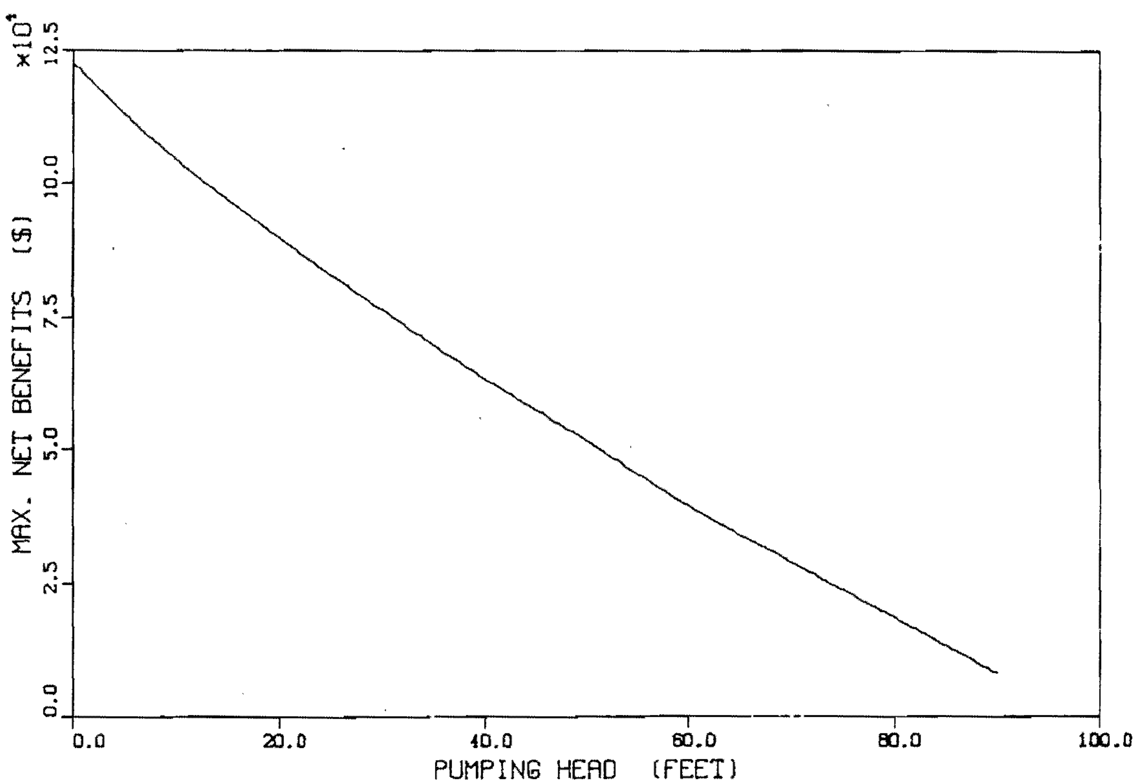


Figure 3-17. Variation of maximum net benefits with the pumping head.

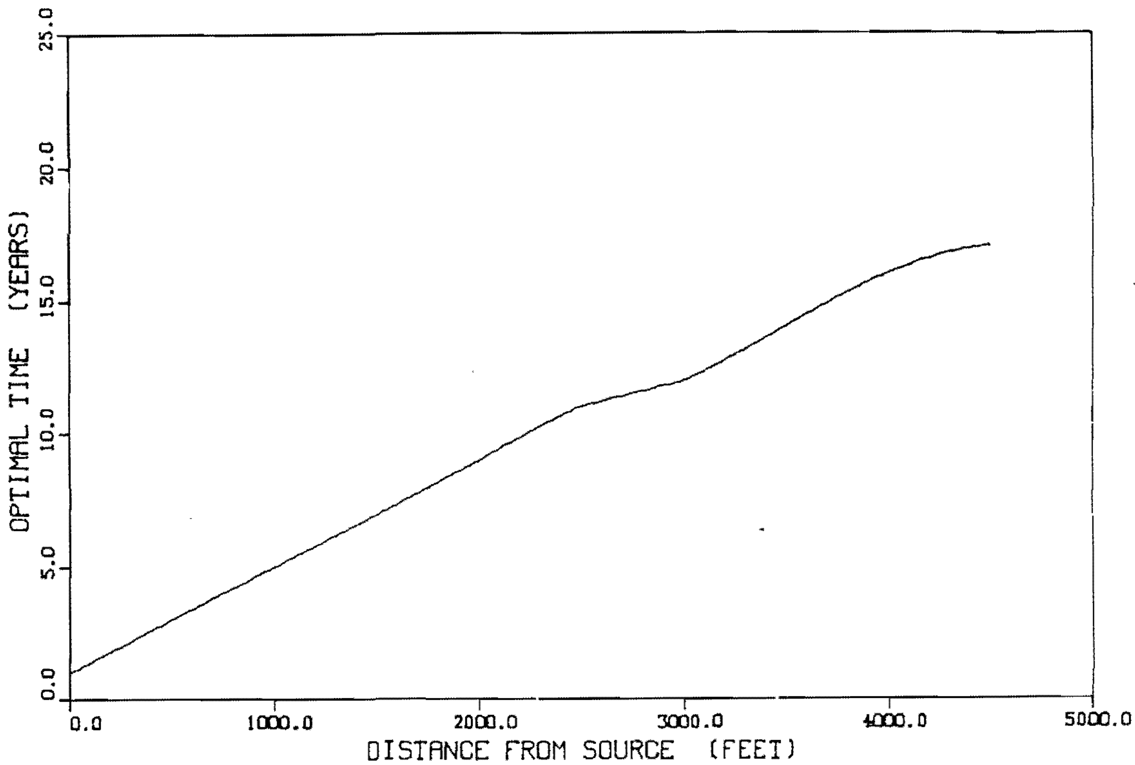


Figure 3-18. Variation of optimal time to start building a dual supply system with distance from the source.

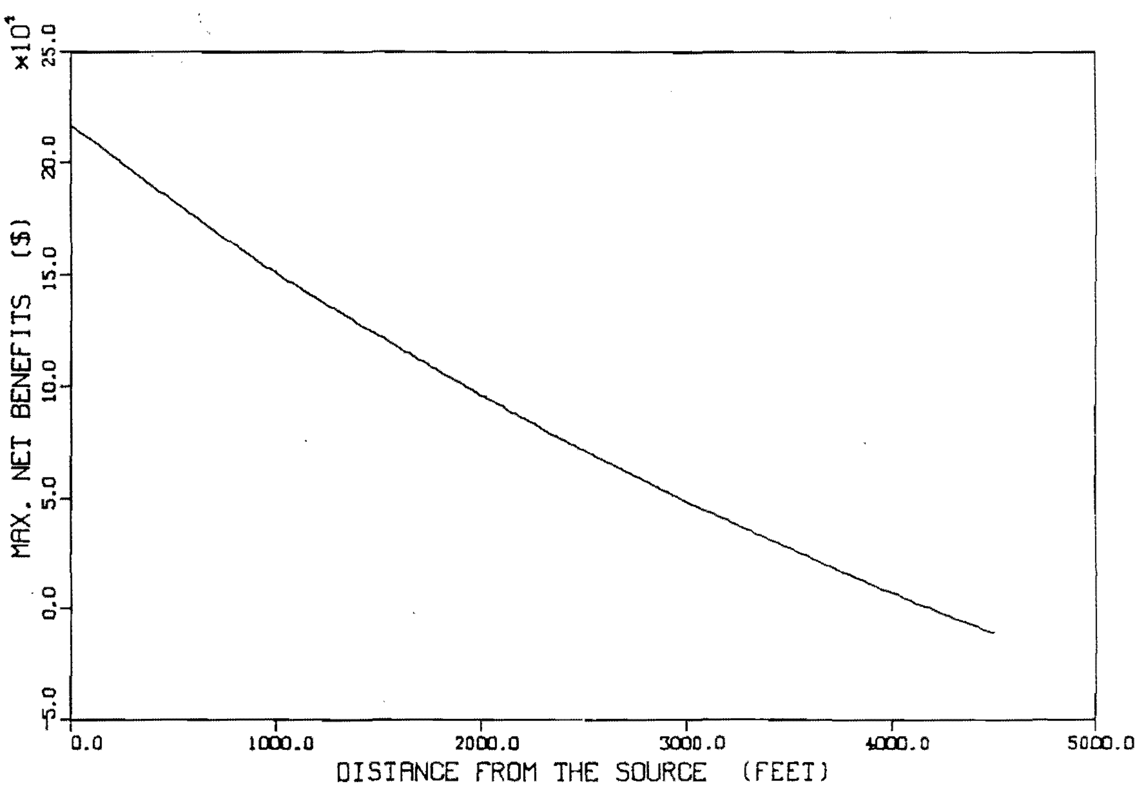


Figure 3-19. Variation of maximum net benefits with distance from the source.

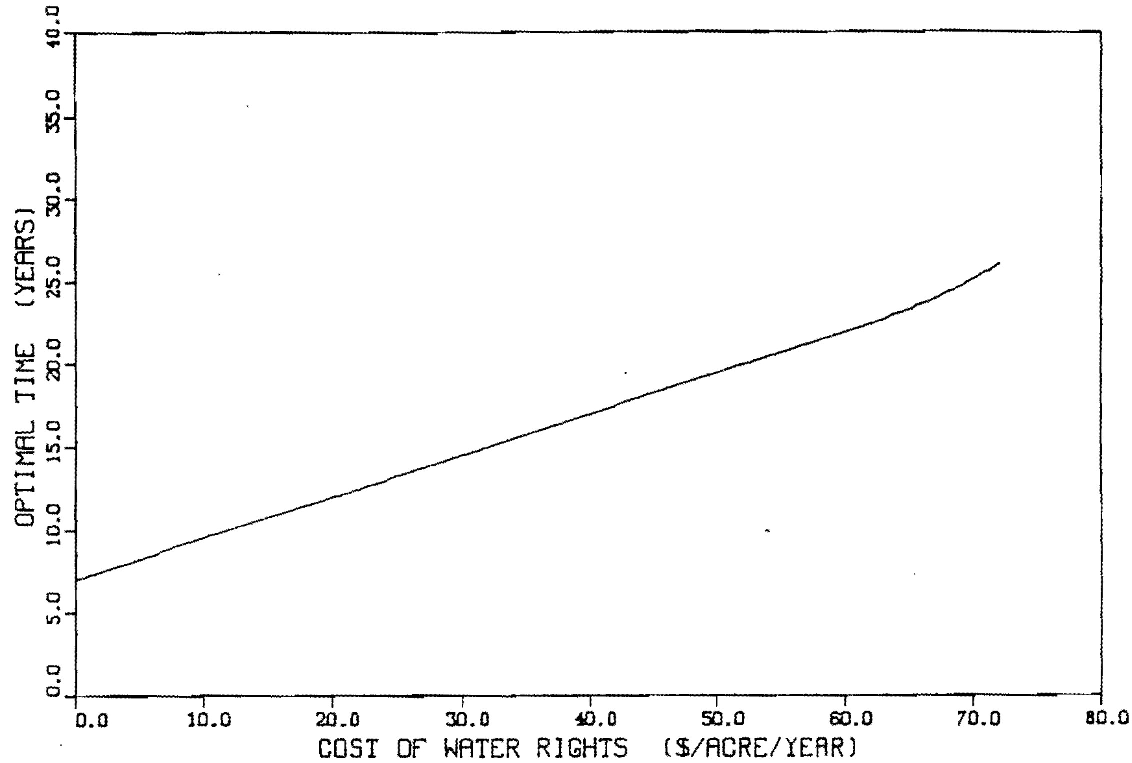


Figure 3-20. Variation of optimal time to start building a dual supply system with cost of water rights.

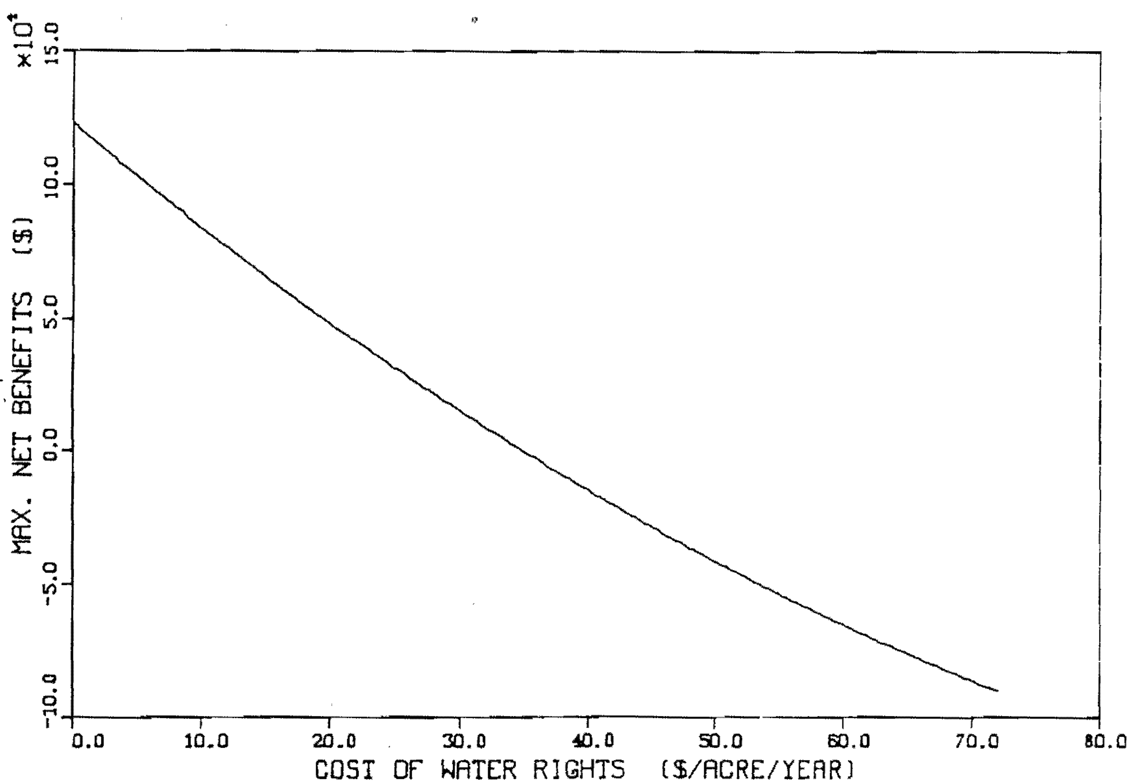


Figure 3-21. Variation of maximum net benefits with cost of water rights.

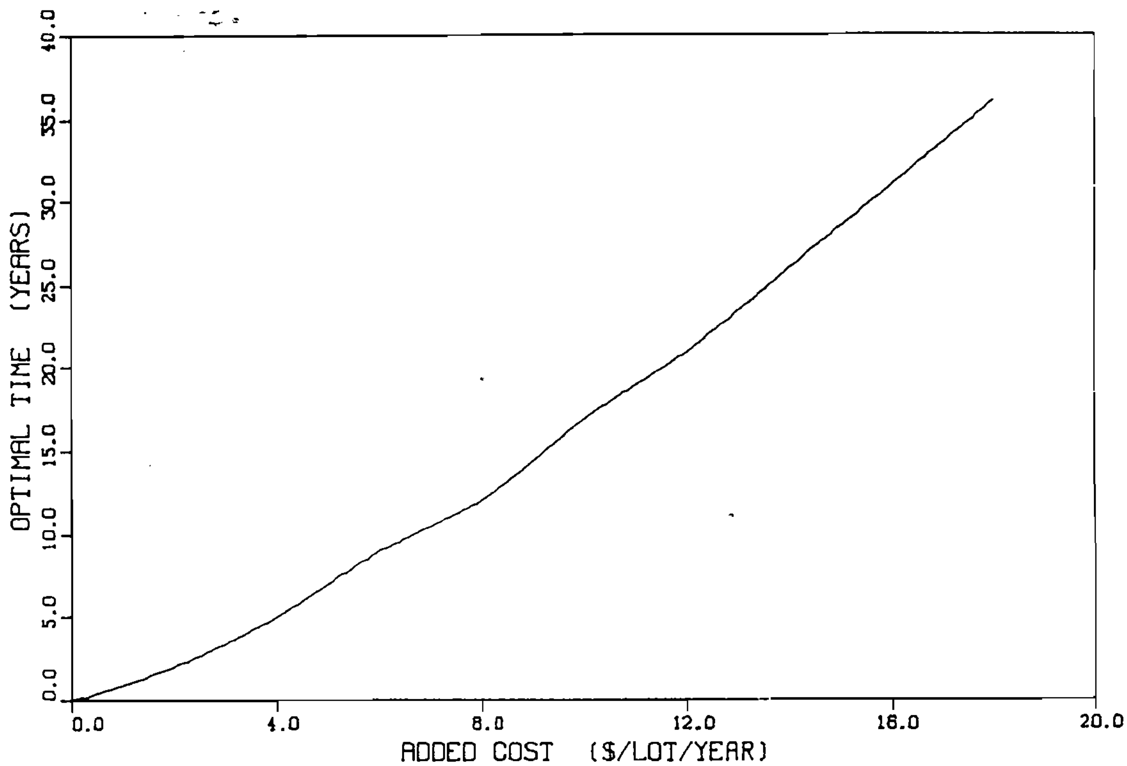


Figure 3-22. Variation of optimal time to start building a dual supply system with added cost for water.

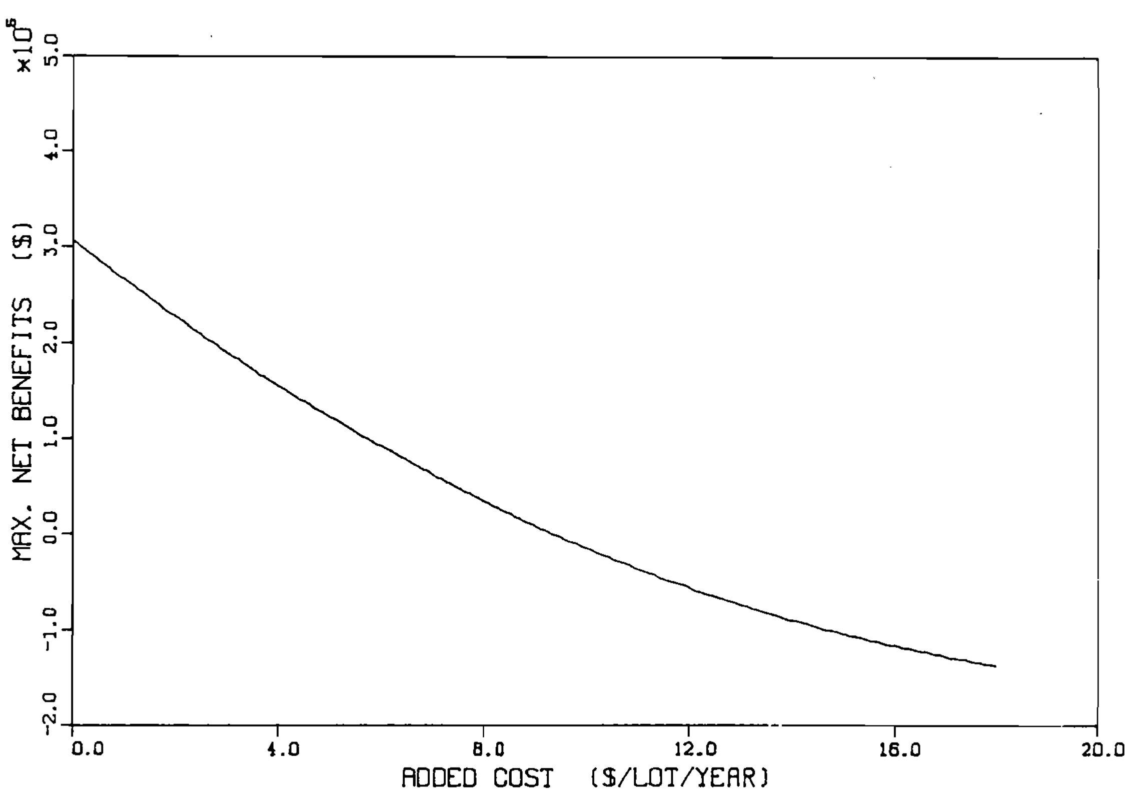


Figure 3-23. Variation of maximum net benefits with added cost for water.

be used to better represent a real world setting for the following reasons:

1. Not all pipes are under paved areas even in urbanized areas.

2. A current dual system planning study for West Jordan, Utah, includes an estimate of $3/LF for paving repair and this lower figure will be used in the West Jordan model application.

Model Application to the City of West Jordan

Background. West Jordan City, located in Salt Lake County, was chosen because it is a rapidly growing area with a surplus of irrigation water and adequate but expensive supplies of culinary-quality water. Planning studies are available for a current project to construct a dual water system in part of this city. This allowed comparison of our generalized model costs to an independent conventional engineering analysis.

The population of West Jordan is estimated at 41,000 in 1986. The current population projections estimate the population of the city at 75,000 and 91,000 in 2000 assuming a population migration of 1,000 and 2,000 people/year, respectively. Recent trends show a population migration of 1,700 people/year, which would put the city's population at 86,000 by the end of this century. The corresponding growth rate would be about 5 percent annually.

Utah Lake water has been delivered through various Salt Lake County canals to agricultural lands in the county for more than 100 years. More specifically, four canals run through the city's limits, and much of the water now being diverted is transported back to the Jordan River where it is carried into the Great Salt Lake. A fifth canal diverts high quality water from Deer Creek Reservoir.

West Jordan City draws its supplies from two sources, mainly groundwater from pumped wells and water purchased from the Salt Lake County Water Conservancy District. Pumping costs are estimated at $60/AF in 1986. SLCWD water rates for 1986 vary between $115.89/AF and $161.54/AF for the City of West Jordan.

The Utah Division of Water Resources has investigated the technical and economic feasibility of a dual water system in the City of West Jordan (Utah Division of Water Resources 1980, 1984). The first study was conducted in a area of 7,500 acres, roughly the area enclosed by the city limits (corresponding to the case 1 model application below). Conclusions from the study were that the dual water system alternative was not economically viable at the present time, unless the price of high quality water increased significantly. A second study was conducted for only part of the city. The area roughly was 600 acres (corresponding to the case 2 model application below). Economic analysis showed that implementation of the dual water alternative would generate net benefits. The investment timing model developed here was applied to both of these projects.

Case 1 - West Jordan City

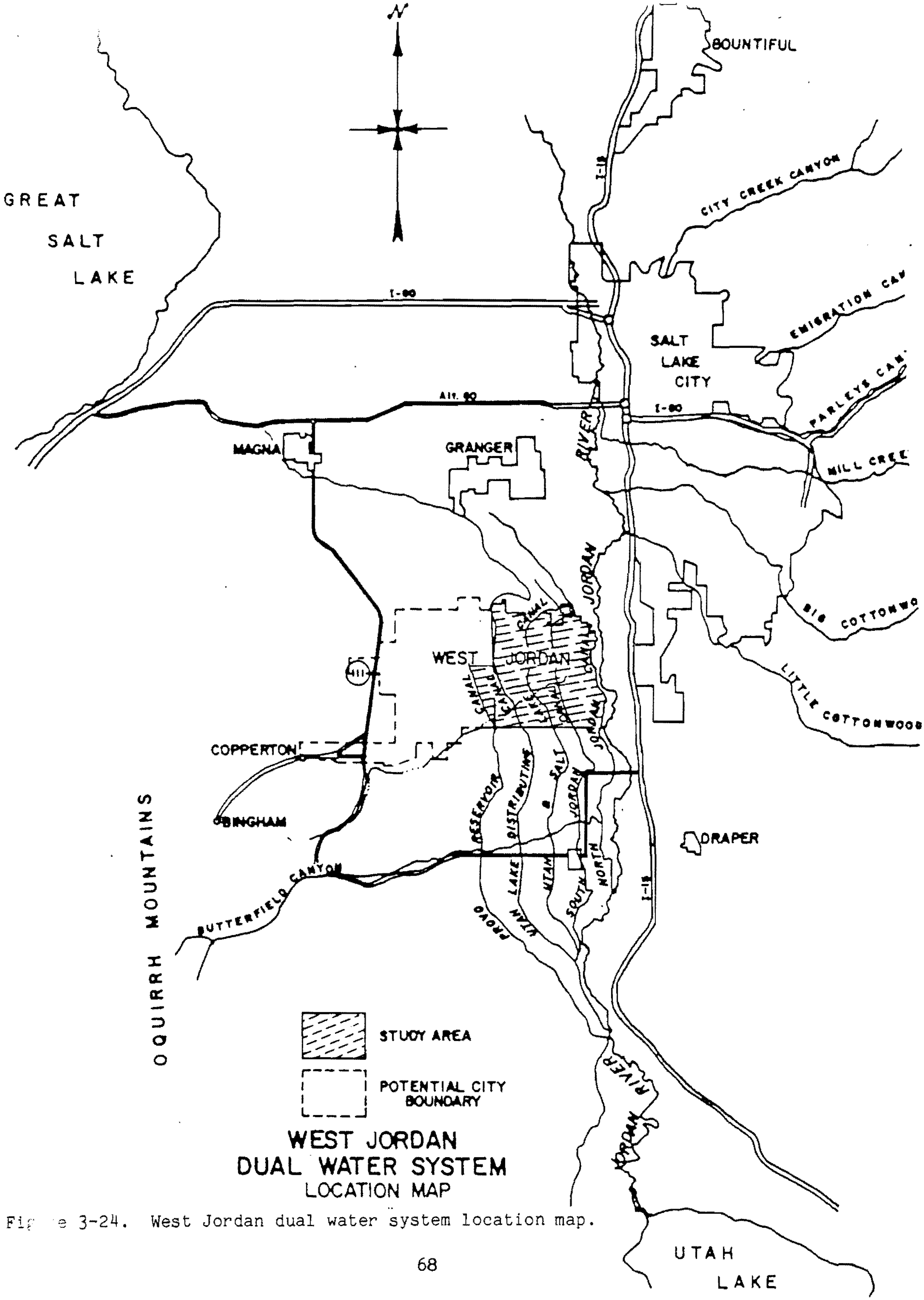
Description of the area. The West Jordan City dual system area encompasses 7,500 acres of gently sloping (0.5-4 percent) land. The location of the study area is shown in Figure 3-24. All of the area prior to about 1940 was in irrigation farming. By 1986 about 50 percent of the land has been subdivided into building lots and houses have been constructed on most of the lots. The current population (1986) is 41,000. There is sufficient land area within the dual system area to accommodate over 80,000 people.

Water rights on the irrigation water are of early priority. Water rights would have to be acquired to meet lawn and garden requirements for the existing residential development. However, the trend in the future is to transfer water rights as agricultural land is being converted into residential areas.

Table 3-11 shows the observed monthly water use in West Jordan during 1985 and the corresponding values computed from the exponential-type demand functions developed by Hansen and Narayanan (1981) for Salt Lake City (SLC). The price of water was taken at $0.51/1000 gal (average price charged by the City of West Jordan in 1985) and the number of municipal connections served by the city was estimated at 10,000. Results show that observed demands were overestimated by approximately 30%, suggesting that water users in SLC are willing to pay more for water than residents in West Jordan, which is consistent with the lower level of income in West Jordan. The SLC demand functions were adjusted to account for the discrepancy and a linear regression analysis was performed on the modified equations. The resulting linear approximations are shown in Table 3-12. They hold as long as the price for water lies within $0.1 and $0.4/100 ft^3, or $0.14 and $0.54/1000 gal.

The general plan of the dual system area, as proposed by the Utah State Division of Water Resources (1980), is shown in Figure 3-25. The area is subdivided into seven subzones, four of which use gravity for pressurization and three require pumping to achieve adequate pressures in the networks. Table 3-13 shows the physical characteristics pertaining to each of the subzones.

Results of the simulation. The model was run using a discount rate of 5.5 percent. It was estimated that it would take the city 14 years to reach 80,000 people, given an initial population estimate of 41,000 people and assuming a 5 percent annual population growth rate. Costs of pipes, reservoirs, and pumping stations reflect 1985 values. Paving costs were chosen at $3/foot. A dual water use of 3 AF/AC/year was assumed in the analysis. A value of 4.25 AF was used for one share of stock of water, and the share was priced at $500. Cost information pertaining to each dual water system is shown in Table 3-14. Benefits from water use were computed using the seasonal pricing model described in Chapter II, with linear demand functions shown in Table 3-12. Benefit information is shown in Table 3-15. The unit cost of groundwater was taken at $60/AF, and the unit cost of imported water was taken at $130/AF.



Fig·re 3-24. West Jordan dual water system location map.

Table 3-11. Observed and computed monthly water use for West Jordan City.

Month	Observed (gal/conn/day)	Computed (gal/conn/day)	Observed / Computed
J	431	550	0.784
F	445	550	0.810
M	427	550	0.776
A	602	720	0.836
M	799	1025	0.780
J	1105	1360	0.813
J	1150	1725	0.667
A	1293	1480	0.874
S	838	1125	0.745
O	477	750	0.636
N	420	550	0.764
D	382	550	0.695

Note: Price of water = $0.51/1000 gal
# of conn = 10,000

Table 3-12. Linear approximation of SLC water demand curves.

$Q = a + bP$, Q in gal/conn/day, P in $/100 ft^3

Month	Total demand curves a	b	r^2
J	871.0	-1199.0	0.93
F	871.0	-1199.0	0.93
M	871.0	-1199.0	0.93
A	1126.4	-1550.6	0.93
M	1603.4	-2207.3	0.93
J	2132.8	-2936.0	0.93
J	2699.1	-3715.6	0.93
A	2329.7	-3207.2	0.93
S	1760.4	-2423.4	0.93
O	1178.7	-1622.6	0.93
N	871.0	-1199.0	0.93
D	871.0	-1199.0	0.93

Month	Outdoor demand curves a	b
A	255.4	-351.6
M	732.4	-1008.2
J	1261.8	-1737.1
J	1828.1	-2516.5
A	1458.1	-2008.0
S	889.4	-1224.3
O	307.7	-423.2

Note: Outdoor demand curves are obtained by horizontally subtracting the indoor demand curves from the total demand curves. January demand curve was taken as representative of indoor demand curves.

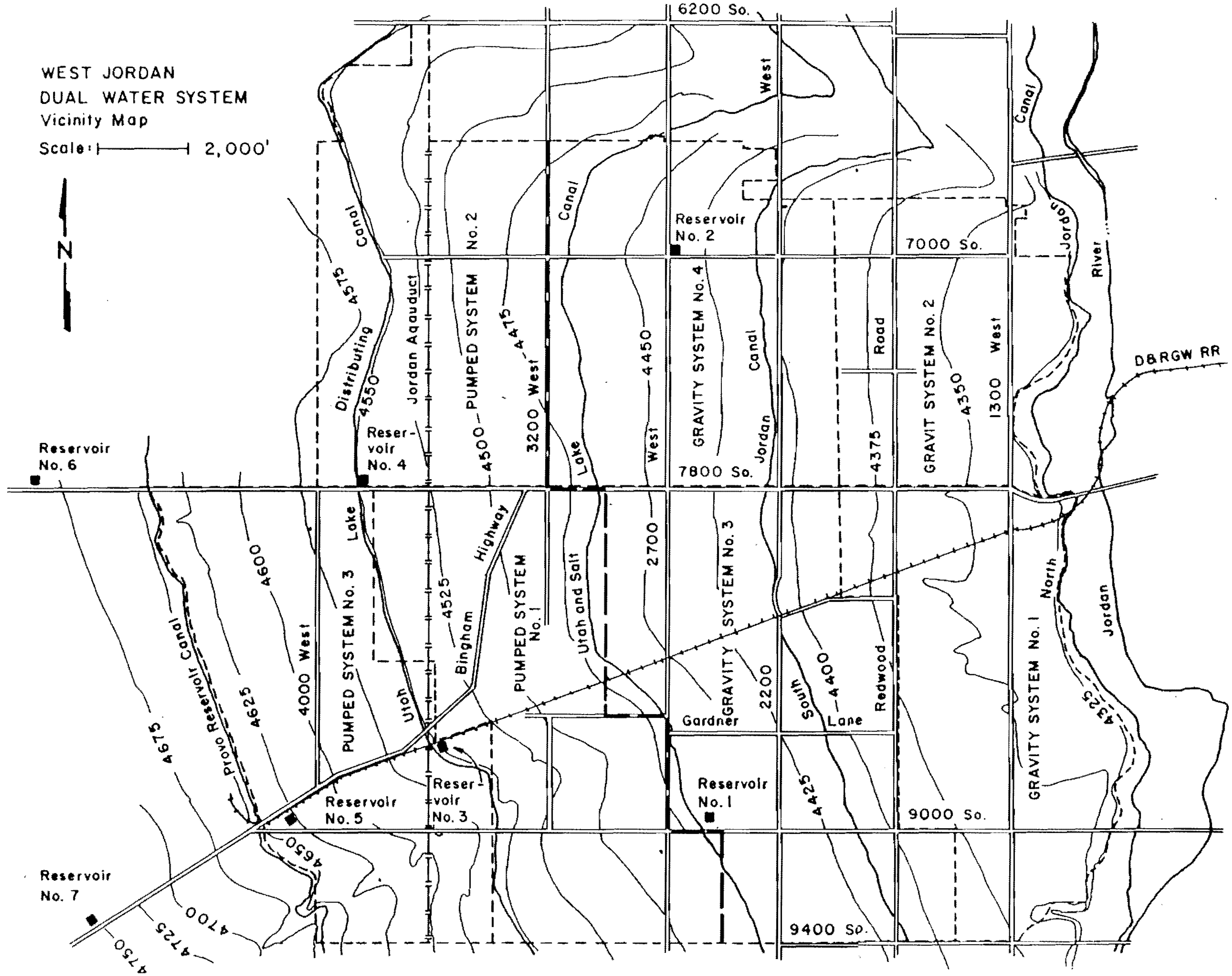


Figure 3-25. West Jordan dual water system vicinity map.

Table 3-13. Physical characteristics of subzones - West Jordan City.

System	Type	Area (acres)	Max. Pop.	Source of Water[a]	Transmission Line Length (feet)	Transmission Line Design Flow (cfs)	Pumping Lift (feet)	Reservoir Cap. (AF)
G-1	Gravity	1,000	10,700	USLC	4,000	32	-	28
G-2	Gravity	700	7,500	USLC	3,500	22	-	19
G-3	Gravity	1,350	14,500	ULDS	3,500	43	-	37
G-4	Gravity	1,100	11,700	ULDS	4,000	35	-	30
P-1	Pumped	1,100	11,700	ULDS	3,500	35	75	30
P-2	Pumped	1,050	11,200	ULDS	6,000	33	175	29
P-3	Pumped	1,200	12,800	ULDS	7,000	38	200	33

[a]USLC: Utah and Salt Lake Canal
ULDS: Utah Lake Diversion Canal

Table 3-14. Cost information on the dual systems - West Jordan City.

System	Network Capital ($)	Network O&M ($/year)	Reservoir Capital ($)	Reservoir O&M ($/year)	Pumping Station Capital ($)	Pumping Station O&M ($/year)	Transmission Line Capital ($)	Transmission Line O&M ($/year)	Water Rights ($)
G-1	1,380,000	11,500	216,000	1,800	0	0	192,000	1,600	113,000
G-2	945,000	7,900	180,000	1,500	0	0	160,000	1,300	138,000
G-3	1,886,000	15,700	252,000	2,100	0	0	202,000	1,700	133,000
G-4	1,600,000	13,400	228,000	1,900	0	0	230,000	1,900	295,000
P-1	1,530,000	12,700	228,000	1,900	156,000	18,400	202,000	1,700	127,000
P-2	1,513,000	12,600	222,000	1,850	258,000	40,400	288,000	2,400	137,000
P-3	1,705,000	14,200	240,000	2,000	301,200	53,200	403,200	3,360	142,000

Note: The capital costs are all increased by 20 percent to allow for contingencies, legal and engineering.

Table 3-15. Benefit information for the City of West Jordan.

Year	Population	No Dual Water Supply System: Total Benefits $	No Dual Water Supply System: Total Benefits $/people	No Dual Water Supply System: Indoor Benefits $	No Dual Water Supply System: Indoor Benefits $/people	With Dual Water Supply System: Outdoor Benefits $	With Dual Water Supply System: Outdoor Benefits $/people
1986	41,000	1.049E6	25.57	7.111E5	17.34	1.025E6	25
1990	49,920	1.245E6	24:94	8.419E5	16.86	1.248E6	25
1994	61,480	1.499E6	24.38	1.000E6	16.26	1.537E6	25
1998	74,640	1.789E6	23.96	1.169E6	15.66	1.866E6	25
2000	80,000	1.903E6	23.57	1.234E6	15.42	2.000E6	25

Results of the simulation show negative net benefits and therefore we conclude that the project should not be built (best benefit cost ratio is 0.93). The overall cost to build and expand the systems was estimated at $13,100,000. The planning report of the Utah Division of Water Resources gives an estimated cost of $13,000,000 in 1980 dollars. Adjustment to 1985 values gives an overall cost of $16,000,000. The difference is in part explained by high unit costs of pipes used in the planning report, which are 20 percent greater than the ones used in the present analysis. The B/C ratio obtained by the UDWR was 0.65.

Three of the irrigation subsystems require pumping. Also, the length of the transmission pipelines from the canals to the regulating reservoirs and back to the irrigated subzones are substantial. The next analysis was done on those subsystems which do not require pumping. These gravity systems cover approximately 4,500 acres. Results of this analysis showed positive net benefits of $0.638 million with a B/C ratio of 1.072. The optimal time to start investing is 1987. Total capital costs to serve 4,500 acres of land were estimated at $8,870,000.

Case 2. West Jordan Special Service Irrigation District

Description of area. The proposed pressure irrigation system is located in an area of gently sloping (2 percent to 4 percent) land which, prior to 1960, was irrigated farmland. The total land area is about 600 acres, 40 percent being subdivided and occupied in 1984. Population in this area was about 2,500 in 1984. Under full development, the system could eventually serve 6,000 people. It is estimated that full development will occur in 2004, which corresponds to an annual growth rate of 5 percent. Figure 3-26 shows the location of the proposed area.

Results of the Simulation

The model was run using the discount rate, unit water demands and paving costs as before. The cost of one share of stock of water (taken at 4.25 AF) was $500. Table 3-16 shows cost information pertaining to the dual system. Benefit information is shown in Table 3-17. Unit costs for ground and imported water were $60/AF and $130/AF, respectively.

Results of the analysis show that the dual water supply system is an economically viable alternative, with benefits of $66,800 and a B/C ratio of 1.08. The optimal time to start investing is 1989. The total capital costs necessary to build and expand the dual water system were estimated at $867,000 in 1985 dollars. The feasibility report for the West Jordan Special Service Irrigation District (Utah Division of Water Resources 1984) shows a total cost of $864,000 in 1984 dollars (907,000 in 1985 dollars) and a B/C ratio of 1.

Summary and Conclusions

A dual water system is one approach to allocating high quality water for culinary purposes and low- or nonpotable-quality water for

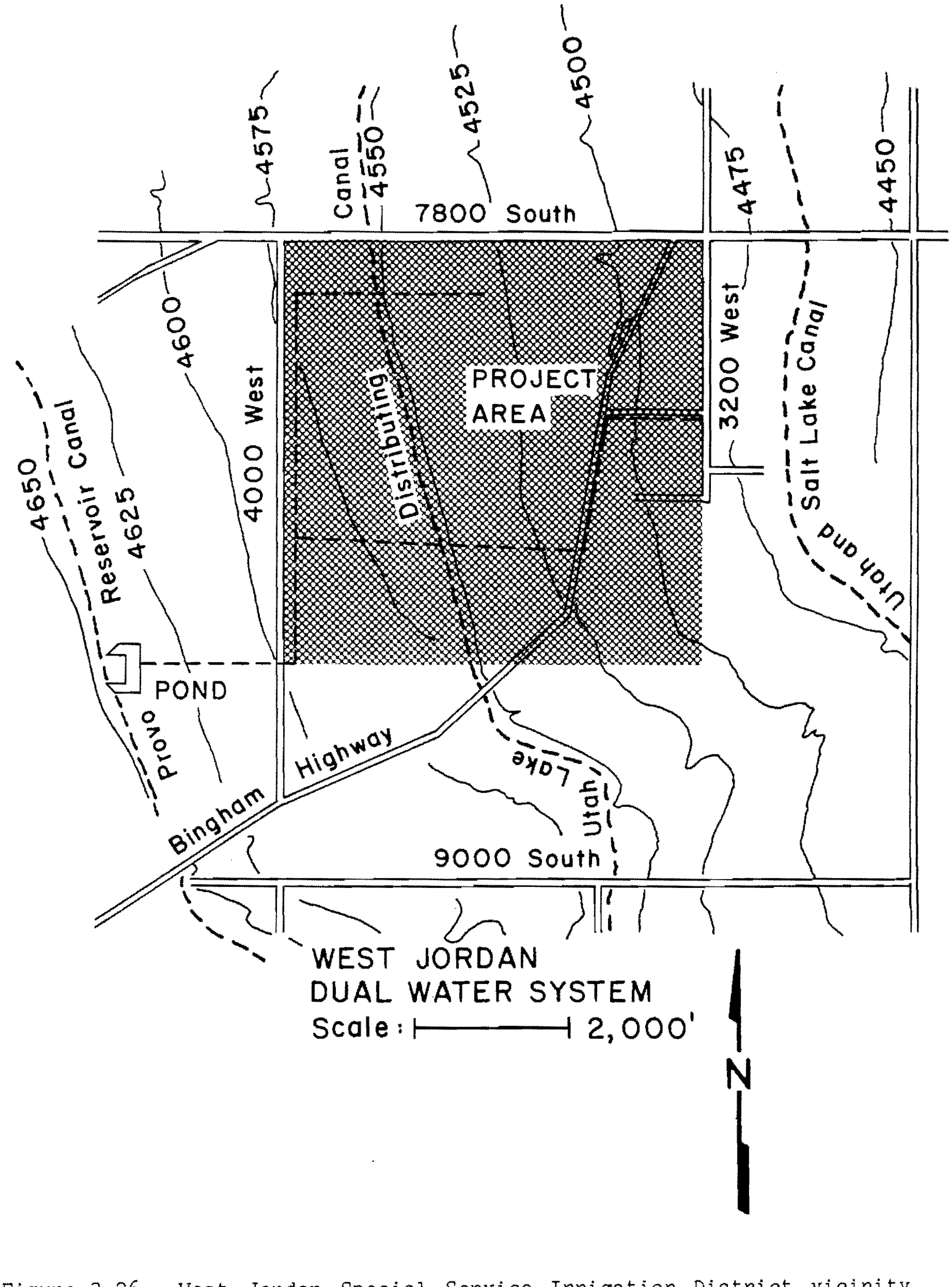


Figure 3-26. West Jordan Special Service Irrigation District vicinity map.

Table 3-16. Cost information on the dual system - West Jordan Special Service Irrigation District.

	Capital Cost ($)	O&M Cost ($/year)
Network	767,000	6,400
Reservoir	144,000	1,200
Pumping station	0	0
Transmission line	64,800	540
Water rights	64,600	-

Note: Capital costs are all increased by 20 percent to allow for contingencies, legal and engineering.

other uses, such as irrigating lawns and gardens. The concept of delivering low quality water under pressure to municipal residences is already widely used in Utah and is receiving an increasing interest in the Western U.S.; dual systems already exist in Idaho, Washington, California, Montana, Wyoming, and Colorado. The ways in which dual systems may produce conservation include:

1. Naturally high quality water is allocated to uses with high quality requirements, therefore, a larger fraction of the population can be supplied with a naturally safe high quality source. This has long been recognized as an important objective from a public health perspective (Okun 1980).

2. The total cost of meeting water demands may be reduced, therefore, increasing social welfare.

A general methodology to evaluate the economic feasibility of dual water systems was elaborated. In a first step, a static analysis (evaluation at a single point in time) was developed. The analysis necessitates the evaluation of:

1. Consumers' and producers' surpluses from water use.

2. Cost (capital and O&M) of the dual water system.

Both consumers' and producers' surpluses are obtained from the multi-source pricing optimization model developed in Chapter II. Required input data are monthly or seasonal water demand functions (indoor, outdoor, and total), water availability from the different sources comprising the region under analysis, and unit cost of treating and delivering water from each source. Generally, price schedules and water demand are available so that total monthly municipal demand functions can be estimated adequately. Monthly indoor demand curves can be well represented by winter demand patterns, and outdoor curves can be obtained by horizontally subtracting the indoor demand from the total

Table 3-17. Benefit information for the West Jordan Special Service Irrigation District.

Year	Population	No Dual Water Supply System: Total Benefits $	No Dual Water Supply System: Total Benefits $/person	No Dual Water Supply System: Indoor Benefits $	No Dual Water Supply System: Indoor Benefits $/person	With Dual Water Supply System: Outdoor Benefits $	With Dual Water Supply System: Outdoor Benefits $/person
1984	2,400	61,368	25.57	41,058	17.10	60,000	25
1990	3,000	74,820	24.94	48,900	16.30	75,000	25
1995	3,700	90,206	24.38	58,806	15.89	92,500	25
2000	4,700	112,612	23.96	71,922	15.30	117,500	25
2004	6,000	141,478	23.57	88,238	14.71	150,000	25

demand curves. Water availabilities as well as unit cost of sources usually can be obtained for any city. However, because the multi-source pricing model necessitates considerable efforts in the preparation of the required input files, a matrix generator was developed that could easily create such files. With the matrix generator, consumers' and producers' surpluses can be easily and rapidly obtained for any sites.

The evaluation of capital and O&M costs of dual systems is normally an expensive task requiring several weeks of effort. Substantial research effort was devoted to development of a generalized model for quickly estimating these costs for any particular site. The dual water system was subdivided into three main components--transmission line, distribution line, and laterals--and detailed hydraulic-cost models were developed for each component. The models were then used in a regression analysis to determine if simpler cost relationships can adequately simulate the cost of dual water systems. Such relationships were derived for the laterals and distribution lines, however, no attempt was made to obtain regression cost functions for the transmission conduits since each case is site specific. In the latter case, a matrix generator was developed to create the input files necessary to run the hydraulic-cost model.

The static analysis for benefits and costs was extended to a dynamic approach where water demand is increasing over time (the total population to be served is growing) and where a dual water system is allowed to expand. The question here was the optimum time to start the construction of a dual water system that would maximize the social welfare. A model that determines the "best" time to start investing in dual systems was developed and the computer code was written in FORTRAN language. The interactive computer program requires very few data and parameters. The user has the possibility to modify parameters such as the interest rate and the unit cost of pipes, and he can perform a dual system analysis for all or parts of the municipality under study.

Results from the regression cost functions were very encouraging. For example, the results of a recent cost estimate by a consulting engineer for a dual water system in West Jordan, Utah, were $907,000 in 1985 dollars (Utah State Department of Water Resources 1984) as compared to $867,000 with the cost functions. Cost analysis of the dual water system in Haights Creek, Utah, revealed a difference of 7.5 percent between the costs from the bid schedule and those obtained from the regression cost functions. The traditionally expensive and time consuming studies required to develop cost estimates for each system can now be done quickly and at much lower cost with the tools developed here.

The timing of investment model was run for a hypothetical example and the sensitivity of the model to various parameters was assessed. Analysis of the hypothetical example demonstrated that the economic viability of the dual water system alternative is particularly sensitive to:

1. Discount rate. An increase in the discount rate had the consequence of postponing the construction of dual water systems and reducing the overall benefits.

2. Population growth. The analysis showed that a fast growing city is a good candidate for the dual water system alternative since large benefits and immediate construction are encouraged by high population growth rates.

3. Unit cost of culinary water. High unit costs to treat and distribute the culinary water have a positive effect on the feasibility of the dual system alternative. Low unit costs caused a delay in the investment and a reduction in the social welfare.

4. Location of the source of irrigation water and need for pumping. The sensitivity analysis showed that a remote source of water and/or necessity of pumping to maintain adequate processes in the irrigation system may cause the dual system to be economically infeasible.

5. Water right acquisition. In the case where water rights come with the land, the model gave larger benefits and early optimal timing of system construction than when water rights have to be purchased.

Thus from the sensitivity analysis, the ideal setting for a dual water system is:

- low discount rate
- fast growing city
- proximity of irrigation water
- gravity-fed irrigation system
- water rights that come with the land
- high cost of culinary water treatment and delivery

The model was also applied to the City of West Jordan. This city is characterized by a high population growth rate (5 percent). About 60 percent of the city would be fed by a gravity system with sources of water near the irrigated zone and 40 percent would need pumping. Water rights come with the land as agricultural land is converted into residential areas. Model results showed that the dual water system is not economically feasible when applied to the entire city, but generates profits if the subareas requiring pumping to maintain adequate pressures in the irrigation systems are removed from the analysis. Application of the model to the West Jordan Special Service Irrigation District (where a dual system is currently being proposed) resulted in positive net benefits. In both the hypothetical and the West Jordan applications, the model results were consistent with the ideal setting characteristics described above. The model results also agreed closely with the engineering studies on the West Jordan total city and the subsystem.

CHAPTER IV

OPTIMAL CAPACITY DETERMINATION OF CONJUNCTIVELY-USED IMPORT WATER

Introduction

Problem Description

With rapid urbanization, many communities in the U.S. will face substantial increases in water demand for municipal, industrial, commercial, and other public uses. In the western states, the traditional approach to cope with this increased demand is to develop new water supplies of higher quality from distant sources. These imports are generally obtained at a higher marginal cost than existing local sources. In areas where importing water is an economically feasible alternative, the capacity of water conveyance systems should be selected optimally considering the possibility of conjunctively using local surface and groundwater along with import water. That is, the quantity of water to be imported should be decided upon conditionally, relative to local water availability. This could result in considerable savings in capacity costs and in the cost of utilizing more expensive import water.

Alternative Approaches to Water Supply Design

Traditionally, the processes of water supply system sizing, operation, and pricing of water deliveries have been conducted relatively independently and without the benefit of market information about the value of water use. Typically, in sizing a municipal water supply system, "requirements" are forecast from per capita use rates and population projections, and a least-cost system is designed to meet these "requirements." Water pricing policies and prices are then set by a political or quasi-political body, and the system is managed, to the extent possible, to satisfy the demands which result from the selected pricing scheme and to meet revenue obligations. These procedures incorporate little feedback between prices and quantities of water demanded and can be expected to result in inefficient use of the water resource and/or unnecessarily large capital investment in water supply facilities.

In contrast to a "requirements" approach, many authors have proposed that municipalities consider water pricing as a tool in the design process to reduce the capital cost of new systems, and in the management of existing systems in order to increase the efficiency of resource use. The point to be made here is that the quantity of water demanded--and hence the quantity of water that must be supplied from new, more expensive sources--is a function of the price charged for water. Therefore, the optimal design for water import facilities should be obtained with reference to both the desired pricing policy (whether a uniform rate across the year or a variable price that changes seasonally) and the price consumers must pay.

Hydrologic Stochasticity and Consumer Benefits

For a variety of reasons, the determination of the combination of water price and system size that maximizes the net benefits derived from water use is not a simple problem. Since water supplies are stochastic, the quantity of water which will be available for use in a future season is unknown. Even if demands for that season are assumed to be deterministic, it is not easy to pick, a priori, the optimal price to charge for water in that season since it is not known whether the amount of water which will be available will be sufficient to meet the quantity demanded at the price selected. It is difficult to determine optimal system capacity for import water even under the assumption that prices can be set after observing supplies. However, in the real world, water prices are inflexible due to high administrative costs involved in changing prices from season to season or year to year. Prices, once selected, are fixed in this analysis. The problem is to find the optimal price (or a set of prices in the case of seasonal pricing) that maximize expected net benefits. If the price is set too low, demands will exceed the quantity available and benefits will be reduced through the imposition of rationing schemes. If the price is set too high, demands will be less than the quantity available and benefits which could be obtained through increased water use will be foregone.

Summary and Objectives

Determining the optimal size of water import facilities is inextricably related to the issue of establishing the optimal water price, and is made more difficult by the stochastic nature of the resource. In light of these complexities, the basic objective of the study was to examine the problem of optimal capacity determination for imported water, conjunctively utilizing local sources which are stochastic. Specifically, the study has sought to:

1. formulate alternative capacity optimization models;

2. use these models to compute the optimal size of import facilities for a municipal supply problem; and

3. compare and contrast the results of the various models in terms of the optimal capacity of the import system and the price and quantity of water demanded.

The following sections describe accomplishments of these specific objectives.

Formulation of Models

General Approach

A wide range of alternatives is available for constructing a model for determining the optimal capacity of import facilities. A central theme of this research is that the optimal size of import facilities will be a function of the modeling approach used in the optimization.

More specifically, modeling approaches which place artificial, nonmarket constraints on the analysis of water supplies and consumer benefits will yield water supply system designs that are larger and more costly than designs that are based on the fundamental concepts of price theory. Two models were formulated to explore this thesis. The first, called the "risk neutral model," is a stochastic programming model which treats benefits of water use as a random variable. It seeks to optimize the expected net benefits of municipal water supply. The second model, the "risk averse" model, is the same as the risk neutral model except that an additional constraint is included which specifies that the probability of shortfall in any month must be less than 5%. For this project, the phrases "risk neutral" and "risk averse" do not have the technical meanings commonly given them in the decision analysis literature. The intention in adopting this terminology is only to convey an attitude toward risk of shortfall. Both models have been constructed so that seasonal or uniform pricing policies could be explored.

The following sections describe the models and also discuss the approach which should be followed to use them in determining the optimal system import capacity.

Benefits and Costs of Water Supply

The gross benefits associated with municipal water use can be expressed as the area under the demand curve for water. If the inverse demand for water in season t is given by $P_t = P_t(Q_t)$, where P_t is the price and Q_t is the quantity demanded at that price, then the gross benefits provided by supplying Q_t units of water is

$$B_t(Q_t) = \int_0^{Q_t} P_t(q)\, dq \qquad (4\text{-}1)$$

If there are n sources of water in season t, represented by supply quantities of q_{1t}, q_{2t}, ..., q_{nt}, and if these have constant marginal supply costs of $C_1 < C_2 < \ldots < C_n$, respectively, then the net benefit, NB_t, of using the quantities q_{it} to provide Q_t units of water is

$$NB_t = B_t(Q_t) - \sum_{i=1}^{n} C_i\, q_{it} \qquad (4\text{-}2)$$

The Risk Neutral Model

The risk neutral model has as its objective the maximization of expected net benefits of municipal water supply. To understand the stochastic model, it is first necessary to understand how expected net benefits of water supply can be calculated. (A similar expected value computation is developed by Crew and Roberts (1970), and is discussed in more detail by McKee (1985).) If a single user has an inverse demand for water in season t given by $P_t = P_t(Q_t)$ and if the user has n stochastic inflow sources that provide quantities q_{1t}, q_{2t}, ..., q_{nt}, which have constant marginal costs $c_1 < c_2 < \ldots < c_n$, then at a price of $P_t = P^*$ and demand $Q_t(P^*) = Q^*$, net benefits in season t can be computed from

$$
NB_t = \begin{cases}
B(Q^*) - c_1 Q^* & \text{if } Q^* \le q_{1t} \\
B(Q^*) - c_1 q_{1t} - c_2(Q^* - q_{1t}) & \text{if } q_{1t} \le Q^* \le q_{1t} + q_{2t} \\
B(Q^*) - c_1 q_{1t} - c_2 q_{2t} - c_3(Q^* - q_{1t} - q_2) & \\
\qquad \text{if } q_{1t} + q_{2t} < Q^* \le q_{1t} + q_{2t} + q_{3t} & \\
\vdots & \\
B(Q^*) - \sum_{i=1}^{n-1} c_i q_{it} - c_n(Q^* - \sum_{i=1}^{n-1} q_{it}) & \\
\qquad \text{if } \sum_{i=1}^{n-1} q_{it} < Q^* \le \sum_{i=1}^{n} q_{it} & \\
B(\sum_{i=1}^{n} q_i) - \sum_{i=1}^{n} c_i q_{it} & \text{if } \sum_{i=1}^{n} q_{it} < Q^*
\end{cases} \qquad (4\text{-}3)
$$

If the random sources have independent probability density functions $f_{1t}(q_{1t})$, ..., $f_{nt}(q_{nt})$, the expected net benefit associated with price P* is:

$$
\begin{aligned}
E[NB_t] = & \int_{Q^*}^{\infty} [B(Q^*) - c_1 Q^*]\, f_1(q_{1t})\, dq_{1t} \\
& + \int_0^{Q^*} \Big(\int_{Q_1^*}^{\infty} [B(Q^*) - c_1 q_{1t} - c_2(Q^*-q_{1t})] f_{1t}(q_{1t}) f_{2t}(q_{2t}) dq_{2t}\Big) dq_{1t} \\
& + \ \ldots \\
& + \int_0^{Q^*} \Big(\int_0^{Q_1^*} (\ldots \Big(\int_{Q_{n-1}^*}^{\infty} [B(Q^*) - C_{n-1} - c_n Q_{n-1}^*] F_n\, dq_{nt}\Big) \ldots) dq_{2t}\Big) dq_{1t} \\
& + \int_0^{Q^*} \Big(\int_0^{Q_1^*} (\ldots \Big(\int_0^{Q_{n-1}^*} [B(\sum_{i=1}^{n} q_{it}) - C_n]\, F_n\, dq_{nt}\Big) \ldots) dq_{2t}\Big) dq_{1t}
\end{aligned}
$$

(4-4)

where

$$
Q_k^* = Q^* - \sum_{i=1}^{k} q_{it}, \quad C_k = \sum_{i=1}^{k} c_i q_{it}, \text{ and } F_k = \prod_{i=1}^{k} f_{it}(q_{it}).
$$

This statement of expected net benefits assumes that there are no inefficiencies in the allocation of water in the event of a shortfall. That is, Equations (4-3) and (4-4) assume that when the total water supply is less than the quantity demanded (i.e., $\sum_{i=1}^{n} q_{it} < Q^*$), rationing mechanisms--such as resalable coupons--are used which eliminate welfare losses associated with rationing. The administration costs of implementing these mechanisms are also assumed to be negligible.

The objective function of the stochastic model is easily formulated from Equation (4-4) by making the following observations and substitutions:

1. q_{nt} is the quantity of water which may be imported, and it has a marginal cost of C_n which is exclusive of any capital costs of the import facilities;

2. q_{nt} has an upper bound, q_{ntmax}, which is determined by the size of the import structures; and

3. the quantity of water available for import in season t is a discrete random variable having a probability density function given by

$$f_{nt}(q_{nt}) = \begin{cases} 0 & \text{for } q_{nt} < 0 \\ 1.0 & \text{for } 0 \leq q_{nt} \leq q_{ntmax} \\ 0 & \text{for } q_{ntmax} < q_{nt} \end{cases}$$

With these additional specifications on the interpretation of the notation in Equation (4-4), the stochastic model becomes:

$$\text{maximize} \quad \sum_{t=1}^{T} E[NB_t] \qquad (4\text{-}5)$$

subject to the following constraints:

$$Q_1 - \gamma_t Q_t = 0 \qquad t = 2, \ldots, T \qquad (4\text{-}6)$$

$$Q_t \leq \sum_{i=1}^{n} q_{itmax} \qquad t = 1, \ldots, T \qquad (4\text{-}7)$$

where all variables are as previously defined. Equation (4-6) represents the set of constraints which requires a uniform pricing policy and could be modified to accommodate seasonal pricing policy as described in Equation 2-10 of Chapter II. Equation (4-7) simply requires that prices be selected so that the quantity demanded in any season will not exceed the combined maximum flows of all sources.

The Chance Constrained Model

To create the chance constrained model from the stochastic model, Equation (4-7) was rewritten as a chance-constraint to ensure that the probability that demand would exceed supply would be no greater than some arbitrary level. For all runs of this model, the probability of shortfall imposed was 5 percent.

Determination of the Optimal Import Capacity

Neither of the models formulated in the preceding sections include information about the capital and operating costs of import facilities, so a solution will not directly identify an optimal design of the import system. The optimal facility size is found by equating the marginal cost of imports to the marginal benefit. Both of the models described above can be solved a number of times, each time using a different value for the maximum possible quantity of water that can be imported. The marginal benefit curve can then be found by plotting the ratio of the incremental change in net benefits (or expected net benefits) to the increment in imports against the quantity of imports. Standard engineering analysis can then be used to obtain the marginal cost curve, and the optimal design found by seeking the import facility size at which the marginal benefit and marginal cost curves cross. The following sections present an example of how the foregoing models can be used, and discuss the implications of the alternative modeling approaches.

Application of the Models

A Hypothetical Water Supply Problem

The models described in the previous sections were applied to a hypothetical water supply problem involving imports to a large municipal system. While the problem is only hypothetical, it is patterned after the municipal water supply situation currently found in Salt Lake City, Utah. The data provided by McKee (1985), describing the seasonal availability of surface and groundwater for Salt Lake City municipal, were used to construct probability density functions for local sources. To simplify the calculation of expected net benefits required by Equation (4-5), all water supply sources were treated as discrete, rather than continuous, random variables. The constant-elasticity demand curves for Salt Lake City already described in Chapter II were used to supply the seasonal benefit functions called for in Equation (4-1) as well as the coefficients in Equation (4-6) which specify the water pricing policy. These seasonal demand curves have the form

$$Q_t = K_t \; P_t^{-\alpha}$$

where K_t is a function of population, seasonal precipitation, and mean temperature, α is the price elasticity of demand, and Q_t and P_t are as previously defined. Values for K_t were taken from Hansen (1981) and adjusted to Salt Lake City 1980 population levels. All prices are in 1980 dollars.

The hypothetical water import problem has five local water sources. Four of these are stochastic surface flows. The fifth local source is groundwater pumping, which is treated as a deterministic supply with upper bounds on the quantity of well water which can be pumped in any given season. The hypothetical problem contrasts with the actual water supply situation in that Salt Lake City really has five major surface sources. The source that has been left out in this analysis is water imports from the Provo River. The water supply costs of the five local sources are taken from marginal cost estimates in Chapter II. Table 4-1 summarizes some basic characteristics of the local supplies.

Table 4-1. Characteristics of local supplies for the hypothetical problem.[a]

Source No.	Salt Lake City Source	Mean Annual Flow (1000 ac ft)	Annual Average Use by Salt Lake City (1000 ac ft)[b]	Assumed Marginal Cost ($/ac ft)
1	Big Cottonwood Cr.	42.4	22.5	66.71
2	Little Cottonwood Cr.	16.3	13.7	71.34
3	Parleys Cr.	15.5	11.0	73.60
4	Pumped Wells	-	6.8	78.75
5	City Cr.	10.7	7.7	81.02

[a]Water year is May-April.
[b]Data from Salt Lake City municipal water supply records, 1961-1979.

In the actual Salt Lake City supply system, two local streams have reservoir storage (Parleys Creek, with about 3200 ac ft, and Big Cottonwood Creek, with about 1700 ac ft). Storage on a stream changes the probability density functions that describe seasonal stream flows. If reservoir operating rules are known, new density functions for water available for municipal supply can be found. The operating rules identified by McKee (1985) were used to derive such density functions for the hypothetical problem.

Application and Results

The two models were each solved for a range of possible maximum seasonal import levels. This was done for both a uniform pricing policy and a seasonal pricing policy. For the seasonal pricing policy, the models were constrained to select seasonal demand quantities (Q_t) such that the month of August and September would have one price, and the remaining months would have another. This was consistent with the findings of Chapter II and McKee (1985), where it was determined that an optimal seasonal pricing policy for Salt Lake City would involve only two price changes per year. Tables 4-2 through 4-5 summarize the results of the model runs for both pricing policies.

Optimal Capacity of Import Facilities

As can be seen from Tables 4-2 through 4-5, the marginal benefit curves for the deterministic and stochastic models are quite similar. This is more easily seen from Figure 4-1, which graphically illustrates the differences between the risk neutral and risk averse models. For any positively-sloped marginal cost curve for new import facilities, the risk neutral model (under either the uniform or seasonal pricing policies) would identify a smaller and less costly "optimal" facility than the risk averse model. Moreover, while the effect of pricing policy is negligible for the risk neutral model, the risk averse model generates very different marginal benefit curves for the two pricing policies. The marginal benefit curve from the seasonal pricing policy lies substantially to the left of that of the uniform pricing policy, and would provide "optimal" facilities considerably smaller and cheaper than the uniform pricing policy. While the selection of a maximum monthly shortfall probability dominates the search for an optimal facility size, the effect of the pricing policy adopted becomes more important as the requirement for security of water deliveries becomes more severe.

The following example will illustrate the costs to society of a more secure water supply. Assume a constant marginal cost curve for the import facility equal to $300/year/ac ft-mo. Plotting this on Figure 4-1 would yield the "optimal" facility sizes listed in Table 4-6 for the various combinations of model types and pricing policies. The table also shows the expected annual benefits, net of facilities costs. In this example, the risk neutral policy generates import facility sizes approximately one-third as large as that of the risk averse model under seasonal pricing, and less than a quarter as large as the risk averse uniform pricing version. Moreover, the net benefits are greater for the risk neutral model than for the risk averse model for either pricing policy.

Price of Water and Quantity Demanded

Tables 4-7 and 4-8 present the optimal price and annual demand found for the stochastic and chance constrained models, respectively. Figure 4-2 shows the maximum price of water as determined by the two models. Obviously, from the standpoint of price to the consumer, the solution identified by the risk averse model becomes competitive with that of the risk neutral model only at very large import capacity sizes. This is also reflected in Figure 4-3, where the total annual quantity demanded is similar for the two models only for very large import facilities.

Conclusions and Caveats

The principal conclusion that can be drawn from the foregoing analysis is that the "optimal" size of import facility is very much a function of the risk of shortfall that society is willing to accept.

Table 4-2. Results of risk neutral model runs, uniform pricing policy.

Run No.	Maximum Monthly Import (1000 ac ft)	Increment of Imports (1000 ac ft)	Mean of Consecutive Imports (1000 ac ft)	Objective Function Value (10^6 $)	Increment of Objective Function (10^6 $)	Marginal Benefit ($/ac ft)
18	0			23.73		
		0.5	0.25		0.43	860
19	0.5			24.16		
		0.5	0.75		0.26	520
20	1.0			24.42		
		0.5	1.25		0.14	280
21	1.5			24.56		
		0.5	1.75		0.07	140
22	2.0			24.63		
		0.5	2.25		0.06	120
23	2.5			24.69		
		0.5	2.75		0.04	80
24	3.0			24.73		
		0.5	3.25		0.03	60
25	3.5			24.76		
		0.5	3.75		0.02	40
26	4.0			24.78		
		1.0	4.5		0.01	10
27	5.0			24.79		

Table 4-3. Results of risk neutral model runs, seasonal pricing policy.

Run No.	Maximum Monthly Import (1000 ac ft)	Increment of Imports (1000 ac ft)	Mean of Consecutive Imports (1000 ac ft)	Objective Function Value (10^6 \$)	Increment of Objective Function (10^6 \$)	Marginal Benefit (\$/ac ft)
28	0			23.79		
		0.5	0.25		0.40	800
29	0.5			24.19		
		0.5	0.75		0.23	460
30	1.0			24.42		
		0.5	1.25		0.14	280
31	1.5			24.56		
		0.5	1.75		0.07	140
32	2.0			24.63		
		0.5	2.25		0.06	120
33	2.5			24.69		
		0.5	2.75		0.04	80
34	3.0			24.73		
		0.5	3.25		0.03	60
35	3.5			24.76		
		0.5	3.75		0.02	40
36	4.0			24.78		
		1.0	4.5		0.01	10
37	5.0			24.79		

Table 4-4. Results of risk averse model runs, uniform pricing policy.

Run No.	Maximum Monthly Import (1000 ac ft)	Increment of Imports (1000 ac ft)	Mean of Consecutive Imports (1000 ac ft)	Objective Function Value (10^6 $)	Increment of Objective Function (10^6 $)	Marginal Benefit ($/ac ft)
38	0			17.08		
		1.0	0.5		2.88	2880
39	1.0			19.96		
		1.0	1.5		1.80	1800
40	2.0			21.76		
		1.0	2.5		1.22	1220
41	3.0			22.98		
		1.0	3.5		0.82	820
42	4.0			23.80		
		1.0	4.5		0.52	520
43	5.0			24.32		
		1.0	5.5		0.31	310
44	6.0			24.63		
		1.0	6.5		0.15	150
45	7.0			24.78		
		1.0	7.5		0.02	20
46	8.0			24.80		

Table 4-5. Results of risk averse model runs, seasonal pricing policy.

Run No.	Maximum Monthly Import (1000 ac ft)	Increment of Imports (1000 ac ft)	Mean of Consecutive Imports (1000 ac ft)	Objective Function Value (10^6 $)	Increment of Objective Function (10^6 $)	Marginal Benefit ($/ac ft)
47	0			21.31		
		1.0	0.5		1.97	1970
48	1.0			23.28		
		1.0	1.5		0.66	660
49	2.0			23.94		
		1.0	2.5		0.41	410
50	3.0			24.35		
		1.0	3.5		0.24	240
51	4.0			24.59		
		1.0	4.5		0.12	120
52	5.0			24.71		
		1.0	5.5		0.06	60
53	6.0			24.77		
		1.0	6.5		0.03	30
54	7.0			24.80		
		1.0	7.5		0	0
55	8.0			24.80		

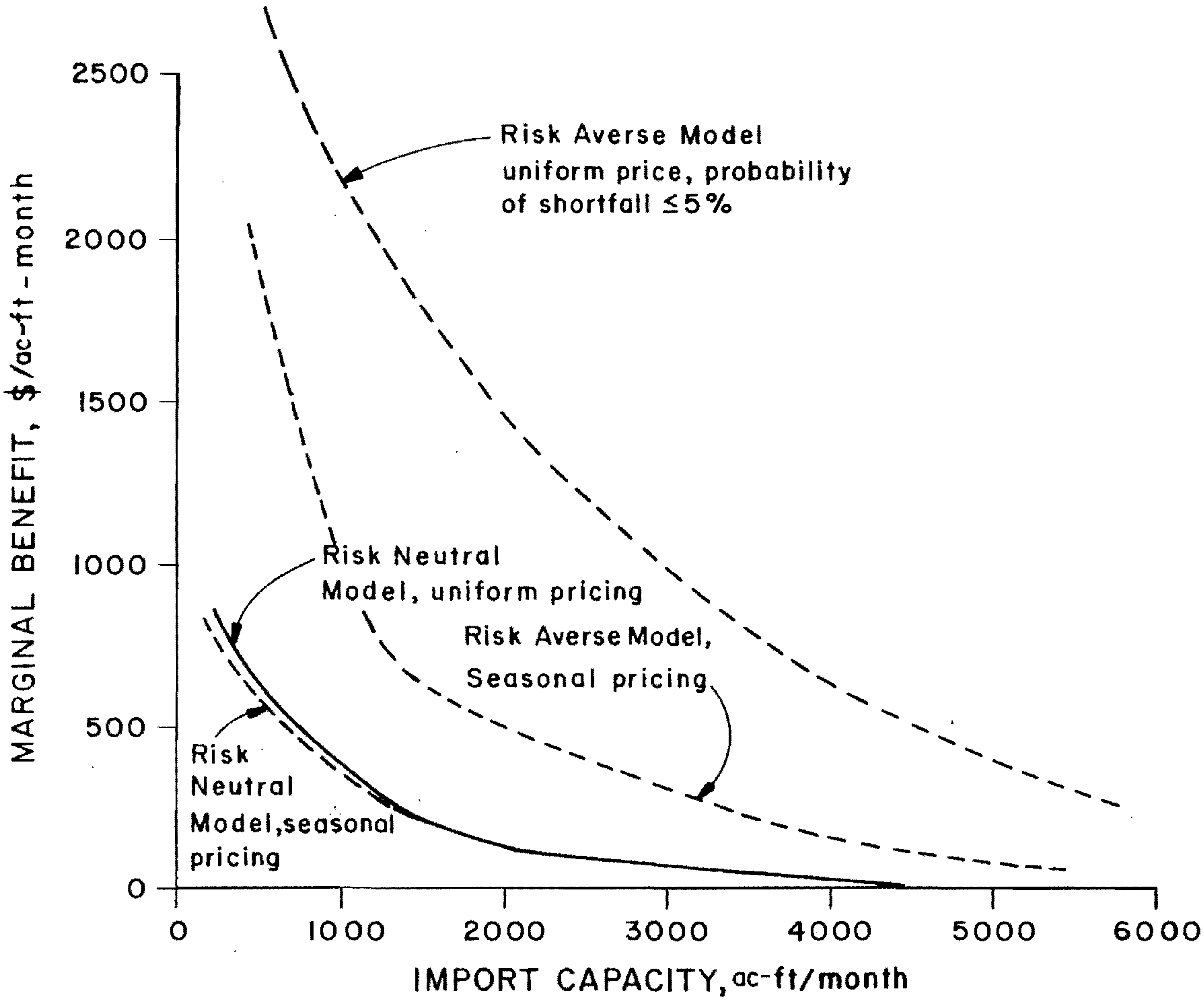


Figure 4-1. Marginal benefit variation with import capacity.

Table 4-6. Summary of price and quantity, risk averse model runs.

Uniform Pricing Policy			Seasonal Pricing Policy		
Import Size (1000 ac ft)	Max. Price of Water ($/ac ft)	Annual Demand (1000 ac ft)	Import Size (1000 ac ft)	Max. Price of Water ($/ac ft)	Annual Demand (1000 ac ft)
0	111.62	87.13	0	111.62	94.0
0.5	99.19	92.09	0.5	99.19	97.6
1.0	88.68	97.06	1.0	90.00	100.4
1.5	84.46	99.30	1.5	90.00	98.6
2.0	86.20	98.34	2.0	90.00	97.9
2.5	86.37	98.27	2.5	86.26	101.6
3.0	86.49	98.20	3.0	90.00	97.8
3.5	86.57	98.16	3.5	90.00	97.8
4.0	86.74	98.07	4.0	90.00	97.8
5.0	87.07	97.90	5.0	90.00	97.8

Table 4-7. Summary of price and quantity, risk averse model runs.

Import Size (1000 ac ft)	Uniform Pricing Policy: Maximum Price of Water ($/ac ft)	Uniform Pricing Policy: Annual Demand (1000 ac ft)	Seasonal Pricing Policy: Maximum Price of Water ($/ac ft)	Seasonal Pricing Policy: Annual Demand (1000 ac ft)
0	537.40	41.69	537.40	56.82
1.0	374.90	49.36	374.90	70.94
2.0	279.80	56.62	279.80	77.44
3.0	216.40	63.88	216.40	83.94
4.0	172.00	71.14	172.00	90.45
5.0	139.80	78.40	139.80	93.50
6.0	115.80	85.66	115.80	95.23
7.0	97.30	92.91	97.30	96.96
8.0	87.30	97.79	90.00	97.79

Table 4-8. Comparison of optimal facility sizes.[a]

Model and Pricing Policy	Optimal Facility Size (1000 ac ft/mo)	Facilities Annual Cost ($10^6)	Expected Annual Net Benefits[b] ($10^6)	Expected Annual Net Benefits Less Facilities Costs ($10^6)
Risk neutral, uniform pricing	1.2	0.36	7.40	7.04
Risk neutral, seasonal pricing	1.1	0.33	7.37	7.04
Risk averse, uniform pricing	5.6	1.68	7.43	5.75
Risk averse, seasonal pricing	3.2	0.96	7.32	6.36

[a]For a constant marginal cost of $300/ac ft-mo.
[b]Does not include import facilities cost.

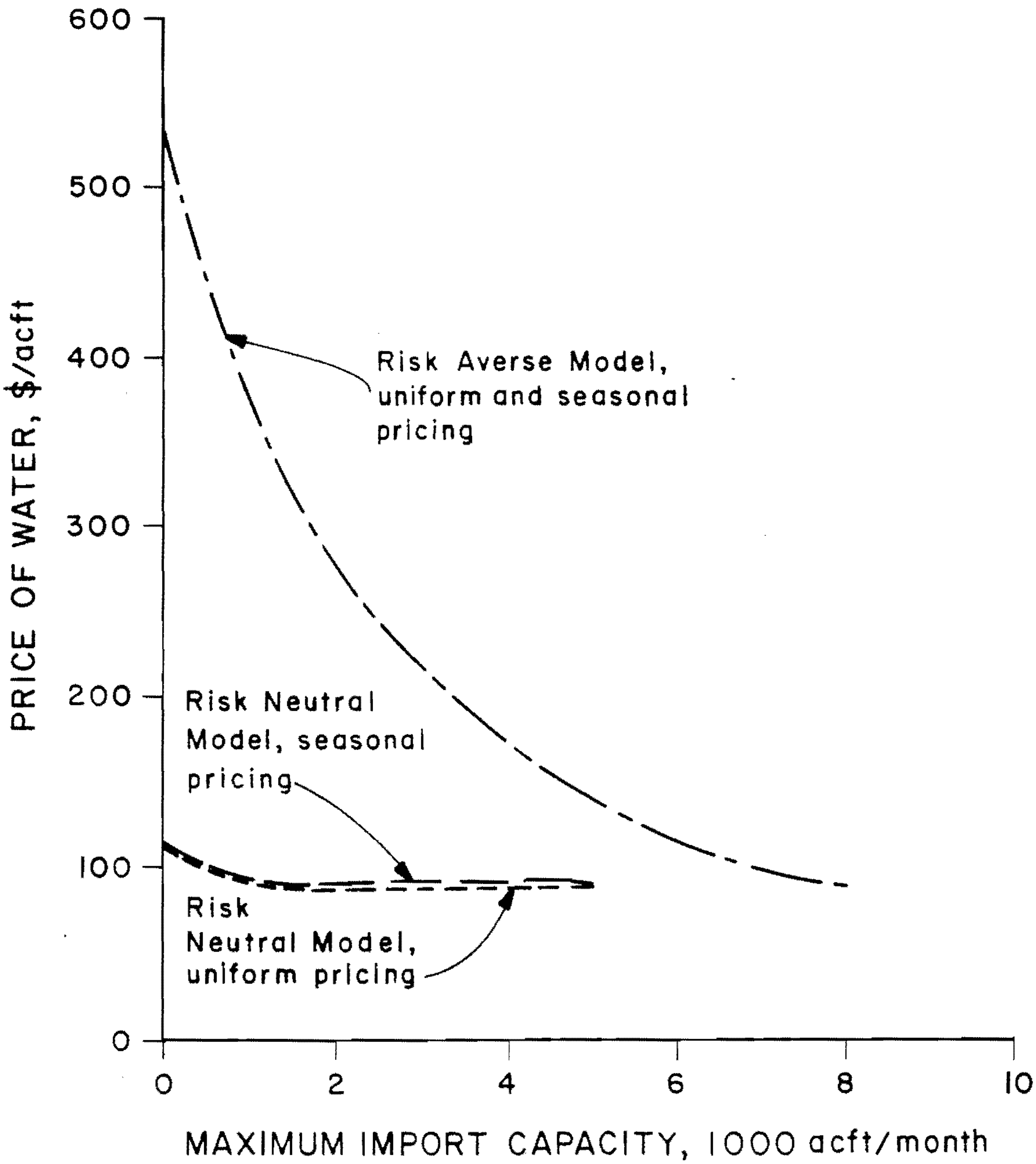


Figure 4-2. Price of water variation with import capacity.

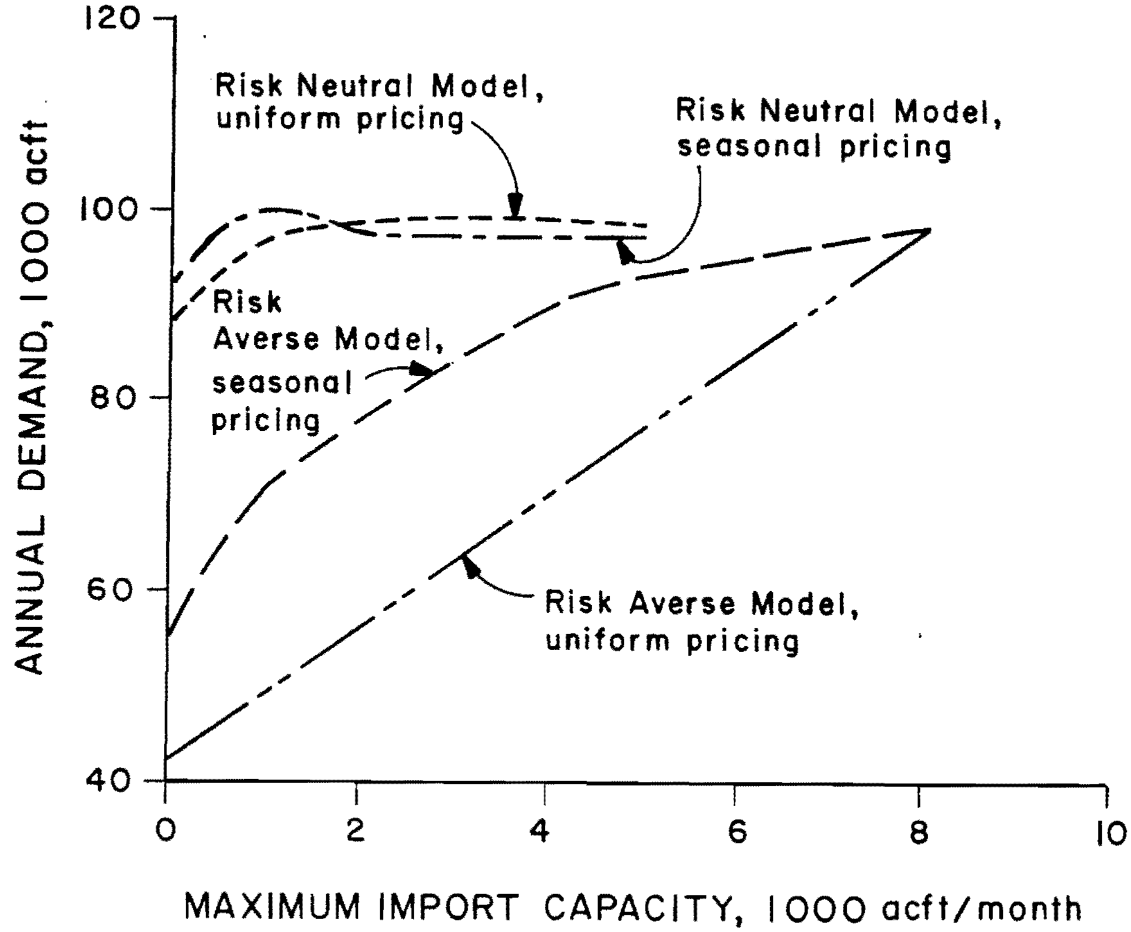


Figure 4-3. Annual demand variation with import capacity.

Obviously, security against shortfall is purchased at a very high price. Moreover, the acceptable risk of shortfall, as arbitrarily selected by public officials (e.g., 5 percent), is typically not close to a market-determined "optimal" level of risk, as reflected in the risk neutral model runs. This may be acceptable if society is risk-averse, but only if society has knowledge of the costs of such security.

A second conclusion is that there is not a significant difference in the optimal facility size whether uniform or seasonal pricing is adopted under expected value maximization as the criteria. This confirms the conclusions of Chapter II. This is however not the case when models include constraints that provide high reliability against short-falls. For a given model type, the seasonal pricing policy has a lower marginal benefit for import capacity than that of the uniform pricing policy as expected, but these differences are significant only when reliability levels are increased.

The preceding analyses and conclusions should be tempered with the following caveats. First, the analyses presented here are based on an assumption of constant population and hence a static demand for municipal water. If demands were allowed to shift to the right through time a dynamic analysis might produce different results. Second, the models assume that the costs of managing shortfall situations are negligible. The solutions therefore overestimate net consumer benefits during shortfall conditions, especially for smaller import facility sizes. The models developed here could be modified to examine the implications of these simplifications if data were available for estimating efficiency losses due to alternative rationing schemes.

CHAPTER V

HOUSEHOLD FLOW RESTRICTING DEVICES

The use of household water saving devices as a means of reducing indoor water use has received a lot of attention recently. In some instances, measures to install water saving devices were taken in response to impending water shortage, while other times these measures were taken in a noncrisis situation. Many studies have been conducted to determine the effects of water conservation devices on water use.

Description of Devices, Costs, and Water Savings

A wide variety of water conservation devices for household use are available on the market. The Office of Water Research and Technology (1977) discussed the nature and objectives of various devices. The following is a summary of that discussion. The devices are grouped under the type of household fixture in which they are used. Water savings and cost of the devices are given in Table 5-1.

1. Toilets. The devices available for use in toilets are:

a) Plastic bottles: As the name implies, these are plastic bottles such as milk bottles. The bottles are filled with water and placed upright in the toilet reservoir. The idea is that a bottle will displace its own volume and thereby reduce the amount of water available for flush. As many bottles as can be accommodated in the toilet reservoir can be used. In order to prevent the bottle from floating, it may need to be weighted down.

b) Plastic dams: These are devices inserted into the toilet reservoir. They are designed to dam off a portion of the reservoir and retain that water when the toilet is flushed. Care needs to be exercised in the choice of a dam so as to select one that is compatible with the type of toilet. Incompatibility may result in inadequate flushing.

c) Dual flush cycle modifications: These devices, when incorporated into existing toilets, enable dual flushing capability--one cycle for solids and one for liquids. The idea is to reduce the volume of water used to flush liquids. These devices are already in use in the United Kingdom. A short pull on the handle releases less water per flush and a longer more persistent pull releases more water per flush.

d) Water saving toilets: This type of toilet has a smaller reservoir (3-5 gallons) than that of a conventional toilet (5 gallons). These toilets are economical in new construction or as replacements for unworkable toilets.

e) Improved ballcocks: They are easily installed in most conventional water closets. By adjusting the ballcocks to maintain a

Table 5-1. Water conserving devices: Costs and water savings.

Device	Cost ($)	Current Water Usage[a]	Water Usage Considering Conservation[a]	Estimated Reduction in Family Water Consumption gals/capita/day[b]
Toilet		5-6 gals/flush		
Toilet inserts	0.5-10		3.5 gals/flush	4.3
Dual flush	5-15		2.5-3 gals/flush	
Water saving toilet	60+		3-5 gals/flush	
Faucets		2-12 gpm		
Aerator	1-5		3/4 gpm	4.9
Spray tap	5-25		1-2 gpm	
Shower Heads		3-8 gpm		
Inserts	0.5-1.5		2.3 gpm	19.5

[a]Schaefer (1979).
[b]Palmini and Shelton (1983).

lower water level in the toilet reservoir, the amount of water used for flush can be reduced without impairing flushing efficiency.

2. Faucets.

a) Faucet aerators: These simple devices reduce splashing. Water is mixed with air and hence the amount of water flowing from a faucet is reduced. The device is inexpensive and easy to install.

b) Spray taps: These taps are designed for use in lavatory sinks and wash basins. As opposed to conventional faucets where water is released in a single stream, with spray taps water is sprayed from the tap. This allows for faster washing and rinsing and hence less water use. These are economical in new construction or as replacements for unworkable faucets.

3. Shower heads.

Flow control devices: These devices limit the flow from shower heads and faucets. They are usually nothing more than orifice restrictors that fit into the supply lines for faucets and shower lines. Flow is usually reduced from 4 gallons per minute and up for conventional showers to 3 gallons per minute. The disadvantage of this device is that a longer time will be required to take a shower.

Examples of Experience Reported in the Literature

In Oxnard, California, water conservation measures were taken in response to the 1977 drought in Southern California (Morgan and Pelosi 1978). During this period the city of Oxnard distributed a water conservation kit free of charge to a single geographic area. The water conservation kits contained: 1) a water guard or dam to reduce the quantity of water flushed in the toilet, 2) a plastic shower head flow restrictor, and 3) a packet of detectable dye tablets to detect leaks from toilet storage tanks. In this study, it was estimated that about 63 percent of the households receiving the kits installed at least one of the conservation devices with higher installation rate among households with relatively higher water consumption. Water savings among installers was about 4490 gallons per household per year. A similar study conducted in San Diego, California, during this period (reported in Palmini and Shelton 1983) showed that water savings was about 5470 gallons per household per year.

The use of household water saving devices in a noncrisis situation was reported by Palmini and Shelton (1983). Their study was done in East Brunswick, New Jersey. About two-thirds of the community's water was consumed by residential customers in 1978 and the population is expected to increase at least 50 percent by the year 2000. The township's application to sink a third deep well was denied by the State Government after surrounding communities objected. The township among other things decided to test the feasibility of using water saving devices as a means of using the available water supply more productively. Conservation packets were distributed free of charge to a select group of households. Each packet contained: 1) three water dams for insertion into toilet tanks, 2) a low flow faucet aerator, 3) a plastic flow-reducing button for insertion into aerators already in place in faucets, 4) a plastic flow-reducing control for insertion into the shower lines, 5) a booklet on water-saving tips, and 6) a water conservation brochure. The table below shows the estimated reductions in water consumption by devices (Palmini and Shelton 1983).

Device	Estimated Reduction in Family Rate of Water Consumption	
	Liters	Gallons/Day/House
Shower head	73.8	19.5
Shower flow control restrictor	73.8	19.5
Faucet aerator	18.5	4.9
Faucet aerator button	18.5	4.9
Toilet water dam	16.2	4.3

From the above table, a household that installed two toilet dams, a faucet aerator, and a shower head or shower flow control would have reduced its daily water consumption an average 33 gpd or about 12,000 gallons per year. In the East Brunswick study, it was estimated that about 67 percent of the households receiving the water conservation packets installed at least one device. By using the proportion of households that installed each device and the above table to the total number of households receiving the packets, it was calculated that the group could save about 2.825 million gallons over a 12-month period. Divided by the number of homes receiving the packets, this gives an average annual savings of 5010 gallons per home among those that had received the water conservation packets. Among those actually installing at least one conservation device, the estimated water savings were 7400 gallons per home per year.

The use of water saving devices reduces the amount of wastewater flowing to treatment plants. This reduced flow affects wastewater treatment operations as follows (Hopp and Darby 1981):

1. Reduces the part of operations and maintenance costs dependent on volume of wastewater treated.

2. Postpones investment on a new plant since it will take longer for the present facility to reach its capacity.

3. Since a water saving device reduces only the quantity of flow, the strength of the wastewater to be treated will be increased.

Davis and Bursztynsky (1980) made a theoretical study on the effect of reduced quantity of wastewater flow on the various units of a treatment plant due to the installation of household water saving devices. Assuming that conservation devices would reduce the quantity of flow to a sewage treatment plant by 20 percent while the mass of pollutants remains the same, they analyzed the effect of this flow reduction on headworks, trickling filters, activated sludge, and waste stabilization lagoons. They concluded that within the range of flow reduction (10-20 percent) that is likely to result from a water conservation program, effects on sewage treatment plants will be minimal. However, they contend that the performance of biological reactors must be improved in order to maintain effluent quality with increased wastewater strength.

Effect of Water Saving Devices in Salt Lake City

The analysis of probable impact of water saving devices on Salt Lake City will be considered at two levels: 1) the effect on the water supply system and 2) the effect on sewage treatment.

Water Supply System

Using Palmini and Shelton's (1983) estimate of 5010 gallons per household per year of reduced water use (7400 times the approximately two-thirds of families actually adopting the use of devices), this would amount to a total saving in Salt Lake City in 1986 of 392 million gallons per year (1.07 mgd) which is about 1.2 percent of the average water use. Since the ratio of peak to average month use in Salt Lake City is 2.42 (Hughes 1980), the savings would be only 0.5 percent during peak periods (the period which determines design capacity).

Using a generalized cost function for present value of reduced cost of expansion of a municipal water system (Deb 1978), the reduction in capital cost due to the devices would be negligible ($15,000). The reduction in O&M cost is more significant. It was estimated by assuming that deep wells are the only source affected by the devices. The marginal cost of this source is $242/mg (from Chapter II), giving an annual O&M saving of $95,000 for a present cost of $862,000 (25 years at 10 percent). The detailed calculations and assumptions related to these quantities are given in Appendix A.

Waste Treatment System

The reduction in flow to the sewage treatment plant is larger percentage wise than that from the supply system because in Salt Lake City only about 60 percent of total water use is indoors (and therefore becomes sewage). The reduction in capital cost is more difficult to determine because an investment timing problem is involved. Whereas with water supply an additional well can be added as required (a small increment in cost) sewage treatment plant capacity expansion is a major undertaking, and therefore done only in relatively large increments. The flows and related costs will be summarized here. Detailed calculations (following Hopp and Darby's 1981 approach) are given in Appendix A.

The existing Salt Lake City plant is operating at 40 mgd and has an average daily capacity of 45 mgd. The city is growing at 1.3 percent annually, and 77 percent of total sewage is generated from residential sources which average 98.4 gpd/person. The reduction in flow from homes using the devices averages 5.14 gpd/person which is a 5 percent reduction. Adjusting this for industrial sewage and for the one-third of homes not using the devices gives a decrease of 2.58 percent in sewage entering the treatment plant. These quantities indicate that if Salt Lake City initiated a conservation program in 1986 it would need to enlarge its treatment plant in 11 years whereas the expansion will be needed in 9 years without the devices. The present values of the reduction in capital cost and O&M cost, respectively, are $3,950,000 and $327,300.

Benefit-Cost Summary

The following analysis assumes that the city pays for the water conservation devices and distributes them free of charge to all customers. It is further assumed that all devices are purchased at the beginning of the conservation program.

If each household is supplied with one faucet aerator, one shower flow constrictor, and one toilet dam, and a household is made up of four persons, then number (n) of each device to be purchased for a 25-year planning horizon is 108,300 (the estimated number of residences).

From Table 5-1:

Device	Unit Cost $	Total Cost $
Water dam	10.00	1,083,000
Shower flow constrictor	1.50	162,450
Faucet aerator	5.00	541,500
Total Cost		$1,786,950

Most homes now have two toilets and at least two faucet aerators would be needed, therefore, the actual cost would probably be closer to almost double this figure or about $3,390,000. The estimated benefits from reduced water use are:

Water Supply:	O&M	$ 862,000
	Capital	15,000
Waste Treatment:	O&M	327,000
	Capital	3,950,000
	Total Benefits	$5,154,000
	Cost of Devices	3,390,000
	Net Benefit	$1,764,000

This apparent net benefit does not include the social costs related to changes in time required and quality of use of the plumbing devices. Therefore, the total social cost very probably exceeds the benefits.

Conclusions

Plumbing devices represent a concept which is helpful in a) rationing water during a drought, or b) during a period of water shortage while water supply capacity is being expanded, or c) during a period when water treatment capacity is being expanded. The devices, however, are not a concept which should be thought of as producing a net social benefit during long-term use.

The reductions in flow (and therefore in utility cost) are much more important for sewage treatment than for water supply. This derives from the following factors: The capital investment for water supply is driven by peak period demand during which the impact of the devices is only 0.5 percent of total demand while the impact on sewage flow is 2.6 percent because large variations in outdoor water use do not effect sewage flow.

CHAPTER VI

SHORT TERM ALTERNATIVES

Introduction

During the 1976-77 drought, three principal mechanisms were used to reduce water use in Utah communities: price increases, maximum monthly use restrictions, and restrictions on outdoor watering times. What follows is an analysis of the response by water users to those rationing approaches. Most of the analysis described here has been published in more detail in Narayanan et al. (1985).

In 1976-77, the below-normal precipitation during the winter and the resulting low spring runoff adversely affected surface water availability. Because of time and financial constraints, the options for augmenting supplies by developing groundwater or constructing facilities for importing water from other areas were not often feasible. Lack of large storage facilities and the concern that the drought might continue into the next year prompted municipalities to ration available supplies. Decisions as to the extent and form of the rationing mechanism imposed depended largely on the municipality's perceptions of the drought's severity and the suitability and effectiveness of the various rationing devices for the specific system.

A fairly large literature on the 1976-77 drought (e.g., Narayanan et al. 1983; Hughes et al. 1978; James and Andrews 1978; California Dept. of Water Resources 1978) provides substantial information on the techniques used to mitigate drought impacts. Consumer responses to these techniques have been reported for California by Bruvold (1979). Ideally, evaluation of these alternative water use reduction policies should balance program accomplishments against the costs of achieving them, since achieving program goals may cost more than is warranted by the results. However, relatively little analysis of the cost effectiveness of even successful programs has been reported. A qualitative discussion is provided by Sharpe (1978) which includes public education measures, pricing, and the use of conservation devices. Certainly the difficulty of measuring widely dispersed costs and benefits of drought relief programs is a strong reason for so few evaluations. To reduce this problem, a better understanding is needed of the factors that determine how successful a given policy will be in reducing water use.

The approach adopted in this report is to integrate the descriptive information on programs and their effects in a variety of communities with a model that contributes to an overall understanding and more effective program design for future droughts. Water use reductions associated with different policies adopted by Utah communities are examined in order to establish the relative effectiveness of each of the rationing devices. The analysis is cross-sectional, using a multiple regression model.

Description of Drought Policies

Three major categories of policies for restricting water use during the drought were implemented in different parts of Utah (Hughes et al. 1978). These were higher prices, mandatory maximum use restrictions, and restrictions on times of outdoor watering. The most common of the three was the restriction on watering time for outdoor use. Of the 33 systems for which information was available, 24 imposed time restrictions. Total hours allowed for outdoor watering in a week ranged between 0 and 105 hours. Nine systems implemented price changes, and five systems imposed mandatory quantity restrictions. There were three systems that had price changes as well as time restrictions. Four systems had both time restrictions and mandatory quantity restrictions. Price increases ranged from \$0.03 to \$1.25 per 1000 gallons (10 percent to 500 percent). The quantity restrictions ranged from 36,000 gallons per connection to 6000 gallons per connection per month. The distributions of normal (average for years 1973-75) water use per day per connection for the 33 communities is shown in Figure 6-1. The water use reductions achieved per day during the drought are shown in Figure 6-2. The mean reduction was 156 gallons per day per connection, with a standard deviation of 214. Although 27 systems reported a reduction in water use, six systems had an increase.

Changes in Prices

The price structure for most of the municipalities included a fixed monthly charge for a connection, and a variable charge for water consumption in excess of a monthly minimum. The fixed charge varied from \$2 to \$11, and allowed the users to consume up to a specified amount which varied from 3000 to 12,000 gallons. Generally, the variable charge ranged from \$0.10 to \$0.30 per thousand gallons. Some of the systems reported increasing multiple block rate structures and a couple of systems had declining multiple block rate structures. Two systems had a flat rate per connection with no variable charges based on the quantity of water consumed.

Price changes during drought included: a) an increase in the minimum charge (either directly or by decreasing the quantity that could be used without additional charge), b) an increase in the price associated with water consumption above the monthly minimum, and c) an increase in the progressivity of the multiple block rates.

The three cases are illustrated in Figure 6-3. In Figure 6-3a, D represents the demand for water. When the minimum charge is raised or the quantity entitlement corresponding to this minimum charge is reduced (from Q^* to $Q^{*'}$), the demand D will shift to D' due to an income effect (normally small), causing a change in quantity consumed from Q to Q'. The cost of the intramarginal units increases with no change in the price of the marginal units. If the income effects are small, such changes will have negligible effect on water consumption.

In Figure 6-3b, the price is changed from P to P'. The quantity consumed will change by an amount determined by the price elasticity of demand for water and the change in the price.

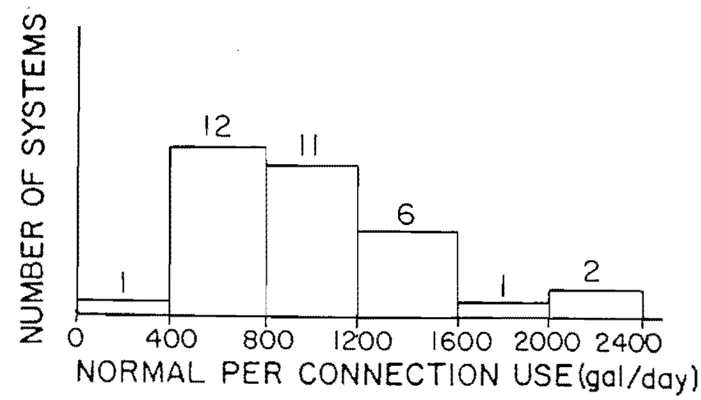


Figure 6-1. Normal water use per connection.

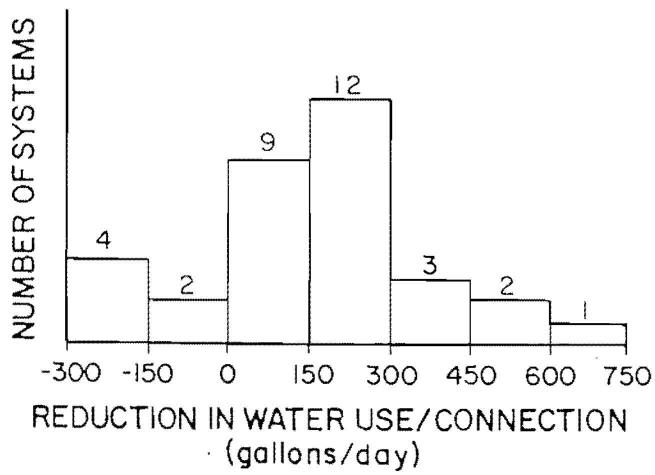
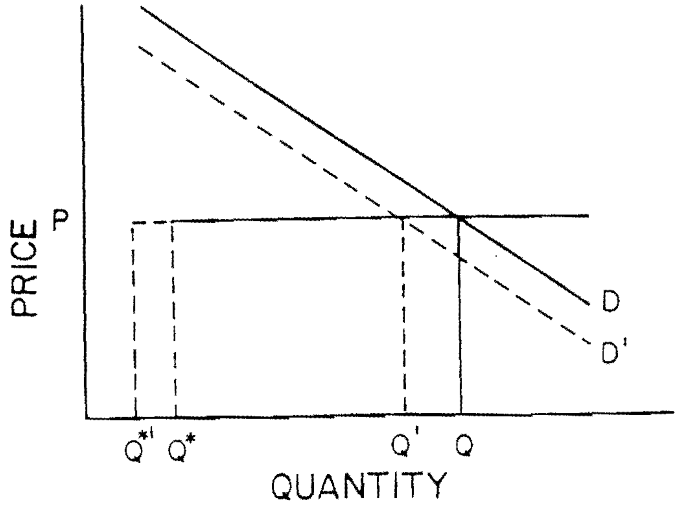
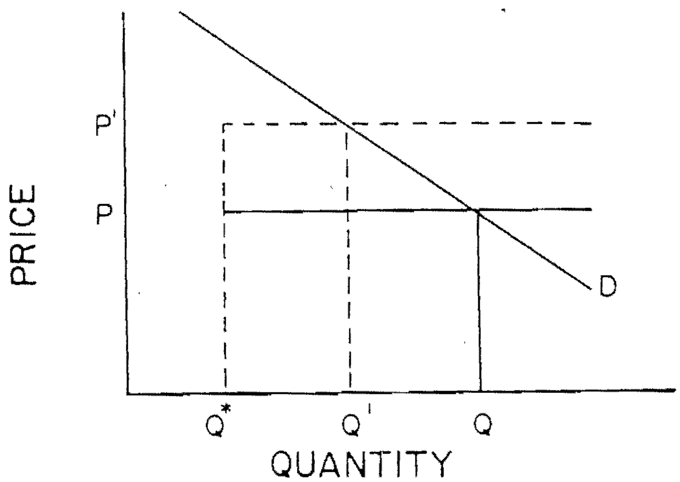


Figure 6-2. Water use reductions.

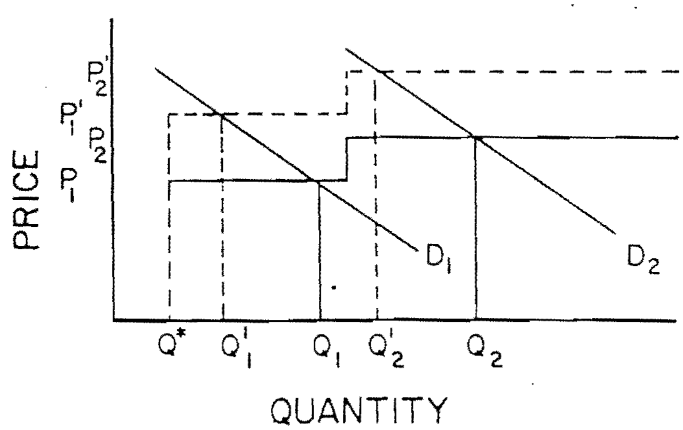
In Figure 6-3c, the demand curves for two users, D_1 and D_2, are shown, each facing a different price P_1 and P_2, respectively. When their prices are increased to P_1' and P_2', their quantity demanded falls from Q_1 and Q_2 to Q_1' and Q_2', respectively. The costs of both the intramarginal units as well as the marginal units will increase. As under the assumption that the income elasticity of demand for water is small, the effect on marginal units can be calculated as for case (b). However, there are additional complications in measuring price changes in this case due to the multiple block rates. The price changes for each block could be different. In order to measure the effective price change, one must know the demand distribution. Since such information was not available to this study, the price change corresponding to the average consumption block was taken to represent the effective price change.



(3a)



(3b)



(3c)

Figure 6-3. Effect of price changes on water use: (a) effect of quantity restriction, (b) effect of price increase, and (c) effect of block rate increase.

Time Restrictions

The most common type of time restriction imposed on outdoor water use was to allow a household to water only on particular days. Usually the restrictions specified the hours for lawn watering, presumably to maintain adequate pressure for fire hydrants. The total hours in a week during which water use was restricted ranged from 4 to 83 in the sample. Many systems imposed the time restrictions on a voluntary basis. Some cities, however, passed an ordinance prohibiting water use for certain times, thus making the restrictions mandatory. Because no special enforcement effort was made in the mandatory cases, no attempt was made to distinguish between the voluntary and mandatory restrictions in the analysis. The total hours of restrictions were computed for each of the systems in the sample.

The effect of time restrictions on outdoor use can be analyzed as follows: a household can be assumed to produce "lawn and garden" output by combining water, labor, and other purchased inputs. The optimal amount of "lawn and garden" is determined by the intersection of the demand and the supply curves. The supply is the marginal cost of producing an additional unit area of "lawn and garden" where water and household labor are inputs. The time restrictions influence the opportunity cost of household labor by shifting the individual's time schedule for watering. In the absence of mechanical devices for watering (such as timers, automatic lawn sprinklers, etc.), the changes required in the time schedule of the homeowner impose additional costs on his time. Under "moderate" time restrictions, this factor (increased opportunity cost of time) may predominate, causing the derived demand for outdoor water use to shift downward. Under more "stringent" time restrictions, the amount of water deliverable to lawn and garden may be severely limited, implying a quantity rationing of outdoor water use.

These concepts are illustrated in Figure 6-4. In this figure, the demand D and marginal cost S curves for "lawns and gardens" are shown. The normal area for lawn and garden A_O is determined by the intersection of D and S. The demand curve for water D_W for this area is shown in Figure 6-5 as derived from given prices for all inputs such as households' time cost, fertilizer, etc. At the initial price P_W, an amount Q_O is used outdoors. When a time restriction is imposed, the opportunity cost of labor increases, causing the demand for water D_W to shift to D_W' assuming water and labor inputs are complementary. This will cause the supply of lawn and garden to shift from S to S'. The new quantity A_O' of lawn and garden is irrigated with Q_O'. A reduction of Q_O to Q_O' is achieved through this policy. However, with "stringent" time reductions, the individual may not be able to use the amount of water he desires. This situation is also shown in Figure 6-5 where the demand shifts to D_W''. The desired quantity at price P_W is Q_O''. However, the amount of water that the user is able to withdraw from the system is Q_O^* (within the given time). The shadow price of water is P_W^* under this scheme for rationing outdoor water use.

While restrictions limiting the times of watering may not affect all the households served from a given system, the number of connections affected will increase with the hours of restriction. Reasons for

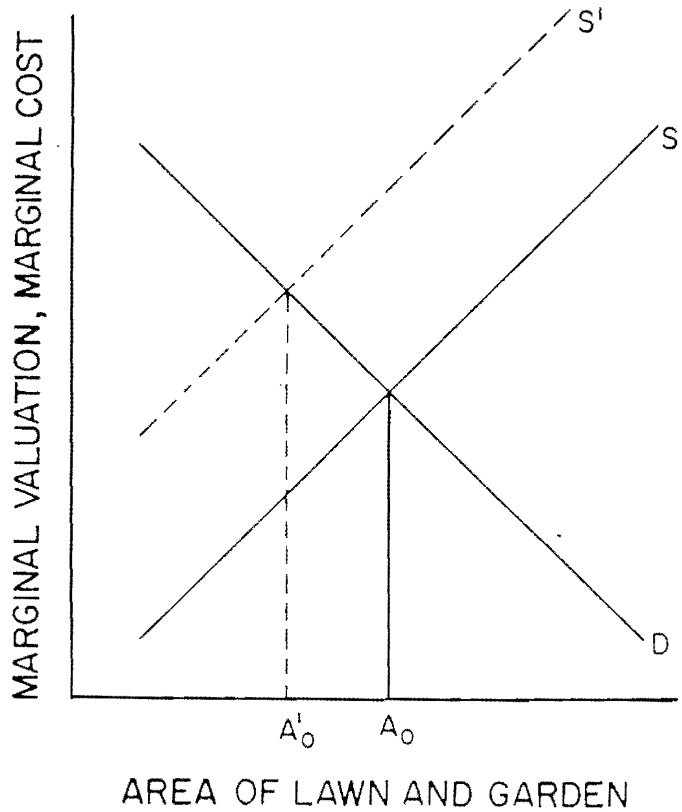


Figure 6-4. Demand and supply for lawn and garden.

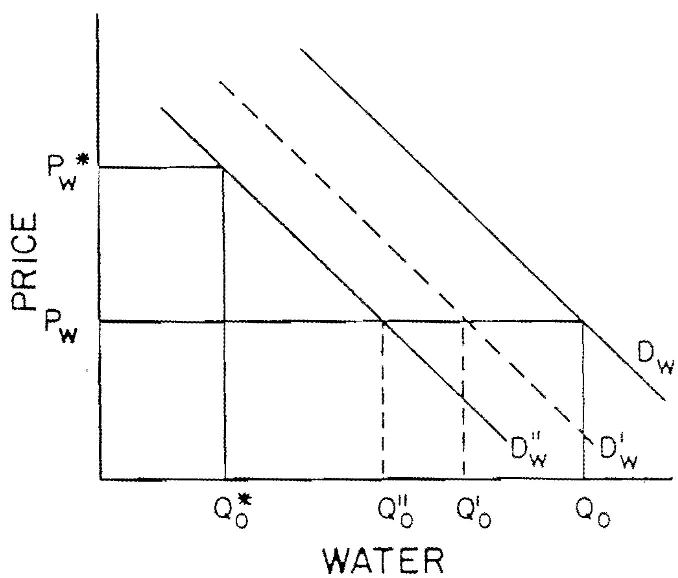


Figure 6-5. Effect of time restrictions on outdoor water use.

differential effects among households include different lot sizes, the shadow prices of labor for gardening and lawn care, and the number of people in the household. The effect on aggregate demand can be illustrated with the aid of Figure 6-6. Let D_1 and D_2 represent two household demands, and let D be the aggregate demand curve. A time restriction will shift D_1 and D_2 downward and hence the aggregate demand D downward to D'. A "severe" time restriction might impose quantity rationing on individual 2 but not individual 1. In this case individual 2 can consume only up to q_2* while consumption by individual 1 is determined by his demand curve. The aggregate demand D is further reduced to D". As the time restriction becomes more severe, a greater shift in the aggregate demand can be expected as more households become affected.

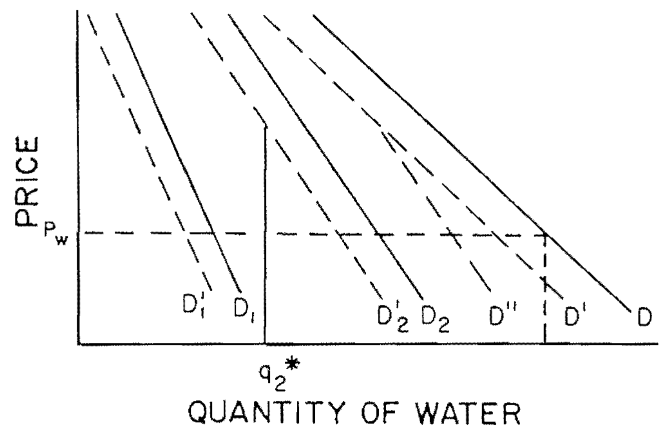


Figure 6-6. Effect of restricting water time on aggregate demand.

Maximum Use Restrictions

According to this policy for restricting water use, the maximum amount of water that can be consumed per month per connection is limited to a specified quantity. The restrictions per connection ranged from 6,000 gallons to 36,000 gallons per month. Unlike time restrictions where only the outdoor water use is affected, the quantity restriction affects both indoor and outdoor uses. However, the restriction allows the household to allocate water between indoor and outdoor use in any manner it chooses, while the time restriction distorts this allocation by restricting only the outdoor use.

Quantity rationing does not affect households that would use less than the rationed amount, in any case. As the ration is reduced, more households are constrained. The economic relationships through which this scheme affects aggregate demand are similar to those for "stringent" time restrictions in that aggregate demand shifts to the left as in Figure 6-6.

An index was constructed to measure the quantity restriction. The need for an index, instead of using the ration quantity directly, arises due to systems that did not have quantity rations. For these systems, a zero value could not be used since it would cause numeric difficulties. Instead, the maximum average monthly use per connection, approximately 60,000 gallons, was used as a restriction for systems that did not use any quantity rationing. An index Q was defined as the ratio of the ration amount to 60,000. This measure is 1 for systems that did not impose rations and between 0 and 1 for those that did. The index falls as the ration quantity decreases.

Other Restrictions

In addition to the above three policies, many of the water supply systems implemented other water use restrictions. These included prohibition of water use for washing parking lots, driveways, and sidewalks, and reductions of water use in city parks. Quantitative measures of such restrictions were not available, and their effects were ignored in the analysis.

Regression Model Formulation

The theoretical basis and details of the model formulation are given in Narayanan et al. (1985) and will not be repeated here. Briefly, the approach is to write a general form of equation where the dependent variable (water demand) is a function of price and other demand determinants including rationing policy variables. The derivative of this equation is then taken in order to determine changes in demand due to each independent variable. The empirical basis for quantifying these changes was the change between drought and nondrought periods. Models were developed in both linear and percentage form. The linear model for which results will be discussed was:

$$X_0-X_1 = \alpha_p(P_1-P_0) + \alpha_{R_0}R + \alpha_{RD}D + \alpha_{R_1}X_0R + \alpha_{R_2}NR + \alpha_Q(1-Q)$$

$$+ \alpha_{R_f}(R_{f_0} - R_{f_1}) + \varepsilon$$

where X is the consumption of water per connection, P is the marginal price, N is the number of people in the household, R_f is the rainfall during the growing season. The drought policy variables are the restriction R, the quantity restriction Q, and the changed price. The subscripts 0 and 1 refer to normal and drought periods, respectively, and the α's are the model coefficients. Finally, D = 1 if voluntary restriction was imposed and 0 otherwise.

Model Results

A statewide water use survey was made in Utah near the end of 1977 jointly by the Utah Water Research Laboratory and the Utah League of Cities and Towns. A section of the survey instrument related specifically to the drought was included (Hansen 1981). Data from 33 cities were sufficiently complete to be used in the regression model. Table 6-1 contains these data. The models in linear and percentage forms were estimated by ordinary least squares. The linear equation and

Table 6-1. Regression model data.

System Name	County	Population 1973-75	Population 1977	Number of Connections 1973-75	Number of Connections 1977	Water Use (million gal/yr) 1973-75	Water Use (million gal/yr) 1977	Change in Water Use (gal/day/conn.)	Price Change ($/1000 gal.)	Percent Price Change	Voluntary Time Restriction (hr/wk)	Mandatory Time Restriction (hr/wk)	Mandatory Quantity Restriction Index (1-Q)	Change in Rainfall (inches)	Percent Change in Rainfall
Aurora	Sevier	613	785	189	242	33	60	−200	0.0	0	0	133	0.0	−0.24	−0.085
Fillmore	Millard	1,736	2,726	724	913	284	297	184	0.0	0	0	0	0.0	0.56	0.166
Heber	Wasatch	3,535	3,448	1,233	1,230	554	416	303	0.0	0	0	147	0.0	−0.43	−0.112
Ivins	Washington	203	331	96	157	28	34	199	0.25	83	0	0	0.0	−0.46	−0.239
Kearns	Salt Lake	13,473	15,092	3,849	4,312	1,267	693	461	0.0	0	0	164	0.67	−0.76	−0.210
Layton	Davis	17,708	19,678	4,184	4,412	1,227	1,076	135	0.15	60	0	0	0.0	0.10	0.024
Lehi	Utah	5,688	7,015	1,658	1,852	386	355	112	0.10	50	0	0	0.0	−1.01	−0.334
Lindon	Utah	2,030	2,514	457	550	153	183	10	0.0	0	96	0	0.0	0.16	0.049
Manilla	Daggett	319	375	184	247	28	48	−109	0.05	10	0	0	0.0	−0.68	−0.178
Pleasant Grove	Utah	6,186	9,077	1,868	2,254	765	1,174	−303	0.0	0	156	0	0.0	−1.01	−0.334
Provo	Utah	59,000	67,744	10,639	11,218	6,331	6,401	67	0.0	0	0	144	0.0	−1.01	−0.334
Riverton	Salt Lake	4,900	6,192	1,232	1,548	288	244	209	0.0	0	0	164	2.0	−0.76	−0.210
Salt Lake Co. WCD	Salt Lake	17,920	19,950	5,973	6,650	1,792	1,466	217	0.0	0	0	164	0.67	−0.76	−0.210
So. David WID	Davis	5,171	6,219	1,620	1,762	246	247	31	0.0	0	0	163	0.0	0.10	0.024
So. Jordan	Salt Lake	3,823	5,009	886	1,165	238	214	233	0.0	0	0	164	0.67	−0.76	−0.210
So. Salt Lake	Salt Lake	8,748	9,197	2,640	2,705	931	1,012	−58	0.0	0	164	0	0.0	−0.76	−0.210
Spanish Fork	Utah	8,779	9,309	2,545	2,756	681	899	−160	0.0	0	0	0	0.0	0.16	0.049
Springville	Utah	9,887	10,816	2,933	3,209	2,237	1,728	614	0.0	0	0	156	0.0	−1.01	−0.334
Taylor-Bennion	Salt Lake	16,678	25,452	4,768	7,272	1,276	1,267	255	0.0	0	0	164	0.0	−0.76	−0.210
Uintah	Uinta	521	712	149	203	61	64	271	0.08	36	0	0	0.0	−0.74	−0.261
Vernal	Uinta	12,563	12,472	3,315	3,043	1,543	1,380	33	0.40	200	160	0	0.0	−0.74	−0.261
Washington Terrace	Weber	7,909	8,540	1,911	2,005	278	283	12	0.0	0	0	158	0.0	−0.35	−0.081
Brigham City	Box Elder	15,367	16,400	3,904	3,964	2,207	1,777	320	0.03	16	0	0	0.0	−4.80	−1.411
East Carbon	Carbon	2,100	2,200	671	747	273	161	523	0.0	0	0	168	0.0	0.19	0.046
Hyrum	Cache	2,955	3,485	946	1,100	524	499	276	0.0	0	0	84	0.0	−3.82	−0.972
Jensen WID	Uintah	571	820	143	205	32	37	127	0.0	0	132	0	0.0	−0.74	−0.261
Kenilworth	Carbon	503	509	108	109	19	9	269	0.0	0	0	0	9.0	0.19	0.046
Monticello	San Juan	1,692	1,900	578	650	195	96	523	1.25	500	168	0	0.0	−0.83	−0.149
North Salt Lake	Davis	2,781	3,573	624	812	480	685	−200	0.0	0	84	0	0.0	0.10	0.024
Orem	Utah	33,801	42,678	7,898	10,042	3,605	3,647	255	0.0	0	63	0	0.0	−1.01	−0.334
Payson	Utah	6,368	8,200	2,000	2,300	1,028	1,000	217	0.0	0	84	0	0.0	0.16	0.049
Price	Carbon	10,564	11,193	4,056	4,332	989	834	140	0.0	0	0	144	0.0	0.19	0.046
West Bountiful	Davis	1,945	2,500	386	615	89	99	190	0.27	117	0	164	0.0	0.10	0.024

the associated statistics are given in Table 6-2. All the individual coefficients are significantly different from zero at the 5 percent level, and the F ratio indicates that the set of coefficients as a whole is significantly different for zero at the 5 percent level.

The model suggests a price elasticity of 0.103 at the base values of P = \$0.25/1000 gallons and X_0 = 1000 gallons per day. The coefficient of time restriction at the reference values is 1.27 for mandatory restriction and -0.58 for voluntary restriction. This implies that an average hour of time restriction per week reduces water use by 1.27 gallons per day if mandatory and increases water use by 0.58 gallons per day if voluntary. Although voluntary restriction increases use at the base values of X_0 and N, systems with large values of X_0 and small values of N (large initial use and small families) would experience use reductions with voluntary restrictions. In fact, only three of the nine systems that had voluntary restriction actually experienced increased consumption. One possible explanation for this effect is that voluntary restriction may cause the consumer to expect more stringent restrictions later in the season and respond by overwatering. In any case, voluntary restriction does not seem to be an effective tool in reducing water use.

Conclusions

The very severe one-year drought of 1976-77 brought forth a large array of drought relief/management programs from every level of government as well as from individual water utilities. In retrospect, the management policies such as pricing, public education, and various rationing concepts at the level closest to the water users (water companies, associations, districts, municipalities, etc.) added motivation for conservation that resulted in sharing the shortages.

Specifically in Utah, the three most common rationing policies were: 1) restrictions on time for outdoor use (24 to 33 systems sampled used this policy); 2) price increases (9 of 33 systems); and 3) mandatory quantity restrictions (5 of 33 systems). Four systems in the sample used both time and quantity restrictions.

A regression model applied to these data gave the following information on policy effectiveness:

1. A price increase of 50 percent leads to a 5 percent decrease in the quantity of water consumed. A price elasticity that is lower during drought than in normal times suggests that users' behavior (demand function) changes during what they perceive as a short-term emergency and that moderate price increases are not so effective in managing consumption during droughts as during normal periods. Short run adjustments are harder to make than long run changes. However, large price increases had major impacts on use. A major system which charged a \$10/1000 gallon penalty for exceeding mandatory quantity limits experienced a 50 percent decrease in use.

2. The effectiveness of time restrictions on outdoor use depends upon the "normal" water use level, the number of people in the

Table 6-2. Estimated coefficients and statistics for linear model testing for differences between voluntary and mandatory restrictions.

	Model D (Equation 13)		
	$R^2 = 0.69$	$\bar{R} = 0.6$	$F(7,26) = 8.19$
Variable	**Coefficient**		**t**
Price	$\alpha_P = 412.1$		2.857
Outdoor Restriction	$\alpha_{R_0} = 2.24$		1.712
Outdoor Restriction Adjustment for Per Capita Consumption	$\alpha_{R_1} = 0.0015$		2.586
Outdoor Restriction Adjustment for Household Size	$\alpha_{R_2} = -0.707$		−2.1
Voluntary Restriction	$\alpha_{RD} = -1.69$		−2.86
Quantity Restriction	$\alpha_Q = 267.7$		1.945
Rainfall	$\alpha_{R_f} = -48$		−1.868

household, and whether or not the restriction was imposed on a voluntary or mandatory basis. An increase in the mandatory time restriction of 1 hour per week decreases total water use by 1.27 gallons per day if the average water use is 1000 gallons per day for an average connection serving 3.5 people. For systems with higher use levels and fewer people per connection, the water use reduction will be greater. For the case of voluntary restriction, water use sometimes increased, particularly for systems with smaller use levels and higher number of people per connection.

3. For every 1000 gallon reduction in maximum monthly water use, a reduction of 4.3 gallons per day in use was observed.

From an economic efficiency point of view, mandatory restrictions on the times of outdoor watering are a poor choice of policy because they affect only one type of use. Unless enforcement costs are significantly higher, mandatory quantity restrictions are better since they allow households to allocate water between outdoor and indoor uses in any way they choose. They do not distort the marginal rate of substitution between indoor and outdoor water uses.

If distributional considerations are not important, the third method, price change, would be a still better alternative since the marginal rate of substitution between water and all other goods used by households would remain equal. However, from the model, it appears that the short-run price elasticity is small and it might take a large increase in price to accomplish a reasonable reduction in use. A 20 percent reduction in water use would require more than doubling the price.

CHAPTER VII

SUMMARY/SYNTHESIS OF CONCLUSIONS

Five different concepts for residential water conservation have been analyzed from an economic efficiency perspective. Each concept was analyzed separately in Chapters II through VI. Each concept could, however, be used in combination with others. This final chapter will include a brief summary of results for each model or concept as well as a comparison of both common aspects and differences among the conservation concepts (Table 7-1). Conditions which are likely to favor or to increase economic efficiency of each concept will also be summarized (Table 7-2).

Seasonal Pricing

A generalized model for comparing economic efficiency of seasonal vs. uniform pricing policy was developed and applied to Salt Lake City. In addition, a model generator for this nonlinear programming model structure was developed so that the model can easily be applied to other systems. The model calculates the optimal prices of water for peak and off-peak seasons and also the loss in social welfare if all seasonal prices are forced to be the same (the uniform pricing policy traditionally used). As part of the optimization procedure, the model also allocates water from each source, each month, and determines reservoir operating policy. Quantitative results are summarized in Table 7-1. Although seasonal pricing reduces the quantity of water demanded by about 10 percent annually, the added cost of metering ($60,000 per reading in SLC) is more than the benefit from seasonal pricing ($56,000 in 1990) and therefore appears not to be justified for SLC. For cities which have less storage and more variable supplies, results would likely be different.

The model developed for this concept proved to be of use in researching both the dual system and the importation capacity concepts, where seasonal pricing was also considered.

Dual Systems

The notion of delivering low quality water under pressure to municipal residences for outdoor irrigation uses is already widely used in Utah and is the subject of increasing interest in the Western U.S. due to the rapid urbanization of previously irrigated areas and the related freeing up of surface water with locally available water rights. Therefore the dual system concept received a relatively large fraction of the total research effort for this study.

A criteria for comparing the relative economic efficiency of single vs. dual systems was developed and computer code was developed for generalized models of both the benefit (demand functions) and cost

Table 7-1. Summary of model results.

Conservation Concept	Study Area	Management of Supply or Demand?	Quantitative Results	Conclusion/Comments
1. Seasonal Pricing	Salt Lake City	Demand	Optimal Prices ($/mg) — Seasonal: Low, High; Uniform — Decrease in Water Use by Seasonal Pricing Year / Low / High / Uniform / Seasonal Pricing 1975 / 205 / 255 / 253 / 2769 mg 1990 / 204 / 303 / 270 / 3437 mg	Seasonal pricing is not justified in SLC because of the added cost of metering
2. Dual System	Hypothetical plus West Jordan	Supply	West Jordan Results / NB Entire city: B/C = 0.93, -0.92 (10^6) 4 subsystems without pumping: B/C = 1.07, 0.64 (10^6) Single subsys. currently proposed: B/C = 1.08, 0.67 (10^6)	Dual systems are particularly efficient where previously irrigated land is urbanizing and where demand for high quality drinking water is approaching supply capacity
3. Imported Water Capacity	Hypothetical	Both	1. Assume constant MC = $300/AF/mo. of capacity 2. Ben from import = change from case (a) with no import	

3. Imported Water Capacity	Cross Ben - Cost	Capacity (AF/mo)	Prob. of shortage at least 1 mo/yr	if Risk Averse	if Risk Neutral	
a) Uniform Pricing with Risk Averse Approach	$7.43 ($10^6$) - 1.68 ($10^6$) = 5.75 ($10^6$) $/yr	5600	5%			Optimal capacity of transmission conduit is very sensitive to policy toward risk, but less sensitivity to pricing policy
b) Uniform Pricing - Risk Neutral	$7.40 ($10^6$) - 0.36 ($10^6$) = 7.04 ($10^6$)	1200	100%	Seasonal pricing increases net benefits despite a much smaller investment in transmission capacity	Same net benefit--therefore, indifferent to pricing policy	
c) Seasonal Pricing - Risk Averse	$7.32 ($10^6$) - 0.96 ($10^6$) = 6.36 ($10^6$)	3200	5%			
d) Seasonal Pricing - Risk Neutral	$7.37 ($10^6$) - 0.33 ($10^6$) = 7.04 ($10^6$)	1100	100%			

Conservation Concept	Study Area	Management of Supply or Demand?	Quantitative Results	Conclusion/Comments
4. Plumbing Devices	Salt Lake City	Demand	System / Change in Flow Water Supply: 1.3% (avg), 0.5% (peak period) Sewage: 2.6% Net benefit in SLC excluding social costs due to quality of service = $1,764,000	Education programs encouraging plumbing devices may be justified but mandatory installation is not.
5. Short Term Alternatives	33 Cities in Utah (1977 Drought)	Demand	Short term pricing elasticity reduced from the normal 0.47 to 0.1. Mandatory restrictions on monthly use per 1000 gallons produced only a 4.3 gallon reduction in average daily use.	Increased prices are ineffective unless such increases are very large (more than double normal rates). Restrictions on time of use may result in increased rather than decreased water use.

Table 7-2. Summary of conditions which favor conservation alternatives (number of X's indicates degree of importance).

Conservation Concept	High Seasonal Variability in Supply Seasonal	High Seasonal Variability in Supply Seasonal	Changes in Technology Which Provides: Reduced Cost of Meter Reading	Changes in Technology Which Provides: User Inform. on Use Rates	High Growth Rate of Demand	Ag. to Municipal Land Use Conversion	High Marginal Cost of Local Water Supply: Groundwater (No Treatment Required)	High Marginal Cost of Local Water Supply: Surface Water (Treatment Required)	Water Use Rate Approaching Capacity of: Delivery System	Water Use Rate Approaching Capacity of: Supply Source	Hydrologic Condition: Below Average Supply	Hydrologic Condition: Drought
1. Seasonal Pricing (Operational Problem Application)	X	X	XX	XX					XX	XX	X	XX
2. Dual System		XX			XX	XX	X	(-)	XX			X
3. Imported Water Capacity (Design Problem Application)												
a) Uniform Pricing with Risk Averse Approach	X	X					X	X		X		
b) Uniform Pricing - Risk Neutral							X	X		X		
c) Seasonal Pricing - Risk Averse	X	X	X	X			X	X		X		
d) Seasonal Pricing - Risk Neutral			X	X			X	X		X		X
4. Plumbing Devices				X			X		X	X	X	XX
5. Short Term Alternatives												
a) Price Rationing				X					X	X	X	XX
b) Quantity Rationing									X	X	X	XX
c) Quantity Rationing for Outdoor Use		X		X					X	X	X	XX

Note: The Xs in the table identify a condition which favors or increases efficiency of the particular conservation concept. The number of Xs indicate degree of importance and a (-) indicates a negative effect.

functions required for the analysis. The benefit/cost relationships at a [illegible]e point in time, were then extended by an investment timing analysis to determine whether immediate or some later time for initiating a dual system maximizes social welfare. Model generators for both the cost and investment timing models were developed. These tools will allow rapid and efficient applications at particular sites.

The detailed cost model developed here was used in a regression analysis to determine if simpler cost relationships can adequately simulate the cost of dual water systems. The results were very encouraging. The traditionally very expensive and time consuming studies required to develop planning level cost estimates for such systems can now be done very quickly and at much lower cost with the tools developed here. For example, the results of a recent cost estimate by a consulting engineer for a dual system in West Jordan, Utah, were only 5 percent different than the costs estimated by this model.

Results of the investment timing model were displayed graphically by varying several of the parameters. Conclusions include:

1. Parameters which increase the net benefits from a dual system are a) low interest rate, b) gravity-fed system versus pumped system, c) high population growth rate; d) high unit cost of treated water, e) source of irrigation water near the irrigated area, f) water rights already associated with the land, and g) a substantial outdoor demand.

2. Factors which tend to delay the optimal timing of system construction are the same as those which make the dual system infeasible (at more severe levels)--the opposite of those listed in 1 above.

3. The ideal setting for a dual system area can therefore be summarized as:

- low discount rate
- fast growing city
- close proximity of irrigation water source
- gravity-fed irrigation systems
- high cost of culinary water treatment and delivery
- water rights that come with the land

Optimal Capacity of Import Water

The seasonal pricing model developed in Chapter II was deterministic in regard to hydrology--that is, it used monthly average values for surface water supply. In Chapter IV, seasonal vs. uniform pricing was again analyzed but with two principal changes: 1) The focus was on determining optimal capacity of imported water transmission facilities conditioned upon availability of local water supply, 2) the local supply sources were now modeled explicitly as stochastic variables, and 3) prices once selected by the model are assumed fixed regardless of water availability in any period. Two types of stochastic models were developed. The first (referred to as risk neutral) maximizes social welfare by allowing a shortage whenever the expected cost of avoiding such shortfalls in supply exceeds the related benefit (measured as consumer's plus producer's surplus). The second model (risk averse) is the same except for addition of chance constraints which limit the probability of a short fall in any month to less than some selected level (5 percent in the results reported here).

Table 7-1 summarizes the contrast in benefits and cost of the risk neutral and risk averse solutions. The principal conclusion that can be drawn from the stochastic model analysis is that the "optimal" size of import facility is very much a function of the risk of shortfall that society is willing to accept. Security against shortfall is purchased at a very high price. Moreover, the acceptable risk of shortfall, as arbitrarily selected by public officials (e.g., 5 percent), may not reflect society's preferences for risk.

A second conclusion is that optimal import facility size is not affected by the choice of pricing policy when expected benefits are maximized. If constraints to insure greater reliability are included, seasonal pricing is preferred. For a given model type, seasonal pricing policy has a lower marginal benefit for import capacity than uniform pricing policy. The differences in marginal benefits become significant for the chance-constrained, risk averse model. The import facility size is smaller and benefits are larger under seasonal pricing in this case.

The conclusions drawn from this analysis should hold for situations much more general than is perhaps obvious given this specific application to importation capacity. There is nothing inherently different about imported water except that it is assumed to have higher marginal cost of development than other (local sources). The analysis could be broadened to include any planning problem where the question of interest is capacity of a particular additional supply source--either local or import.

Conservation by Household Plumbing Devices

There is a large literature on the use of flow restricting devices in households. The literature includes costs of the devices and quantifies effects on water use; however, it does not provide sufficient data on indirect costs of this conservation concept to allow modeling of resulting changes in consumer surplus. For example, although the cost of installing a flow restricting device in a shower head and the level of flow restrictions are known, the additional time required to complete a shower and more importantly, modeling of the change in the water users shower related utility function (a quantitative representation of the "shower experience") is not possible with existing data. Similarly the cost of water saving type toilet or toilet reservoir volume reduction are known; but a model of the user's perspective on increased probability of requirement for multiple flushes due to inadequate initial success (the change in "toilet experience") is not possible with existing data. The analysis related to this topic was limited to a comparison of benefits related to reduction in water supply and waste treatment costs and costs of the devices. The analysis (summarized in

Table 7-1) shows a small net benefit from use of the devices; however, this ignores the social costs related to added time and reduced quality of facility use.

Short Term Alternatives

The three principal approaches to restricting water use during the 1977 drought in Utah were: 1) higher prices, 2) mandatory maximum use restrictions, and 3) restrictions on times of outdoor watering (with the latter being most common). A regression model for water use reduction as a function of various conservation policies during 1977 at 33 Utah cities was developed. Conclusions include: 1) price elasticity of demand is lower during droughts than in normal times (doubling the price will result in only a 10 percent decrease in use), so price increase as a rationing device could lead to significant income distributional changes, 2) time restrictions on outdoor use were effective for cases where normal water use was high, but actually increased water use in some cases where normal water use was low (apparent overirrigation in anticipation of possible worsening future conditions), and 3) mandatory restrictions on monthly use produced a much less than proportional reduction in average daily use (see Table 7-1).

Metering

The question of level of water use reduction due to adding household meters to a municipal system was not addressed. However, any report on municipal water conservation should remind the reader that the single most effective method of water conservation is the addition of meters and setting an appropriate price to a previously unmetered system. The effect on water use reduction is usually dramatic--much more so than any of the five concepts analyzed here. The working assumption for this study was that any water utility seriously concerned about conservation will already have installed individual service meters and then proceed to consider the concepts analyzed here.

General Conclusions

The five approaches to municipal water conservation analyzed here were shown to produce widely varying results in terms of economic efficiency and conditions where each may be appropriate. Table 7-2 summarizes the latter conditions. As might be expected, all conservation techniques become more useful in situations where water use is approaching the capacity of either the physical facility or the hydrologic source. In this situation either supply may be managed by 1) importing water and 2) initiating a dual system, or demand may be managed by a) pricing policy, b) using flow restricting devices, or c) rationing.

An interesting result of this study relates to the on-going dialogue between those who favor reducing water use by management of demand (the "conservers"), and those who favor continually increasing supply (the "developers"). In this study conservation approaches which produced net benefits were importation of water and constructing dual systems (the development approaches) along with judicious use of pricing policies. The seasonal pricing model application shows that seasonal pricing is not justified in SLC because related costs exceed the benefits. Since Salt Lake City has a substantial margin of safety between its water supply and demand, changing seasonal pricing policy from the present uniform pricing should not yield dramatic benefits. The water importation model results show that seasonal and uniform pricing have the same effect on optimal capacity of import transmission facility. If greater reliability is required, pricing policies impact both benefit and capacity size. The short term alternative analysis showed that price elasticity is much smaller than during normal conditions and large price increases may be required to change water use. Rationing and flow restrictions have little value in water conservation. The important results of this study relate not to the numbers generated in these specific case studies but rather to the generalized tools which have been developed for providing quicker and less expensive answers to such questions in <u>any</u> city. Since the models incorporate correct welfare economic principles they can be expected to provide answers to either the conserver vs developer or the economist vs traditional engineering controversies regarding water management. These answers will be as variable as the level of those parameters identified here as being important.

A final point should be made regarding the mistaken notion that conservation always means using less water. The dual system concept allows the allocation of naturally high quality water purposes and lower quality water to outdoor irrigation--thereby serving a much larger fraction of the populations with naturally safe drinking water, even though the net result is use of more total water for municipal purposes. This represents conservation in two important ways: 1) the <u>quality</u> of our most renewable resource is conserved and 2) economic efficiency is increased thereby increasing social welfare.

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APPENDIX A

DETAILED CALCULATIONS FOR COST SAVINGS IN SALT LAKE CITY WATER SUPPLY AND SEWAGE TREATMENT SYSTEMS DUE TO FLOW RESTRICTING DEVICES

A. Water Supply System

Capital cost of distribution mains: $1.01\ d_{av}^{1.29}\ L_m\ 5280$

d_{av} = average cost diameter

L_m = total length of distribution main

Savings 1.07×10^6 gal/day

Water Use: 287 gal/person/day for Salt Lake
4 people/connection

$d_{av} = 6.2\ POP_1^{0.065}$ — POP_1: population in thousands

$L_m = 125.39\ P_d^{-0.458}\ POP_1$ — P_d: population density in people/sq. mile

Assumptions: water conservation devices will reduce d_{av} but <u>not</u> L_m

Additional yearly cost:

$$\Delta cost_t = 5332.8\ K_d^{1.29}\ K_{L_m}\ P_d^{-0.458}\ [POP_t \times POP_t^{.084} - POP_{t-1} \times POP_{t-1}^{.084}]$$

Now, with water conservation devices a population equivalent will be used. The yearly costs become:

$$\Delta cost^*_t = 5332.8\ K_d^{1.29} K_{L_m} P_d^{-0.458}\ [POP_t \times POP^{*\,.084}_t - POP_{t-1} \times POP^{*\,.084}_{t-1}]$$

where

$$POP^*_t = POP_t \times \left(\frac{\text{water use - savings}}{\text{water use}}\right) = K_s\ POP_t$$

The savings will be $\Delta cost_t - \Delta cost^*_t$ using interest = 10%

$$\Delta cost^*_t = 5332.8\ K_d^{1.29} K_{L_m} P_d^{-0.458} [POP_t^{1.084} K_s^{.084}$$

$$- POP_{t-1}^{1.084}\ K_s^{.084}]$$

$$= 5332,8\ K_d^{1.29} K_{L_m} P_d^{-0.458} K_s^{.084} [POP_t^{1.084} - POP_{t-1}^{1.084}]$$

$$\Delta cost^*_t = K_s^{.084}\ \Delta cost_t$$

$$\text{Savings} = \Delta cost_t - \Delta cost^*_t = \Delta cost_t - K_s^{.084}\ \Delta cost_t$$

$$\text{Savings} = \Delta cost_t [1 - K_s^{.084}]$$

Those are yearly savings.

To compute total savings, we do:

$$\text{Total savings} = \sum_{t=1}^{T} \frac{\Delta cost_t\ [1 - K_s^{.084}]}{(1 + r)^t}$$

$$\Delta cost_t = 10,000\ K_d^{1.29}\ K_{L_m}\ P_d^{-0.458} [POP_t^{1.084} - POP_{t-1}^{1.084}]$$

Total reduction in capital cost (present value) = $15,000.

Savings in operating cost of deep wells:

Marginal cost = $242/mg
Average use reduction = 392 mg in 1986 = $95,000

$95,000/year growing at 1.3% annually, 10% interest rate.

$$\sum_{i=1}^{40} \frac{95,000 \times (1.013)^i}{(1.1)^i} = \sum_{i=1}^{40} 95,000 \times \left(\frac{1.013}{1.1}\right)^i$$

$$= \sum_{i=1}^{40} \frac{95,000}{(1.085883)^i} =$$

$$CRF = \frac{i(1 = i)^{40}}{(1+i)^{40} - 1} = .089187 \text{ with } i = .085883$$

$$\text{thus present value} = \frac{95,000}{.089187} = \$1,065,178$$

B. Sewage Treatment System

Population

From population data presented in Hansen et al. (1979), the Salt Lake City population growth can be represented by the following:

$$P = P_o e^{Kt} \tag{A-1}$$

where

P_o = 313,000

K = growth rate = 0.013

t = time in years from base (1986)

Operation and Maintenance Cost (OM) Savings

$$OM = 872 (P_e Q)^{0.488}; \text{ EPA (1978)} \tag{A-2}$$

where

OM = annual O & M cost ($)

P_e = population equivalent treated by plant

= $(P/b) = (P_o/b)e^{Kt}$

Q = average daily flow (M & D)

b = proportion of total treated sewage generated from residential sources

= 0.77 in SLC.

Substituting known values

$$P_e = 406{,}493 \, e^{0.013t} \tag{A-3}$$

The average daily flow, Q is given by

$$Q = (C \, P_e)/10^6 \tag{A-4}$$

where C is wastewater generated/capital/day. Average daily sewage treated presently (SLC) = 40 MGD. From Equation A-1, estimated population (1986) = 313,000

$$C = \frac{40*10^{6}}{313,00} = 98.4 \text{ gpcd}$$

Therefore

$$OM = 872 \left[\cdot \frac{CP_o e^{Kt}}{10^6} \right]^{0.488}$$

Substituting known values and collecting like terms

$$OM = 2,535, \cdot e^{0.0127t} \qquad (A-5)$$

Assuming continuous compounding, the present equivalent O & M cost (POM) is:

$$POM = B e^{(0.0127-i)t} \qquad (A-6)$$

where

B = 2,535,957

i = discount rate

Integrating Equation A-6 to sum the costs over the time period from year x to year T and to obtain the net present value of the series of O & M costs, TPOM,

$$TPOM = \left(\frac{B}{0.0127 - i} \right) [e^{(.0127-)T} - e^{(.0127-i)x}] \qquad (A-7)$$

Assume water conservation measure reduces wastewater from a household by an average of 100S%, 100a% of households actually use the conservation measure and 100b% of the wastewater is from residential sources, then total wastewater flow is reduced by 100abS%.

a = 0.67 from both Palmini and Shelton 1980, and EPA (1977)

b = 0.77 for Salt Lake City.

From the literature, using shower flow control restrictor, faucet aerator and a toilet water dam, average annual water savings = 7,500 gallons/family of 4; = 5.14 gpcd

Therefore:

$$S = \frac{5.14}{C} = \frac{5.14}{98.4} = 0.05$$

The present value of O & M cost with the devices:

$$TPOM' = TPOM\ (1 - abS)^{0.488} = 0.9873\ TPOM \qquad (A\text{-}8)$$

and present cost of O & M cost savings due to household water conservation measure, OSAV is:

$$OSAV = TOM\ (1 - 0.9873) = 0.0127\ TPOM \qquad (A\text{-}9)$$

or a savings of 1.27% in O & M cost.

From Equation A-7, assume discount rate i = 10%; design period T = 25 and conservation measure is to start now (x = 0)

$$OSAV = \underline{\$327,320} \qquad (A\text{-}10)$$

Construction Cost Savings

Construction cost (CC) can be represented by:

$$CC = 52,000\ P_D^{0.461}\ Q_D^{0.429}; \quad \text{EPA (1977)} \qquad (A\text{-}11)$$

where

Q_D = design flow (MGD);

P_D = the design population equivalent.

Assume the design flow can be estimated as 2.25 times the average daily flow (Fair et al. 1968). Without household water conservation:

$$Q_D = 2.25\ (10^{-6}\ \frac{CP_o}{b}\ e^{KT} - Q_{max}) \qquad (A\text{-}12)$$

The above equation implies that when the capacity of the existing wastewater treatment plant is reached, a second treatment plant will be constructed with sufficient capacity to handle the excess flow due to increased population and industrial/commercial growth expected throughout the time horizon of the project.

For SLC, Q_{max} = 45 MGD; C = 98.4 gpcd; P_o = 313,000; K = 0.013.

Therefore:

$$Q_D = 2.25\ (40\ e^{0.013T} - 45) = 23.3 \qquad (A\text{-}13)$$

With household water conservation measures,

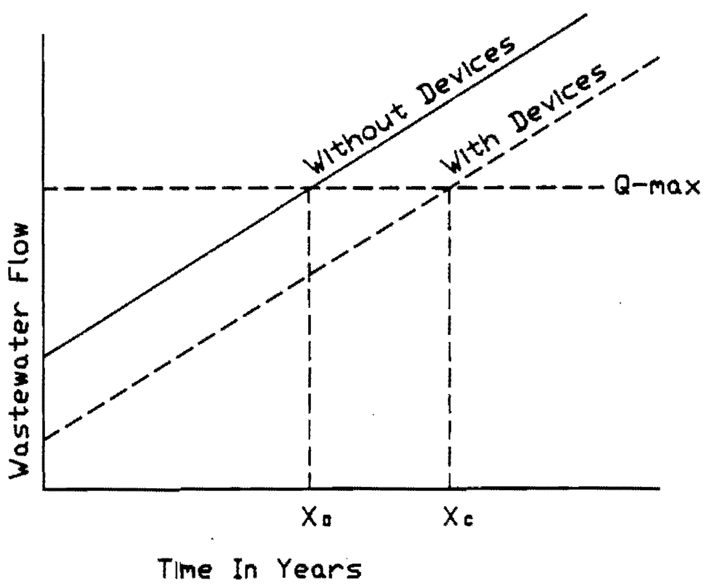
$$Q_D' = 2.25\ (40\ (1 - abS)e^{.013T} - 45)$$

$$= 2.25\ (38.968\ e^{0.013T} - 45) = 20.1 = 13.7\% \qquad \text{(A-14)}$$

The design population equivalent P_D can be expressed as:

$$P_D = (P_o/b)\ (e^{0.013T} - e^{+0.013X_o}) \qquad \text{(A-15)}$$

and it is defined as the population equivalent in excess of that which can be handled by the existing wastewater treatment facility. X_o is the time at which present treatment plant capacity is reached without household water conservation.



$$X_o = \frac{1}{K} \text{Log}_e \left(\frac{10^6\ \text{Qmax b}}{CP_o} \right) = 9 \text{ years}$$

with household conservation measures

$$X_c = \frac{1}{K}\ \text{Log}_e \left(\frac{10^6\ \text{Qmax b}}{CP_o(1 - abS)} \right) = 11 \text{ years}$$

Without conservation measures, the present equivalent of the construction cost is given by:

$$\text{PCOST} = 52{,}500\ P_D^{0.461}\ Q_D^{0.429}\ e^{-iX_o} \qquad \text{(A-16)}$$

From Equation A-15, $P_D = (313{,}000/b)(e^{.013T} - e^{.013X_o})$

Let design period T = 25 yrs.

Therefore:

$$P_D = 105{,}652 \quad \text{(A-17)}$$

From Equation A-13, $Q_D = 23.3$

From Equation A-14, $Q_D' = 20.1$

Decrease in design flow = 13.73%.

From Equation A-16, PCOST = $\$17.057*10^6$ (A-18)

With water conservation measures

$$PCOST' = 52{,}500\ P_D^{0.461}\ (Q_D')^{0.429}\ e^{-iX_c} \quad \text{(A-19)}$$

$$PCOST' = \$13.107*10^6 \quad \text{(A-20)}$$

The net present value of the construction cost savings due to household water conservation measures CSAV is:

$$CSAV = PCOST - PCOST' = \$3.95*10^6$$

% savings in construction cost = <u>23.16%</u>

For the Salt Lake City area, estimated decrease in flow to sewage treatment plant due to use of water savings is about 5%. This reduction is well below the level (20%) that Davis (1980) gives as the limit above which flow reduction tends to affect the operation of a sewage treatment plant.

The analysis indicates that flow reduction has a very small effect on the operation and maintenance cost (only 1.3% reduction); however, construction cost savings is over 23%. The large decrease in construction cost is due to the delay in construction (from 9 to 11 years) and the decrease in design flow (23.3 to 20.1 MGD).