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RURAL RESIDENTIAL WATER DEMAND IN KENTUCKY: AN ECONOMETRIC AND SIMULATION ANALYSIS

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ABSTRACT

This study proposed that demand management through pricing policies can be used in conjunction with supply management to solve water supply problems in Kentucky. Economic principles were shown to apply to rural residential water use. From the economic model, a hyperbolic demand function was theorized. The mathematical form of this function used quantity of water as a function of price, income, value of residence, evaporation, and persons per residence. This function was estimated using ordinary least squares regression. A log-linear model was found to be a satisfactory representation of the demand function. Price was the only independent variable which was significant and had an elasticity of (-.92).

As an application of pricing to demand management, the estimated regression equation was used in a simulation analysis. The simulation was used to determine the reservoir capacity necessary to supply the needs of 4,000 households given three different price levels for water. Reservoir size was determined by simulating reservoir size as a function of outflow as estimated from the demand function plus an assumed low flow rate and inflow from the Thomas-Fiering Model. This technique illustrated that price does affect the quantity of water demanded which in turn effects reservoir capacity requirements.

DESCRIPTORS:

Water Demand, Elasticity of Demand, Water Management, Model Studies

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

In the past water has generally been relatively abundant; however, today this is no longer the case. Water has become a resource that is relatively scarce. Recently, widespread public concern has been voiced with regard to the availability of water for residential purposes. To underscore the problem, Congress established the National Water Commission in 1968 to review the water requirements in the United States. The Commission (1973, p. 259) made three recommendations with regard to water management for residential and other uses:

> 7-21. "Water management agencies should review their metering and pricing policies. Wherever economically justified, meters should be installed and water deliveries measured. Where feasible, water and sewerage charges should be based on two considerations: (a) the costs that users impose upon the system, and (b) the costs imposed on society from the loss of the use of the resource for other purposes. Provision should also be made for recovery of unintended windfall benefits conferred upon affected properties by construction of facilities.
>
> 7-22. Where water is a scarce resource, states should investigate the legal and institutional feasibility of imposing withdrawal charges on self-supplies of water diverting from surface and ground water sources as a means of imposing efficiency in water use.
>
> 7-23. All federal agencies that supply water to users should adopt a uniform policy of cost-based pricing in all future water supply contracts, and, wherever practicable, extend that policy to classes of users who are not now charged."

The reason for concern by the Commission becomes evident when it is recognized that water use in the United States quadrupled since 1900 while population only doubled. Seasonal and daily peaks in water use cause complex problems, while costs of building water facilities have increased substantially. It is, therefore, timely that research is directed toward providing information useful in solving a growing problem of residential water scarcity in the United States.

Problem

Previous research on water demand has been primarily concerned with the availability of irrigation water in the West. Research projects have focused on residential water demand in urban areas; however, few studies have focused on residential demand in rural areas. This author is aware of only one study on rural residential water usage in Kentucky (Rosenstiel 1970).

Two major sources of residential water in Kentucky are ground and surface water. Rainwater is used as a source of residential water in rural areas where ground and surface water are especially scarce. Ground water has been gradually decreasing in importance because the depth at which the water is found makes it uneconomical for use, and the high mineral content makes it undesirable. Thus, surface water is the most important water source. Since surface water is not readily available everywhere, many communities build water reservoirs.

Water supply reservoirs are generally built large enough to ensure an adequate supply of water to a community at all times. Overinvestment in plant and equipment occurs when utilities attempt to ensure enough water for daily and seasonal peaks. At present, water demand considerations are not fully recognized in design analyses. Simulation models, utilizing information on demand parameters obtained in this study in conjunction with hydrologic parameters, could be used to eliminate overinvestment in water reservoirs. This can be accomplished by raising the price of water to lower the quantity of water demanded during periods of high demand or low supply.

Objectives

The objectives are:

1. To estimate a demand relationship for water by residents of rural areas in Kentucky. It is postulated that price, income, evaporation, value of residence, and persons per household affect the water demand function.
2. To use the estimated demand relationship in a simulation model to show the effect of different pricing levels on the size of water reservoir required by a given number of customers.

Two approaches make this study unique:

1. Price data used in the analysis show a larger variation for rural residential use than is the case in other studies. This makes it possible to estimate elasticities of demand over a wider range of price levels than in past studies, and
2. To the authors' knowledge, this is the first rural residential water study that uses elasticities of demand and other parameters in a simulation model to show how different price levels for water can affect the size water reservoir required to meet the needs of a specific size community.

The establishment of a demand relationship will enable water utility managers to set rates consistent with economic efficiency criteria. To achieve efficiency various pricing strategies are available:

1. Differential pricing by quantity demanded,
2. Differential pricing by season,
3. Differential pricing by time period.

The first strategy uses a rate schedule that depends upon the amount of water used. Presently, customers who use large quantities of water are charged a lower price per unit. An alternative strategy, which will be discussed later, involves pricing water at higher rates as water use increases to improve economic efficiency. Differential pricing by season is a method of decreasing (increasing) water usage in times of inadequate (ample) supply. Non-pricing methods are frequently used instead of differential pricing methods in times of water shortage. Non-pricing methods often take the form of a quota. For example, customers may be prohibited from using water for certain purposes such as lawn watering. Pricing methods are more efficient than quotas because they give the customer the choice of purchasing water at a higher price or reducing use. The last strategy involves setting a higher rate for water used during peak periods of the day. Using this pricing method, water would be used more evenly throughout the day. Hence, less storage and equipment capacity would be required.

Water Management

In a market economy, prices determine the uses made of scarce resources. Price has not been used to allocate water among users since water traditionally has not been considered scarce. This attitude is changing with the increasing difficulty and expense in obtaining sufficient quantities of potable water. Price can be used to allocate water while maximizing social welfare if the distribution of income is considered appropriate by society. This result is achieved when water is supplied at a price in which the value to consumers of the marginal (last) unit of water purchased equals the price of that unit.

The construction of a demand function for water follows a procedure similar to that used for other economic (scarce) goods. An individual will pay a very high price (probably everything he owns) for the first units of water he receives. When the level of consumption at which an individual considers 'necessary' for life is reached; the price he is willing to pay for extra units of water decreases. The individual will only accept additional units of water at lower and lower prices as he consumes more and more water. The concept of diminishing marginal utility thus underlies the demand for water just as it underlies the demand for other scarce goods.

Traditionally, water utility managers have adjusted water quantities rather than prices as changes in demand occur. The major reason for emphasis on supply (quantity) management by utility managers is that water utility managers have traditionally viewed the total quantity of water demanded by consumers to be essential. Historically, water has been available at low cost, and economists have not become involved in water demand management. Hence, in the past, water investment decisions have been delegated to the political and not the economic sphere.

By allowing water to be supplied by the 'requirements' type of forecasting, the range of our choices has been constrained. Judith Rees (1969, p. 28) comments:

> "It would be impossible to rectify shortages of all goods by increasing the supply, as the economy's resources are not indefinitely expandable. There appears to be no rational grounds for allowing water supplies to be extended to meet all foreseeable 'needs', when the supply of most other commodities is only increased by foregoing alternative goods. It is possible that the construction of additional water supply capacity is diverting resources away from uses valued more highly on the margin by consumers."

We must begin to reappraise the policy of supplying water without regard to cost. The premise of this study is that future water supply problems are primarily economic. Pricing is a powerful tool that could be used to allocate water in a manner that maximizes social benefit.

Considerable research has been conducted on water demand. Much research has focused on demand for irrigation water. However, a few studies have been conducted for residential water demand. Wong (1972) indicates possible reasons for the paucity of available literature on residential water demand. He states that the problem is due to the absence of an economic policy on municipal water demand. He expresses four additional problems encountered in water demand studies.

First, there are difficulties associated with making econometric analyses for residential water demand. Numerous data problems arise in undertaking a water demand study. Water consumption data are at best only 'guestimates' because of the errors arising in measuring water withdrawn by a household. Some systems do not have metering. Others combine residential water use with other uses which makes it impossible to determine the amount of water used by each household. Billings vary from one month to one year which makes it difficult to determine seasonal water uses. As a result, there is a considerable range in water use among households in different water districts. In Kentucky, an additional problem may exist. Rural households have been known to supplement the purchased water with additional water sources (Rosenstiel 1972). Differences in quality of water and service will also affect water purchase. Unless these differences can be quantitatively measured, the empirical analysis cannot be done with a high degree of confidence.

A second difficulty arises with regard to price data. There is no uniform water pricing policy. Most water utilities sell water using a declining block rate (the rate decreases as consumption increases in the form of blocks that allow a specific amount of water). There is a difference in the number of blocks for each utility and the amount of water sold with the minimum bill (a fixed rate for the first units of water sold). Some systems will include a sewerage charge with the water bill. Rate determination is complicated by the pervasive belief that water should be nominally priced, since many water systems are public, and the water utility could be subsidized through taxes to keep water rates artifically low.

The third problem arises with income data for residences. A number of studies have used mean family income obtained from the Census of Population or the tax roles. Other variables, such as assessed property value, size of lot, and the number of rooms per dwelling are also often used. Income and other socioeconomic data need to be properly matched with the respective water district. Frequently, water districts do not correspond with the same geographic boundaries in which the income data were collected.

Finally, there exists the problem of sample reliability. With time-series data, the period chosen may be too short (e.g., five years or less for a series); while with cross-sectional data, the sample may be too small (e.g., six or seven observations as a sample for a state). The result would be a sample with only a few degrees of freedom which will reduce sample reliability. Thus, data problems make econometric analyses difficult.

Previous Studies on Water Use

Wong's (1972) study was concerned with residential water demand in Northeastern Illinois. The first part of his study was a time-series analysis of Chicago and its outlying communities from 1951-1961. The second part was a cross-sectional analysis of 103 communities which he stratified into four community size groups: 25,000-over, 10,000-24,999, 5,000 - 9,000, and 4,999 and less. His basic statistical method was ordinary least squares (OLS) regression analysis. Average per capita municipal demand was regressed on price per unit, average household income, and average summer temperature. A multiplicative form was used to fit the demand function.

Wong found that over time both income and average summer temperature had a significant impact on water demand in Chicago, with simple correlations of .74 and .77 respectively. In Chicago, price was found to be nonsignificant, but for its outside communities, price was found to be significant at the 5 percent level and income was nonsignificant. Per capita demand was found to be relatively inelastic with respect to price and income.

Rosenstiel (1970) completed a rural residential water study in a Kentucky county to describe characteristics of domestic water use among rural residences and to delineate factors affecting water purchase. He studied 39 households that purchased water from a rural water vender who hauled water with a truck. Every customer had an alternative source of water (rainwater). Only 59 percent of the customers purchased water regularly. People in the study purchased 1,000 to 24,000 gallons of water annually at a mean price of $5.83 per 1,000 gallons. Rosenstiel's equation contained 13 variables of which price and income were found significant at the .001 level of significance at 25 degrees of freedom.

The Chiogioji and Chiogioji (1973) study is an extensive review of literature and source of theoretical and empirical findings dealing with residential, commercial, and industrial water use. The study attempted to measure the effectiveness of adjusting water prices to conserve the use of water supplies. Recommendations were made as to the adjustments which must be made if pricing is to be used as an effective water management tool. In order to verify and collaborate the literature, the investigators interviewed key executives of water utilities located in Washington, D. C. and throughout the United States. Empirical data gathered in the Washington metropolitan area indicated that price increase did have an impact on water consumption; however, reductions lasted only a year or two. Data revealed that in the years in which price increases occurred, twelve out of eighteen price increases resulted in a decrease in per capita consumption.

A time-series and cross-sectional study on residential, commercial, and industrial water use was conducted by Headley (1963) on fourteen cities in the San Francisco-Oakland metropolitan areas. Significant positive relationships between family income and residential water purchases were found both with cross-section and time-series data. Elasticities of demand for residential water with respect to income were larger in the cross-sectional analysis than in the time-series analysis. After estimating demand parameters, Headley formulated a projection model for 1975 predicting a 5.8 percent to 10.7 percent increase in residential water use over the 1959 level. He concluded that family income is an important variable in the projection of future water demand and that it is a good proxy variable for water use factors such as lot size, number of bathrooms, automatic washers, etc.

Gottlieb (1963) utilized detailed reports on water use in Kansas from 1952-1958. For one-third of the reported systems, basic water rates in 1956 were identical to those charged in 1952, while between 1956 and 1958, 76 percent of the systems had unchanged rates. For two periods of years, 1952-57 (in which there were 40 systems) and 1956-58 (in which there were 79 systems), Gottlieb classified the water systems as 'increasing-rate' or 'all other'. One-fifth of the systems over the 1956-58 period, raised rates at a mean of 24.3 percent, while two-thirds raised rates at a mean of 32.5 percent in the latter period. The 'all other' system experienced a decline in per capita water use of 6.7 percent from 1952-57 and 20 percent from 1956-58. The 'increasing rate' system experienced a decline of 16 percent and 26.4 percent respectively. In conclusion, 'increasing rate' systems did show a greater decrease in water use during the periods indicating that price does affect water consumption.

Based on a theoretical model revealing how individuals respond to a commodity uncertain in supply, Turnovsky (1969) estimated demand functions for water in situations where supplies are known to be stochastic. The data came from a sample of nineteen small Massachusetts' towns. Separate functions for household demand and industrial demand were estimated in two cross-sections, 1962 and 1965. In his household regression equation, per capita consumption and planned per capita consumption were a function of the variance of supply, average price of water, index of per capita housing space, and the percentage of population under age 18. The industrial model replaced the index of per capita housing space and the percentage of population under age 18 with an index of per capita industrial production. Time-series data from 1950-52 and 1950-65 were used to estimate the variance of supply. Turnovsky found price, uncertainty as measured by supply variance, and housing space to be significant for household demand. For industrial demand only the first two variables were significant. Firms were found to be more responsive to price and uncertainty than households.

Howe and Linaweaver (1967) concentrated on the effect that price had on the quantity of water demanded by residential customers for indoor and outdoor uses. They found that water users do respond to a price increase from zero to some positive rate imposed by metering. This response is illustrated in Table 1, which refers to averages for 10 metered and 8 flat-rate areas, all in the Western United States. Two items which stand out are: (1) average household uses do not differ substantially between metered and flat-rate areas; (2) sprinkling uses and peak demand are vastly different.

In the 39 residential study areas used in this study, average annual use per capita ranged from 47 gpcd (gallons per capita per day) to 437 gpcd.

TABLE 1

WATER USE IN METERED AREAS AND FLAT RATE AREAS
(October, 1963 through September, 1965)

	For 10 Metered Areas	For 8 Flat-Rate Areas
	(gal/day/per dwelling unit)	
Annual Average		
Leakage and Waste	25	36
Household	247	236
Sprinkling	186	420
Total	458	692
Maximum Day	979	2,354
Peak Hour	2,481	5,170
Annual	(Inches of Water)	
Sprinkling	12.2	38.7
Potential Evapotranspiration	29.7	25.7
Summer		
Sprinkling	7.4	27.3
Potential Evapotranspiration	11.7	15.1
Precipitation	0.15	4.18

Source: (Linaweaver, Beebe, and Shrivan, 1966.)

The average number of persons per dwelling unit ranged from 1.8 to 4.9. The maximum day to average daily water usage ratio ranged from 1.57 to 5.41 and peak hour average from 2.47 to 16.5.

Howe and Linaweaver found from fitting the regression equations that price elasticity for metered public sewer areas was approximately -.23, quite 'inelastic'. The income elasticity, as measured by the surrogate of property value was approximately .35 for all public sewer areas. Population density (measured as the number of persons per dwelling unit) strongly affected domestic demand; while frequency of billing and the regional price index appeared to have no significant impact on demand or upon price elasticities.

Grima's (1972) study focused on the identification of variables that affect the level of residential water use and the level of the related investment in water supply in South Central Ontario. Data collection occurred in 1967, and at the time, two-fifths of the population in the study area had non-metered residential water. Linear and log-linear forms of the regression equations were fitted. Water use by households was averaged over a year (the summer period and the winter period). The fitted equations for metered and single-unit dwellings included assessed sales value of residence, number of persons per dwelling unit, the marginal price, and the fixed bill as independent variables. The partial regression coefficients were all significantly different from zero and had the expected signs. After testing both linear and log-linear forms, he found that the log-linear form provided a better fit. Price elasticity during the winter period was -.75 and for the summer period it was -1.07. Income elasticities were .48 for winter and .51 for the summer period.

The second objective of Grima's study was to obtain an approximate estimate of the impact of policy alternatives on investment requirements. The assumptions made were:

1. The community served consisted of 200,000 people living in 50,000 single unit dwellings.
2. Required investment was $150 per resident for residential water supply, and
3. Changes in capacity demand have a proportionate affect on 65 percent of the required investment.

If $300 per capita is required to build a municipal water supply system, the total required investment is $60 million of which half is ascribed to residential water users. Of this $30 million, it is possible to effect 65 percent by reducing the design capacity (Table 2).

<u>Summary</u>

The objective of a literature review is to gain a better understanding of the significance of factors affecting residential water use. Previous attempts to model residential water use indicate a wide variety of approaches and of the type of sample data collected. There are also some discrepancies in the results. Nonetheless, previous studies do provide a basis for going beyond the approach of estimating requirements and attempt to model water use in terms of the identification of relevant explanatory variables.

TABLE 2

THE EFFECT OF DEMAND MANAGEMENT ON RESIDENTIAL WATER USE AND INVESTMENT REQUIREMENTS

Policy Alternative	Reduction in Water Use (Avg. Summer Day)	Reduction in Investment[a]	
	Percent	Percent	$ Million
Meter, marginal charge = 40¢/1,000 gal.	23	15	4.5
Meter, marginal charge = 60¢/1,000 gal.	50	32.5	9.8
Meter, marginal charge = 80¢/1,000 gal.	63	41	12.3
Charge a marginal price of 60¢ instead of 40¢/1,000 gal.	35	23	6.9
Charge a marginal price of 80¢ instead of 60¢/1,000 gal.	26	17	5.1

[a]Total investment ascribed to residential water use is $30 million.

Source: (Grima 1970, p. 190).

CHAPTER II

RESEARCH PROCEDURES

It has traditionally been argued that a rate charged for water should cover the total costs of service including a 'fair' rate of return for investors in the water company. Presently, average cost pricing (average cost being equal to the total cost of making water available to the user divided by the units of water produced) is often used by water utilities. One way for the water company to recover total costs is to set price (P) equal to average cost (AC) so that $P \cdot Q = AC \cdot Q$ (where Q = quantity), or total revenue equals total cost. Water utility managers often consider the average cost principle fair because:

1. Water utilities are expected by society to supply water to their customers cheaply without 'excess' profit.
2. Every customer pays the entire cost of the units of water consumed instead of paying only the additional cost of producing these units.
3. The customer is not required to pay more for the water than the actual costs of supply.
4. The average cost price is a reliable criterion for investment, and
5. Average cost pricing covers the entire expenditure of the undertaking (Gupta, 1968, p. 25).

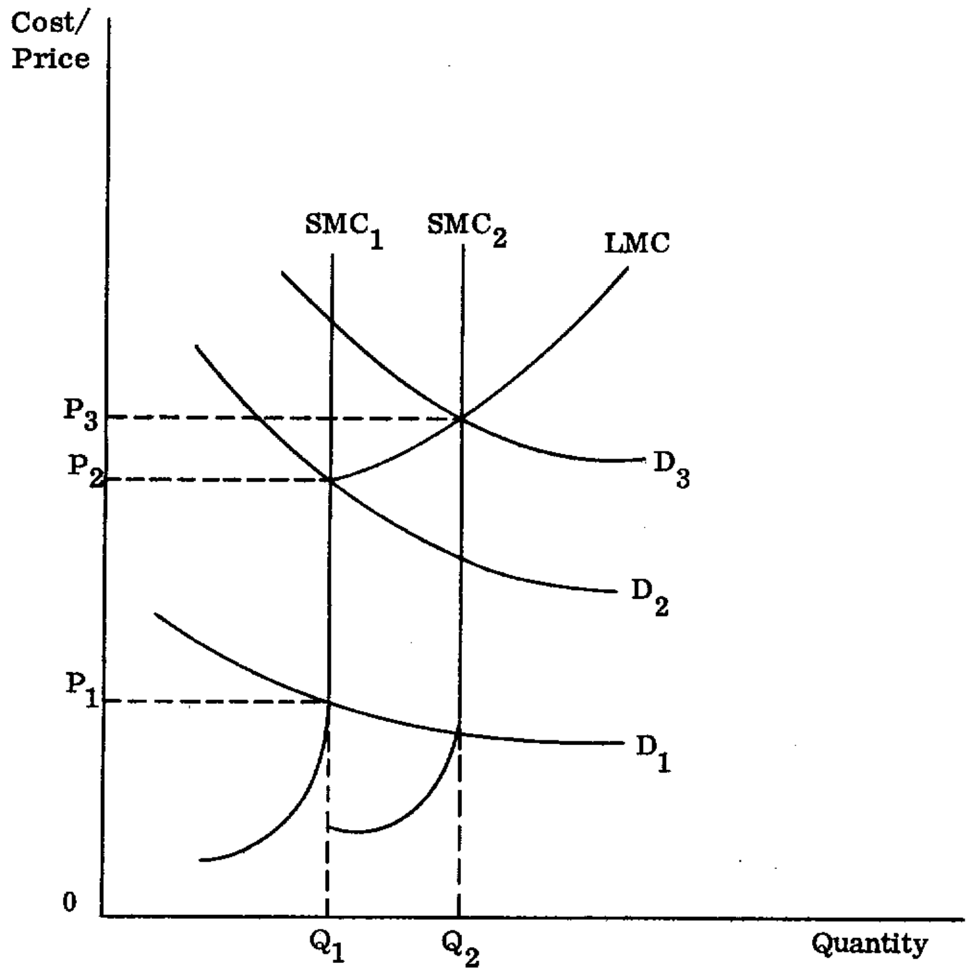
However, the economist seeking efficiency might prefer marginal cost pricing (marginal cost being equal to the addition to total cost attributable to an incremental 'unit' increase in water supply). Economic efficiency is obtained when society receives the greatest total benefit from its scarce resources. In order to become efficient, output of any commodity in a society should be at a level where marginal costs equal marginal benefits (the point where price is equated to marginal cost). At this point, the well-being of society is maximized and the industry is at a Pareto efficient level of output (a point where every reorganization that augments the value of one variable necessarily reduces the value of another).

Pricing Models

Figure 1 depicts a marginal cost pricing model. In this case, Pareto efficiency is obtained because price (P_1) is equal to short run marginal cost (SMC_1). The SMC_1 schedule, which is the water supply function, increases gradually until full capacity is reached. The function then becomes vertical. The long-run marginal cost function (LMC) represents operating and capacity costs, and increases steadily. Equilibrium will occur where price (P) equals SMC_1, until SMC_1 equals LMC. If demand increases beyond this point, the building of additional capacity represented by SMC_2 is justified because marginal benefits exceed marginal costs.

This pricing system is based on the assumption that the water utility industry is an increasing cost industry. The water utility industry in Kentucky as a whole, exhibits increasing average costs over time because as water supplies become insufficient, new reservoirs are built or present facilities are expanded. Cost data for residential water production are not readily available; however, Grima (1972, p. 132) gives two reasons for expecting the costs of residential water to increase over time.

> 1. "As new subdivisions are opened up away from the source of water, pumping and related costs should increase to overcome the friction of distance and this cost is additional to the increase in pumping costs per million gallons produced; mains transmission average costs would also tend to increase slightly if the density of building is reduced.



Source: (Adapted from Warford, 1966, p. 97).

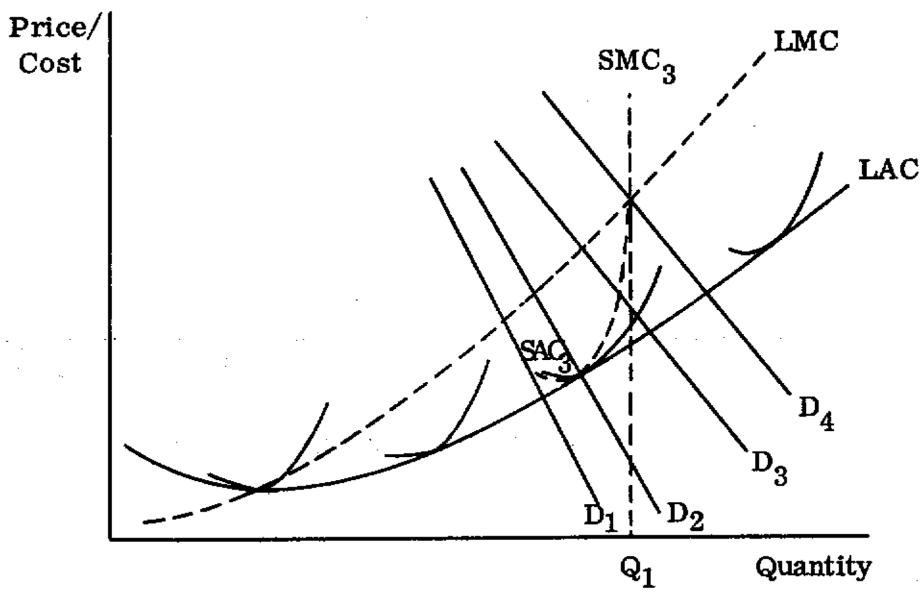
Fig. 1.--Marginal cost pricing.

2. Peak demands for residential water are increasing faster than average daily demands. This is due to higher income and larger lawns. Supply facilities (source development, treatment, distribution, and storage facilities) are expanded to cope with the higher peak demand and there is more excess capacity during off-peak periods. The proportion of idle plant during the off-peak season will increase over time thus increasing average costs."

Figure 2 illustrates short and long-run average and marginal cost functions for water supply. Assume that the third incremental unit is the latest addition to the water supply system. If demand is D_1, short-run marginal cost pricing will produce a loss because short-run marginal cost (SMC_3) is less than short-run average cost (SAC_3). If the demand function is D_2, total revenue will equal total cost under marginal cost pricing (since price = marginal cost = average cost). If demand shifts further to the right where short-run marginal cost (SMC_3) exceeds short-run average cost (SAC_3), marginal cost pricing will produce a profit. The optimum size reservoir (Q_1) will occur where long-run marginal cost (LMC) intersects short-run marginal cost (SMC_3).

Kentucky Water Pricing Model

Figure 3 represents a pricing model for Kentucky water utilities. In Kentucky, municipal water utilities build and operate water supply reservoirs. Rural water districts, which do not own supply reservoirs, purchase water from the municipalities. The price at which water is sold depends upon the cost of the reservoir, that is, the more expensive the reservoir, the higher the price charged for water. The amount of excess capacity depends upon the cost of the reservoir. A water utility with a more expensive reservoir will build less excess capacity and accept the greater risk of running low on water. In the model, (SMC_1) and (SMC_2) represent short-run marginal cost functions for two municipalities.



Source: (Grima, 1972, p. 135).

Fig. 2.--Average and marginal cost functions of water supply.

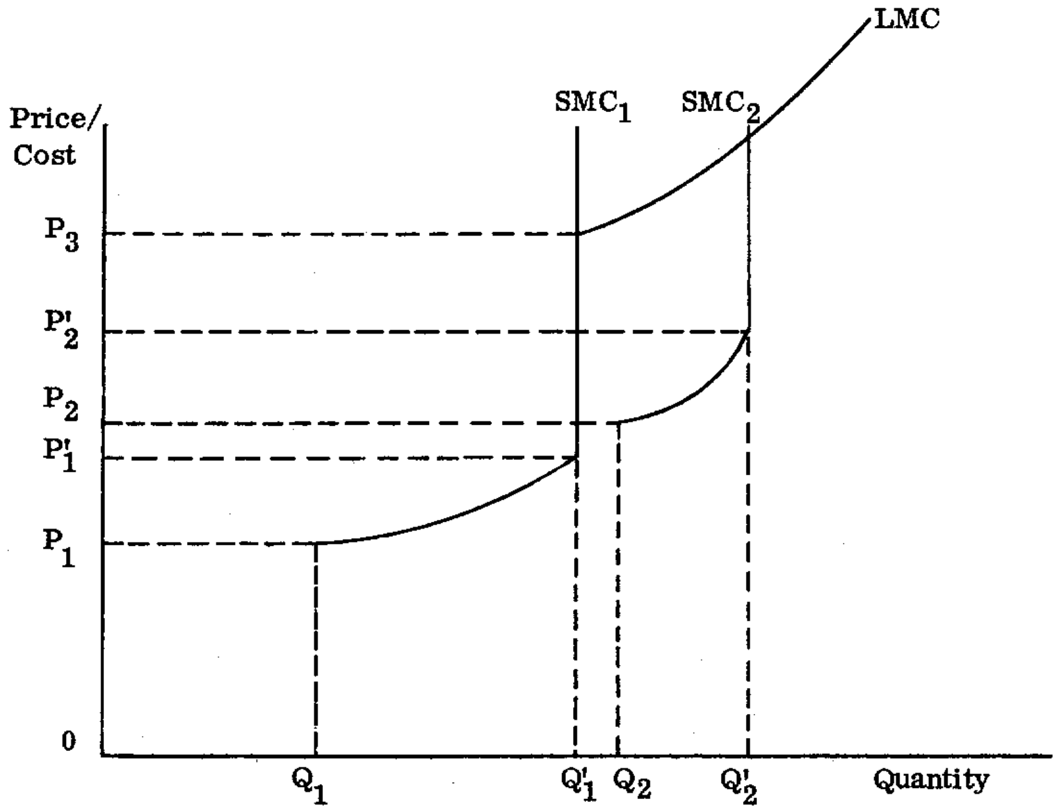


Fig. 3.--Kentucky water pricing model.

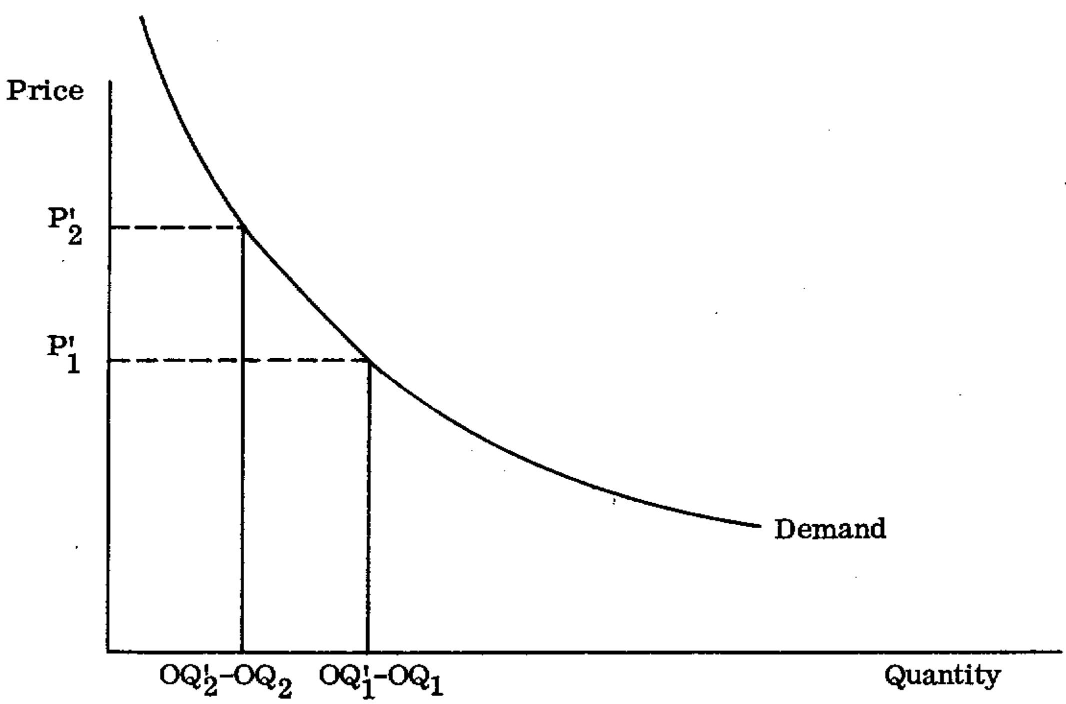


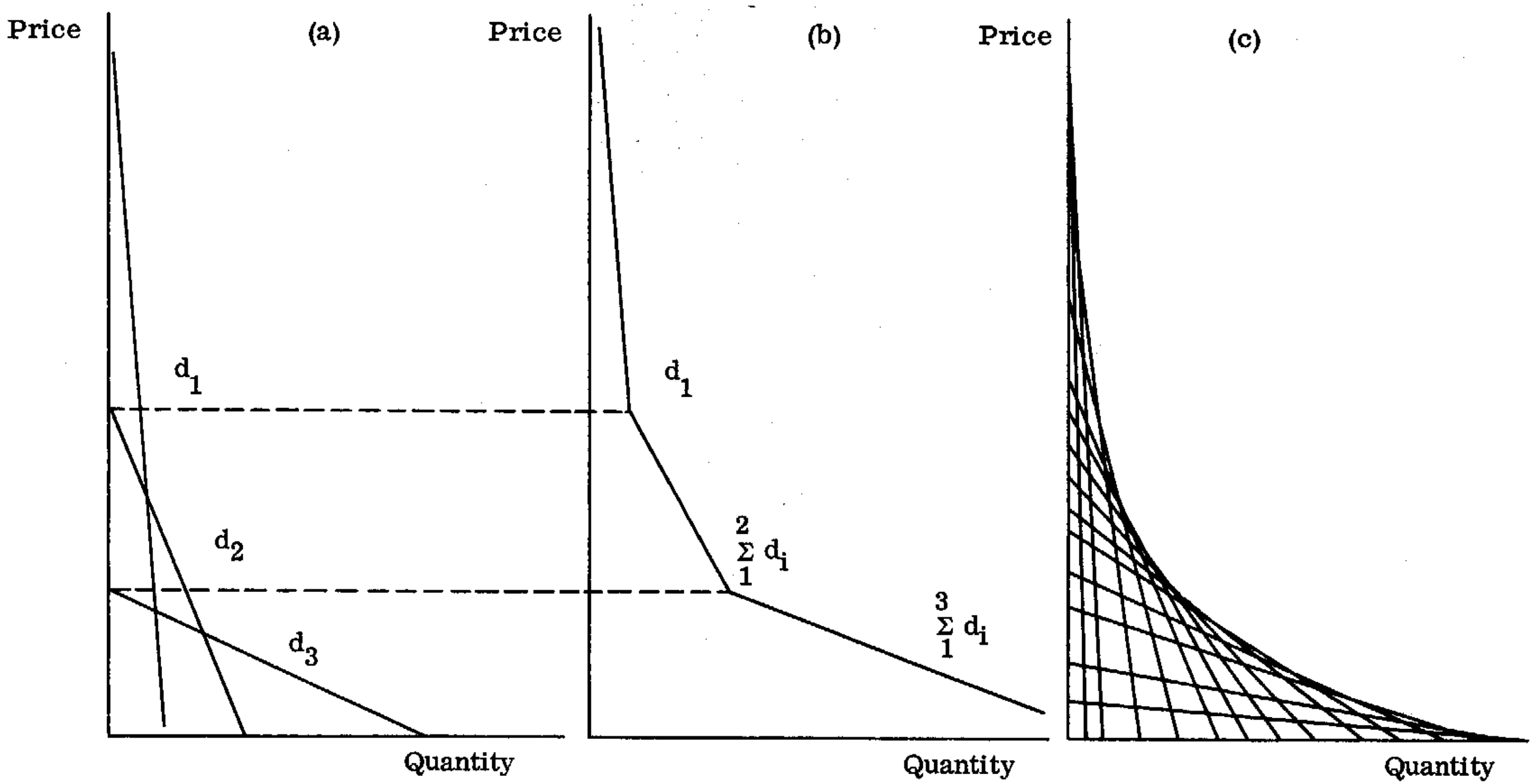
Fig. 4.--Demand function for residential water.

Municipality 1 sells water to its customers at price (P_1), a price high enough to cover its fixed costs. At price (P_1) the municipalities' customers demand ($O\ Q_1$) units of water, leaving an excess capacity of ($O\ Q_1' - O\ Q_1$) which will be sold to the rural water district at price P_1'. Municipality 2 will sell ($O\ Q_2$) units of water to its customers at price P_2. This leaves an excess capacity of ($O\ Q_2' - O\ Q_2$) which is sold to the rural water district at price P_2'. The information obtained from this model can be used to trace out the supply functions for two rural water districts. By adding additional supply functions to the model, it is possible to trace out the rural residential demand for water (Figure 4).

Theoretical arguments for a curvilinear demand function were expressed by Grima (1972, p. 92). He stated that:

> "The (coefficients of the) independent variables measuring income level and the number of persons in residence should show decline in slope as they (the variables) increase. As the assessed sales value increases the use of water may be expected to increase proportionally at first but beyond some point the use of water will not increase as fast. For example, water uses for personal hygiene and car washing do not increase indefinitely with income. There are some water uses that may decline with income (e.g., a high-income family takes longer holidays as income rises).
>
> The same logic applies to the number of persons in residence. In the house there are some uses of water that do not depend on the size of family (e.g., lawn-springling, leakages). As the number of persons in the dwelling unit increase such water uses are averaged over a larger number of persons."

Figure 5(a) depicts a model of three demand functions for residential water use. D_1 represents the demand for essential water uses such as drinking, cooking, washing clothes, personal hygiene, and waste removal. The demand for such purposes has a very steep slope and the consumer is willing to pay a very high price to consume small quantities of water. The slope of (D_2) is slightly less steep than (D_1) and denotes demand for water of



Source: (Adapted from Grima, 1972, p. 93).

Fig. 5.--Curvilinear demand function.

lesser importance to the household such as, for lawn watering, and appliances such as a dishwasher or garbolator. Demand function (D_3) is nearly horizontal and indicates the demand for water of least importance, such as leakages, careless use in sprinkling, and 'waste'. For these uses, the consumer is willing to pay only a very low price and will consume large quantities of water. The three demand functions are summed horizontally in Figure 5(b). In Figure 5(c) additional demand functions were added to depict a continuum of specific water uses ranging from water for drinking to water for 'waste'. An aggregate demand function for residential water use can be constructed by horizontally summing the series of individual demand functions. This aggregate demand function illustrates that the total residential demand function is curvilinear.

Past Elasticity Studies

Table 1 (Appendix A) summarizes prior research results establishing price and income elasticities for water. The objective in reviewing past elasticity information is to better understand the demand for water. However, it is apparent that there are discrepancies among empirical estimates of price and income elasticities Table 1 (Appendix A). The range of results makes comparisons between studies difficult and suggests differences in the type, source and quality of data used in the studies. Some studies have reported inelastic price and income relationships. Howe and Linaweaver (1967) observed that per capita water consumption in non-metered areas is generally much higher than in metered areas. Hence, the demand for water may be relatively elastic in the higher price ranges.

Bain, Caves and Margolia (1966, p. 162) comment on the usefulness of elasticity information:

"The price elasticity of demand also has significance in separate, but related, ways. It is involved, for instance, in determining the economic justifiability of any water project that is designed to supply water in volume to a previously unwatered area, or to substantially augment the water supply in an area. . . at a determinable added cost per unit of added water supplies. In such advance consideration, there must be a definite allowance for the effect of a price of water sufficient to cover the added cost on the amount of water which will be demanded from the new supply. This is particularly essential where introduction of the new supply entails higher water costs and prices than those previously experienced in the area. If due allowance is not made for the effect on demand of elevated water prices, a project may be undertaken which is designed to supply more water than would be economically most desirable for the area."

Metering

There is evidence in the literature to show that metering does reduce residential water consumption. The American Water Association Committee (1973, p. 287-288) reported:

"In 1957, a rate increase that raised sewer-service charges up to 100 percent of the water bill was passed in Owensboro, Kentucky. This increase discouraged the use of water for lawn sprinkling and has had a long-lasting effect on the water usage of the residential customers on the system.

The total level of cost appears to influence water usage in all classes of service to some extent. An examination of total revenues and water usage by customer class for 23 utilities indicated that in areas where the average cost to the residential customer was 60-70¢/1,000 gal, customer usage averaged approximately 70 percent of that experienced in areas where the cost was 20-30¢/1,000 gal. In more arid areas, where maintenance of residential lawns is dependent upon extensive irrigation, an even greater difference in residential water use with increasing cost is indicated."

Hanke and Boland (1971, p. 677-81) interviewed 180 persons in Boulder, Colorado and found that more than 50 percent of the respondents consciously altered their water use habits in response to price increases. An earlier study in the same city (Hanke and Flack, 1968, p. 1364) revealed that if water use in a dry year and wet year are averaged; annual water use is reduced by thirty-four percent and summer use is reduced by thirty-seven percent through metering (Table 3). There was also no tendency for residents to return to former use habits during the six years following metering (Table 4).

Although there are numerous other examples of how metering and pricing increases have reduced water consumption, there are still many critics of the use of price as a water management tool. Hanke (1970a, p. 1254) refutes the argument that price increases cause only temporary water use reductions when he states:

> "Another generally accepted and erroneous variant of the water-is-different philosophy suggests that the installation of meters and price increases rapidly become ineffective in reducing water use. This view can be clarified by realizing that a functional relation at one point in time is not a trend over time. For example, let us assume that the demand for residential water in 1965 is represented by D_{1965} below. If flat rates (a zero price) exist, the quantity of water demanded will be Q_{fr}. The installation of meters in 1965 will reduce the quantity demanded from Q_{fr} to Q_m when the metered rate is P_m. When one views the market a few years later in 1968, he will notice that the demand function has shifted to the right represented by D_{1968}. This shift could have been caused by changing tastes, increased incomes, population increases, alterations in habits, or changes in other parameters of the demand function. If metered rates are maintained at P_m, the quantity of water demanded will increase from Q_m to Q_{fr}.
>
> The increase in water used from 1965 to 1968 should not lead one to conclude that price increases (metering) are not effective after three years. If flat rates were again imposed in 1968, the quantity of water demanded would equal Q'_{fr}, which

TABLE 3

EFFECT OF METERING -- BOULDER, COLORADO

Year	Percent Metered	Annual Use gpcd	Winter gpcd	Summer gpcd
1960	5	243	154	365
1965	100 (wet year)	149	107	206
1964	100 (dry year)	172	111	257

Source: (Hanke and Flack, 1968, p. 1364).

TABLE 4

GENERAL TYPES OF REACTIONS TO METERING INTENSITY OF REACTION, PERCENT OF THOSE RESPONDING

	More	Less	Same	Don't Know
Watched Sprinklers	51.1	1.7	43.3	3.9
Repaired Outside Leaks	11.0	0.0	67.0	22.0
Stopped Sprinkling Parts of the Yard	35.1	0.0	57.2	7.8
Permitted Yard to Turn Brown	26.7	1.7	66.1	5.6
Watered at Night	25.4	0.0	67.2	7.2
Repaired Inside Leaks	6.2	0.0	79.4	14.4
Reduced Use: Household Purposes	30.0	2.2	62.2	5.6
Washed Car at Home	1.7	37.2	52.8	8.3

Source: (Hanke 1970b, p. 1,384).

is considerably greater than the 1968 use under metered rates. Price changes induce movements along a demand function, whereas other factors cause the locus of the function to change. One must be cognizant of both sets of phenomena if sound projections of water consumption are to be made" (Figure 6).

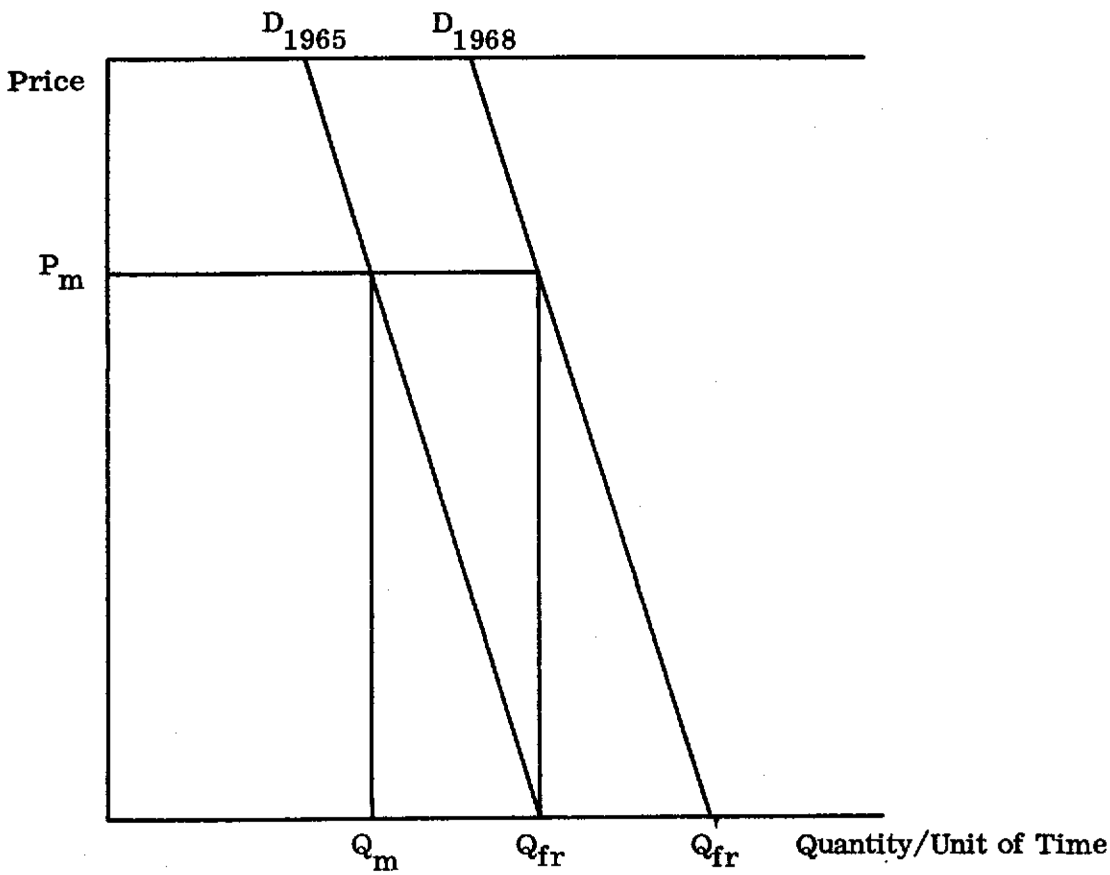
Mathematical Form of the Theoretical Model

A simple single equation model rather than a more complex simultaneous equation model, is an appropriate mathematical representation of the demand function for rural residential water use. The theoretical model clearly reveals that while the price of water is affected by the supply of water (amount of excess capacity in the reservoir), the supply of water available to rural water systems is not affected by the price. This is because the excess capacity of the municipal reservoir was designed merely as a safety valve; not for the purpose of selling water to rural water systems. Thus, when price is plotted on the vertical axis, the supply functions become vertical functions of zero elasticity. Supply functions which evolve from reservoirs of alternative sizes, trace out an 'average' demand function for rural residential water (Figure 7). It is hypothesized that

$$(1) \quad Q_d = f(P, I, V, E, N)$$

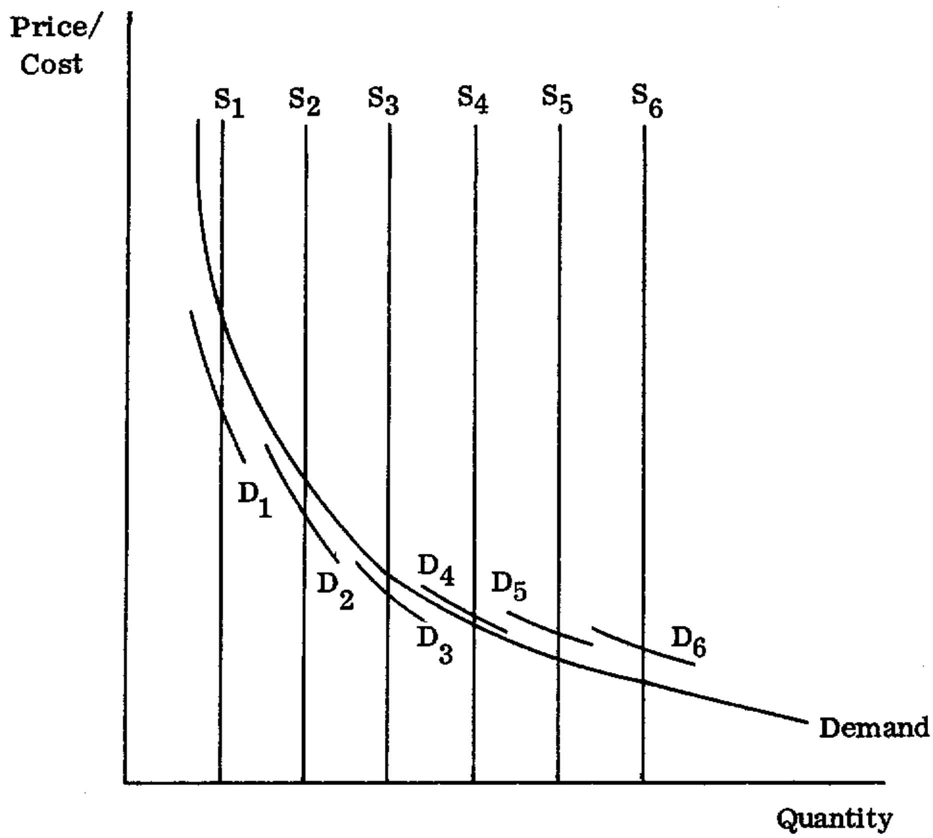
where

Q_d = quantity of water demanded by users in thousands of gallons/dwelling unit/year;



Source: (Hanke, 1970a, p. 1254).

Fig. 6.--Demand over time.



Source: (Adapted from Shepherd, 1963, p. 163).

Fig. 7.--Demand adjusted by completely inelastic supply functions.

P = average water bill in dollars/1,000 gallons;

I = mean income in thousands of dollars/dwelling unit/year;

V = value of residence in thousands of dollars;

E = evaporation in inches for June through September;

N = number of persons per dwelling unit.

The variables I, V, E, and N are hypothesized to shift the demand function in the price-quantity plane.

Price

Rural residential water in Kentucky is priced in two parts: (1) a minimum bill which includes a specific amount of water per billing period, and (2) a series of decreasing block rates which allow a specified amount of water after the amount provided under the minimum bill has been consumed. In this study, the average water bill is used because it is the price at which all the water sold to the rural water district will be consumed. Although the average price is one which no customer pays, average price has the advantage of reflecting in a general way the level and structure of rates. It is not possible to *a priori* specify the exact size of the coefficient on this variable. However, theory developed in the chapter suggests that the sign on the coefficient will be negative (that less water will be consumed at high prices).

Income

The income of the consumer profoundly affects consumption patterns. In the case of residential water demand, income will affect the variety, number, and frequency of use of water-complementary appliances. Once water-complementary appliances are purchased, little reduction in their use might be anticipated in response to an increase in water rates. Moreover, high income families would be less likely than low income families to be concerned with an increasing water bill.

Value of Residence

Previous water demand studies have used value of residence as an exogenous variable. The value of a residence depends on a number of variables which affect water use. Among these are the number of bathrooms, the presence or absence of a garage, and lot size. Higher priced homes will generally utilize greater amounts of water than low or medium priced homes.

Evaporation

Water use is also dependent on the amount of water that is required for lawns, gardens, shrubs, and flowers. The evaporation rate is a good indicator of the amount of water required for outside uses. Increased evaporation rates occur in hot and dry areas. An American Water Works Association (1958, p. 1,408) task group found that water use was twice as great in areas with dry summers than in areas with no distinct dry season.

Number of Persons per Dwelling Unit

Most residential water is used in the bathroom. This particular use is a function of the number of persons in a residence. It is estimated that each person will use about 30 to 40 gallons of water daily for personal hygiene (Grima, 1972, p. 87). However, other studies have not always revealed clear evidence of a positive relationship between persons in residence and the demand for water. Inadequate variation in the data may be one explanation for the nonsignificance in many studies.

CHAPTER III

DATA AND RESULTS

Data on residential water use for 1972 were collected from rural water districts. Districts were located throughout Kentucky and varied in size from about 15 to 2064 customers, Table 2 (Appendix A). Some districts crossed county borders while others covered only a section of a county. Information obtained from rural water districts was used in an econometric analysis to empirically estimate parameters of the theoretical model outlined in Chapter II. Least squares regression techniques were employed in estimating model parameters.

The general stochastic form of the demand model was

$$(2) \quad Q_d = f\ (P,\ I,\ V,\ E,\ N,\ u)$$

where

Q_d = quantity of water used in thousands of gallons/year/dwelling unit (obtained from the Kentucky Public Service Commission);

P = average water bill in dollars/1,000 gallons (obtained from the Kentucky Public Service Commission);

I = mean income in thousands of dollars/year/dwelling unit (obtained from the Population Census, 1970);

V = value of dwelling unit in thousands of dollars (obtained from the Housing Census, 1970);

E = evaporation in inches for June through September (obtained from the Climatological Data - Kentucky, 1972);

N = number of persons/dwelling unit (obtained from the Housing Census, 1970);

u = stochaster error term assumed to be normally distributed with a zero mean and a constant variance.

It was shown in Chapter II that only a single equation model is needed to capture the structural relationship influencing the demand for water from rural water systems. This is because the elasticity of supply for water to rural water systems is on an a priori theoretical basis assumed to be zero. On the basis of the theoretical model, the expected signs on the model parameters are $\frac{\partial Q_d}{\partial P} < 0$, $\frac{\partial Q_d}{\partial I} > 0$, $\frac{\partial Q_d}{\partial V} > 0$, and $\frac{\partial Q_d}{\partial E} > 0$, and $\frac{\partial Q_d}{\partial N} > 0$. The partial derivative with respect to price ($\frac{\partial Q_d}{\partial P}$), represents the negative slope of the demand function (Figure 4), while the partial derivatives with respect to the other parameters,

$\frac{\partial Q_d}{\partial I}$, $\frac{\partial Q_d}{\partial V}$, $\frac{\partial Q_d}{\partial E}$, $\frac{\partial Q_d}{\partial N} > 0$, represent shifters of the demand function in the price-quantity plane.

Two qualifications must be made when interpreting results:

1. Regression coefficients estimated in the study may be regarded as estimates of the corresponding parameters only if a sample of the population is randomly collected. In this study, the sample is not random, and the results cannot be interpreted without qualification. The main objectives of the study were to obtain elasticity estimates and to examine the explanatory power of other independent variables (demand shifters). To meet the objectives, it was necessary to delete 57 observations typically consisting of unmetered sales, or water use figures that did not differentiate residential from other uses. Some observations were on urban areas or private institutions which were not a part of this study.
2. Data on price, water use, and evaporation were for 1972 while data on income, value of residence and persons per household were for 1970. Since water use, income and

value of residence tend to increase over time, coefficients on explanatory variables may be inflated (but probably to only a minor extent).

A Linear Demand Function

As a starting point for analysis, a simple linear demand function was estimated of the form

$$(3)\quad Q_d = B_o + B_1P + B_2I + B_3V + B_4E + B_5N + u$$

where

$(B_1, \ldots, B_5)$ = vector of parameters to be estimated using ordinary least squares regression.

Equation (3) was estimated via ordinary least squares (OLS) using the stepwise procedure outlined in Draper and Smith (1966). The usual OLS assumptions as outlined in Draper and Smith (1966, p. 86) were made.

The fitted equation for the linear model was

$$(4)\quad Q_d = 12.97 - \underset{(2.67)}{12.37P^{**}} + \underset{(4.92)}{1.71I} - \underset{(2.16)}{0.85V} + \underset{(1.24)}{1.62E} + \underset{(18.32)}{10.78N}$$

$R^2 = .15 \quad F = 5.08^{**} \quad n = 150$

**Significant at .01 level
(standard errors are in parentheses)

All of the coefficients had the expected sign with the exception of value of residence. Price was the only variable significant at the .01 level. Value of residence was highly intercorrelated with income (Table 3, Appendix A). This may partially explain why the sign on value of residence was not as theorized.

Table 4 (Appendix A) lists the means, standard deviations, and ranges for the variables. The range and standard deviation for price and quantity data used in this analysis were substantially greater than for data used in previous research. These data provided useful information on water use in the higher price ranges and increased the predictive range of the equation.

Log-Linear Model

The theoretical model outlined in Chapter II, Figure 4, suggests a demand function in a hyperbolic form which exhibits the following characteristics:

1. The first partial derivative with respect to price is negative, $\frac{\partial Q_d}{\partial P} < 0$, indicating that the demand function is downward sloping. Remaining coefficients are demand 'shifters' and are treated as constants when finding the derivative.
2. The second partial derivative with respect to price must be positive, $\frac{\partial Q_d^2}{\partial^2 P} > 0$, indicating that the demand function is concave from above.
3. The function is asymptotic with respect to the P and Q axes.

A power type function satisfies these criteria

(5) $Q_d = \alpha_o P^{\alpha_1} E^{\alpha_2} N^{\alpha_3} V^{\alpha_4} I^{\alpha_5} u$

Two notable features of this model are:

1. Elasticities with respect to price, income and other explanatory variables are constant, that is:

$$(6)\quad \frac{\partial Q_d}{\partial P} \cdot \frac{P}{Q_d} = \alpha_1, \quad \frac{\partial Q_d}{\partial E} \cdot \frac{E}{Q_d} = \alpha_2, \quad \frac{\partial Q_d}{\partial N} \cdot \frac{N}{Q_d} = \alpha_3,$$

$$\frac{\partial Q_d}{\partial V} \cdot \frac{V}{Q_d} = \alpha_4, \quad \frac{\partial Q_d}{\partial I} \cdot \frac{I}{Q_d} = \alpha_5, \text{ and}$$

2. The function generates a hyperbola which has a first derivative with respect to price which is negative.

$$(7)\quad \frac{\partial Q_d}{\partial P} = \alpha_1 \alpha_o \; P^{\alpha_1 - 1} E^{\alpha_2} N^{\alpha_3} V^{\alpha_4} I^{\alpha_5} < 0$$

(since $\alpha_1 < 0$ and P, E, N, V, I, > 0)

and a second partial derivative with respect to price which is positive.

$$(8)\quad \frac{\partial Q^2{}_d}{\partial^2 P} = \alpha_1^2 - \alpha_1 \; \alpha_o P^{\alpha_1 - 2} E^{\alpha_2} N^{\alpha_3} V^{\alpha_4} I^{\alpha_5} > 0.$$

In its present form, equation (5) is not linear and cannot be estimated using ordinary least squares regression. The equation is intrinsically linear; however, and can become linear by performing a log transformation on both sides of the equation

$$(9)\quad \ln Q_d = \ln \alpha_o + \alpha_1 \ln P + \alpha_2 \ln E + \alpha_3 \ln N + \alpha_4 \ln V +$$

$$\alpha_5 \ln I + \ln u$$

Equation (9) is clearly linear in the natural logarithms (base e) of the variables since the parameters (α_i) are constants. This equation can be fit using ordinary least squares regression. The function that is generated will be asymptotic to both axes in all planes. This occurs because zero cannot be represented on the logarithimic scale. (Note that as $P \rightarrow 0$,

$Q \rightarrow +\infty$; conversely as $Q \rightarrow 0$, $P \rightarrow +\infty$). Thus, this functional form fulfills the theoretical constructs established in Chapter II. Parameters of equation (9) were estimated via ordinary least squares (OLS). The usual OLS assumptions (Draper and Smith, 1966, p. 86) were made with respect to the logarithmic model.

The fitted equation for the log-linear model was

$$(10)\quad \ln Q_d = 3.20 - \underset{(.05)}{.92} \ln P^{**} + \underset{(.16)}{.29} \ln E^{*} + \underset{(.33)}{.33} \ln N + \underset{(.15)}{.14} \ln V - \underset{(.22)}{.14} \ln I$$

$R^2 = .68$ $\quad F = 61.93^{**}$ $\quad n = 150$

**Significant at .01 level
*Significant at .10 level
(standard errors are in parentheses)

Price and evaporation were significant at the .01 and .10 level respectively. Income, value of residence, and persons per household were nonsignificant at the .10 level. The coefficient of determination for the log-linear model was .68, compared with .15 for the linear model. The improvement in the coefficient of determination by changing from the linear to the log-linear model provides strong empirical support for the theoretical model in Chapter II which indicated that the demand function was hyperbolic in the price-quantity plane.

The price elasticity for rural residential water use was a constant (-.92). This indicates a price elasticity near unity. Hence, a one percent increase in price would generate a .92 percent decrease in quantity demanded. A comparison of this elasticity with those in Table 1 (Appendix A), indicates that it is larger than estimates from most other studies. This study involved price data which exhibited a higher mean and standard deviation than most previous studies; thus the price elasticity should be relatively high. The finding supports the contention that the demand for water is relatively elastic even in the higher price ranges. Hence, price does have an effect on water consumption and can be used as an effective water management tool.

The income elasticity for rural residential water use (-.14) was not significantly different from zero at the .10 level. A comparison of this elasticity with those in Table 1 (Appendix A) indicates that it is substantially lower than income elasticities found in previous studies. Since income data used in this study were collected from the same source as many previous studies (i.e., the Population Census), the zero income elasticity seems to indicate that rural residents react differently than do their urban counterparts. This difference may be due to the lower average income with smaller variance in rural areas. The lower mean income decreases the purchase and use of water-complementary appliances in rural areas. Rosenstiel (1970) found that rural residences use little water for non-essential uses such as lawn watering, leakages, and 'waste'. The income elasticity for rural residential water use would probably be low since these non-essential uses have the greatest affect on the income elasticity.

The income elasticity from the preceding model cannot be used with much confidence since its sign is not as expected and its standard error (.22) is very high. However, the efficiency of the estimate can be improved by eliminating other variables and estimating the model

$$(11) \quad Q_d = \alpha_o P^{\alpha_1} I^{\alpha_2} u$$

which can be transformed by taking the natural log of each side into

$$(12) \quad \ln Q_d = \ln \alpha_o - \alpha_1 \ln P + \alpha_2 \ln I + \ln u$$

which can be fitted using OLS as

$$(13) \quad \ln Q_d = 4.15 - .92\, P^{**} + .18\, I^{*}$$
$$(.05) \qquad (.13)$$

$R^2 = .67 \qquad F = 151.23^{**}$

**Significant at .01 level
*Significant at .10 level
(standard errors are in parentheses)

The income elasticity (.18) has the expected sign and is a more efficient estimate. A one percent increase in income will result in a .18 percent increase in the quantity of water demanded.

An examination of the coefficient of determination value contained in Table 5 (Appendix A) indicated that after price entered the model, the amount of variation explained by additional variables increased very little. For this reason, income, value of residence, evaporation, and persons per household were deleted from the model. Thus, the final demand function was

$$(14) \quad Q_d = \alpha_o P^{\alpha_1} u$$

which was transformed to

$$(15) \quad \ln Q_d = \ln \alpha_o - \alpha_1 \ln P + \ln u$$

and fitted by

$$(16) \quad \ln Q_d = 4.51 - .92 \ln P^{**}$$
$$(.05)$$

$R^2 = .67 \qquad F = 298.39^{**}$

**Significant at .01 level
(standard error in parentheses)

This relationship between quantity and price is illustrated in Figure 8. By comparing this model with the preceding log-linear models, it can be seen that the price elasticity has not changed significantly. This indicates that price is nearly orthogonal (uncorrelated) with the other variables in the model.

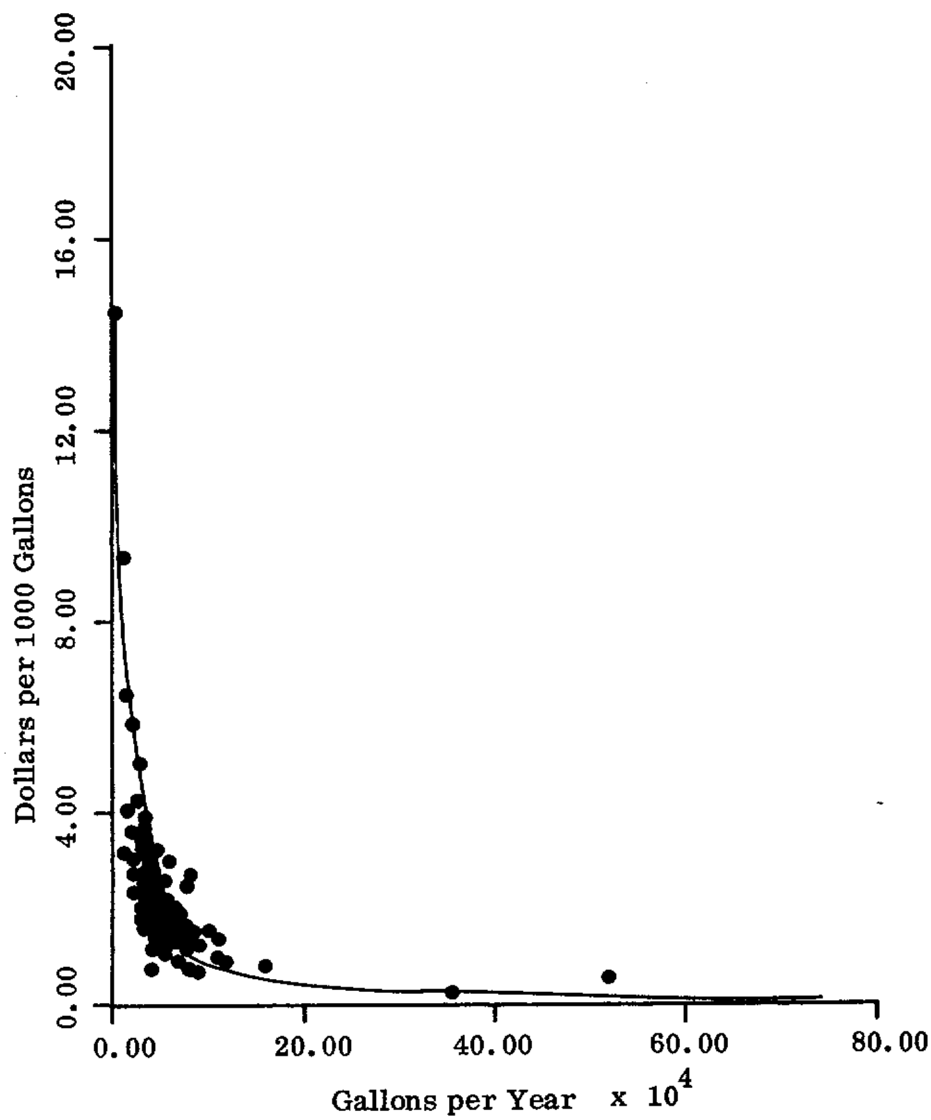


Fig. 8.--Demand function for water, 150 Kentucky water districts, 1972.

Data Correspondence

Since multicollinearity probably was not inflating standard errors of regression coefficients, the non-significance of some explanatory variables may be due to data correspondence problems. Data obtained from the Census were aggregated on a county level. However, water districts seldom covered an entire county, and sometimes crossed county lines. To resolve this correspondence problem, census data were recollected at the enumeration district level. With the census data, enumeration district data were then reaggregated to obtain a completely accurate correspondence of the census data for a few of the water districts. A list was made of those water districts which have boundaries that crossed county lines, and those which occupied less than one-fourth of the area in a county. From this list a sample of twelve water districts was randomly drawn.

The following t test was used:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\dfrac{\Sigma X_1^2 - (\Sigma X_1)^2/n + \Sigma X_2^2 - (\Sigma X_2)^2/n}{n(n-1)}}}$$

to test the difference two means for income and value of residence where:

X_1 = data for n water districts from county census data, and

X_2 = data for n water districts from enumeration census districts.

The null hypothesis was:

$$H_o: \bar{X}_1 - \bar{X}_2 = 0 \qquad H_A: \bar{X}_1 - \bar{X}_2 \neq 0$$

A comparison of nine water districts for income and eight water districts for value of residence was tested from the original sample of twelve districts (Tables 6 and 7, Appendix A). The reason for the deletion of some of the sampled districts from the t test analysis was data collection problems. Maps on the boundaries of all twelve districts were unavailable and enumeration data for some of the districts were not in the file.

The results obtained from the t tests illustrated that the differences between the means for county data and enumeration district data for income and value of residence were not significantly different from zero. Hence, county Census data used in the analysis appear to adequately represent Census data for the individual water districts, and the nonsignificance of the demand shifters cannot be attributed to a correspondence problem. There is strong empirical support for the contention that price is the only important explanatory variable affecting water use in rural Kentucky water districts.

CHAPTER IV

A SIMULATION MODEL

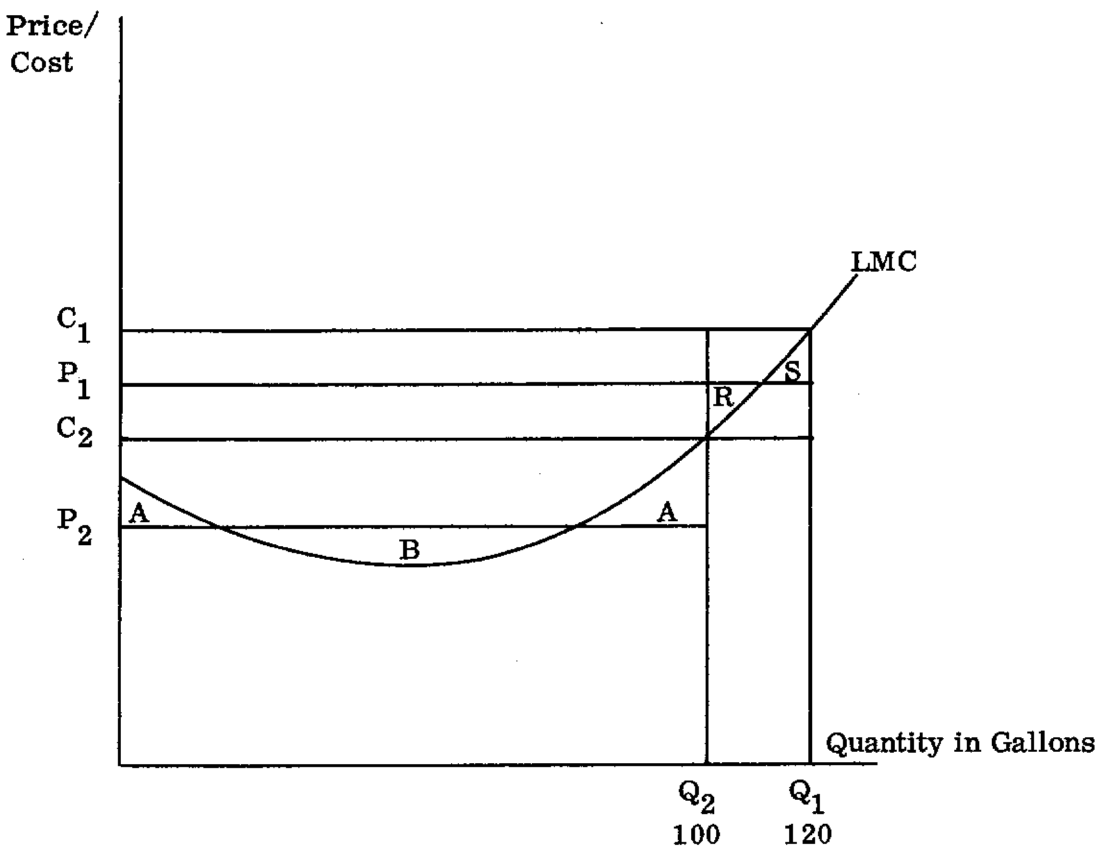
The impact of pricing on the consumption of water has been discussed in previous chapters. The discussion has focused on how pricing can be used to allocate water in Kentucky but the influence of pricing on reservoir size has not been discussed. In this section, a pricing framework which could be used to allocate water in Kentucky is proposed.

Increasing Block Rate Structure

Figure 9 depicts a long-run marginal cost pricing model. If the marginal cost of providing water is increasing, consumers who use more water on the average are imposing greater costs on consumers who use less than the average amount of water. Thus, consumers who use 120 gallons/day are imposing an extra cost of $(C_1 - C_2)$ for the extra 20 gallons/day/consumer. To achieve efficiency, the consumer who demands large quantities of water should be charged a price equal to the marginal cost (C_1) for the extra 20 gallons/day.

In order to cover total costs, the revenue must equal $\Sigma C_i Q_i$ where Q_i is the quantity of water and C_i is the cost of producing that quantity of water in the ith segment of the production function. To recover total costs, a price should be set at P_2 where the shaded areas A and B are equal. A second price should be set at P_1 where the areas of the shaded parts R and S are equal. These two price levels would ensure an efficient pricing rate and cover total costs.

As illustrated in the theoretical section (Chapter II), resources are optimally allocated when price is set equal to marginal cost. This



Source: (Grima, 1972, p. 177).

Fig. 9.--Long-run marginal cost pricing.

condition is satisfied when the highest price in the pricing structure is set equal to the long-run marginal cost. This type of rate structure should be preferred to the average cost pricing method because it allows consumers to purchase a reasonable quantity of water at a low price. Users demanding large quantities of water have the option to purchase more water at a higher price. Thus, water utility managers can offer small quantities of water to all consumers at low prices, and can sell water to those who demand more at a price that reflects the cost of production.

Grima (1970, p. 178) lists other advantages of this increasing block rate schedule as:

1. "This schedule is simple to administer;
2. It makes possible the recovery of expenditures through water revenues;
3. It approximately equates marginal price with the long-run marginal costs, at the same time the medium or low price block would reflect the short-run marginal cost;
4. It would make frequent changes of price unnecessary;
5. It would serve the same purpose as summer charges; if consumers pay a higher price for water demanded during peak periods the demand on the maximum day would decrease in general;
6. This schedule takes into account the fact that the use of high quality water by individuals for essential purposes is beneficial to society as a whole and should therefore be supplied free or at low cost."

Peak Load Rate Structure

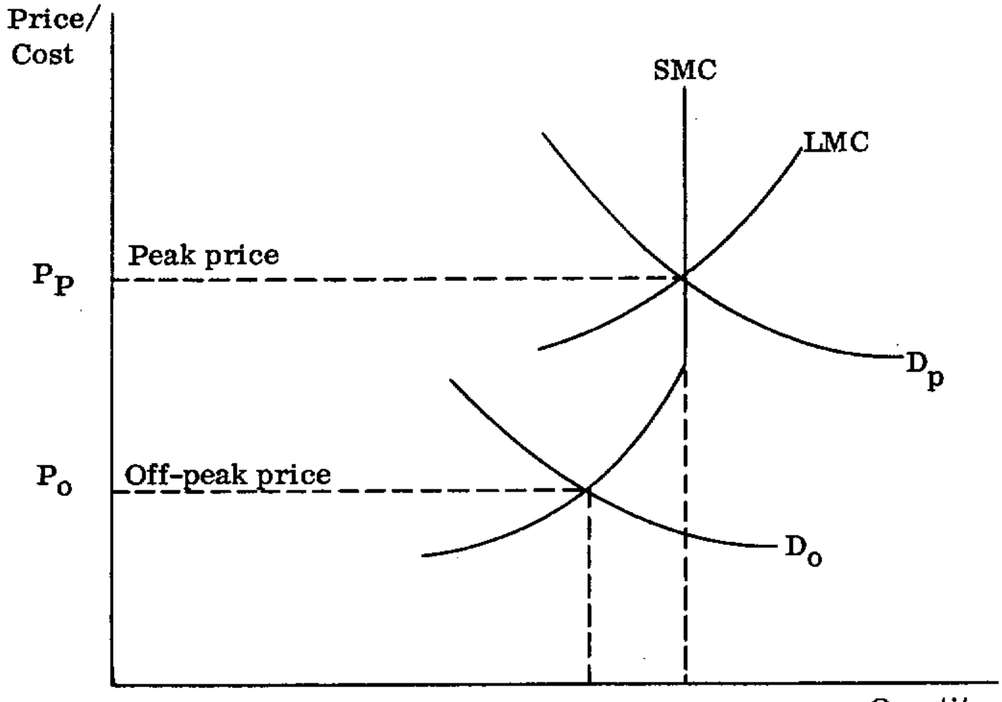
The pricing schedule suggested above could be used to reduce peak loads. The rate structure for this marginal cost pricing schedule would consist of three rates. The first rate (a commodity rate) would be set very low and would cover the costs of providing water at low water consumption.

The second rate would vary with the short-run marginal cost of supply and would affect those consumers who contribute moderately to peak demand. The third rate would be in effect for those consumers who contribute substantially to peak demand and would be set where demand equals the long-run marginal cost. This type of pricing schedule allows a cheap water rate to cover basic costs, a moderate rate to utilize capacity that would otherwise remain idle, and a high rate to influence some consumers to reallocate use from peak to off-peak periods. This type of pricing structure can be used to curb both daily and seasonal peaks without changing the block structures.

Figure 10 depicts a theoretical model illustrating the use of an increasing block pricing structure for pricing water during peak demands. At peak demand, the price of water (P_p) is set at the intersection between the demand function (D_p), the supply function (SMC) and the long-run marginal cost function (LMC). During the off-peak period, price (P_o) would be set where the demand function (D_o) and the short-run marginal cost function (SMC) intersect.

Kentucky Pricing Structure Model

Figure 11 is an illustration of a proposed marginal cost pricing model for rural water systems in Kentucky. In the model, D_1 represents the demand function for municipal water use and SMC_2 is the supply function. As illustrated in the theoretical model in Chapter II , the municipality sells OQ_2 units of water to its customers at price P_3. The excess capacity remaining after the municipal needs are met (OQ_5 - OQ_2), is sold to the rural water district at price P_4. D_2 is a composite demand function because it represents the demand for both municipal plus rural residential water use. This water system is not operating at its most efficient point because the highest price (P_4) does not equal the long-run marginal cost



Source: (Adapted from Rees, 1969, p. 14).

Fig. 10.--Peak and off-peak water price adjustments.

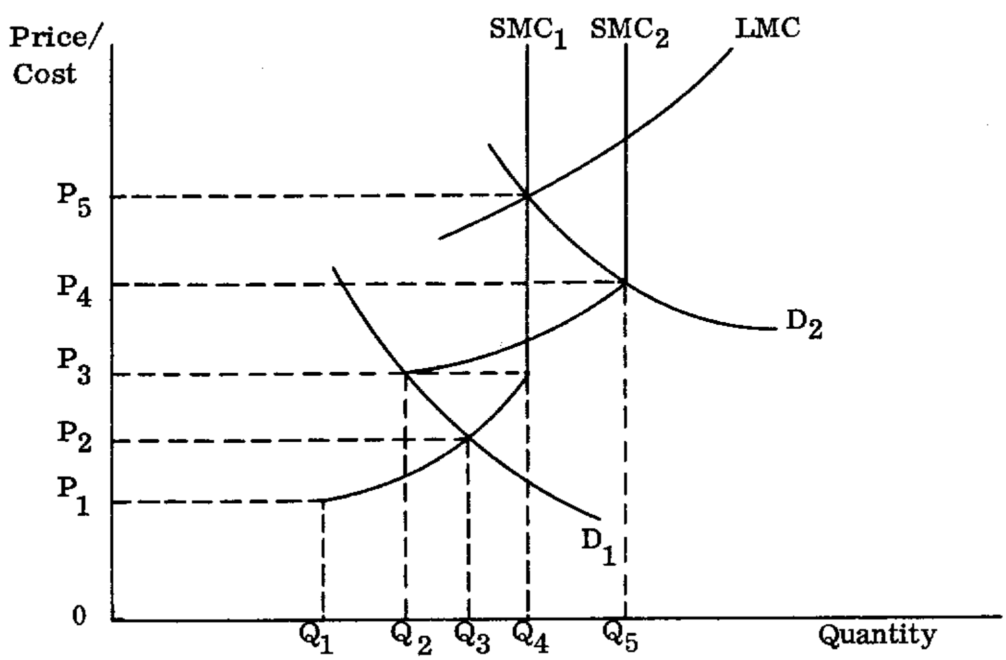


Fig. 11.--Kentucky marginal cost pricing model.

function (LMC). Since the price for peak water use is set below the most efficient price; the municipality operates a larger water reservoir than is necessary to supply the needs of both municipal and rural water users.

To solve the problem of 'over-sizing' the water reservoir, the municipality should build the size reservoir (SMC_1) which would reach capacity where the composite demand function (D_2) intersects the long-run marginal cost function (LMC). By building a smaller reservoir, the municipality is able to lower the price of water in the first block to P_1 (the commodity charge). At price P_1, both municipal customers and the rural water district would be able to purchase OQ_1 units of water. The next price block could be set at the intersection of SMC_1 and D_1 or at some intermediate point up to capacity (OQ_4). This price block ensures the use of excess capacity which would otherwise remain idle at a price which covers the short-run marginal cost (SMC_1). The highest price (P_5, the capacity charge) would be set at a price which equates D_2 (the composite demand function) with the long-run marginal cost function (LMC) and the supply function (SMC_1).

By using this pricing structure, a municipality is able to select the optimal size reservoir (eliminating costly over-sizing). It ensures that the municipality is operating efficiently by charging the customer a price that covers the marginal costs of producing the water he purchases. The municipality is able to lower peak load consumption by setting the highest block rate equal to the long-run marginal cost of production which reduces the amount of excess capacity needed and permits the building of a smaller reservoir. In turn, the smaller reservoir lowers the cost per unit of water which increases consumer surplus.

Kentucky Water Simulation Model

Estimates of demand parameters developed in this study were used in an engineering simulation model to illustrate the effect that different price levels have on required reservoir capacity. The demand function provides an important contribution to the accuracy of the simulation model. Without the demand function, engineers can only estimate water withdrawal from a reservoir. Since water use is a function of the price of water, these estimates may be subject to a substantial error. The demand function also increases the possible applications of the simulation model by linking the demand side (which has traditionally been considered fixed) with the supply side of water management problems.

In the simulation analysis the following assumptions were made:

1. The drainage basin for the reservoir was 4 square miles;
2. The water district consisted of 4,000 households;
3. There were 2.8 persons per household;
4. The minimum low flow rate (evaporation, seepage, etc.) was 3.4 inches per year.

The outflow of water from the reservoir was equal to the demand for water ($Q_d = 90.92P^{-.92} \times 4000$) plus the low flow rate. To increase the accuracy of the simulation analysis, the demand function was adjusted for monthly differences in demand. This was accomplished by using data obtained by Dowell (1967) on the percentage of annual distribution of water demand for Lexington, Kentucky. The annual quantity of water demanded was allocated monthly on the basis of the percentages of monthly demand contained in Table 5.

Inflows of water into the reservoir were simulated based on the Thomas-Fiering Normal Model (Maass et al., 1962). The equation for the model was

$$(20) \quad X_t = \bar{X}_t + \frac{r_t S_t}{S_{t-1}} (X_{t-1} - \bar{X}_{t-1}) + S_t \sqrt{1 - r_t^2} \quad \varepsilon$$

TABLE 5

ANNUAL DISTRIBUTION OF WATER DEMAND
FOR LEXINGTON, KENTUCKY, 1966

Month	Percent	Month	Percent
January	7.1	July	9.9
February	7.3	August	9.5
March	7.9	September	9.5
April	7.7	October	8.1
May	8.0	November	7.3
June	10.0	December	7.6

Source: (Dowell, 1967).

where

X_t = monthly streamflow in month t,

$\bar{X}_t$ = mean monthly streamflow in month t,

r_t = correlation coefficient between flows in month t and t-1,

S_t = standard deviation of monthly flow in month t,

ε = a standard normally distributed random deviate, and

t = time (monthly).

The model states that the flow in month t depends upon the flow in the previous month plus a random component. All of the parameters in the equation were estimated using 31 years of historical data from a drainage basin in Kentucky. From the equation 50-year simulated runs of flow data were generated. Fifty years was taken as the design life of the reservoir.

The inflow and outflow equations were then incorporated in the following equation

$$(21) \quad S_t = S_{t-1} + X_t - D_t \qquad O \leq S_t \leq S_{max}$$

where

S_t = reservoir storage at the end of the month t,

X_t = inflow during month t,

D_t = outflow during month t, and

t = time (month).

The model states that the amount of water in storage at the end of the month is equal to the amount of water in storage at the beginning of the month plus the difference in the inflow and outflow during the month.

Reservoir storage required to meet the monthly demand (D_t) for all months during a 50-year period was determined by initially assuming a reservoir capacity. This reservoir was assumed to be initially full. Equation (21) was applied month by month to the reservoir for a 50-year period based on the demand model and inflows generated by equation (20). If the value of

S_t became negative at any time, the assumed reservoir capacity was increased and the process repeated. The final reservoir capacity was the minimum capacity that prevented S_t from becoming negative during the 50-year period.

Since each 50-year simulated streamflow record generated by equation (20) represents only one of an infinite number of possible streamflow records, the reservoir capacity determined by the above procedure is a random variable. The resulting uncertainty in reservoir capacity was evaluated by repeating the entire process 100 times. This produced 100 estimates for the required reservoir capacity. The capacity that met the demand requirement for the entire 50-year period 99 percent of the time was selected as the final estimated reservoir capacity. This capacity was determined by fitting the Extreme Value distribution Type I for maximums to the estimated reservoir capacities and then determining from this distribution the capacity that was adequate on 99 percent of the cases. Three different price levels for the demand function were used in the simulation analysis. The results of the simulation analysis are shown in Table 6. The results provide empirical support for the theory presented in the previous chapters. An increase in the price of water does affect the quantity of water demanded. This, in turn, affects the storage requirement. Although the price and quantity of water changed by a factor of 4 from $.50 to $2.00 and 169,750 gallons to 47,750 gallons respectively, the storage requirement decreased by a factor of 2.9 from 2,773 acre feet to 960 acre feet or by about two-thirds as much. At the higher price range, price and quantity changed by a factor of 2, from $2.00 to $4.00 and 47,750 gallons to 25,325 gallons respectively, while the storage requirement decreased by a factor of 1.3 from 960 acre feet to 747 acre feet. This finding seems to indicate that a change in price will create a slightly less than proportionate change in storage requirement.

Hence, the theoretical relationship between price and reservoir size discussed earlier is validated (see Figure 11). It was illustrated in Chapter II that the demand function for rural residential water is a demand for excess capacity, since the municipal water districts sell excess capacity to the rural water districts. Figure 12 depicts the demand function for rural residential water use. Assume that a rural water district is paying $2.00 per thousand gallons of water and purchases 47,750 gallons per household annually. If the water utility increases the capacity price to $4.00, it will create a decrease in capacity water use from 47,750 gallons to 25,325 gallons or by 22,424 gallons per household annually.

In Figure 11 it was shown that reservoir size was directly related to the quantity of excess capacity demanded. The simulation model illustrated that a decrease in the quantity of water demanded by 22,425 gallons would result in a decrease in capacity requirement from 960 acre feet to 747 acre feet or by 213 acre feet. Figure 13 illustrates the effect of a price change for excess capacity on reservoir size using the pricing model depicted in Figure 11. Assume that the municipal water utility was operating a reservoir at SMC_2. With this size reservoir, the municipality was selling 47,750 gallons per household of excess capacity to the rural water district at $2.00 per thousand gallons. If the municipality raises the capacity price for water to $4.00 per thousand gallons there will be a decrease in capacity demand by 22,425 gallons per household. This decrease in capacity demand by 22,425 gallons per household will result in a decrease in the reservoir capacity necessary to meet the needs of a community of a 4,000 households by 213 acre feet as shown by SMC_1.

TABLE 6

SIMULATION RESULTS

Price $/1,000 gallon	Quantity Demanded gallon/year/ household	Storage Acre Feet	Quantity Demanded gallon/person/ day
.50	169,750	2,773	166
2.00	47,750	960	47
4.00	25,325	747	25

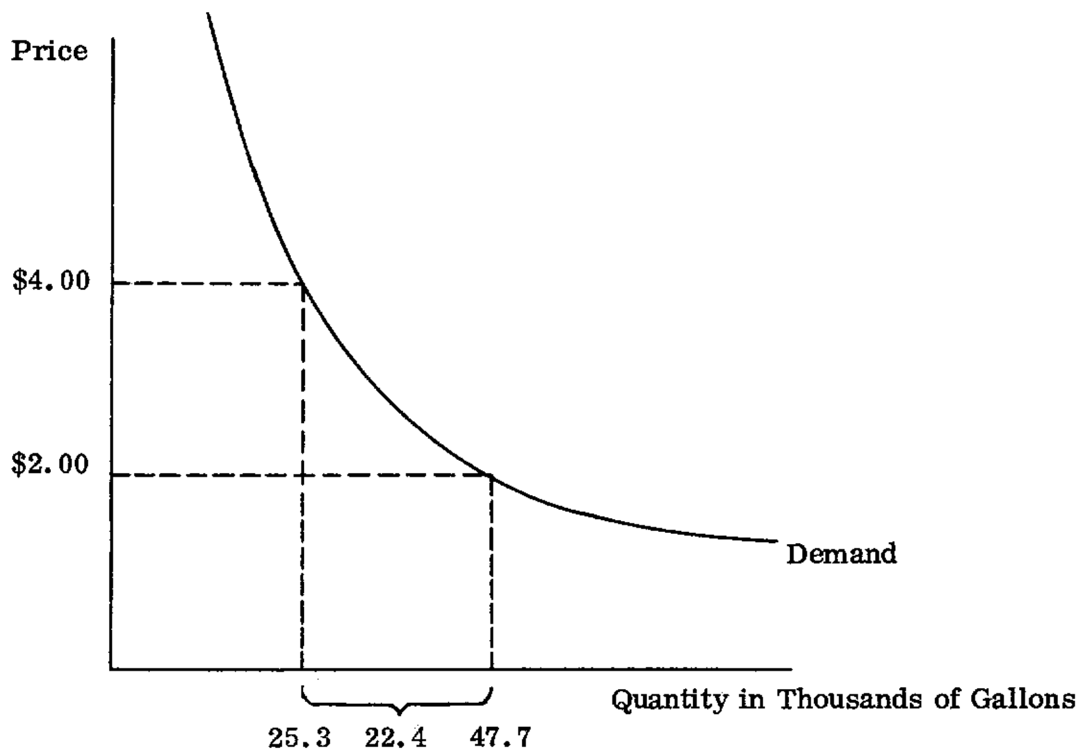


Fig. 12.--Excess capacity demand function.

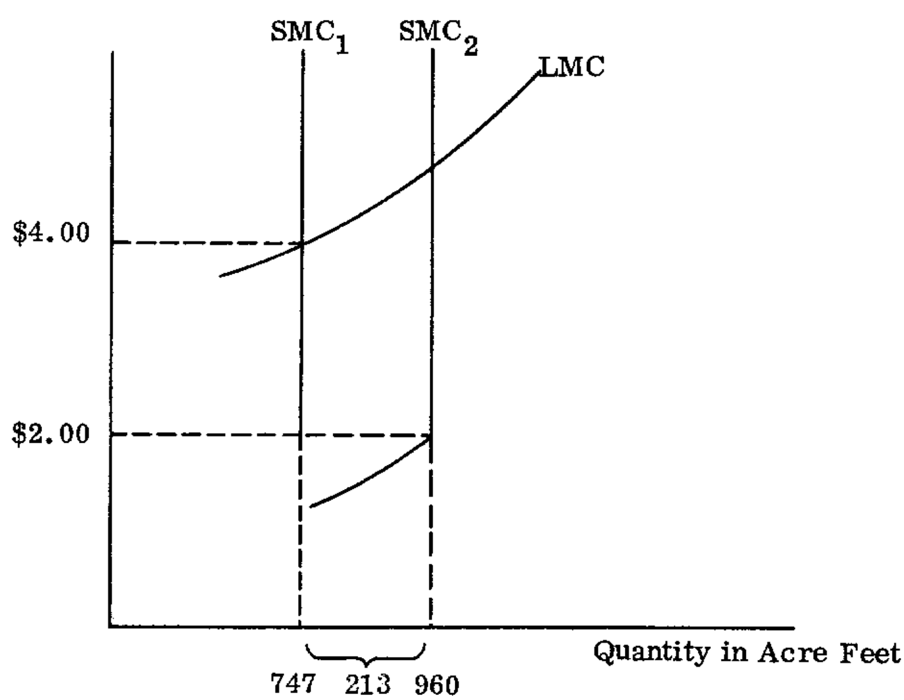


Fig. 13.--Effect of price change on reservoir size.

CHAPTER V

CONCLUSIONS

This study has proposed that demand management through pricing policies can be used in conjunction with supply management to solve water supply problems. It has been shown that economic principles can be used to increase the efficiency of water distribution. Principles outlined in this study can be implemented by utility managers and regulatory agencies. Historically, economics has assumed a subordinate role to engineering and political considerations in water policy. This under-emphasis of pricing policies resulted from the availability of abundant, low cost water supplies. However, today the factors that permitted the supply of low cost water no longer exist. Thus, water has been transformed from a free to an economic good and society must consider other approaches to the management of water resources.

In Kentucky, surface water is the most important source of residential water. Since many communities do not have an adequate source of water; reservoirs are built to meet water requirements. Water supply reservoirs are generally built large enough to supply a community's needs at all times. Since peak water use is greater than average water use, communities generally build larger reservoirs than necessary to supply basic needs. This study used economic principles to analyze this supply problem.

Chapter III illustrated the economic principles that apply to rural residential water use. In Kentucky, municipalities build and operate water supply reservoirs and rural water districts purchase water from the municipalities. Municipalities build excess capacity into their reservoirs as a 'safety-valve'. This excess capacity is sold to the rural water districts at a price that covers the marginal costs of producing the water. From the theoretical model, a hyperbolic demand function was theorized. The mathematical form of this function used quantity of water as a function of price, income, value of residence, evaporation, and persons per residence. This function was estimated using ordinary least squares regression. A single equation model, instead of a more complicated simultaneous equation system could be used because the supply function was perfectly inelastic $(\frac{dQ_d}{dP} \cdot \frac{P}{Q_d} = 0)$. A linear form of the model was initially estimated. A log-linear model was found to be a better representation of the demand function. Price was the only independent variable which was significant and had an elasticity of (-.92).

As an application of pricing to demand management, the estimated regression equation was used in a simulation analysis. The simulation was used to determine the reservoir capacity necessary to supply the needs of 4,000 households given three different price levels for water. Reservoir size was determined by simulating reservoir size as a function of outflow as estimated from the demand function plus an assumed low flow rate and inflow from the Thomas-Fiering Model. This technique illustrated that price does affect the quantity of water demanded which in turn effects reservoir capacity requirements.

Conclusions and Policy Considerations

Based on the review of literature on the demand for water and the theoretical and empirical analysis in this study, the following conclusions and policy recommendations are drawn:

1. Based on data collected from rural water districts in Kentucky, the demand for rural residential water can be depicted as: $Q_d = 90.92\ P^{-.92}$.

2. The demand for residential water, as in other economic goods, is a decreasing function of price. It was illustrated in the theoretical section (Chapter II) that the demand function for residential water is downward sloping and the empirical analysis (Chapter III) of the mathematical form supports this conclusion. Thus, increases in the price of water result in decreases in the quantity demanded. This finding contests the viewpoint that "water is different" and supports the use of demand analysis in water management.

3. The demand function for residential water use is hyperbolic. The model depicting the three different demand functions for different water uses (Chapter II) illustrated that the demand function would be curvilinear. The statistical tests (Chapter III) empirically verified this conclusion (the R^2 for the log-linear model was .67 compared with an $R^2 = .15$ for the linear model). This finding indicates that pricing strategies will have the greatest effect on water consumption in the lower and middle price ranges.

4. The analysis reveals that the elasticity of demand for residential water with respect to price is not as inelastic as has been believed. The reason for the inelasticity of demand in many past studies can probably be attributed to the inability of many investigators to obtain data in the higher price ranges. The evidence obtained on price data in this study indicates that the price elasticity for residential water is near unity

(-.92). This implies that price can be used as an effective tool for controlling the demand for water.

5. Demand shifters (income, value of residence, evaporation, and persons per residence do not appear to have a significant impact on rural residential water use. None of these variables were significant at $\alpha = .05$. The reason for the nonsignificance of these variables could not be attributed to multicollinearity or data correspondence problems as illustrated by the t tests. A possible cause of the inflated standard errors on the coefficients for these variables is due to the lack of variance in the data. Variation in these variables was lost when the data from individual households were aggregated and averaged over a county or enumeration district to obtain the Census figures.

6. Policy variables relating to demand management should be taken into consideration when forecasting and designing capacity for residential water systems. Simulation analysis is an excellent method of modeling demand and hydologic parameters for use in making water management decisions. Simulation analysis was used in this study to illustrate how different price levels affect required reservoir storage capacity (Chapter IV). Water utility managers can use simulation models to 'size' reservoirs and predict the effect that different pricing schemes would have on water use and capacity requirements.

7. Average cost pricing should be replaced with marginal cost pricing. The primary goal of water resources

managers should be to allocate water efficiently. The pricing model (Chapter II) illustrated that marginal cost pricing ensures economic efficiency in the water utility industry. Society obtains maximum benefits per costs and the optimum allocation of resources when goods and services are efficiently allocated. When water is not efficiently allocated, consumers who purchase less water are subsidizing those who purchase more (Chapter IV). This leads to overinvestment in water services and underinvestment in other goods and services.

8. Decreasing block rate schedules should be replaced with increasing block rate schedules where the average cost of supplying water is increasing. A three tier pricing schedule is recommended where the lowest rate (the commodity rate) allows consumers to purchase a small amount of water at a low price. The next rate would be set where short-run marginal costs are increasing to ensure the use of capacity that would otherwise remain idle, and the highest rate (the peak load rate) should be set where long-run and short-run marginal costs intersect (Chapter IV). It was illustrated that this is an efficient pricing structure which provides all consumers with a reasonable amount of water at a low price while providing additional water to consumers at a rate which covers costs. This system is easy to administer and the rates work effectively for either peak or off-peak pricing situations.

9. The system of charges selected should cover the full costs of water services. When water systems are expanded or modified, water rates should be changed

to reflect changes in costs. Some people have argued that since water is a necessity, it should be offered to consumers at very low prices because user charges and prices are regressive (i. e., water services represent a larger portion of a poor than rich family's income) and thus discriminate against low income users. The argument is that water services, which are usually provided in the public sector, should be financed out of tax revenues rather than through a pricing system. On the basis of the theory presented (Chapters II and IV) the above statements are untenable. It is not clear that marginal cost (cost-based) pricing increases the burden on the poor. The pricing models depicted in Chapter IV illustrated that when prices do not cover the full costs of supplying water, those who consume less water subsidize those who consume more. The less affluent who have small lawns and few water-complementary appliances, make up the difference in revenue for the more affluent, higher water using families. If income distribution is the objective, a more appropriate device might be the tax structure or welfare payments rather than tampering with economic efficiency.

<u>Recommendations for Further Studies</u>

Recommendations for further analysis in water demand and management are:

1. Demand functions for municipal water use could be estimated for Kentucky. Wherever possible, an attempt should be made to estimate separate functions for industrial, commercial and residential water users.

Separate demand functions could be fit in each category for summer, winter and annual water use when proper data can be found.

2. A limitation to pricing analysis is the limited knowledge compiled on the production and cost functions for water utilities. An important contribution to the literature would be the estimation of these functions to empirically test the theoretical pricing models.
3. The reason for the nonsignificance in the demand shifters may have been due to the lack of variance in the data resulting from the aggregating and averaging of the data over a district. Data on an individual household basis could be collected to find out what effect rate changes have on individual households. These results could be compared with the number and frequency of use of water-complementary appliances in the home.
4. Further simulation studies combining demand and hydrologic parameters can be done. An ongoing study in the Agricultural Engineering Department at the University of Kentucky is using information on demand parameters from this study to simulate the water in storage in a reservoir when the price paid for water is a function of the amount of water in storage.

APPENDIX A

TABLE 1

A COMPARISON OF ESTIMATED PRICE AND INCOME ELASTICITIES OF DEMAND FOR RESIDENTIAL WATER IN PREVIOUS STUDIES

Investigator	Year	Type of Analysis	Price Elasticity	Income Elasticity
Metcalf	1926	29 Waterworks Systems Cross-sectional	-0.65	
Larson and Hudson, Jr.	1951	15 Illinois Communities Cross-sectional		0.70
Hanson and Hudson, Jr.	1956	8 Illinois Communities Cross-sectional		0.55
Seidel and Baumann	1957	American Cities Cross-sectional	-0.12 to -1.0	
Fourt	1958	34 American Cities Cross-sectional	-0.39	0.28
Renshaw	1958	36 Water Service Systems	-0.45	
Milliman	1963	Speculation	-0.3 to -0.4	
Gottlieb	1963	Kansas Cross-sectional	-0.66 to -1.24	0.28 to 0.58
Wong, et al.	1963	Northeastern Illinois Cross-sectional	0.01 to -0.72	
Headley	1963	S. F. - Oakland, 1950-59 Time-series		0.00 to 0.40
Gardner and Schick	1964	43 Northern Utah Water Systems Cross-sectional	-0.77	
Flack	1965	54 Western Cities Cross-sectional	-0.12 to -1.0	
Bain, et al.	1966	41 Californian Cities Cross-sectional	-1.099	

(cont'd.)

TABLE 1.--Continued

Investigator	Year	Type of Analysis	Price Elasticity	Income Elasticity
Howe and Linaweaver	1967	35 Study Areas Cross-sectional	-0.21 to -0.23	0.31 to 0.37
Conley	1967	24 S. Californian Communities Cross-sectional	-1.02 to -1.09	
Turnovsky	1969	19 Massachusetts Towns Cross-sectional	-0.05 to -0.40	
Grima	1970	91 Observations Cross-sectional	-0.93	0.56
Wong	1970	Chicago, 1951-1961 Time-series	-0.02 to -0.28	0.20 to 0.26
		Four Com. Sz. Grps. Cross-sectional	-0.26 to -0.82	0.48 to 1.03

Source: (Wong, 1972, p. 42).

TABLE 2

KENTUCKY WATER DISTRICTS
(October, 1972)

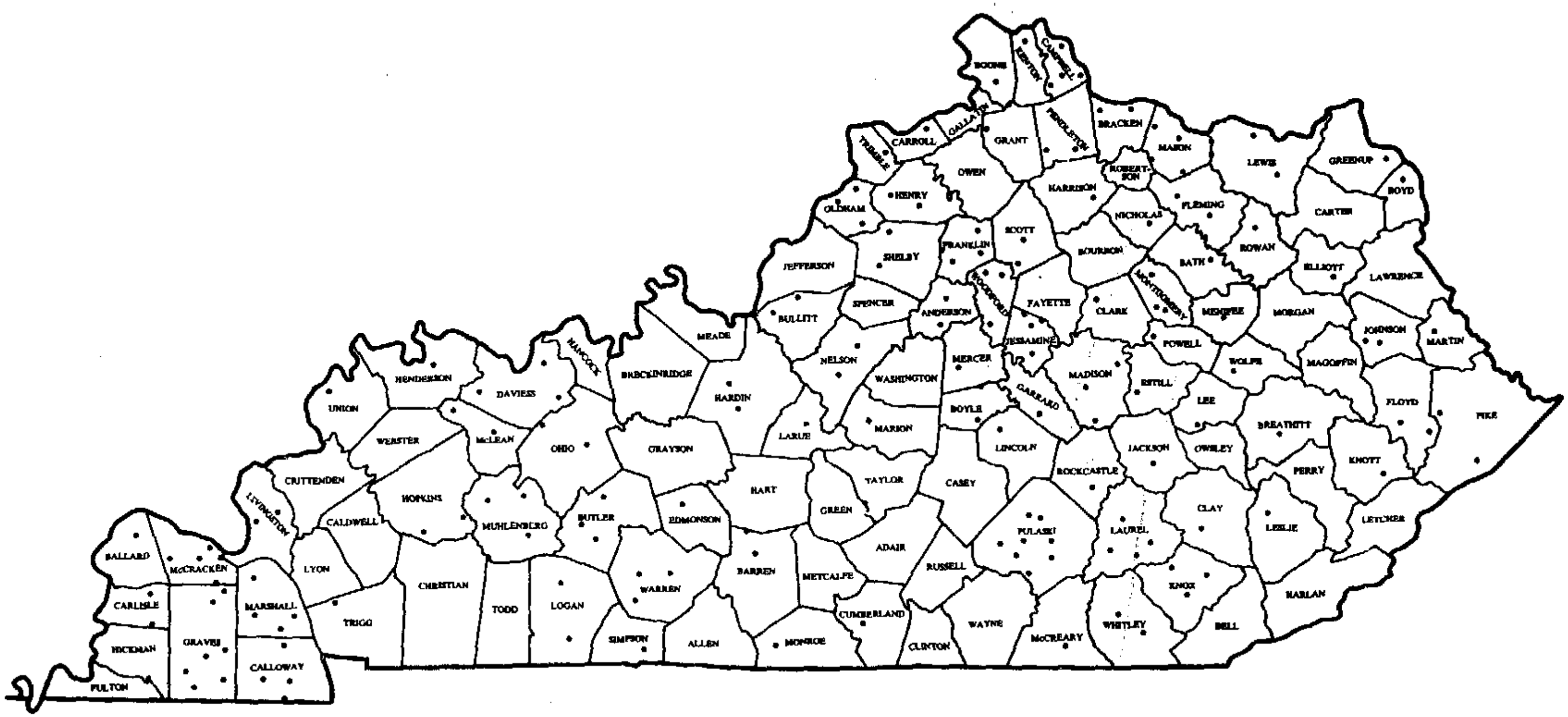


TABLE 3

CORRELATION COEFFICIENTS, LINEAR MODEL

	Q	P	V	I	E	N
Q	1.0000					
P	-.8176	1.0000				
V	-.0055	.1099	1.0000			
I	.0487	.0080	.7293	1.0000		
E	.0714	.0270	.3860	.5352	1.0000	
N	.0047	-.0123	.2041	.1297	-.3923	1.0000

TABLE 4

MEANS, STANDARD DEVIATIONS, AND RANGES

	Mean	Standard Deviation	Ranges
Q	56.39	50.71	2.87 - 521.48
P	2.27	1.48	.27 - 14.49
V	11.68	3.05	5.00 - 18.90
I	6.59	1.51	3.52 - 11.28
E	23.10	4.20	14.77 - 26.89
N	2.87	.29	2.3 - 3.4

TABLE 5

SUMMARY TABLE, LOG-LINEAR MODEL

Variable	Multiple R	R Square	RSQ Change	Simple R	B	Beta
P	.8176	.6685	.6685	-.8176	-.9235	-.8253
E	.8229	.6772	.0087	.0714	.2904	.1113
N	.8250	.6806	.0034	.0572	.3275	.0553
V	.8257	.6817	.0011	-.0055	.1351	.0729
I	.8262	.6826	.0009	.0576	-.1351	-.0501
(Constant)					3.1954	

TABLE 6

t TEST FOR INCOME DATA

ΣX_1 =	68,867	$\bar{X}_1$ =	7,652	ΣX_1^2 =	552,134,895
ΣX_2 =	67,883	$\bar{X}_2$ =	7,543	ΣX_2^2 =	524,312,423
X_1 =	county data	X_2 =	enumeration district data		

$n = 9$

$$t = \frac{7{,}652 - 7{,}543}{\sqrt{\dfrac{552{,}134{,}895 - \dfrac{(68{,}867)^2}{9} + 524{,}312{,}423 - \dfrac{(67{,}883)^2}{9}}{9(9-1)}}}$$

$= .51$ $\quad t_{.95} = 1.746$ $\quad$ 16 degrees of freedom

The null hypothesis is not rejected. H_0: $\bar{X}_1 - \bar{X}_2 = 0$

TABLE 7

t TEST ON VALUE OF RESIDENCE DATA

ΣX_1 =	87,786	$\bar{X}_1$ =	10,973	ΣX_1^2 =	1,041,920,920
ΣX_2 =	94,200	$\bar{X}_2$ =	11,775	ΣX_2^2 =	1,142,100,000

X_1 = county data X_2 = enumeration district data

n = 8

$$t = \frac{10{,}973 - 11{,}775}{\sqrt{\dfrac{1{,}041{,}920{,}920 - \dfrac{(87{,}786)^2}{8} + 1{,}142{,}100{,}000 - \dfrac{(94{,}200)^2}{8}}{8(8-1)}}}$$

= .568 $t_{.95}$ = 1.761 14 degrees of freedom

The null hypothesis is not rejected. H_o: $\bar{X}_1 - \bar{X}_2 = 0$

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