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Economic Aspects of Urban Water Supply: Some Reflections on Water Conservation Policies

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ECONOMIC ASPECTS OF URBAN WATER SUPPLY: SOME REFLECTIONS ON WATER CONSERVATION POLICIES

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STEVE H. HANKE is a Professor of Applied Economics at the Johns Hopkins University, Baltimore, Maryland 21218, U.S.A. He spent several months at the International Institute for Applied Systems Analysis as a Research Scholar, contributing to the project "Water Management: Modeling Techniques for Estimating Regional Water Demand and for Demand/Supply Integration" supported jointly by IIASA and the Stiftung Volkswagenwerk, Hannover, Federal Republic of Germany.

PREFACE

Water supply planning has traditionally been carried out in two steps: first, water requirements are forecast; and second, water systems are planned to meet these requirements. This traditional approach served water planners well until the 1960's. Then costs began to increase dramatically but regulators failed to allow revenues to increase as rapidly. As a result, the traditional approach to water supply planning became inadequate. To reduce costs and reduce waste, planners began to consider water conservation policies. Moreover, some planners began to explore the merits of using an economic approach to system planning.

This monograph reflects my involvement in both the economic research required to develop a general economic approach to water system planning and the attempts to apply benefit-cost analysis to the evaluation of water conservation policies. With encouragement from Janusz Kindler, Chairman of the Resources and Environment Area of the International Institute for Applied Systems Analysis (IIASA), I have attempted to present, in a systematic manner, my reflections on my research and applied experience. The work was carried out within the framework of the project "Water Management: Modeling Techniques for Estimating Regional Water Demand and for Demand/Supply Integration" supported jointly by IIASA and the Stiftung Volkswagenwerk, Hannover, Federal Republic of Germany. I anticipate that these reflections will assist researchers and practical planners in developing integrated research programs on the economics of water supply and also in applying economic analysis to the practical problems that face water system planners.

The monograph develops the general principles required to apply the economic approach. The intent is to familiarize the reader with the economic way of thinking about water conservation. In addition, specific examples and numerical results are presented. Hopefully, this will allow the readers to gain an appreciation for the "how to" aspects of the economic approach to planning.

In closing, I would like to express my appreciation to those who offered valuable comments on early drafts of this monograph: Andy Anderson, Jesse Ausubel, Lennart de Mare, Don Erlenkotter and Janusz Kindler.

Steve H. Hanke
Baltimore, Maryland U.S.A.
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Chapter 1

WATER SUPPLY AND ECONOMICS

Traditional Water Supply Planning

Two elements are central to traditional water supply planning: a water requirements forecast and a cost minimizing strategy to supply the requirements. Three steps are necessary to produce a water requirements forecast. First, a population forecast is made. This is usually accomplished by extrapolating past trends. Second, a forecast of per capita water use is prepared. Again, the technique used is commonly an extrapolation of past trends. A water requirements forecast is then produced by multiplying the population figures times the per capita use figures.

After a water requirements forecast is produced, the problem shifts to an evaluation of the alternative means of meeting the requirements. This problem is one of selecting a cost minimizing supply strategy.

Traditional water supply planning, therefore, accepts water requirements as a given,and then cost minimizing systems are designed to meet the fixed or given requirements. At no point in the traditional process are benefits balanced with costs. Rather, the benefits associated with meeting water requirements are implicitly assumed to always exceed costs. The only real analytical problem is to minimize the costs of meeting a fixed objective, namely the water use requirements.

Until the 1960's, the traditional method of water supply planning appeared to serve water systems well. Supplies were usually adequate, and total revenues were sufficient to meet the real costs of supply.

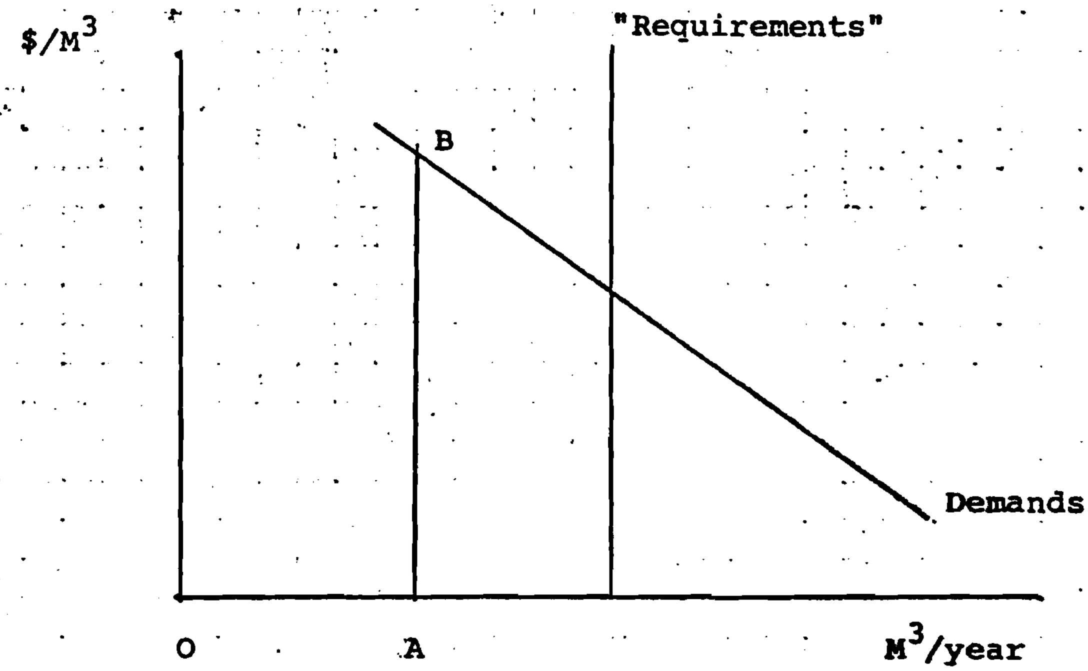
The sixties, however, brought with them inflation. Inflation increased the costs of making investments in both new and replacement facilities. These cost increases contributed to serious problems for water supply systems. Water supply revenue sources are regulated directly or indirectly by political or quasi-political bodies. Hence, revenues are not determined by the free play of supply and demand in unregulated markets. This arrangement for setting allowed revenues and the fact that regulatory bodies have either been unwilling or incapable of responding to cost increases has resulted in insufficient water system revenues. Herein lies the core of the problem faced by water system planners.

Without sufficient revenues, water systems have begun to deteriorate and new capacity has become increasingly difficult to finance (Carron and MacAvoy, 1981). Faced with a financial crisis, some water supply planners have begun to question traditional planning methods. Rather than assuming that requirements are fixed and must be met, planners are beginning to ask: what are the benefits and costs associated with alternative water conservation policies? (Binnie International (Australia) Pty. Ltd. et al., 1977; Hanke, September, 1978; Hanke, 1980(a); Hanke, 1980(b); Hanke, February 1981; Hanke, April 1981; Hanke, 1982; and Gilliland and Hanke, 1982.)

The Economic Approach to Water Supply Planning

The economic approach requires that the benefits and costs of alternative policies be estimated. Some water supply planners have begun to adopt the economic approach to water supply planning. The objective of this approach is to avoid waste in the allocation of resources. The economic approach involves forecasting demands, not requirements (see Figure 1.1). These demands have an economic meaning: for each level of water use, the demand

Figure 1.1 "Requirements" and Demands



represents the incremental or marginal valuation that consumers place on that unit of water use. For example, the value or benefit of the A^{th} unit of water consumed in Figure 1.1 is equal to AB. The demand function, is therefore, a marginal or incremental benefit function. A supply function (Figure 1.2), which represents the least-costly combination of resources required to produce alternative quantities of water, is the second element in the economic approach. To produce the A^{th} unit of water in Figure 1.2, the cost is AB, which represents the incremental or marginal cost of the A^{th} unit. Therefore, the supply function is a marginal cost function. To avoid waste and allocate resources efficiently, plans must be made so that demands and supplies are equal. In Figure 1.2, this balance of marginal benefits and costs occurs at the consumption-production level OA.

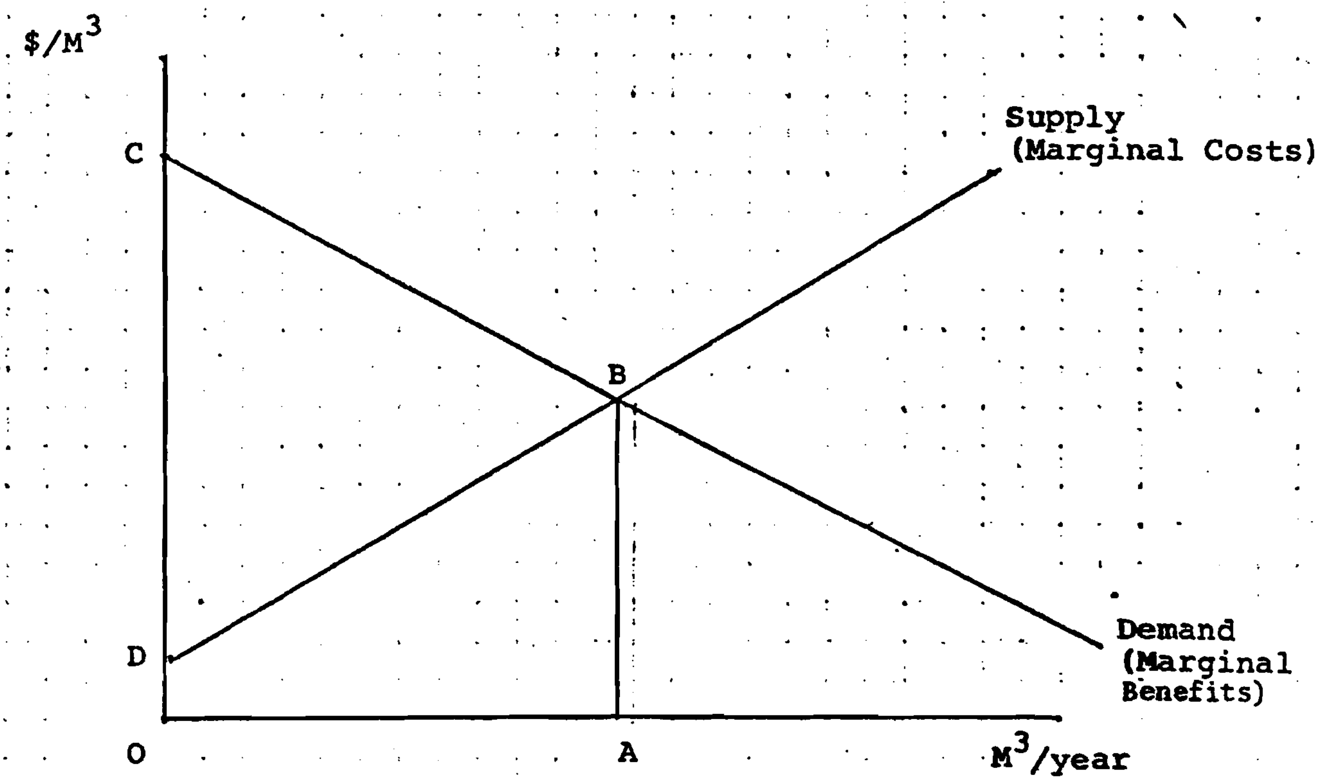
The economic balance of demands and supplies avoids waste and is efficient because:

(1) Production is increased by using low-valued resources first. Production is increased by moving along the supply function from left to right (from D to B in Figure 1.2).

(2) Production is allocated to high-valued uses first. Production is allocated by moving along the demand function from left to right (from C to B in Figure 1.2).

(3) Production and consumption (supply and demand) are balanced at an efficient level. Production and consumption are expanded as long as their marginal costs are less than their marginal benefits, and production and consumption are balanced at the point where their marginal benefits equal their marginal costs. In our example (Figure 1.2), demand and supply are efficiently

Figure 1.2 Demand and Supply Integration



balanced at an output level of OA. We do not expand production and consumption beyond this level, since any increment would generate marginal costs that exceed marginal benefits, and this would result in economic waste. Alternatively, if we fail to expand output to OA, economic waste occurs, since the marginal costs of expansion up to OA are less than the marginal benefits.

The Plan for this Monograph

The purpose of this monograph is to apply economic analysis to the problem of urban water supply planning. Since the economic approach represents a departure from the traditional approach, emphasis is placed on the development of general economic principles and the practical application of these principles to the specific problems that frequently confront those who are responsible for urban water supply planning and management.

The plan for the monograph is to first present the basic concepts and tools for analysis. This is accomplished in Chapters two through five and Appendix 1. The concepts and tools are applied to urban water supply problems in Chapters six and seven. In the eighth and final chapter, we discuss the policy implications and insights which can be derived from using economic analysis to integrate urban water supply and demand.

Chapter 2

A BENEFIT-COST MODEL

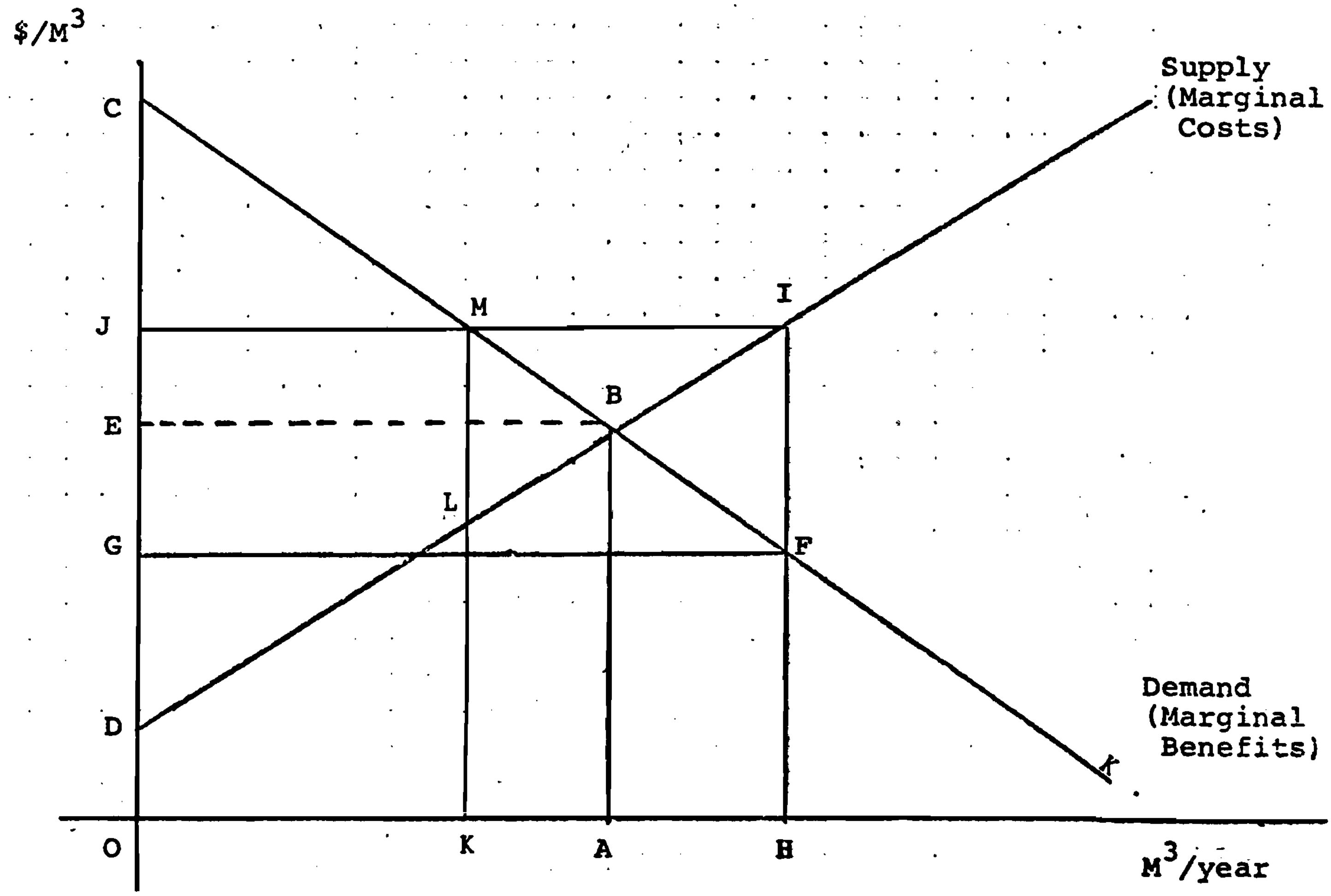
On the Economic Objective and Criterion for Choice

In order to make statements about the desirability of an action or policy, we must state our objective and determine a criterion for choice. Since we limit the scope of our analysis to economics and the attainment of efficiency in the allocation of resources, our objective is to maximize the net benefits from the use of resources. We wish, therefore, to maximize the net benefits (the difference between the total benefits and total costs) of using resources. This is accomplished by pursuing an action or policy as long as its marginal or incremental benefits exceed its marginal or incremental costs. If this criterion for choice is employed, resources will be used efficiently and waste will be avoided.

We illustrate the principles and define the terms, which we use throughout this monograph, by the use of Figure 2.1. Our objective is to maximize the difference between total benefits and total costs. Since the marginal benefit function is the first derivative of the total benefit function, we determine the total benefits of consumption by integrating the marginal benefit function over the relevant range of water use (for numerical examples, see: Powers, 1978). If water is rationed to the highest valued users first, starting at point C on the demand function first and then moving to the right toward point B as consumption is increased, then the total benefits from consuming 0A units will be equal to the area OCBA.

Since the marginal cost function is the first derivative of the total cost function, we determine the total costs of production by integrating the marginal cost function over the relevant range of water production.

Figure 2.1 Benefits and Costs



If water is produced from the least costly sources first, then the total costs of producing OA units will equal ODBA.

In our example and with our criterion for choice, we can observe that net benefits are at a maximum when OA units are efficiently consumed and produced. At this level of water use, demands and supplies are balanced and net benefits are equal to the area CBD, which is the difference between total benefits (OCBA) and total costs (ODBA). An efficient plan should be targeted to produce OA units efficiently and to ration them efficiently to consumers.

The method that will achieve an efficient outcome and avoid waste is to produce an efficient level of output, OA (see Figure 2.1), and ration it by setting price equal to OE, the marginal cost of OA units. By applying this method, the efficient output will be produced; it will be rationed to the highest valued uses; and as a result, the net benefits will be at a maximum, area DCB.

If the price is set above OE, the efficient level, economic waste will occur and the efficient plan will not be achieved. For example, a price of OJ will result in consumption of OK and net benefits equal to the area DCML. To eliminate the waste associated with this suboptimal result, we must lower the price to OE and increase output to OA. This will increase efficiency, since the marginal benefits of consumption exceed the marginal costs of production in the range of output and consumption KA. The increase in net benefits will equal the area LMB.

If the price is set below OE, the efficient level, economic waste will occur and the efficient plan will not be achieved. There are several possibilities that could exist. One possibility involves the necessity of nonprice rationing. We use a simple example to illustrate the nature of the waste associated with this possibility. If the output is OA, the efficient level, and the price is set at OG, then the quantity of water demanded would exceed the system's output by AH units. To ration the capacity OA and retain the price of OG, we must employ some form of nonprice rationing. If we could devise a "perfect" nonprice rationing mechanism -- one which would eliminate the uses represented by the segment of the demand function BF -- and if this could be implemented with no administrative costs, then we could obtain the efficient output, ration consumption to the highest valued uses, and obtain the maximum net benefits. However, such a system of nonprice rationing cannot be devised. Although a nonprice rationing system can constrain consumption to OA units, it cannot guarantee that only the highest valued uses, represented by the segment CB on the demand function, will be served (Hanke, 1980(b)). In fact, some of the lower valued uses, which are represented by the segment of the BF of the demand function, will be substituted for some of the higher valued uses, which are represented by segment CB on the demand function. As a result, the total gross benefits of OA units of consumption with nonprice rationing -- which would equal the area OCBA, if consumption was allocated to the highest valued uses first -- will be less than the area OCBA. Hence, with nonprice rationing, the net benefits of OA units of consumption will be less than the area DCB, which represents the maximum net benefits of OA output and consumption. In addition to these reduced benefits, nonprice rationing will impose another cost, the administrative cost of the nonprice rationing system.

Another possibility that can occur when the price is set below OE is the following: nonprice rationing is not imposed; then excess demands exist (if the price is OG and output is OA, excess demands equal AH); the quality of service deteriorates; and political pressure to expand capacity results. In this example, the total demands of OH can be met by expanding output with an increment in capacity of AH. This expansion will be wasteful because the marginal costs exceed the marginal benefits in the range of output and consumption AH. The waste of expanding output and consumption from OA to OH is determined by subtracting the gross costs of that increment, which equal the area ABIH, from the gross benefits, which equal the area ABFH. The result is a net loss or waste of the increment in capacity equal to the area BIF.

A Benefit-Cost Model for Water Conservation

Since water supply systems' revenue sources are regulated and have been limited in many cases to levels that are below the real costs of maintaining existing systems, some water supply planners have abandoned the traditional approach to planning. Instead, they have begun to focus on water conservation programs and methods of managing water demands. In addition, some water supply planners have begun to use the economic approach as a means of evaluating alternative water conservation policies. In short, tight budget constraints have introduced a new discipline into water supply planning. The economic approach has offered a new means of avoiding economic waste and accommodating fiscal discipline.

The economic approach differs from the traditional approach, which assumes that meeting water use requirements is desirable *per se*. Rather, the economic approach has as its objective the avoidance of economic waste and the maximization of net benefits. Given this objective, meeting fixed water use requirements or alternatively conserving water may or may not be desirable. The desirability of either of these policies will depend on the benefits and costs associated with each. Since the determination of benefits and costs is central to the economic approach to planning and since water conservation is the dominant policy presently under consideration, we focus directly on the measurement of the benefits and costs of water conservation. However, we should note that the economic tools that are developed are necessary and can be used to evaluate the benefits and costs of system expansion.

To evaluate the desirability of conservation policies, we need a benefit-cost model for water conservation. Based on the economic concepts presented, we first define a change in total benefits. The change is the savings in resources which is expected to result from the introduction of a water conservation policy. The incremental benefits (ΔB) are calculated by taking the product of the reduction in water use resulting from the policy (Q) and the marginal cost of water (MC):

$$\Delta B = Q \cdot MC. \tag{2.1}$$

Second, we define the change in costs (ΔC). The change is the sum of: (1) the resource costs to the water utility or authority of adopting the policy (U) (These could include such items as water meters, conservation devices, leakage detection programs, educational programs and enforcement programs.), (2) the resource costs to the consumers (E) (These could include such items as the purchase and installation of conservation devices, the value of time and effort used to repair leaks.), and (3) the value of "useful" consumption foregone (F) (This figure is equal to benefits lost because consumption is less after the policy is introduced.). Hence, the incremental costs are represented by:

$$\Delta C = U + E + F. \tag{2.2}$$

With these definitions, and our objective of maximizing net benefits from any conservation policy, we can state that any conservation policy is desirable only if the change in benefits exceed or are equal to the change in costs:

$$Q \cdot MC \geq U + E + F. \tag{2.3}$$

Thus, equation (2.3) becomes our criterion for choice or our benefit-cost model, for determining whether a conservation policy is desirable.

Chapter 3

DEMAND ANALYSIS

To implement our benefit-cost model (Equation 2.3), we must analyze the demand for water. Two types of demand information are required. First, we must identify the determinants of water use that can be modified or controlled by water authorities. Each of these determinants is a potential water conservation policy, and is, therefore, a candidate for benefit-cost analysis. Once we identify each determinant, we must be able to predict the impact of each on water use. That is, we must be able to predict water use without the conservation policy and water use with the policy. The difference between these two values is the change in water use which results from the use of the conservation policy. It is equal to Q in our benefit-cost model.

Second, we must be able to identify the demand function for water. This is necessary, so that we can estimate the value of "useful" consumption foregone when a water conservation policy is introduced. Once we have estimated the reduction in water use that will accompany a conservation policy, we must estimate the value of water that will no longer be consumed. This value is represented by F in our benefit-cost model.

On the Determinants of Water Use

Price - the price charged per m^3 of water is one of the determinants of water use. Price is controlled directly by water authorities and/or regulatory bodies. Since water use is negatively correlated with price, price is considered to be an important conservation measure. To measure the impact of price changes on water use (Q in Equation 2.3), we need to estimate price elasticities of demand for various types of urban water use; where the price elasticity is a dimensionless number that expresses the responsiveness of water use to changes in price. For relatively large changes in price, the price elasticity is given by the following formula:

$$e = \frac{P + \Delta P}{Q} \cdot \frac{\Delta Q}{\Delta P}, \tag{3.1}$$

where e = the price elasticity of demand, P = original price of water, Q = the original quantity of water use, ΔP = the change in price, and ΔQ = the change in water use. In cases where ΔP and ΔQ become small, then the elasticity formula given by Equation 3.1 becomes:

$$e = \frac{dQ}{dP} \cdot \frac{P}{Q}. \tag{3.1'}$$

In all cases, the price elasticity coefficient will have a negative sign, indicating a negative relationship between water use and price. Also, when the absolute value of the elasticity coefficient is greater than 1.0, water use is relatively responsive to a change in price; whereas, water use is relatively unresponsive, when the absolute value of the coefficient is less than 1.0.

There have been many studies in which price elasticities have been estimated for urban water use (Hanke, September 1978). Most of them have been conducted in the United States. Since they vary widely in quality, we should use caution when using the results.

The most reliable estimates of price elasticities are derived from studies that have the following characteristics (for more details, see: Hanke and Mehrez, December 1979 and Hanke and deMaré, August 1982):

(1) metered water use data is used to construct the demand models;

(2) data are disaggregated by user class, and these user classes are defined, so that they contain customers who are similar and thought to have similar responses to price changes;

(3) water use and price data are collected at one location for a relatively long time-series, with a relatively large number of real price changes.

One study that has these characteristics was conducted in Malmö, Sweden (Hanke and deMaré, August 1982). Table 3.1 provides a summary of the data that were collected. Several points are particularly noteworthy. The time-series data used were for 14 semi-annual time periods, starting with the last quarter of 1971 and ending with the third quarter of 1978. The cross-section data that were used were from a stratified sample of 69, single-family houses in Malmö. (The 69 houses were separated into two groups. One group was constructed in the period 1936-1946 and the other 1968-1969.) The water use data were obtained from semi-annual, metered water use records. The income data were from income tax records. The number of adults and children occupying each house and rainfall per semi-annual period were all from records maintained by the city of Malmö. The price of water was the real marginal price per m^3. Its value remained constant for each house in each billing period, regardless of the quantity of water that each house used. During the period under study the nominal price per m^3 was changed five times and the real price changed in 12 of the 14 semi-annual periods.

Using a pooled, time-series, cross-section approach, the demand for residential water demand in Malmö was estimated. The model used was a

Table 3.1. Characteristics of the Malmö data.

Variable	Mean	Standard Deviation	Type of Data
Quantity	75.2106	36.2893	TS-CS
Income	49497.0000	21781.0000	TS-CS
Adults	2.0500	0.7460	TS-CS
Children	0.9260	1.0418	TS-CS
Rainfall	39.1324	7.7768	TS
Age of Houses	0.5401	0.4986	CS
Price of water	1.7241	0.3190	TS

Notes:

It is important to note that the data contain no proxies. The data represent real values for the variables studied.

Quantity = quantity of metered water per house, per semi-annual period, in m^3.

Income = real gross income per house in Swedish Crowns (actual values reported per annum and interpolated values used for mid-year periods).

Adults = number of adults per house, per semi-annual period.

Children = number of children per house, per semi-annual period.

Rainfall = rainfall per semi-annual period/6, in mm.

Age of Houses = a dummy variable with a value of 1 for those houses built between 1968 and 1969 and a value of 0 for those houses built between 1936 and 1946.

Price of Water= real price in Swedish Crowns per m^3 of water, per semi-annual period (includes all water and sewer commodity charges that are a function of water use).

TS = time-series data (14 semi-annual periods, starting with the last quarter of 1971 through the first quarter of 1972 and ending with the second and third quarters of 1978.

CS = cross-section data (69 houses which have remained with the same. head-of-household during the seven-year study period.

Prices and incomes were deflated to real values by using the Swedish consumer price index.

Source: (Hanke and de Maré, August 1982) static, equilibrium model that assumes a linear relationship among the variables. The results of applying ordinary least squares regression analysis to the data are contained in Table 3.2.

The equation and estimates of parameters are statistically significant. Furthermore, the signs of the independent variables are as we expected.

With the results obtained, elasticities can be derived. It is the information on price elasticities that is required to estimate the impact of price changes on water use. This elasticity information is summarized in Table 3.3.

Recall that to evaluate the benefits and costs of a price increase, we must estimate Q in Equation 2.3, where Q represents the change in water use that will result from a price increase. This is accomplished by using price elasticities. For example, if the original price for water in Malmö was 2.0 Swedish Crowns per m^3, water use was 100,000 m^3 and we consider a 50 percent price increase, then consumption would decrease (if all other determinants of water demand remain constant) by 7.5 percent or 7,500 m^3. Hence, the value of Q in Equation 2.3 would equal 7,500 m^3. To make this calculation, all we must do is multiply the elasticity (-.15) times the percentage price increase (.50) and then multiply the result (-.075) times the original water use (100,000 m^3).

Water Use Restrictions - Water use restrictions are regulations which require water users to use their existing stock of water-using equipment in an involuntary way, so that water use is reduced. Although these restrictions are widely used, primarily during droughts and short-term emergencies, there is only one study which measures the impact that restrictions have on water use and determines restriction elasticities (Hanke and Mehrez, 1979).

Table 3.2. Demand Equations for Malmö.

Linear Model

$$Q = 64.7 + 0.00017 \text{ Income} + 4.76 \text{ Adults} + 3.92 \text{ Children} - 0.406 \text{ Rainfall} + 29.03 \text{ Age of Houses} - 6.42 \text{ Price of Water}$$

	Income	Adults	Children	Rainfall	Age of Houses	Price of Water
	(3.26)	(2.98)	(3.09)	(2.12)	(11.54)	(1.99)

$R^2 = 0.259$

Notes:

1. The numbers in parentheses are t statistics.

2. For the degrees of freedom in our equations, the critical value for the t statistics, at the 5 percent level of significance, is 1.98.

3. Tests for milticollinearity, serial correlation (the Durbin-Watson test) and heteroskedasticity (the Goldfeld-Quant test) have been made to insure that the methodology (OLS analysis) is consistent with the assumptions required to obtain unbiased estimates of the parameters and t statistics. The equations presented passed these tests. Hence, the price elasticities derived are efficient elasticities.

4. It is important to realize that our pooled data are dominated by cross-section data. Hence, the value of the R^2, which would be low for a pure time-series study, is satisfactory for our pooled analysis because of the large variation across individual units of cross-section observation which is inherently present in the data. For purposes of estimating elasticities in this context, the t statistics are most important and these are significant at the 5 percent level for each coefficient in our model.

Source: (Hanke and de Maré, August 1982)

Table 3.3. Elasticities for Malmö.

Variable	Elasticity
Income	+0.11
Adults	+0.13
Children	+0.05
Rainfall	-0.21
Price of Water	-0.15

Notes:

The general concept of elasticity as follows:

elasticity = $\frac{dD}{dI}\frac{I}{D}$, when D = the dependent variable and I = the independent variable. A linear demand function has a different elasticity at each point. It is suggested that the mean values of D and I be used to determine a single elasticity for linear equations. For example, the price elasticity for the demand model is computed as follows:

$$-6.42 \left(\frac{1.724}{75.2}\right) = -0.15.$$

Source: (Hanke and de Maré, August, 1982)

To conduct this study, multiple regression analysis was used to analyze time-series data for a 30-year period (1946-1975) for Perth, Western Australia. During this period, water use restrictions were employed in the summer months (December, January and February) in 13 of the 30 years studied. These restrictions were directed at reducing sprinkling use for residential water use. The restrictions consisted of bans on the use of outside sprinklers. The use of hand-held garden hoses was allowed.

The equation of best fit for the month of December was found to be:

$$(3.2) \quad \log_e Q = -4.35 + 2.509 \log_e T_{max} - 0.025 \log_e Rain - 0.214 \log_e Res,$$

where Q = mean daily water use per account in imperial gallons, T_{max} = mean maximum daily temperature in °F for each month, Rain = total rain in millimeters for each month, and Res = a dummy variable which receives the value of 2, if restrictions were used, and the value of 1, if restrictions were not used.

In much the same way as price elasticities allowed us to predict the impact of price increases on water use, restriction elasticities allow us to predict the impact of water use restrictions on water use. The restriction elasticity in equation 3.2 is given by the coefficient of $\log_e$ Res and is equal to -0.214. (Note that the restriction elasticity for January is -0.222 and February is -0.162.)

Using Equation 3.2, and setting T_{max} = 86.4°F, Rain = 2 mm, and Res = 2 with restrictions and 1 without restrictions, we compute estimates of water use for December of 917 imperial gallons per account per day with restrictions. For each day in December and for the average water customer, water use is reduced by 127 imperial gallons or 14 percent due to imposition of water use restreictions. Therefore, if we want to operationalize our benefit-cost model for water use restrictions on the average customer in Perth, Western Australia for the month of December, we must substitute the value of 3937 imperial gallons for Q in Equation 2.3. (To obtain this value (3937), we subtract 790 from 917 and multiply by 31.)

Even though only one study has produced restriction elasticity estimates, we should note that these elasticities are consistent with engineers' rules-of-thumb which are used in North America to predict the impact of restrictions (Grima, 1972). For example, engineers often assume that water use will be about 85 percent normal, when water use restrictions of the type evaluated in Perth are imposed (for similar results, see Table 3.4).

As is the case with price elasticities, we must conclude that the limited information that we have on restriction elasticities, must be applied with caution. Although our restriction elasticities conceptually measure the proper quantities which are relevant for a benefit-cost study, they represent a limited data base: they are for residential water use, at one location and for one type of water use restriction. To be able to make generalizations that are based on sound analysis, we must conduct more studies with time-series data, at different locations and with various types of restrictions for different classes of water users.

Water Meters - Water meters provide another method for conserving water. Consumers who purchase metered water must pay a price per m^3, while unmetered customers do not. Hence, metered customers have a greater incentive to control their use, than do unmetered customers.

Table 3.4 The Impact of Water Use Restrictions (Perth, Western Australia)

Month	Water Use* Ratio	Water Use with Restrictions (as a % of use without restrictions)
December	$\frac{2^{-0.214}}{1^{-0.214}}$	86.2
January	$\frac{2^{-0.222}}{1^{-0.222}}$	85.7
February	$\frac{2^{-0.162}}{1^{-0.162}}$	89.4

*Note that the exponents in each ratio are the restriction elasticity coefficients

The impact of water metering on water use can be seen by reviewing the data in Table 3.5. These data, which were collected on a cross-sectional basis from 18 locations in the United States indicate that residential users who were metered used less water than those who were unmetered. In metered areas, average sprinkling use was about 45 percent that of unmetered areas. Household use for domestic purposes was not significantly different between the metered and unmetered areas.

Another carefully controlled cross-sectional study in Israel, however, indicates that household use can be reduced by the installation of meters (Kamen and Dar, 1973). The Kamen and Dar study included a sample from apartments in which sprinkling use did not occur. Their sample included 1157 apartment units (households), located within apartment buildings, which were metered with 1157 separate water meters. In addition, 469 apartment units located within apartment buildings, which were not individually metered, were included. In the second group, each whole building which contained apartment units was metered. A review of Table 3.6 indicates that domestic use in the apartment units that were individually metered was about 75 percent of those that were unmetered. Moreover, the use in each of the metered apartments was more closely grouped around the mean use per apartment for the metered than for the unmetered apartment units.

One study has evaluated the impact of metering at one location, Boulder, Colorado, U.S.A. over time (Hanke, 1970a). Time-series data for domestic and sprinkling use, from 1955-1968, and for 3086 customers were used. Residential customers were unmetered from 1955-1961 and metered from 1962-1968. This study found that domestic and sprinkling water use were 65 and 51 percent, respectively, of what they had been prior

Table 3.5 Water Use in Metered and Unmetered Areas

	Metered Areas (10)	Unmetered Areas (8)
	(gal/day per dwelling unit)*	
Annual Average		
Leakage and waste	25	36
Household	247	236
Sprinkling	186	420
Total	458	692
Maximum Day	979	2354
Peak Hour	2481	5170

*Data were collected for eighteen locations in the U.S.A. from October 1963 - September 1965, and at 15 minute intervals.

Source: (Howe and Linaweaver, 1967)

Table 3.6. Annual Per Capita Water Use by Town and Type of Metering.

Town	Apartment Unit Unmetered	Apartment Unit Metered
	(m^3 apartment unit)	
Jerusalem	56.0	48.0
	S.D. = 35.5	S.D. = 38.4
	S.E. = 4.37	S.E. = 3.21
Tel Aviv	86.4	65.3
	S.D. = 58.2	S.D. = 38.5
	S.E. = 3.75	S.E. = 2.31
Dan Region	87.3	57.3
	S.D. = 241.0	S.D. = 36.4
	S.E. = 20.1	S.E. = 1.96

Notes:

1. S.D. = standard deviation
2. S.E. = standard error

Source: (Kamen and Dar, 1973)

to metering. Moreover, the impact on water use of installing meters in 1962 was slightly greater in 1968 than in 1962. That is, the long-term impact was slightly greater than the short-term impact. Table 3.7 presents the data required to determine the impact of metering on water use (the value of Q in Equation 2.3).

Leakage Detection and Control - Another determinant of water demand (water production), which can be controlled by water utilities, is the water production lost through system leakage. Leakage demands do not come from the final users, since no one uses water lost by leakage. Rather, they are demands which are a function of the physical characteristics of the systems and the way in which systems are operated. To determine the impact of leakage detection and control programs on water production, we must establish a relationship between inputs for leakage detection and control and the output, which is reduced system leakage. With such a relationship or production function for leakage detection and control, we can determine the amount of water saved by applying various levels of detection and control effort.

Figure 3.1 represents a production function for leak detection and control for the city of Perth, Western Australia. The values for annual water saved can be used to determine Q in our benefit-cost model. For example, the impact of increasing leak detection and control workers from A to B (Figure 3.1) is equal to CD, which is equal to Q in our benefit-cost model.

On the Demand Function for Water

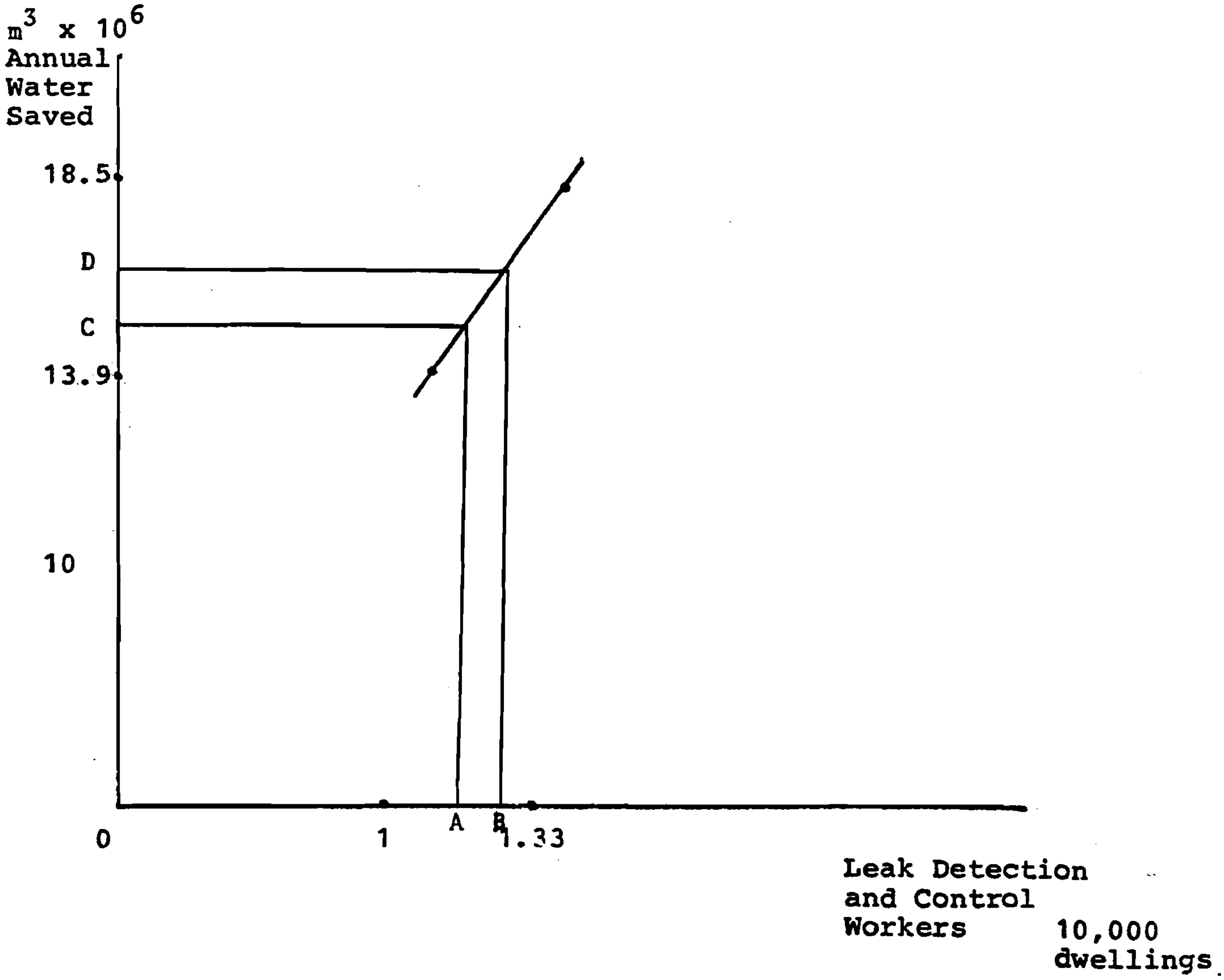
In addition to elasticity estimates, our benefit-cost model requires us to be able to locate the demand or marginal benefit function over the

Table 3.7. The Impact of Water Meters on Residential Use (Boulder, Colorado, U.S.A.)

Type of Use	Water Use* Ratio	Water Use with Meters (as a percent of use without meters)
Domestic	$\frac{2^{-0.62}}{1^{-0.62}}$	65
Sprinkling	$\frac{2^{-0.97}}{1^{-0.97}}$	51

*Note that the exponents in each ratio are the metering elasticities.

Figure 3.1 Production Function for Leak Detection and Control (Perth, Western Australia).



Source: (Binnie International (Australia) Pty.Ltd., et al., 1977) range of consumption and output being considered. Recall that the area under the demand function equals the total benefits of consumption. Therefore, the value of "useful" consumption foregone, F in our benefit-cost model, is determined by measuring the area under the demand function from the consumption level which would exit with the conservation policy to that which would exist without the conservation policy.

If we can specify the demand function mathematically, we can compute the value of the area under the demand function over the relevant range of consumption by taking the integral of the demand function over this range of consumption. For most practical problems, however, we will not have a demand function that can be used for direct computations of "useful" consumption foregone. We often only know the price per m^3 and the level of water use. That is, we only have information about one point on the demand function. In addition, we will be able to make a reasonable estimate of the price elasticity coefficient or a range of price elasticity coefficients. With these parameters, however, we can construct a demand function indirectly, and determine the value of "useful" consumption foregone.

We begin by construction a linear demand curve (Demand_1 in Figure 3.2). We know that:

P_1 = the price per m^3 of water in period 1,

Q_1 = water use in period 1, and

e = the price elasticity coefficient.

We also know that for discrete changes in price:

$$e = \frac{\Delta Q}{\Delta P} \cdot \frac{P_1}{Q_1}. \qquad (3.3)$$

We can determine the slope of a linear demand function by rearranging (3.3)

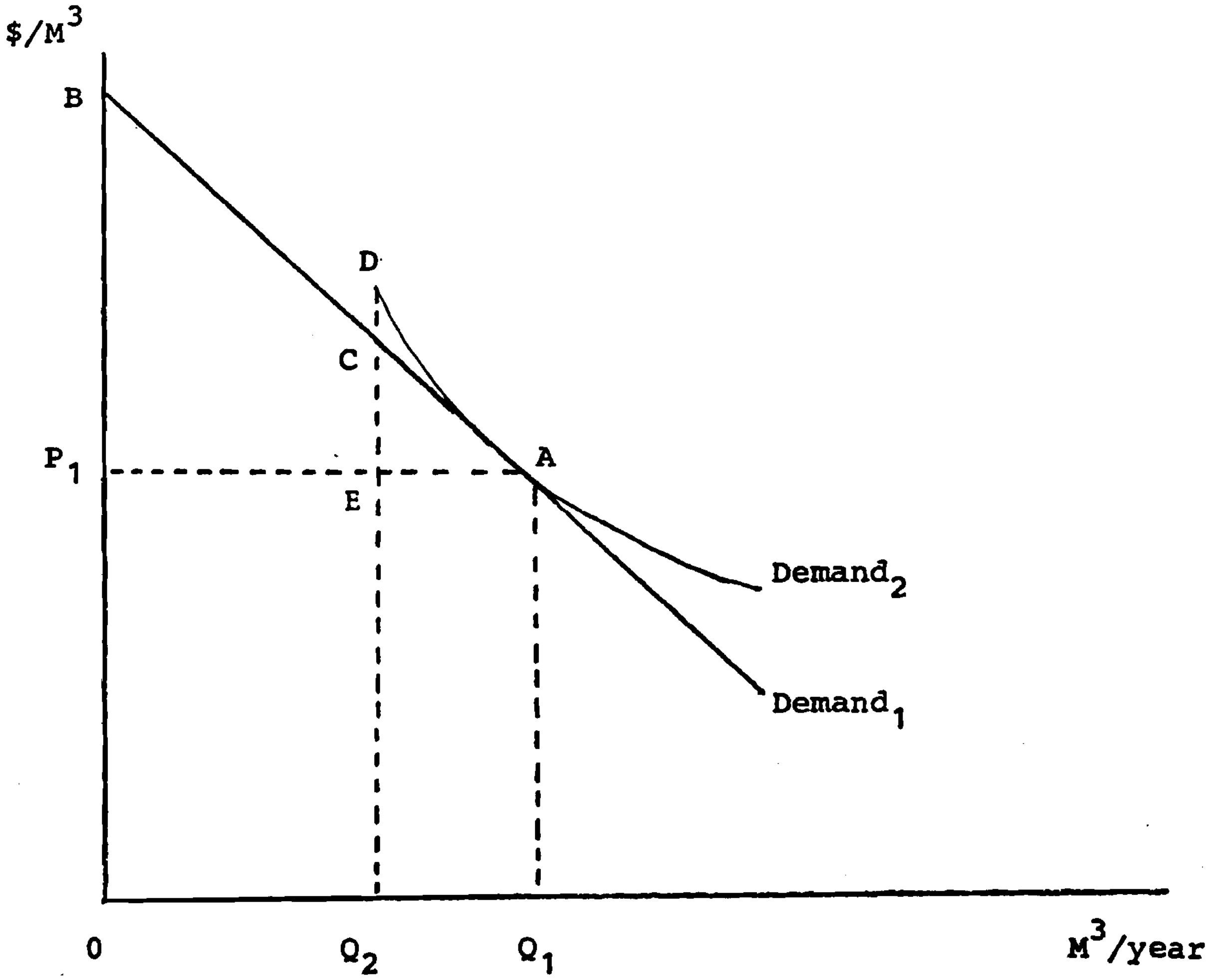


Figure 3.2 The Construction of Demand Functions

(3.4) $$\frac{\Delta P}{\Delta Q} = \frac{1}{e} \cdot \frac{P_1}{Q_1}.$$

Now let us use our analysis to construct a demand function (Figure 3.2). We know the values of P_1 and P_2. Hence, we know the location of point A. We also know the value of the price elasticity coefficient at point A. By solving Equation 3.4, we can determine the slope of the demand function that bisects point A. By using this information, we can construct a linear demand function (Demand_1) that has an intercept on the vertical axis of Figure 3.2 at point B. To compute the value of "useful" consumption foregone that is associated with a reduction in consumption from Q_1 to Q_2, we must:

(1) take the original price (OP_1) times the reduced consumption (Q_2Q_1). This equals the area Q_2EAQ_1 on Figure 3.2.

(2) then take the difference between the original price (OP_1) and a price (Q_2C) that would generate consumption at the new lower level (OQ_2). This difference is CE. We then multiply CE times the reduced consumption Q_2Q_1, and multiply the answer by 0.5. This procedure yields the area CEA on Figure 3.2.

(3) add the results obtained in steps (1) and (2) to obtain F, the value of "useful" consumption foregone. In this case, F is equal to the area Q_2CAQ_1 on Figure 3.2.

Since the absolute value of the price elasticity coefficient increases as we move from point A to point B on our linear demand curve and we usually only have one estimate of price elasticity, it is often desirable to use a constant elasticity demand function to predict changes in water use. Such a constant elasticity demand function is curvelinear, and has the following functional form:

(3.5) $$Q = a\,P^{e},$$

where Q = the water use per period, a = nonprice factors that determine water use, P = the price per m^3 and e = the price elasticity coefficient. A constant elasticity demand function is represented by $Demand_2$ on Figure 3.2, and can be derived by using the same method that we employed in the linear case.

It is interesting to note that most conservation programs generate relatively small reductions in use, when compared to the total water used. Therefore, the use of either the linear or curvilinear form of the demand function will generate values for "useful" consumption foregone (F in Equation 2.3) which are very close to each other. For example, if water use is reduced from Q_1 to Q_2 because of a conservation program, the value of F would be equal to the area Q_2CAQ_1 with the linear demand function and Q_2DAQ_1 with the curvilinear demand function. The difference between the two measures of F is equal to CDA, and is relatively small. Hence, even though the constant elasticity demand function is often the most convenient for predicting changes in water use, the linear demand function associated with it can be conveniently used for determining the "useful" consumption foregone.

Chapter 4

MARGINAL COST ANALYSIS

In the last chapter we discussed methods for determining the values for reduced water use and "useful" consumption foregone. We dealt with the demand-side of the conservation problem. In this chapter we deal with the supply-side of the problem and analyze the marginal cost of urban water supply. This allows us to determine the value of another term in our benefit-cost model.

On the Nature of Water Supply Systems

Before we analyze the marginal cost of water supply, it is important to describe the general nature of urban water supply systems, since the measurement of marginal cost is an activity that requires a specialized knowledge of the engineering and technology of the industry. For our purposes it is important to distinguish among three types of works within a water system: (1) water source works, (2) water treatment works, and (3) water distribution works. The water source works include all of the components associated with obtaining water and delivering it to treatment facilities. These components can include reservoirs, groundwater well fields and transmission mains. They are necessary to supply water to treatment facilities or generate annual yield for the water system. They are usually designed to meet average annual daily demands. The size and nature of source works are a direct function of the water used by final users.

In many systems, the raw water generated by the source works requires treatment prior to use. The treatment works usually include a treatment plant and small storage reservoirs. These facilities are generally designed to meet maximum day demands, which usually occur in the summer sprinkling season. The size and nature of these facilities, like the source works, are a direct function of the water used.

After appropriate treatment, the treated water is ready to be distributed. The distribution works can consist of distribution mains, storage reservoirs and tanks. Although these facilities are designed to meet maximum day and maximum hourly use, their size and nature, unlike source and treatment works, are usually a direct function of the number and type of users as well as regulations associated with the provision of water for fire fighting purposes.

On the Relevant Concept of Marginal Cost

The concept of marginal cost that we use depends on our objective. Our application of marginal cost information is for the evaluation of the benefits and costs of water conservation programs, and our objective is to maximize the difference between total benefits and costs of these programs. Hence, we define the marginal cost of water so that it allows us to measure the opportunity cost of using (or saving) an increment of water. To measure these marginal or forward-looking costs, we measure the value of other products that the inputs used to produce water could have been used to produce. This measure differs from the standard, static, neo-classical cost analysis, which was represented in our discussions and diagramatic treatment of costs in Chapter two. Our earlier treatment dealt with an exposition of basic principles and the method of reasoning required in the economic approach. While our earlier treatment was appropriate for pedagogic purposes or what is often termed "textbook economics," it is too simplistic to be useful operationally (Turvey 1969).

A general definition of marginal cost, which allows us to estimate the opportunity cost of water use in operational dynamic terms, is straightforward. To estimate the marginal capital cost for any year, y, we can compute the present worth in year y of planned system costs with a small increment in permanent output starting in year t, where t can equal y. We then subtract from it the present worth in year y of system costs with the increment in permanent output starting in year t+1. This difference is then divided by the size of the permanent increment in use, to obtain the marginal capital cost per unit of output. Hence, the marginal capital cost is a measure of the effect of use upon the total system costs, where the relevant total system costs include only those investments which are planned to satisfy increases in use or demand, and where the opportunity cost is measured in terms of a slowing down or a speeding up of the growth in water use and associated investments.

It should be recognized that the permanent output increment used to estimate marginal capacity costs represents nothing more than a convenient analytical device for estimating the marginal impact, brought about by a small permanent change in output occurring in year t, on the entire future time stream of costs. In a practical sense, we need simply to forecast the future growth (or decline) in the demand for water services up to the end of the planning horizon, superimpose a small constant increment on this forecast, and then observe the change in present worth of the facilities resulting from the constant increment in the forecast.

The marginal running cost per unit of output or use is added to the marginal capital cost, to yield a total marginal cost for each unit of output used. The running costs include only those costs that vary with water use (largely electricity and chemicals). To obtain a marginal running cost for year y, we estimate the total running cost and divide by the total water used in year y.

The economic interpretation of our definition of marginal cost is of particular interest. The definition and measurement of marginal running cost presents us with little difficulty. This results from the fact that the opportunity cost of output occurs at the same time when the output is produced. The marginal capital cost concept, however, is more complex. In this case, there is a displacement in time, between the time when a permanent increment in use or output occurs, and the time when its opportunity cost occurs. For example, when a permanent increment in use utilizes an increment of system capacity, there is often no need for immediate reduction in any alternative outputs, and no opportunity cost occurs at that time. However, resources which could be used to produce something else will eventually have to be used to produce system capacity sooner than was originally planned. This represents the opportunity cost of adding a permanent increment to use today. Our marginal cost concept is designed to measure this "displaced" opportunity costs. If we set prices equal to marginal cost, then consumers will receive a signal as to the opportunity costs that their current use imposes.

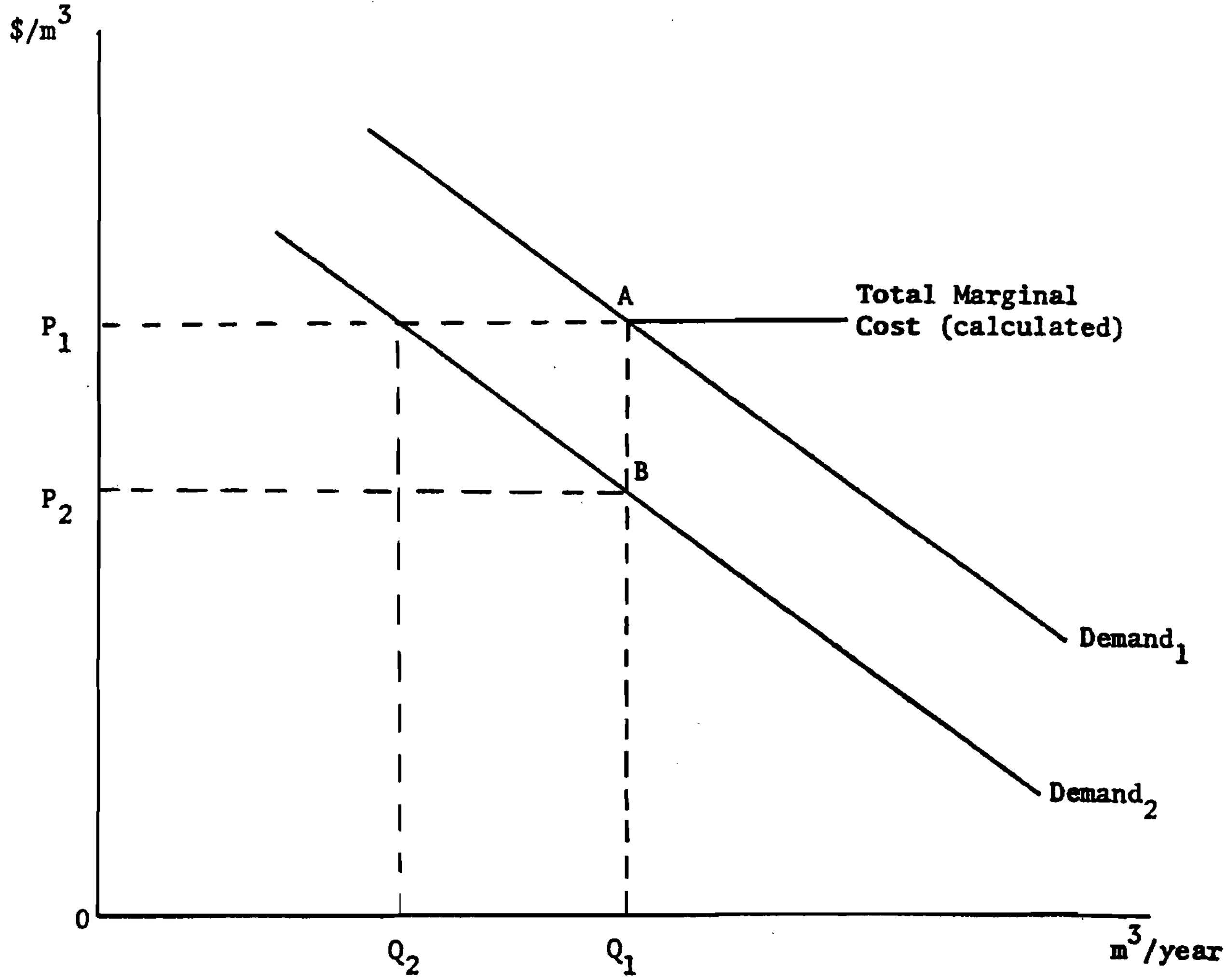
Another example will further illustrate our reasoning. The use of system capacity by a permanent increase in use is analogous to the use of an inventory of raw materials in a production process. If output or use occurs today, the opportunity cost of the use of the raw materials does not occur today. However, the use today results in the inventory having to be replenished sooner than planned. Hence, the use of the inventory today is not without its opportunity cost. It is this future or "displaced" opportunity cost that must be computed as of today, the time when it is caused, if prices of the goods produced are to reflect the real costs of the resources used to produce them. Our marginal cost concept is designed specifically for measuring these "displaced" opportunity costs.

Before computing the marginal cost, it is important to recognize that the total marginal cost, calculated by the method outlined above, may not be the relevant total marginal cost for our benefit-cost model. If, as a result of an original overinvestment in capacity or falling demands, a water utility has capacity that is larger than the efficient level, then the calculated total marginal cost will exceed the relevant total marginal cost.

We illustrate the existence of a divergence between the calculated and relevant marginal cost by evaluating costs in the case where water demands are falling (see Figure 3.1). We begin by observing magnitudes in year one: the current price is OP_1; the currend demand function is $Demand_1$; the current water use and capacity is OQ_1; and the calculated total marginal cost is Q_1A per m^3. If the demand function is falling and is equal to $Demand_2$ in year two, then the calculated total marginal cost exceeds the relevant marginal cost.

The reason for this divergence between the calculated and relevant marginal costs is because a price set at the calculated marginal cost (OP_1) would cause the water use to fall to OQ_2 in year two. Since this use level is below the use level where demand equals existing capacity (OQ_1), waste occurs. Waste can be eliminated by simply reducing the price to OP_2, a

Figure 4.1. Calculated and Relevant Marginal Costs



level that will equate use and capacity in year two. In this example, therefore, the relevant marginal cost is QB, which is equal to the price level that will equate use to capacity in year two.

The relevant marginal cost is equal to the calculated one, if a price set at the calculated marginal cost equates use with new capacity. If a price set at the calculated marginal cost level causes use to fall below existing capacity, then the relevant marginal cost is not equal to the calculated one. In this last case, the relevant marginal cost is below the calculated one, and is equal to the level at which a price set equal to the relevant marginal cost would equate use with existing capacity. The rule, therefore, for determining the relevant marginal cost is that the relevant marginal cost is equal to the calculated one, unless the calculated one is at a level that exceeds the price that would equate use with existing capacity. If this latter situation exists, then the relevant marginal cost will be lower than the calculated one, and will be equal to the price that equates use and existing capacity. Situations that will cause the calculated marginal cost to exceed the relevant one will occur when demand is falling, per our example, or when the original capacity is too large.

On the Measurement of Marginal Cost

In this section, we use our definition of marginal cost to measure the marginal cost of water for Perth, Western Australia.

Perth, Western Australia[1]- Perth is a rapidly growing city. For example, between 1946 and 1975 the number of water accounts or connections

[1]Note that we will use Perth for purposes of applying our benefit-cost model to various conservation programs (see Chapters 6 and 7). Also, note that, unless stated otherwise, all of our analyses will consider "normal" conditions. That is, all water use, water supply and cost calculations are made on the basis of average (mean) conditions. These are appropriate for all long-term analyses

increased from 96,000 to 245,000. Perth is located on Australia's West Coast at a latitude of 32°S. Its climate includes wet winters and dry summers. Most residents live in detached, single-family dwellings. Suburban sprawl is a common feature, with the density of development being 8.5 dwellings per gross residential hectare.

In 1976 the total water produced was distributed to the following user classes: (1) metered residential in-house use (20 percent), (2) metered residential sprinkling (outdoor) use (36 percent), (3) metered non-residential use (15 percent), (4) unmetered use (14 percent) and leakage (15 percent). In addition to this distribution among user classes, it is of importance to note that 73 percent of the annual water produced occurred in the summer period (November-April).

Water Use and Investment Program - The first step to implement our definition of marginal cost is the preparation of a water use forecast. Table 4.1 represents the forecast of water use for Perth. This forecast is based on the assumption that the policy variables controlled by the utility, such as price, will remain constant (in real terms) over the next 20 years. This forecast is, therefore, a requirements forecast. The important elements of the forecast, for purposes of marginal cost analysis, are the permanent increments in annual use (ΔQ_A), summer use (ΔQ_S) and winter use (ΔQ_W). It is these increments in use that determine the schedule for investments in supply that are strictly a function of water use.

The next step in our analysis is to forecast the investments that are required to meet the growth in water use. Once the water use forecast has been constructed, we sequence and schedule the projects that will meet the requirements in the least costly manner. These are summarized in Table 4.2.

Table 4.1 Annual Water Use and Connections

Year	Q_A	ΔQ_A	Q_S	ΔQ_S	Q_W	ΔQ_W	r	C
1976	193.0		140.9		52.1			254.1
		8.2		6.0		2.2	.042	
1977	201.2		146.9		54.3			263.6
		9.1		6.6		2.5	.046	
1978	210.3		153.5		56.8			274.1
		9.2		6.7		2.5	.043	
1979	219.5		160.2		59.3			284.8
		9.7		7.1		2.6	.045	
1980	229.2		167.3		61.9			295.8
		9.8		7.2		2.6	.042	
1981	239.0		174.5		64.5			307.0
		10.1		7.3		2.8	.043	
1982	249.1		181.8		67.3			318.3
		10.3		7.6		2.7	.041	
1983	259.4		189.4		70.0			229.8
		10.3		7.5		2.8	.040	
1984	269.7		196.9		72.8			341.3
		8.2		6.0		2.2	.030	
1985	277.9		202.9		75.0			351.5
		8.4		6.1		2.3	.030	
1986	286.3		209.0		77.3			362.1
		8.8		6.4		2.4	.031	
1987	295.1		215.4		79.7			373.0
		9.0		6.6		2.4	.031	
1988	304.1		222.0		82.1			384.1
		9.3		6.8		2.5	.030	
1989	313.4		228.8		84.6			395.7
		9.6		7.0		2.6	.031	
1990	323.0		235.8		87.2			407.5
		9.9		7.2		2.7	.030	
1991	332.9		243.0		89.9			419.8
		10.1		7.4		2.7	.031	
1992	343.0		250.4		92.6			432.4
		10.5		7.7		2.8	.030	
1993	353.5		258.1		95.4			445.3
		10.8		7.8		3.0	.031	
1994	364.3		265.9		98.4			458.7
		11.0		8.1		2.9	.030	
1995	375.3		274.0		101.3			472.4
		11.6		8.4		3.2	.031	

Notes: continued ....

Table 4.2 Planned System Investments

Year	I_A	I_S	I_W
1976	$ 7.94	$ 1.62	$ 6.32
1977	6.54	0.86	5.68
1978	4.98	2.97	2.01
1979	9.16	3.84	5.32
1980	8.28	2.80	5.48
1981	4.28	3.01	1.27
1982	5.92	2.46	3.46
1983	7.30	2.22	5.08
1984	7.13	1.90	5.23
1985	6.70	1.54	5.16
1986	8.30	2.45	5.85
1987	10.68	3.40	7.28
1988	21.41	3.79	17.62
1989	18.85	3.24	15.61
1990	13.16	2.05	11.11
1991	24.05	2.85	21.20
1992	18.96	3.10	15.86
1993	12.49	1.43	11.06
1994	12.50	1.50	11.00
1995	13.50	2.50	11.00

Notes: continued ....

Notes: (for Table 4.1)

1. Q_A = Annual water use in $m^3 \times 10^6$
2. ΔQ_A = Change in annual water in $m^3 \times 10^6$
3. Q_S = Summer water use in $m^3 \times 10^6$ (November - April).
4. ΔQ_S = Change in summer water use in $m^3 \times 10^6$
5. Q_W = Winter water use in $m^3 \times 10^6$ (May - October)
6. ΔQ_W = Change in winter water use in $m^3 \times 10^6$
7. r = Annual rate of change in water use
8. C = Number of connections or clients.

Notes: (for Table 4.2)

1. Planned system investments are only those components that are strictly a function of water use as reflected in Table 4.1. These include: source works, trunk and transmission mains, treatment plants and service reservoirs.
2. All costs are in 1976 prices X 10^6.
3. I_A = Total investment to meet growth in annual use (includes all investments noted in 1).
4. I_S = Total investment to meet growth in summer water use (includes trunk mains, treatment plants and service reservoirs).
5. I_W = Total investment required to meet growth in winter and base watch use (average day rate). This includes source works (reservoirs, well fields and transmission mains.

Note that only those investments whose capacity and timing are determined strictly by changes in water use are included in Table 4.2. It is only these investments that are relevant for our analysis, since the marginal cost concept is based on the measurement of the opportunity cost of using more (or less) water.

For Perth's system, these investments include the construction of source works (both reservoirs and wells), transmission mains, treatment facilities and associated service reservoirs. Until the latter part of the 1980's, water resources of a quality similar to those currently being exploited will be developed, then ground water of a relatively low quality is scheduled for development. Although other investments are planned -- the expansion of the distribution system, expenditures for routine replacement and the upgrading of certain parts of the system -- we do not include them in Table 4.2. They do not represent an opportunity cost of water use and are not relevant for the determination of the marginal cost of water.

The scheduled investments that are relevant for marginal cost analyses can be classified in several ways. First, if we wish to compute a marginal capital cost for water use on an annual basis, we must aggregate all relevant investments scheduled for each year (see second column of Table 4.2). In this case, I_A provides the basis for computing the marginal capital cost for water use, a cost that is uniform throughout the year. Second, if we wish to compute two marginal capital costs for water use, which are differentiated by season (summer and winter), we must disaggregate the relevant investments scheduled for each year (I_A) into summer investments, I_S (see third column of Table 4.2), and winter and base investments, I_W (see fourth column of Table 4.2).

In the case of Perth, I_A consists of all investments which were mentioned previously as being a function of water use. The summer investments, I_S, include those that are designed to meet maximum day and week use, which occurs in the summer period. Trunk mains, treatment plants and associated service reservoirs are included in I_S. The winter and base investments, I_W, include all source works and associated transmission mains, since these components are designed to generate annual yield for the system.

Calculated Marginal Costs - Given our projected water use, planned investments and a real (inflation free) rate of interest of 10 percent, we are ready to calculate marginal costs for 1976. We begin by computing the total annual marginal cost (see Table 4.3). This marginal cost is uniform throughout the year. It contains two components: (1) the total annual marginal capital cost of 1976 use, which is equal to $0.47/m^3 and (2) the expected marginal running cost of 1976 use, which is equal to $0.04/m^3. Hence, the total annual marginal cost is $0.51/m^3. This marginal cost can be interpreted as the average marginal cost of 1976 use, since we have allocated all investments (I_A) over the annual permanent increment in 1976 use (ΔQ_A).

Note that we have used a ten-year horizon for purposes of computing marginal cost. Given our ability to forecast water use and related investments, we believe that a ten-year horizon is the most appropriate one for our computations. For purposes of computing marginal cost, therefore, we recommend that a ten-year rolling plan for water use and investments be formulated in each year. For computations in 1976, this would result in a forecast from 1976-1985, and for 1977, we would revise our forecasts to include the period 1977-1986. The values for the period 1977-1986 may not necessarily, therefore, be the same as those presented in Tables 4.1 and 4.2 since we will have had one more year's experience and an opportunity to reformulate our forecasts.

Table 4.3 Total Annual Marginal Cost Calculations

Year	1976 Present Worth of I_A with Permanent Increment in Use	1976 Present Worth of I_A without Permanent Increment in Use	Change in Present Worth
1976	$ 7.22	$	$ + 7.22
1977	5.40	6.56	- 1.16
1978	3.74	4.92	- 1.18
1979	6.25	3.40	+ 2.85
1980	5.14	5.68	- 0.54
1981	2.42	4.67	- 2.25
1982	3.04	2.19	+ 0.85
1983	3.41	2.76	+ 0.65
1984	3.03	3.09	- 0.06
1985	2.58	2.75	- 0.17
1986		2.35	- 2.35
Total	42.23	38.37	+ 3.86

(1) Total Change in 1976 Present Worth = $ 3.86 x 10^6

(2) Permanent Increment in Use (ΔQ_A) = 8.2 m^3 x 10^6

(3) Total Annual Marginal Capital Cost of 1976 Use = (1)/(2) = $ 0.47/m^3

(4) Marginal Running Cost of 1976 Use = $ 0.04/m^3

(5) Total Annual Marginal Cost of 1976 Use = (3)+(4) = 0.51/m^3

Notes: 1. Present Worth is computed by using a real (inflation apart) discount rate of 10%. For estimates of real rates, see: (Hanke and Anwyll, 1980).

2. The marginal running cost is calculated by dividing the annual purification power and pumping costs by the total water use.

For some purposes the total annual marginal cost calculations may be too "crude" a measure (Hanke, 1975). Our next set of marginal cost calculations avoids some of this "crudeness" by focusing in more detail on the nature of marginal costs within the year 1976. Instead of averaging the marginal costs over the entire year, we break the year into two seasons: the winter season (May-October) and the summer season (November-April). The purpose of this division is to identify forward-looking or marginal costs with more precision.

We know that in Perth, summer water use requires relatively more investments in supply than does winter water use. Seasonally differentiated marginal cost colculations allow us to reflect these cost differentials. We begin by computing what are defined as winter and base marginal costs (see Table 4.4). To do this, we allocate I_W investments, which are the investments required or designed at rates not to exceed the average day use, over the annual increment in use for 1976. This yields a winter and base marginal capital cost of 1976 use of $\$0.31/m^3$. To obtain the total winter and base marginal cost of 1976 use, we must add to the $\$0.31/m^3$ figure the marginal running cost of $\$0.04/m^3$. This yields a total of $\$0.35/m^3$.

The next step is to compute the summer marginal cost (see Table 4.5). To do this we allocate I_S investments, which are the investments required or designed at rates that exceed the average day use (for example, maximum day and hour rates) over the increment in 1976 summer use. This yields a summer marginal capital cost of $\$0.22/m^3$. To obtain the total summer marginal capital cost, we add the base marginal capital cost of $\$0.31/m^3$, which represents the marginal cost of serving average day demands. This yields a total summer marginal capital cost of $\$0.53/m^3$. By adding the marginal running cost of $\$0.04/m^3$ to this figure, we obtain a summer marginal cost of 1976 use of $\$0.57/m^3$.

Table 4.4 Winter and Base Marginal Cost Calculations

Year	1976 Present Worth of I_W with Permanent Increment in Use	1976 Present Worth of I_W without Perment Increment in Use	Change in Present Worth
1976	$ 5.75	$	$ + 5.75
1977	4.69	5.22	- 0.53
1978	1.51	4.27	- 2.76
1979	3.63	1.37	+ 2.26
1980	3.40	3.30	+ 0.10
1981	0.72	3.09	- 2.37
1982	1.78	0.65	+ 1.13
1983	2.37	1.61	+ 0.76
1984	2.22	2.15	+ 0.07
1985	1.99	2.02	- 0.03
1986		1.81	- 1.81
	Total 28.06	25.49	2.57

(1) Total Change in 1976 Present Worth = $ 2.57 x 10^6

(2) Permanent Increment in Use (ΔQ_A) = 8.2 m^3 x 10^6

(3) Winter and Base Marginal Capital Costs of 1976 Use = (1)/(2) = $ 0.31/m^3

(4) Marginal Running Cost of 1976 Use = $ 0.04/m^3

(5) Total Winter and Base Marginal Cost of 1976 Use = (3)+(4) = $ 0.35/m^3

Notes: 1. Present worth is computed by using a real (inflation apart) discount rate of 10%. For estimates of real rates, see: (Hanke and Anwyll, 1980).

2. The marginal running cost is calculated by dividing the annual purification, power and pumping costs by total water use.

3. Note that I_W represents the capital required to meet growth in average daily demands (Q_A/365); therefore, the permanent increment in use for our calculations in this table is the annual figure ΔQ_A, and the marginal cost is for all winter use and the non-peaking or base part of the summer use.

Table 4.5 Summer Marginal Cost Calculations

Year	1976 Present Worth of I_S with Permanent Increment in Use	1976 Present Worth of I_S without Permanent Increment in Use	Change in Present Worth
1976	$ 1.47	$	$ + 1.47
1977	0.71	1.34	- 0.63
1978	2.23	0.65	+ 1.58
1979	2.62	2.03	+ 0.59
1980	1.74	2.38	- 0.64
1981	1.70	1.58	+ 0.12
1982	1.26	1.54	- 0.28
1983	1.04	1.15	- 0.11
1984	0.81	0.94	- 0.13
1985	0.59	0.73	- 0.14
1986		0.54	- 0.54
	Total 14.17	12.88	1.29

(1)	Total Change in 1976 Present Worth	= $1.29 x 10^6
(2)	Permanent Increment in Use (ΔQ_S)	= 6.0 m^3 x 10^6
(3)	Total Summer Marginal Capital Cost of 1976 Use	= (1)/(2) = $ 0.22/m^3 + (3) from Table 4.4 ($ 0.31/m^3) = $ 0.53/m^3
(4)	Marginal Running Cost of 1976 Use	= $ 0.04/m^3
(5)	Total Summer Marginal Cost of 1976 Use	= (3)+(4) = $ 0.57/m^3

Notes: 1. Present worth is computed by using a real (inflation apart) discount rate of 10%. For estimates of real rates, see: (Hanke and Anwyll, 1980).

2. The marginal running cost is calcualted by dividing the annual purification, power and pumping costs by total water use.

3. The marginal winter and base capital cost, without I_S, has been computed on an annual basis (see Table 4.4). To obtain the total summer marginal capital cost, we must add the marginal base capital cost ($ 0.31/m^3) to the marginal capital cost of summer marginal capital cost ($ 0.22(m^3), which is computed on the basis of I_S alone, to obtain the total summer marginal cost of 1976 use of $ 0.53/m^3. For a more complete treatment of this topic, see: (Hanke, February 1981).

The Relevant Marginal Costs - In 1976 the price which balances demands with system capacity is $\$0.106/m^3$. This price is charged for all water used during the year, and is much lower than the marginal costs which we have calculated for 1976 use. Since this price balances demands with supplies, it is the relevant marginal cost for 1976 use. The reason that it is lower than the calculated marginal costs is because Perth has used the traditional approach to water supply planning. That is, they have forecast requirements and have built capacity to meet them. As a result, the existing capacity is too large, when viewed from an economic perspective.

We estimate the price elasticity coefficients for water use to be -0.24, -0.29 and -0.10 for annual, summer and winter periods, respectively. Therefore, if we charge prices equal to our calculated marginal costs (on either a uniform annual basis of $\$0.51/m^3$ or a summer-winter basis of $\$0.57/m^3$ for summer water and $\$0.35/m^3$ for winter water), water use would be less than the 1976 levels, and idle capacity would result. To compute the relevant marginal cost under these conditions, we must simulate the prices which would balance demands with 1976 use levels (our target). These simulated prices are equal to the relevant marginal costs for each year, until they reach the level of our calculated marginal cost. At this point, new investment in supply capacity is finally justified, and the calculated marginal cost becomes the relevant marginal cost.

We have computed the relevant marginal costs for annual and the summer-winter season. These are presented in Tables 4.6, 4.7 and 4.8. These computations are of particular importance for our analyses of water conservation in Perth, since our benefit-cost model always requires that we use relevant marginal costs, when making benefit calculations. It is of interest to note

Table 4.6 Simulated Relevant Annual Marginal Costs

Year	Q_A	Relevant Marginal Cost
1976	193.0	$ 0.106
1977	193.3	0.125
1978	193.5	0.150
1979	193.7	0.178
1980	193.9	0.213

Notes: 1. Q_A in $m^3 \times 10^6$

2. Relevant Marginal Cost in $\$/m^3$

3. Growth in yearly use is based on values for r in Table 4.1.

4. Elasticity for Q_A = e = 0.24

5. The values r and e are used in the model for integrating demand and supply which is presented in Chapter 5.

Table 4.7 Simulated Relevant Summer Marginal Costs

Year	Q_S	"Relevant" Marginal Cost
1976	140.9	$ 0.106
1977	141.0	0.122
1978	141.1	0.142
1979	141.1	0.164
1980	141.3	0.190

Notes: 1. Q_S in $m^3 \times 10^6$

2. Relevant Marginal Cost in $\$/m^3$

3. Growth in yearly use is based on values for r in Table 4.1

4. Elasticity for $Q_S = e = - 0.29$

5. The values of r and e are used in the model for integrating demand and supply which is presented in Chapter 5

Table 4.8 Simulated Relevant Winter Marginal Costs

Year	Q_W	"Relevant" Marginal Cost
1976	52.1	$ 0.106
1977	52.1	0.159
1978	52.1	0.247
1979	52.5	0.350
1980	54.9	0.350

Notes:
1. Q_W in $m^3 \times 10^6$
2. Relevant Marginal Cost in $/$m^3$
3. Growth in yearly use is based on values for r in Table 4.1
4. Elasticity for Q_W = e = . 0.1
5. The values fo r and e are used in the model for integrating demand and supply which is presented in Chapter 5

that from 1976-1980 the relevant marginal costs, when computed on an annual basis, are less than the calculated marginal costs. This indicates that no increment in investment is justified during this period. By reviewing Tables 4.7 and 4.8, we also observe a divergence between calculated and relevant marginal costs, when we divide water use and costs into summer-winter seasons. However, if we use the summer-winter division, investments are justified for the winter and base period in 1979 (see Table 4.8). The relative rapid rise in relevant marginal costs in the winter results from the fact that water use in this period is relatively insensitive to price changes. Hence, prices must be raised more rapidly in the winter than in the summer to hold water use to the 1976 target levels.

Chapter 5

ON DEMAND-SUPPLY INTEGRATION

For purposes of calculting water use without and with conservation, Q in our benefit-cost model, simulating the relevant marginal costs (Tables 4.6-4.8) and predicting the level of any conservation policy which will balance demands with supplies, it is convenient to develop a demand-supply model.

The Demand-Supply Model[1]

As we have shown in Chapter 3, there are numerous determinants of the demand for water which can be controlled by water utilities. We shall call these determinants policy parameters. As we increase the level of any of these policy parameters, the level of water use or production will be reduced.

The sensitivity of water use to changes in the real level of a policy parameter is its elasticity. One relationship between water use and the policy parameter can be expressed as follows:

$$Q = a\,P^{e}, \tag{5.1}$$

where Q = the quantity of water use, P = the real value of the policy parameter, a = a constant, and e = the policy parameters' elasticity, which is always negative.

[1]A program that allows us to implement, on a programable calculator, the concepts presented in this chapter is presented in Appendix 1. The policy parameter which allows us to integrate demand and supply is price.

Equation 5.1, the policy-water use equation, is the basic equation for integrating demand and supply. To predict water use over time, however, we need to know how variables, other than the policy parameter, affect water use. In our model we can accommodate this by the use of the following equation:

$$Q_2 = r\,Q_1, \tag{5.2}$$

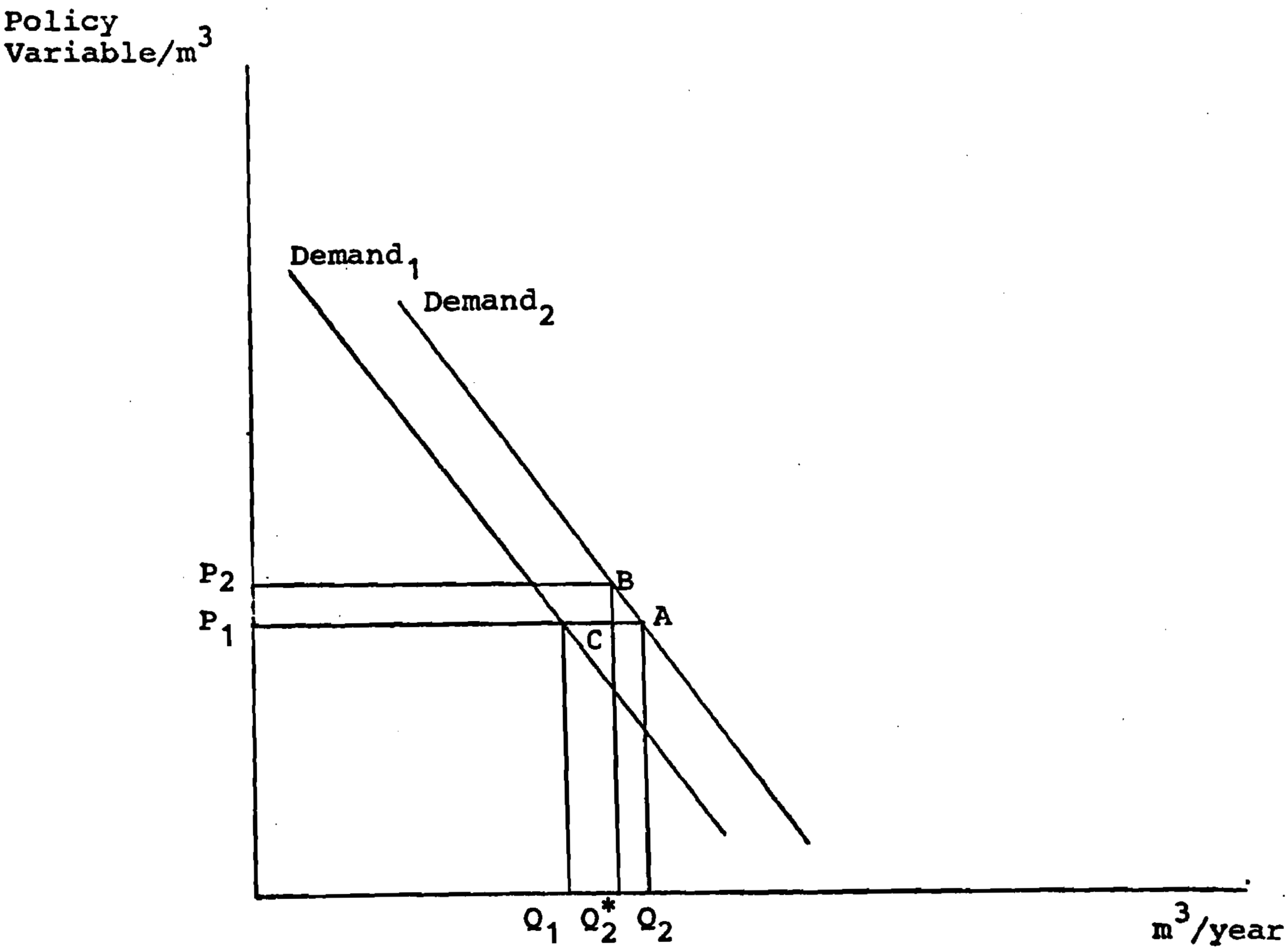
where Q_2 = water use in period two, when the real value of the policy parameter in period two is equal to that in period one; r = the growth rate in water use from period one to two plus 1.0, when the real value of the policy parameter in period two is equal to that in period one; and Q_1 = water use in period one. If the real value of the policy parameter changes from period one to period two, Equation 5.3 is required to determine the final equilibrium water use in period two:

$$Q_2^* = \left(\frac{P_2}{P_1}\right)^e Q_2, \tag{5.3}$$

where Q_2^* = water use in period two, when the real value of $P_2 \neq P_1$; P_2 = the real value of the policy parameter in period two; P_1 = the real value of the policy parameter in period one; and e = the policy parameters' elasticity.

The operation of Equations 5.2 and 5.3 can be seen by reference to Figure 5.1. The initial level for our policy parameter is P_1. With this policy and the demand function for period one (Demand_1), we observe that the quantity of water demanded in year one is Q_1. To predict water use in year two, with no change in the real value of the policy parameter, we use Equation 5.2. By multiplying Q_1 by r, we obtain Q_2. This value, Q_2, is read off the demand function that exists in period two (Demand_2). To

Figure 5.1 Predicting Water Use



predict the impact of an increase in the value of the real policy parameter in period two, we apply Equation 5.3. This operation causes us to move leftward along the demand curve ($Demand_2$) in period two (from A to B), and results in a final prediction of water use in period two of Q_2^*. This final prediction takes into account both the "natural" growth, r, and the elasticity impact of increasing the real value of the policy from P_1 to P_2.

For any level of supply, therefore, we can use our model to change the value of a policy parameter to balance demand and supply. To illustrate this point, the reader is referred to Figure 5.6 of the last chapter. If we wish to constrain water use (demand) to the level OQ_A, we must set the prices so that they are equal to the simulated marginal cost for each year. We will illustrate further applications of this model in Chapters 6 and 7, where we discuss price and nonprice rationing methods for water conservation.

Chapter 6

RATIONING BY PRICE

Water can be rationed and demands balanced with supplies by using two different types of policy parameters: price and nonprice policies. In this chapter we discuss the use of price as a conservation device (see also: Hanke, 1972; Hanke, 1978; and Hanke, February 1981).

Prices and Benefit-Cost Analysis

Our benefit-cost model allows us to evaluate whether increases in prices are an economic conservation policy. We recall that our benefit-cost model (Equation 2.3) is

$$Q \cdot MC \geq U + E + F, \tag{6.1}$$

where Q = reduction in use resulting from a conservation policy, MC = relevant marginal cost, U = resource cost to the utility of adopting a conservation policy, E = resource cost to the consumers of adopting a conservation policy and F = the value of "useful" consumption foregone. Moreover, recall that the left-hand side of this equation equals the benefits from conservation and the right-hand side equals the costs. Hence, to achieve maximum net benefits, we should apply a conservation policy as long as $Q \cdot MC \geq U + E + F$.

If we are using price to balance demands and supplies, we know that a price set equal to the marginal cost will lead to an efficient allocation of resources and a maximization of net benefits in the context of benefit-cost analysis.[1] We demonstrate this fact by the use of our benefit-cost

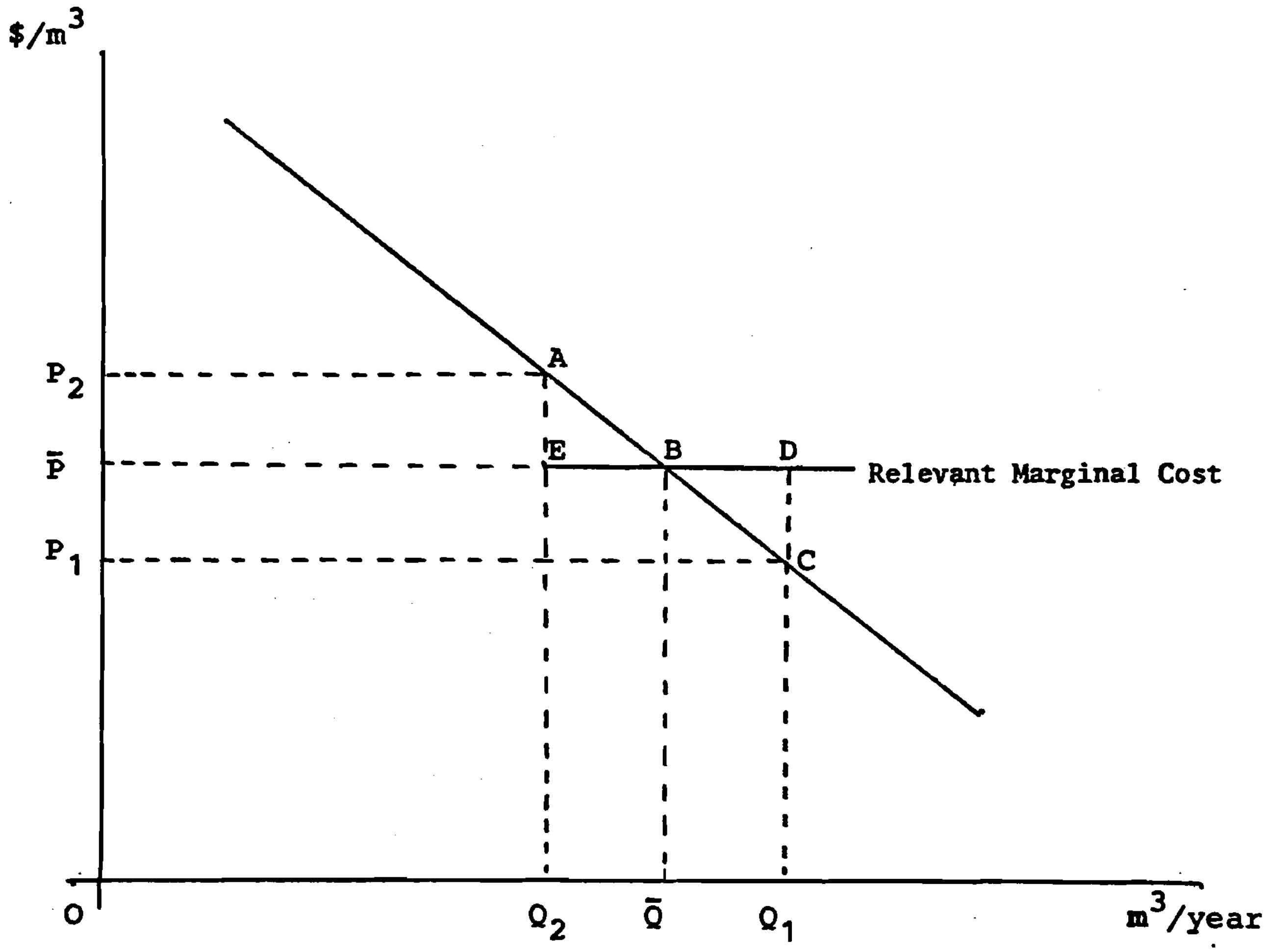
[1] For this demonstration to be always true, we must assume that E and U equal zero, which is a reasonable assumption for price increases for metered customers.

model. Annual marginal costs for any year are constant, given our approach to marginal cost analysis. Marginal benefits, as represented by the demand function, are always negatively related to water use. We also know that marginal benefits equal the marginal cost where the two functions intersect (see Figure 6.1). Therefore, we know that the incremental benefits generated by increasing price from a level below the marginal cost to the marginal cost level must exceed the costs of such a change. In Figure 6.1, if price is P_1 and use is Q_1, a small price increase will generate benefits of Q_1D and costs of Q_1C per m^3. The benefits of conservation will continue to exceed costs until we reach a price of $\overline{P}$ and use of $\overline{Q}$. At this level, price will equal the marginal cost, and the price increase from P_1 to $\overline{P}$ will have increased net benefits by the area BDC. Net benefits from increasing price will be at a maximum at this price ($\overline{P}$). Further increases will add to the costs of conservation, represented by "useful" consumption foregone, by more than they add to the benefits. For example, a price change from $\overline{P}$ to P_2 will generate net costs equal to the area AEB. Hence, in all cases a price set equal to the marginal cost will maximize net benefits, and any deviation in price from the marginal cost will be wasteful.

On the Benefits and Costs of Marginal Cost Pricing in Perth

Uniform Annual Price - We apply by using data from Perth, Western Australia for the year 1977, the economic principles of pricing outlined in the preceding section. Our purpose is to perform a benefit-cost analysis for marginal cost pricing as a conservation device. We wish to evaluate the economic consequences of increasing the level of prices to the marginal cost (with conservation), rather than leaving the prices at their existing real level (without conservation). We begin our analysis by evaluating uniform marginal cost pricing, with the marginal cost and prices being determined on an annual basis. In this case, the same price is changed for all water used throughout the year.

Figure 6.1 Pricing Policies and Benefits and Costs



The first step to evaluate the benefits and costs of marginal cost pricing for Perth is to determine the marginal cost in 1977. This computation has been made by simulating the relevant marginal costs. The results are displayed in Table 4.6. For 1977, the marginal cost is $\$0.125/m^3$ (see the second column of Table 6.1). Recall that since the existing system capacity is too large, the relevant marginal cost of $\$0.125/m^3$ is less than the calculated marginal cost of $\$0.51/m_3$. Also, note that the relevant marginal cost is the one that is necessary, so that a price set equal to it will approximately balance demand with the target capacity of 193.0 $m^3 \times 10^6$.

The next step is to compute the change in water use resulting from the conservation increasing the price from $\$0.106/m^3$ to a price set at the marginal cost of $\$0.125/m^3$. We must obtain a value for Q. In this case, water use without a price increase would equal 201.2 $m^3 \times 10^6$, and would exceed our target capacity. While with a price increase to the relevant marginal cost, water use would be reduced to 193.3 $m^3 \times 10^6$. Hence, Q is equal to 7.9 $m^3 \times 10^6$ (201.2 $m^3 \times 10^6$ - 193.3 $m^3 \times 10^6$).

To compute the change in benefits which result from increasing the price to the relevant marginal cost, we must multiply Q times MC. In this case, the change in benefits are equal to $987,500 (see the first three columns of Table 6.1).

We now turn to the computation of the costs of this conservation program. We assume that both U and E will be equal to zero for price increases. Therefore, the value of "useful" consumption foregone, F, becomes the only cost associated with increasing the price. To compute F, we compute the value of the area under the demand function between 193.3 $m^3 \times 10^6$ and 201.2 $m^3 \times 10^6$ by using the techniques presented in the last section of Chapter 3. This calculation yields a figure for "useful" foregone consumption of $912,450.

Table 6.1 Benefits and Costs of Price Rationing

Reduced Use ($m^3 \times 10^6$)	Marginal Cost ($)	Change in Benefits ($)	Water Utility Costs ($)	Water Consumer Costs ($)	Value of "Useful" Consumption Foregone ($)	Change in Costs ($)	Net Benefits ($)
Q	MC	Q • MC	U	E	F	U + E + F	[Q•MC] - [U+E+F]
7.9	0.125	987,500	0	0	912,450	912,450	75,050

Notes:

1. Q = 201.2 - 193.3 = 7.9 (see Tables 4.1 and 4.6)

2. For MC, see Table 4.6

3. F is computed by using the technique presented in Chapter 3. With a price elasticity of -0.24, F is equal to \$0.106 X 7,900,000 = \$837,400, plus (\$0.125-\$0.106) = \$0.019 X 7,900,000 X 0.5 = \$75,050, or a total of \$912,450. This amount can be visualized by viewing Figure 5.1. The amount is analytically represented by the following: $(OP_1) \times (Q_2 - Q_2^*) = CAQ_2Q_2^*$, which is \$837,400 for Perth; plus $(P_2 - P_1) \times (B-C) \times 0.5 = ABC$, which is \$75,050 for Perth; or a total of $BAQ_2Q_2^*$, which is \$912,450 for Perth.

As our theoretical demonstration showed, a price increase to the marginal cost level will always generate net benefits. In the case of Perth for 1977, these benefits are $75,050.

Summer-Winter Prices - It can be demonstrated that, when marginal costs are different in the summer season than in the winter season, seasonally differentiated prices set separately at the summer and winter marginal costs yield net benefits, when compared with a policy of setting prices on an annual basis at the annual marginal cost (Hanke, 1971). However, this demonstration is one of the general principle. It does not take into account the increased administrative costs associated with switching from uniform annual prices to summer-winter prices. Therefore, it is necessary to use benefit-cost analysis to determine whether an annual uniform or seasonsl pricing structure is the most desirable.

For Perth in 1977, it is important to remember that the system is not in economic equilibrium; capacity is too large. Hence, if prices are set at the level of the calculated marginal costs, water use would be reduced to a level well below existing system capacity. This would result in unused capacity and economic waste. Therefore, we simulated demands and supplies, to determine the relevant marginal costs (Tables 4.6, 4.7 and 4.8). These were lower than the calculated marginal costs. Moreover, given the fact that the absolute value of the price elasticity is less in the winter (-0.1) than in the summer (-0.29), smaller summer price increases are required to constrain summer use to its original target level than is the case for winter prices and use. The result, in this ease, is a situation in which the relevant marginal costs for the winter (the off-peak) season are higher than during the summer (peak) season. This situation reverses itself after the system comes into an economic equilbrium and capacity is adjusted to its proper level. As we would normally expect, when the system is in an economic equilibrium, the calculated marginal costs are equal to the relevant costs, and they are higher in the summer (peak) season than in the winter (off-peak) season.

With this background information, we now evaluate the benefits and costs of switching from the current uniform pricing system to a summer-winter system in which the summer and winter prices are set at their respective relevant marginal costs for 1977. Using the same approach as we employed for uniform prices, we generate benefit-cost data. These are presented in Table 6.2. The result of using seasonal prices is a net loss of $394,500 for 1977. Losses result because the seasonal pricing structure would require the utility to read meters quarterly, instead of annually, so that the utility could render seasonal bills. This additional meter reading results in an increase in the utility's costs of $500,000.

We should also mention that a switch to summer-winter prices would require the winter prices to exceed those for the summer, during the period when the system was out of economic equilibrium. Since the summer-winter marginal cost relationship would change when the system come into equilibrium, the summer-winter price relationship would also change. These changes, would no doubt, be difficult to justify to consumers. Hence, they would require yet more expenditures for public education, and would increase U above the value which we have estimated.

Concluding Observations on Pricing

Our analysis allows us to make the following observations: (1) In cases where meter reading and billing expenses remain constant, we know

Table 6.2 Benefits and Costs of Seasonal Price Rationing

Season	Reduced Use ($m^3 \times 10^6$)	Marginal Costs (S)	Change in Benefits ($)	Water Utility Costs ($)	Water Consumer Costs ($)	Value of "Useful" Consumption Foregone ($)	Change in Costs (S)	Net Benefits ($)
	Q	MC	Q • MC	U	E	F	U + E + F	[Q•MC] - [U+E+F]
Summer	5.9	0.122	719,800			672,600		
Winter	2.2	0.159	349,800			291,500		
Total	8.1		1,069,600	500,000	0	964,100	1,464,100	- 394,500

Notes:

1. The input data required to construct this table are contained in Tables 4.1, 4.7 and 4.8.

2. U has been estimated on the basis of costs required to read water meters four times per year with seasonal prices, rather than the current practice of annual readings with uniform prices.

that a switch from uniform annual prices set below marginal cost to a uniform annual price set equal to the marginal cost will always generate net benefits. (Note that this is also true for a switch from uniform annual prices set above the marginal cost to a uniform annual price set equal to the marginal cost.) This means that formal benefit-cost analysis is not required in this case. However, the analysis may be desirable to demonstrate to regulators the gains associated with this change in pricing policy. If the utility costs are increased by making the switch to uniform annual prices set at the marginal cost, we do not know if the switch will be desirable *a priori*. Hence a formal benefit-cost calculation must be performed to determine the desirability of the change in policy.

(2) Since additional meter reading and billing expenses, as well as expenditures for public education, will usually be required when switching from uniform annual prices to summer-winter prices set at marginal costs, a formal benefit-cost analysis of the policy change will always be required.

Chapter 7

RATIONING WITH AND WITHOUT NON-PRICE CONSERVATION POLICIES

In Chapter 3 we reviewed several nonprice methods of water conservation, These included: leak detection and control, water meters and water use restrictions. Since these policies are not necessarily associated with marginal cost pricing, we must evaluate the benefits and costs of each to determine its desirability. This chapter is devoted to this task. Again, we use Perth, Western Australia for our analysis.

Leak Detection and Control

Our benefit-cost model can be used for the purpose of evaluating waste control programs (Hanke, April 30, 1981). Those programs reduce leakage in water system. They, therefore, reduce the quantity of water that a water company must produce, without reducing the quantity of water that consumers use. Since this type of conservation program does not directly affect consumers, two variables, E and F, can be eliminated from our model. The appropriate decision rule for evaluating the desirability of waste control programs, therefore, becomes:

(7.1) $$Q \cdot MC \geq U$$

Equation 7.1 shows us that waste control is economic if the change in benefits, which is the product of the quantity of water saved by repairing system leaks (Q) and the marginal cost of water (MC), exceeds or is equal to the change in the costs of detecting and repairing leaks (U).

For Perth, leakage is 15 percent of total production, and is equal to 30.2 $m^3 \times 10^6$ in 1977. We evaluate the benefits and costs of two waste control policies. The first policy (Option I) would reduce system leakage to 7.5 percent of the total production or 15.1 $m^3 \times 10^6$, and the second policy (Option II) would reduce leakage to 5 percent of the total production or 10.1 $m^3 \times 10^6$.

To compute the benefits of these two options, we evaluate the left-hand side of Equation 7.1. Reduced water production (Q) is the first variable in 7.1. Option I would yield a total reduction in production of 15.1 $m^3 \times 10^6$, while Option II would yield a reduction of 23.1 $m^3 \times 10^6$ (see Table 7.1 for a display of our results).

By multiplying the reduced water production (Q's) by the appropriate marginal cost (see Chapter 4, Table 4.6), we compute the values for change in benefits from each leakage control option. The values for the change in benefits is given in the fourth column of Table 7.1. Option I would yield $1,887,500 and Option II would yield $2,887,500 in 1977.

Next, we compute the change in the costs of detecting and repairing system leaks for both options or the right-hand side of Equation 7.1. These costs are given in the fifth column of Table 7.1. The cost of Option I would be $280,000 and of Option II would be $382,500. These estimates are based on the following assumptions:[1] (1) under both options a specialized waste control team would be established; (2) 80 percent of its costs would be for labor and the remainder capital equipment; (3) Option I would require one waste prevention worker per 10,000 dwellings; and (4) Option II would require one worker per 7,500 dwellings. It is important to realize that

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[1]These assumptions are reflected in Figure 3.1, which is the production function for leak detection and control in Perth.

Table 7.1 Benefits and Costs of Waste Control

Waste Reduction Option	Reduced Leakage	Marginal Cost	Change in Benefits	Change in Costs	Net Benefits
	$Q(10^6 m^3)$	MC ($)	Q•MC ($)	U ($)	Q•MC U ($)
I 7.5% of Total Production	15.1	$0.125/m^3$	1,887,500	280,000	1,607,500
II 5 % of Total Production	23.1	$0.125/m^3$	2,887,500	382,500	2,505,000

Perth's projected leakage detection costs are lower than would be expected for many other water systems. Routine capital replacement occurs now without the aid of a specialized waste control program. The primary purpose of Perth's waste control program would be to redirect capital replacement expenditures to those areas where leakage is greatest. Hence, neither Option I nor Option II would increase the level of Perth's capital replacement expenditures. Both options, however, would greatly increase the productivity of these expenditures.

By subtracting the change in costs from the change in benefits, we obtain the net benefits from waste control for both options (see column six of Table 7.1). Given our objective of maximizing net benefits and our decision rule , Option II is clearly superior to Option I. Furthermore, we should consider increasing our waste control efforts beyond those of Option II, since the incremental benefits of moving from Option I to Option II are $897,500, while the incremental costs are only $102,500. This indicates that additional net benefits could be generated by applying detection and control effort beyond Option II.

Water Meters

The installation of water meters is often considered as a water conservation policy (Hanke, February, 1982). This option does exist in Perth, since in 1977, 17,968 of its customers were not metered. This group consisted of small residential users and commercial establishments. Unmetered water use is estimated to be 14 percent of the total production or 28.2 $m^3 \times 10^6$ in 1977.

We evaluate the conservation policy of universal metering, which would require the installation of 17,968 water meters. To compute the benefits of this policy, we first evaluate the resulting reduction in water use. We predict that the metering of unmetered users will reduce their use by $9.9 \text{ m}^3 \times 10^6$ or by 35 percent. (We estimate this figure by applying a water use ratio, which is based on data presented in Chapter 3, Table 3.6). If we multiply this reduction by the marginal cost, we obtain the change in benefits (see Table 7.2).

To evaluate the change in costs associated with universal metering, we first compute the change in the water company's resource costs. These costs include the annualized costs of 17,968 new water meters and their installation as well as the increased costs of reading these meters one time per year. This annual cost is equal to $241, 342. It is displayed in the fifth column of Table 7.2.

The next cost term in our model is E. It represents the resource costs to consumers of metering. These costs are represented primarily by increased effort to repair leaks inside commercial and residential buildings and also increased time devoted to monitoring water use activities. We do not make an estimate of these costs because of a lack of data. However, it is important to realize that these costs are probably quite small (Hanke, 1970(b)).

The last cost term in our model is F, or the value of "useful" consumption which is foregone because water use is reduced by the installation of water meters. We use the techniques presented in the last section of Chapter 3 to evaluate this term. The numerical values are displayed in the seventh column of Table 7.2.

Now we are ready to compute the change in costs, U + E + F. The values for the change in costs are given in the eighth column of Table 7.2. The total change in costs for the period under study is $766,042.

Table 7.2 Benefits and Costs of Water Meters

Reduced Use	Marginal Cost	Change in Benefits	Water Company Costs	Water Consumer Costs	Value of "Useful" Consumption Foregone	Change in Costs	Net Benefits
$Q (m^3 x 10^6)$	MC($)	Q · MC($)	U($)	E($)	F($)	U + E + F	[Q·MC][U+E+F]
9.9	$0.125/m^3$	1,237,500	241,342		524,700	766,042	471,458

Notes: 1. This figure is based on the assumption that 17,968 meters were purchased at $ 55.65/meter. Annualized at 10 percent interest over seven years, the initial investment of $ 1,000,000 equals $ 205,406 per year. To obtain U, we added to this annual cost $ 35,936, which reflects extra meter reading costs.

By subtracting the change in costs from the change in benefits, we obtain the net benefits from metering. Given our objective of maximizing net benefits and our decision rule, universal metering for Perth would be an economic conservation policy, since it would generate net benefits of $471,458 in 1977.

Water Use Restrictions

Water use restrictions are yet another conservation policy that can be evaluated by use of our benefit-cost model (Hanke, 1980(a) and Hanke, 1980(b)). In Perth, water use restrictions have only been used in the dry summer months of December, January and February. We limit our analysis of restrictions to these months. We begin by estimating the impact of restrictions on water use. To accomplish this task we use water use ratios of 86.2, 85,7 and 89.4 for the months of December, January and February, respectively (see Table 3.3). These ratios indicate the water use with restrictions, as a percent of water use without restrictions. By applying these water use ratios to water use without restrictions of 29.6, 28.0 and 27.8 $m^3 \times 10^6$ for December, January and February, respectively, we obtain use with restrictions. If we subtract these latter values from the former, we obtain values for Q in our benefit-cost model. These values are displayed in the second column of Table 7.3.

With a marginal cost of $\$0.125/m^3$ for each month, we can compute the monthly change in benefits by multiplying the values for reduced water use by the marginal costs. The results are displayed in column four of Table 7.3.

We now move to the cost side of our benefit-cost model. We assume that the costs to the utility are equal to zero. This will lead to an understatement

Table 7.3 Benefits and Costs of Water Use Restrictions

Month	Reduced Use ($m^3 x 10^6$) Q	Marginal Costs ($) MC	Change in Benefits ($) Q·MC	Water Utility Costs ($) U	Water Consumer Costs ($) E	Value of "Useful" Consumption Foregone ($) F	Change in Costs ($) U+E+F	Net Benefits($) [Q·MC]-[U+E+F]
December	4.09	0.125	511,250			576,690		
January	4.00	0.125	500,000			572,000		
February	2.94	0.125	367,500			455,700		
Total	11.03		1,378,750	0	0	1,604,390	1,604,390	- 225,640

Notes: 1. To estimate F, we use the techniques presented in the last section of Chapter 3, with a summer price elasticity for the demand function in each month of E = - 0.29.

of the total costs of restrictions, since the utility will have to administer the restriction program. However, we have no reliable information on this cost component. Furthermore, these costs will probably be relatively small when restrictions are imposed for short durations. They will increase with the length of time that restrictions are used, since the prolonged use of restrictions will require some type of semi-permanent administrative staff for policy-making and compliance purposes.

We also assume that the customer costs (E) will be zero. Again this assumption is based on a lack of reliable data. It does not imply that these costs do not exist, since customers will have to spend more time tending to their lawn sprinkling with restrictions than without them.

The only cost element associated with restrictions that we estimate is the value of "useful" consumption foregone. To estimate the value of "useful" consumption foregone, we use the techniques presented in Chapter 3. The results of our analysis are presented in column seven of Table 7.3. It is important to realize that our estimate of F might be somewhat lower than the actual value. Our estimate of F is based on the assumption that the lowest valued uses of water will be the ones eliminated by restrictions first. Even though this is the objective of most water system planners, in reality some "high-valued" use is probably included with "low-valued" use that is restricted from the market (for a discussion, see Chapter 2). As a result, our estimate of the F values is probably too low (Hanke, 1980(b)).

Our analysis indicates that under "normal" (mean) conditions, water use restrictions would not be economic in Perth. The type of restrictions that have been and in Perth are too strong to be economic, under "normal" conditions, and conservation at the levels analyzed is wasteful.

Let us turn from "normal" supply conditions to the situation of drought conditions. In this case, "normal" capacity and cost figures (the ones we have used to this point) are not the relevant figures. During drought, effective capacity or supply is reduced, and therefore, the relevant marginal cost -- the marginal cost level at the point where demands equal to new effective capacity -- is higher than normal.[1] Therefore, the marginal value of the last unit of water available in droughts is higher, and restrictions might be economic under some drought cases. We now analyze those cases.[2]

We begin with the "normal" conditions which are represented in Table 7.3. This means that under "normal" conditions supply and demand are balanced at 29.6, 28.0 and 27.8 $m^3 \times 10^6$ for December, January and February, respectively. This balance occurs at a real price in 1976 of $\$0.106/m^3$. Although water use restrictions of the type used in Perth, are not economic as a long-term policy. We wish to analyze how serious drought must become before restrictions would be justified.

By using the "normal" conditions as a baseline or starting point, we simulate, by using our demand-supply integration model developed in Chapter 5, the relevant marginal costs that would be associated with "effective" capacity levels under drought conditions. We determine the "effective" capacity level, so that marginal costs -- those where demand is equated

[1]Note that the relevant marginal costs under drought conditions are simulated by using the demand-supply integration model presented in Chapter 5.

[2]Note we have not analyzed price, leak detection and control or water meters in the "abnormal" case, since each of them, in a practical sense is designed as a long-term policy to respond to "normal" conditions.

to the new "effective" capacity -- are just high enough to generate changes in benefits (Q • MC) which equal the change in cost figures. These simulated "effective" capacities and marginal costs are displayed in Table 7.4. Our analysis indicates that restrictions can be justified under drought conditions, when "effective" capacities in December fall from the "normal" level of 29.6 to an "effective" level of 27.3 $m^3 \times 10^6$, in January from 28.0 to 25.7 $m^3 \times 10^6$ and February from 27.8 to 24.9 $m^3 \times 10^6$. Therefore, restrictions, which are designed to meet short-term emergencies, are indeed justified under certain drought conditions, even though they are not justified under "normal" conditions.

Table 7.4 Benefits and Costs of Water Use Restrictions - A Break-Even Analysis

Month	Reduced Use ($m^3 x 10^6$) Q	Marginal Costs ($) MC	Change in Benefits ($) Q•MC	Water Utility Costs ($) U	Water Consumer Costs ($) E	Values of "Useful" Consumption Foregone ($) F	Change in Costs ($) U+E+F	Net Benefits ($) [Q•MC]-[U+E+F]	"Normal" Capacity Levels (m^3 x 10^6)	Break-Even "Effective" Capacity Levels (m^3 x 10^6)
December	4.09	0.141/m^3	576,690			576,690	576,690	0	29.6	27.3
January	4.00	0.143/m^3	572,000			572,000	572,000	0	28.0	25.7
February	2.94	0.155/m^3	456,000			455,700	455,700	300	27.8	24.9

Notes: 1. To estimate F, we use the techniques presented in the last section of chapter 3, with a summer price elasticity for the demand function in each month of ė = 0.29.

2. The baseline or strating point for this analysis is the state of "normal" conditions.

3. Marginal costs simulated for "effective" capacity level which are balanced with demand at levels which generate "relevant" short-term marginal costs that when multiplied by Q's will generate change in benefit figures equal to the change in cost figures. These capacities are 27.3, 25.7, and 24.9 m^3 x 10^6 for December, January and February, respectively, as opposed to "normal" capacities of 29.6, 28.0 and 27.8 m^3 x 10^6.

Chapter 8

CONCLUDING OBSERVATIONS

Water conservation is the major policy that is currently being debated by water utilities throughout the world. These policies are seen by many water supply planners as a solution to their financial problems. We have used an economic approach to analyze these policies, and have concluded that water conservation (the balancing of demands with supplies at lower levels of use) can only be justified when its incremental benefits exceed its incremental costs. To demonstrate this fact, we have presented the principles and tools required to analyze the problem. We have also applied them to a water utility in Perth, Western Australia. In the case of Perth, we reached some useful conclusions about the economics of conservation (see Table 8.1).

The mix of policies that would allow Perth to solve its problems of revenue insufficiency, avoid economic waste and improve economic efficiency would include:

(1) the adoption of a uniform marginal cost tariff schedule, with the same price per m^3 being charged throughout the year and being set at the relevant marginal cost in each year. This will mean that the real prices of water in Perth should be increased each year to balance demands with existing capacity(see Table 4.6). It also implies that future capacity expansion, that would be required if the traditional planning approach was retained, can be deferred. No new capacity will be required until the price (the relevant marginal cost) reaches $0.51/$m^3$ (see Table 4.3). This deferral will result in a significant reduction in Perth's financial requirements.

Table 8.1 Desirability of Conservation Parameters (Perth

Policy Parameter	Desirability of Conservation ("Normal")	Desirability of Conservation (Drought)
Uniform Marginal Cost Prices	Yes	Not analyzed
Summer-Winter Marginal Prices	No	Not analyzed
Leak Detection and Control	Yes	Not analyzed
Meters	Yes	Not analyzed
Restrictions	No	Yes

(2) the adoption of a systematic leak detection program. Again, the use of the economic approach will allow Perth's water system planners to demonstrate, in a systematic way, that economic waste could be eliminated by a leak detection program.

(3) the adoption of universal water metering. The economic approach demonstrates the advantages of universal metering for Perth.

Before concluding, it is important to realize that, to determine the desirability of water conservation, we must have data to operationalize our benefit-cost model. In particular, we need data on the determinants of water use and the elasticities of each. In addition, data on the relevant marginal costs should be calculated and/or simulated. At present, these data are not generally available for most water utilities. Therefore, to evaluate water conservation policies, water utilities must first begin to collect and analyze data that have economic significance. If this is done, then debates on the desirability of balancing demands with supplies at lower levels of use can be framed in a more useful context. Moreover, water supply planners will be able to justify their proposed policies before regulatory bodies and the public in a more systematic and rigorous way.

Appendix

A PROGRAM FOR INTEGRATING DEMAND AND SUPPLY

The model for integrating demand and supply, which we presented in chapter 5, can be made operational with the use of a computer or a programmable calculator. For most purposes, however, a programmable calculator provides the most flexible and efficient means of operationalizing our model.

In this appendix, we present a program for use on a programmable calculator, the Texas Instruments model 58c. This calculator and program were used to make the calculations for demand-supply integration which appear in the text.

As noted in chapter 5, two equations are needed to integrate demand and supply:

$$(A1.1) \qquad Q_2 - r\,Q_1 \quad ,$$

where Q_2 = water use in period two, when the real price of water in period two is equal to that in period one; r = the growth rate in the water use from period one to period two plus 1.0, when the real price of water in period two is equal to that in period one; and Q_1 = the water use in period one. If the real price of water changes from period one to period two, equation (2) is required to determine the final equilibrium water use in period two:

$$(A1.2) \qquad Q_2^* = \left(\frac{P_2}{P_1}\right)^e Q_2 \quad ,$$

where Q_2^* = water use in period two, when the real price of water in period two is different from that in period one; P_2 = the real price in period two; P_1 = the real price in period one; and e is the price elasticity of demand coefficient; which is always negative.

To program these equations on the Texas Instrument 58c, we key in the following information:

Step Number	Key Entry	Press
1	76	L61
2	11	A
3	43	RCL
4	00	00
5	65	X
6	43	RCL
7	01	01
8	95	=
9	42	STO
10	05	05
11	43	RCL
12	02	02
13	55	÷
14	43	RCL
15	03	03
16	95	=
17	45	y
18	43	RCL
19	04	04
20	95	=
21	65	X
22	43	RCL
23	05	05
24	95	=
25	42	STO
26	06	06
27	43	RCL
28	01	01
29	32	X≷t
30	43	RCL
31	06	06
32	77	X≥t
33	10	E'
34	25	CLR

Step Number	Key Entry	Press
35	08	8
36	08	8
37	08	8
38	08	8
39	08	8
40	08	8
41	08	8
42	08	8
43	08	8
44	08	8
45	91	R/S
46	42	STO
47	10	10
48	43	RCL
49	02	02
50	75	-
51	43	RCL
52	10	10
53	95	=
54	42	STO
55	02	02
56	55	÷
57	43	RCL
58	03	03
59	95	=
60	45	y^x
61	43	RCL
62	04	04
63	95	=
64	65	X
65	43	RCL
66	05	05
67	95	=
68	42	STO
69	06	06
70	77	$X \geq t$
71	10	E'

Step Number	Key Entry	Press
72	61	GTO
73	00	00
74	47	47
75	91	R/S
76	76	Lb1
77	12	B
78	42	STO
79	00	00
80	91	R/S
81	76	Lb1
82	13	C
83	42	STO
84	01	01
85	91	R/S
86	76	Lb1
87	14	D
88	42	STO
89	02	02
90	91	R/S
91	76	Lb1
92	15	E
93	42	STO
94	03	03
95	91	R/S
96	76	Lb1
97	16	A'
98	42	STO
99	04	04
100	91	R/S
101	76	Lb1
102	10	E'
103	91	R/S
104	76	Lb1
105	17	B'
106	43	RCL
107	02	02
108	91	R/S
109	00	

Now, we are ready to use our demand-supply integration program:

Step Number	Key Entry	Press	Display
1	r	B	r
2	Q_1	C	Q_1
3	P_2	D	P_2
4	P_1	E	P_1
5	e	A'	e
6		A	Q_2^* or 8888888888
7	If 8888888888($Q_2^* < Q_1$)	CLR	
8	Decrease in P_2	R/S	Q_2^*
9		B'	P_2

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