DESIGNING WATER RATE STRUCTURES TO PROMOTE CONSERVATION

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Abstract

A growing number of water providers are implementing rate structures intended to promote water conservation. The impact of an increasing block rate structure on residential water demand is examined for Tucson, Arizona. Time-series regressions on demand suggest that Tucson Water customers base consumption decisions on the previous month's average price rather than the marginal price of water. This behavior, coupled with a substantial monthly service charge, results in the rate structure discouraging, rather than encouraging, conservation. An alternate pricing structure based on distinguishing indoor and outdoor water uses is presented. Issues of economic efficiency and social equity are considered.

Introduction

The arid Southwest is experiencing rapid growth in industry and population, resulting in a surge in municipal water consumption. The scarcity of reliable water supplies in the area, coupled with the predominance of nonmarket allocation mechanisms for water resources, has resulted in a potentially serious long-term imbalance between water supply and water demand. The problem is acute in southeastern Arizona, a burgeoning area without reliable surface water supplies and with a rapidly declining groundwater table. Water resource managers at various levels of government have been aware of the situation for some time, and have taken a variety of actions to alleviate the problem.

When first confronted by a natural resource shortage, often the initial response is to search for ways to augment existing supplies. Rather than adapting to the environment, humans possess the ability, and tendency, to modify the environment for their purposes. Thus, it is not surprising that much of the water management activity to date has concentrated on the supply side of the ledger. These engineering approaches include enhancing local water supplies by increasing natural recharge, recycling or recharging treated effluent, and importing water, both from neighboring groundwater basins and from distant rivers.

As water resource planners exhaust the more cost-effective approaches to supply augmentation, more emphasis is given to demand-side management. Recent actions taken to curb the growth in municipal consumption include state-imposed mandatory conservation goals, amended building codes requiring low-flow plumbing devices, and local government-sponsored publicity campaigns urging water consumers to "slow the flow" and "beat the peak." It appears that these programs are having an impact on water demand. However, the evidence to date suggests that the most effective policy tool for encouraging water conservation is water price.

Residential demand, one of the larger and fastest growing segments of water demand, has repeatedly been shown to be price responsive -- that is, increasing the price of water consistently produces measurable decreases in water demand. Issues left unresolved include the proper method of measuring this price effect, the magnitude of various price effects on demand, and the most efficient way to design a rate structure to maximize residential water conservation. Closely associated with efficiency issues are concerns about the equity, or fairness, of various rate structure features. These are the issues addressed by this study.

Conservation Goals and Rate Structure Design

Public and private water companies almost always enjoy a monopoly within their prescribed service areas. Because these water utilities do not compete with other firms in the local market, the prices they charge for water are not determined by competition. Therefore, water utilities can, and increasingly do, design rate structures which are intended to encourage water conservation.

The simplest and most direct method of altering water rates to promote conservation is to institute an across-the-board price increase. However, municipally-owned utilities generally are prohibited from showing a profit, while the profits of investor-owned water utilities in this state are regulated by the Arizona Corporation Commission. Thus, the challenge is to design a rate structure which reduces demand without increasing net revenues. A number of rate structure features have been proposed or implemented with this general goal in mind. The variety of approaches taken is not simply due to uncertainty over which is most effective in reducing water demand. Some rate structure features are intended to reduce particular components of water demand.

Consider the multiple conservation goals of various water managers in Tucson, Arizona. If the city water utility is faced with the prospect of major capital expenditures because it can no longer meet peak demand, it may opt for a rate structure that increases the price of water during the time of day or season of year that peak demand occurs. If the county wants to postpone the date when the capacity of their sewage treatment system is reached, they would be interested in rates that encourage conservation of water consumed indoors. If the goal is to reduce groundwater pumping, water rates should encourage reductions in total demand. However, the state-mandated goal is to reduce groundwater overdraft. Assuming effluent can be recycled or recharged, a rate structure that reduces outdoor water demand is preferred.

Fortunately, the number of potential conservation goals is exceeded by the number of rate structure features at the disposal of the water resource manager. Increasing and decreasing block rates, lifelines, service charges, peak demand surcharges, seasonal differentials, and lift and remote area surcharges are some of the more frequently used rate features. These can be combined in various ways to design water rate structures intended to further multiple policy objectives, such as maximimum consumer benefits, efficient operation and equitable sharing of costs, as well as water conservation. The result is often a complex structure, with the price of water being a function of how much is consumed, by whom it is consumed, and when it is consumed. Yet, the effect of the rate structure on demand will conform to classical economic theory, and therefore the water manager's expectations, only if water consumers are fully aware of and react rationally to all of its features. To date, this has been taken as an article of faith, rather than a proven fact.

Consumer Perceptions of Price and Water Demand Models

Whether water consumers are fully aware of and react to all the features of the rate structures they face can be restated as a single question: What do consumers perceive the price of water to be? Traditionally, demand studies for goods and services have regressed time series or cross-sectional data on price, income, and other explanatory variables onto the quantity of the good or service purchased. The coefficient on the price term is then used to compute the price elasticity of demand for the product. Price elasticity is a unitless parameter than can be thought of as the percent change in demand for the product caused by a one percent change in the product price:

$$E_{price} = \frac{\Delta Quantity}{\Delta Price} \times \frac{Price}{Quantity}$$

The problem encountered when attempting to determine the price elasticity for water is the lack of a unique price for water, because rate structure features can make the price of water a function of quantity purchased, time of year, and other factors.

There are two measures of price which are well defined for any quantity purchased under any type of rate structure. Average price (AP) is the total water bill divided by the total quantity purchased. Marginal price (MP) is the increase in the bill caused by the last unit of water purchased. Average price was frequently used as the measure of price in early studies because of flat rates in the areas studied or because of insufficient detail in available data. As rate structures grew more complex and water utility records improved, marginal price was increasingly adopted as the measure of price to which well-informed, rational consumers respond. It was subsequently recognized that two price terms are needed to express most water pricing structures, i.e., the marginal price of the last unit purchased and a lump-sum income effect term equal to the difference between what the consumer's bill would have been if each unit had been priced at the marginal price, and the actual water bill. This term, D, has the same units, and in theory the same coefficient, as income.

Consider as a typical rate feature the simple two-step increasing block rate structure in figure 1. Q is the quantity of the good purchased, P_1 is the price of the first Q_1 units, and P_2 is the price of all $(Q - Q_1)$ subsequent units. Marginal price is P_2. Average price is the bill over the quantity, or:

$$AP = [P_1Q_1 + P_2(Q - Q_1)]/Q$$

The lump-sum income effect term, D, is:

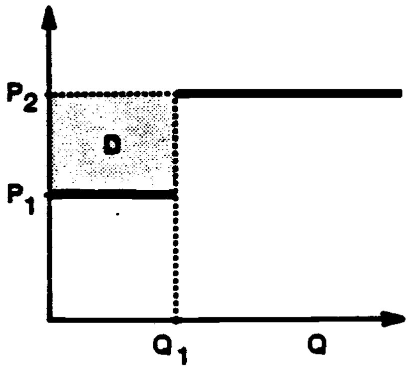
$$D = (P_2 - P_1)Q_1$$

A function expressing the demand for water by well-informed, rational consumer is:

$$1) \quad Q = B_0 + B_1(I + D) + B_2MP + B_3Z$$

Figure 1

Increasing Block Rate Structure



where I represents income, D is the lump-sum income effect term, MP is marginal price, and Z is a set of other explanatory variables. This model of consumer behavior assumes that water utility customers are aware of all the details of the rate structure.

Assume instead that consumers facing complex water rate structures are generally unaware of the details of rate structures. If the only price information they have is contained in water bills from previous billing periods, then consumers know the total bill and the amount consumed. Therefore, they can compute the average price paid. However, they can compute neither the marginal price they face, nor the lump-sum income effect term. The demand function for these consumers unaware of rate structure features can be expressed as:

$$2) \qquad Q = B_0 + B_1 I + B_2 AP_L + B_3 Z$$

where AP_L represents the lagged average price.

If consumers are aware of the details of a water rate schedule, they will react to the marginal price and lump-sum income term. If they are unaware of the rate features, they will react instead to the lagged average price. We define α, $0 < \alpha < 1$, to be the level of consumer awareness of the rate structure. If $\alpha = 0$, consumers are unaware of the structure and react to AP_L. If $\alpha = 1$, consumers are aware of rate features and react to MP and D. Equations 1) and 2) can be expressed by the single demand model:

$$3) \qquad Q = B_0 + B_1(I + \alpha D) + B_2[AP_L + \alpha(MP - AP_L)] + B_3 Z$$

When $\alpha = 1$, equation 3) reduces to 1); when $\alpha = 0$, it reduces to 2). Therefore, 3) can be used to determine the level of consumer awareness of rate structure features, as well as the price elasticity of demand for water.

An Empirical Test of Consumer Price Awareness

My colleaue, Dr. Alberta Charney, and I estimated the price elasticity and level of consumer awareness of the water rate structure using monthly consumption data for Tucson, Arizona. The following variables for the period January 1974 through September 1977 are used to estimate equation 3):

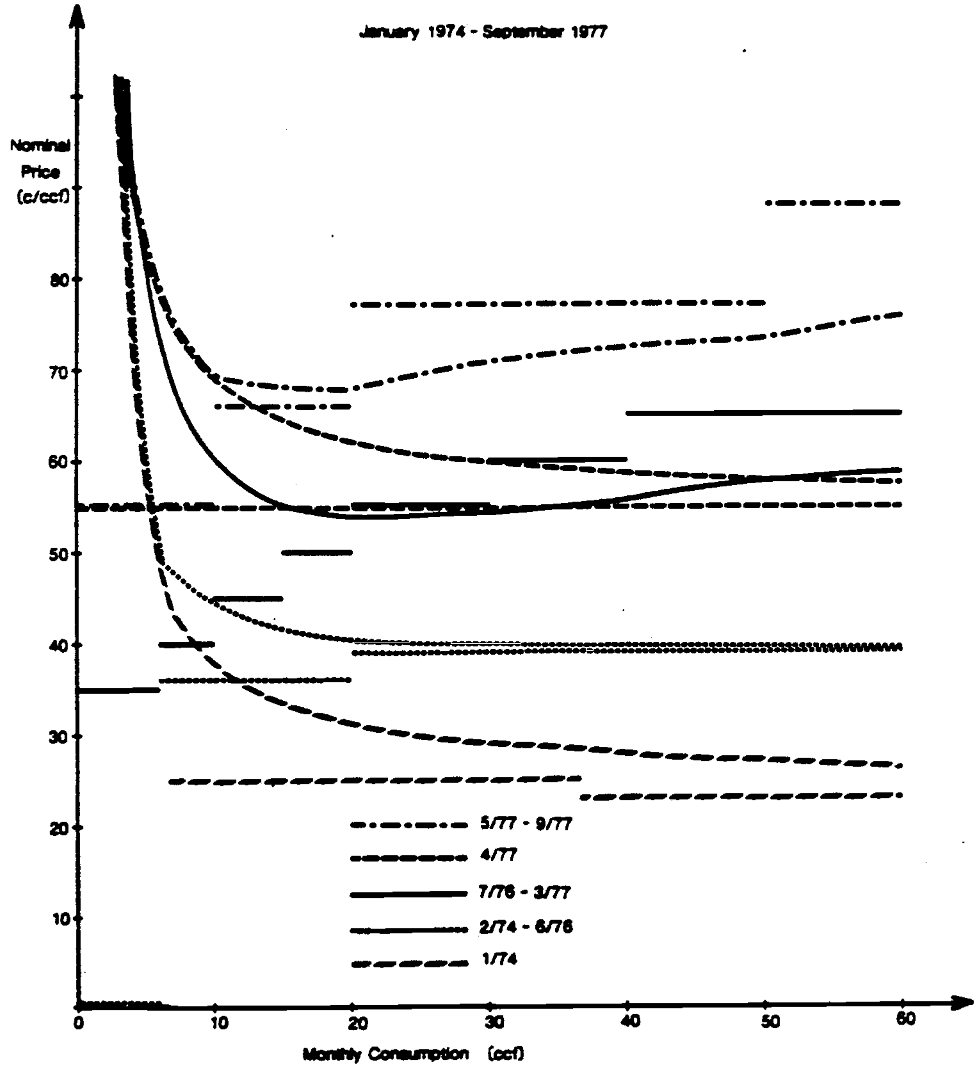
Q = monthly household water consumption in ccf (1 ccf = 100 cubic feet)
MP = marginal price of water, cents per ccf, deflated by the Consumer Price Index (CPI, 1967=1.00).
AP = average price of water, cents per ccf, deflated by the CPI.
D = difference between what the typical household would pay if all water were priced at MP and what the typical household actually pays, dollars per month, deflated by the CPI.
I = monthly personal income per household, dollars, deflated by the CPI.
Z = monthly evapotranspiration of Bermuda grass minus effective rainfall during those times when grass is not dormant, hundredths of inches; 0 during those times grass is dormant.

During this time period, Tucson Water customers faced a variety of water rate structure features (see figure 2). These included a flat rate structure, declining block and increasing block structures with from two to eight steps, service charges ranging from \$1.40 to \$3.00, six ccf lifelines, seven ccf

Figure 2

Block Rate Marginal Prices and Average Prices for Tucson, Arizona

January 1974 - September 1977



lifelines, and no lifeline at all. Nominal marginal prices ranged from 23¢ to 88¢ per ccf, depending on quantity consumed.

Water bills during this period contained sufficient information for consumers to calculate AP_L, but not MP or D. Differences between average and marginal prices were substantial, and were a function both of service charges and steps between block rates. Thus, the data provide a rigorous test of the classic economic assumption that consumers are aware of, and react to marginal prices. This assumption is identical to the hypothesis that $\alpha = 1$ in equation 3), or that equation 1) is the proper model of consumer behavior.

Equation 3) cannot be easily estimated in its current form due to the multiplicative interaction of α and other coefficients. Therefore, it is rewritten as:

4) $$Q = C_0 + C_1 I + C_2 D + C_3 AP_L + C_4 MP + C_5 Z + e$$

subject to the constraints:

$$C_0 = B_0 \qquad C_1 = B_1 \qquad C_2 = \alpha B_1$$
$$C_3 = (1 - \alpha)B_2 \qquad C_4 = \alpha B_2 \qquad C_5 = B_3$$

where e is a normally-distributed, random-disturbance term with mean 0 and constant variance.

Equation 4) is estimated unconstrained and under the constraints corresponding to eleven alternative values of α (α = 0.0, 0.1, ..., 0.9, 1.0). Results of the unconstrained regression and regressions for α = 0.0 and α = 1.0 are reported in Table 1:

Table 1

Regression Estimates for Period 1974.01 - 1977.09

$$Q = C_0 + C_1 I + C_2 D + C_3 AP_L + C_4 MP + C_5 Z + e$$

Constraints	C_0	C_1	C_2	C_3	C_4	C_5	$\bar{R}^2$	Se	E_{price}
None	-25.73 (-1.42)	0.05 (2.58)	1.06 (0.90)	-0.19 (-1.38)	-0.03 (-0.18)	0.02 (8.22)	0.781	2.982	———
$\alpha = 0.0$ $C_2 = 0$ $C_4 = 0$	-24.90 (-1.41)	0.05 (2.64)	———	-0.28 (-5.75)	———	0.02 (11.40)	0.788	2.938	-0.53
$\alpha = 1.0$ $C_1 = C_2$ $C_3 = 0$	-11.59 (-0.57)	0.04 (1.73)	0.04 (1.73)	———	-0.46 (-3.59)	0.02 (10.10)	0.709	3.440	-0.68

Note how the calculated price elasticity is strongly affected by the assumption as to the value of α. If consumers are assumed to be aware of and react to marginal prices (α = 1), a one percent increase results in a 0.68 percent demand decrease. If consumers are assumed to react to lagged average price, demand will fall by 0.53 percent. Thus, the correct value of α is necessary for water managers to predict the effects of price changes on demand. Resulting sum-squared errors from the eleven constrained regressions may be compared with the sum-squared error from the unconstrained regression to calculate F-statistics used for testing hypotheses for the value of α. The general null and alternative hypothesis for any value of α may be written as follows:

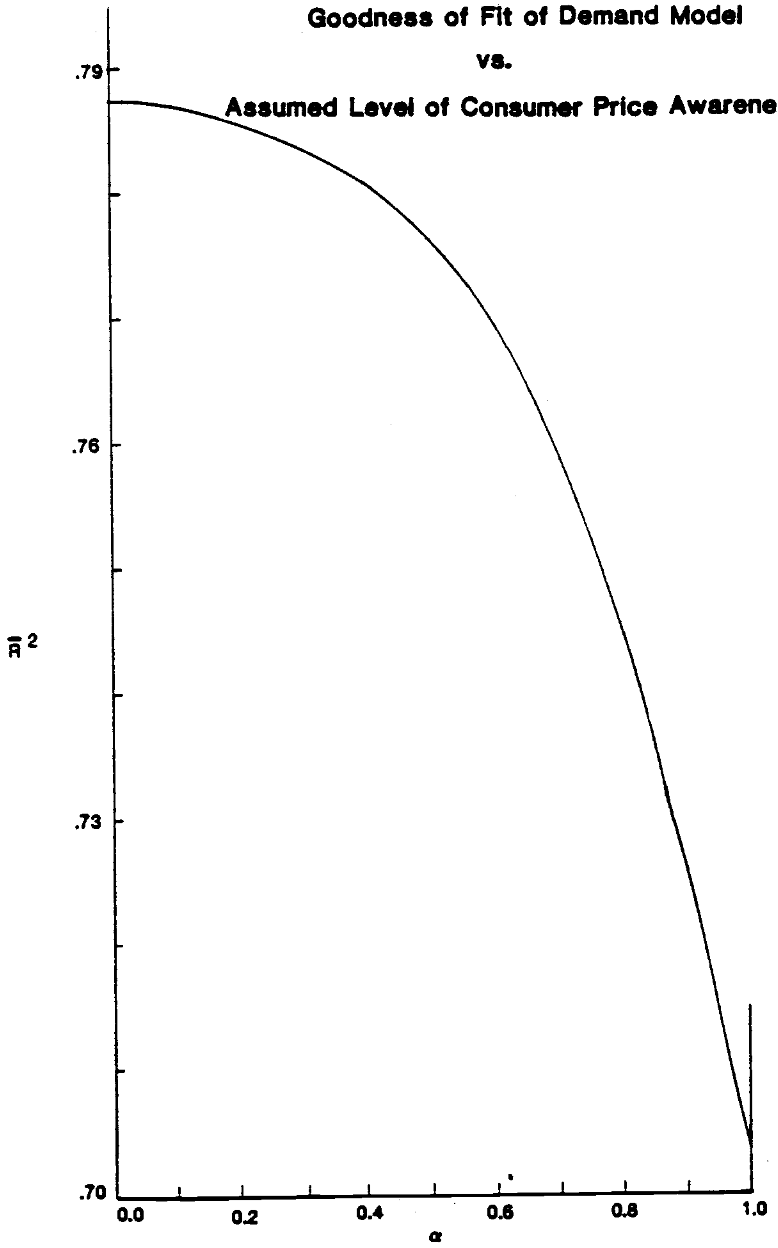
H_0: $C_2 = \alpha C_1$ and $\alpha C_3 = (1 - \alpha) C_4$

H_a: Constraints do not hold

The null hypothesis is rejected at the 0.99 level of confidence for α = 1.0 and α = 0.9 and at the 0.95 level of confidence for α = 1.0, 0.9 and 0.8. Although smaller values of α cannot be rejected at these confidence levels, the best-fit equation is demonstrated to be the equation with α = 0.0 (see figure 3). Therefore, consumers are shown to be significantly less than completely aware of the water price structure, and there is strong evidence that they react to lagged average prices and not to marginal prices.

These results are based on data several years old. One might wonder whether Tucson Water customers have become more aware of the rate structure features over time. However, in the intervening seven years, the rate structure has changed 13 times. There are now separate rate structures for winter and summer seasons and annual adjustments to the marginal prices. The size of the service charge relative to the total bill has roughly doubled, and the number of price blocks has increased. Finally, two recent consumer surveys have concluded that 75 and 90 percent of the respondents are not aware of the increasing block nature of the rate structure. Therefore, it is safe to conclude that most Tucson Water customers continue to react to AP_L, and not MP.

Figure 3
Goodness of Fit of Demand Model
vs.
Assumed Level of Consumer Price Awareness



Consequences of Average Price Demand

What are the consequences of consumers reacting to the lagged average price of water rather than to the marginal price and difference term? Consider figures 4a and 4b, the current winter and summer Tucson Water rate structures. The marginal price increases in steps with the quantity of water purchased, with the rate blocks increasing at a faster rate during the six summer months than during the winter season. Having price increase with quantity is intended to encourage conservation. However, our analysis has shown that consumers are not

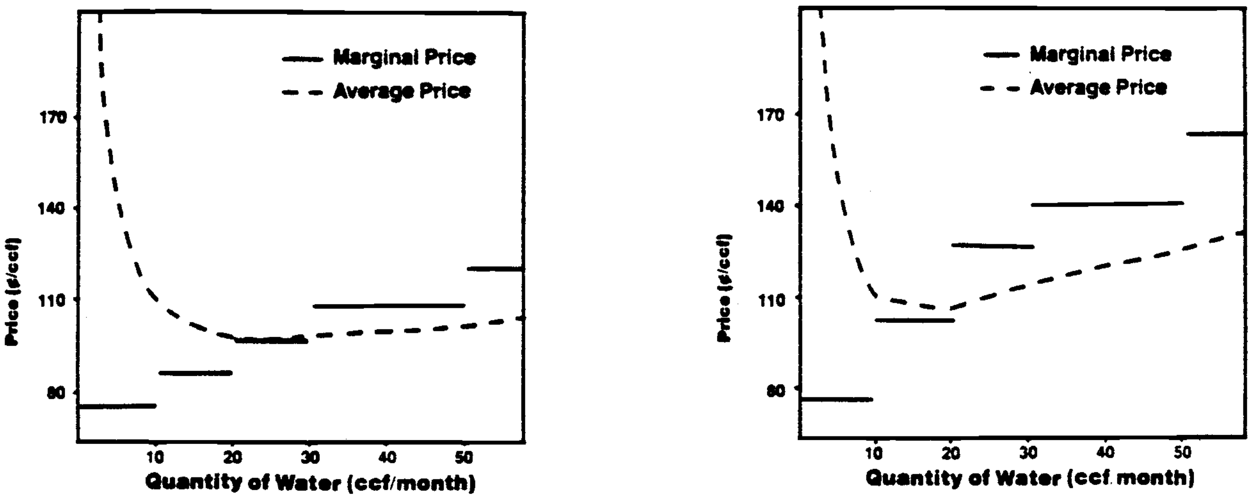
Figure 4

a

Winter
Residential Rate Structure
Tucson Water

b

Summer
Residential Rate Structure
Tucson Water

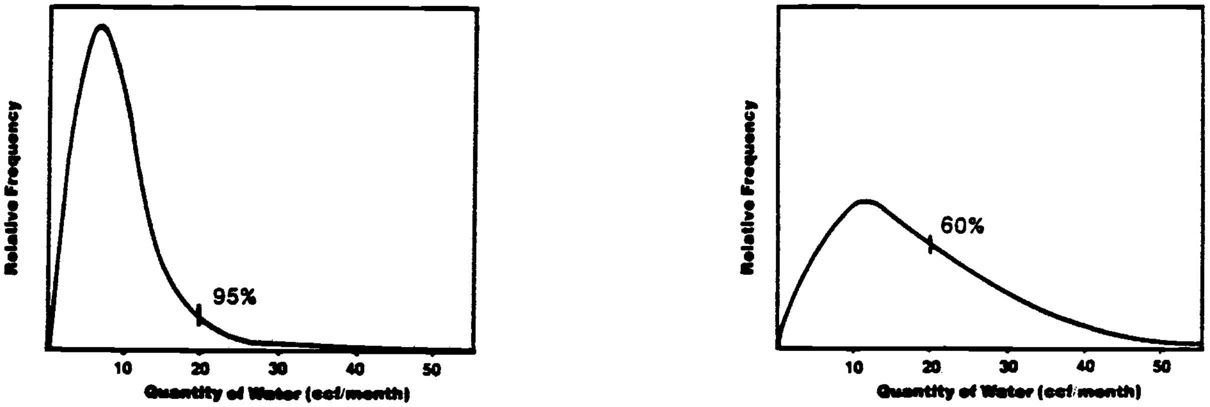


c

Relative Frequencies of
Residential Water Demand
Winter Months

d

Relative Frequencies of
Residential Water Demand
Summer Months



aware of the marginal price. They are reacting instead to the lagged average price, which, due to the monthly service charge, decreases with quantity up to 20 ccf. Beyond this point it increases, but at a lower rate than MP. Consumers whose water purchases fall on the declining portion of the AP curve perceive a disincentive to conserve water. For example, if the typical customer decreases her February consumption by 10 percent, her bill falls by only seven percent. The frequency distributions in figures 4c and 4d indicate that 95 percent of individually-metered Tucson Water customers fall on the declining portion of the AP curve in the winter, as do 60 percent in the summer. Thus, the lack of consumer awareness of the rate structure, coupled with the effect of the service charge on the average price curve, results in consumers perceiving an incentive to consume, rather than to conserve water.

The rate structure is designed to further water management goals other than encouraging conservation. The summer-winter rate differential is intended to decrease water demand during the months of peak demand, which is associated with landscape irrigation. To the extent that this seasonal price differential discourages outdoor uses of water, the management goal of reducing groundwater overdraft is also furthered. However, the fact that a rate structure feature encourages desired behavior does not justify its use. One must inquire whether other rate designs would be more efficient in furthering these same goals, and if the rate structure treats persons equitably.

Consider two hypothetical households. The first has only two persons, but has a large amount of water-thirsty landscaping and a swimming pool. Assume this household consumes 10 ccf of water in winter months and 25 ccf per month in summer. The second household contains six people, but has desert landscaping, and so consumes 25 ccf of water per month year round. Clearly, the first household is contributing to both the summer peaking problem and to groundwater overdraft. The second household is consuming water indoors at a constant rate, and so is not contributing to either of these problems. Yet their summer water bills are the same. Viewed another way, the six-person household is paying 98¢ per ccf in the winter and $1.10 per ccf in the summer, even though they are using the same amount of water for the same purposes. The two person household is paying an average price of $1.10 per ccf <u>year-round</u>, even though their summer use is higher, and is contributing to groundwater overdraft.

An Alternate Rate Structure

Often when policy analysts compare different methods for allocating a resource, they discover tradeoffs between solutions which are efficient in an economic sense and solutions which appear to be more equitable. In this instance, though, replacing the current rate structure with one that distinguishes indoor and outdoor water consumption may be superior in both efficiency and equity terms.

The billing records for 1000 randomly chosen, individually metered residential Tucson Water customers for the period May 1982 through April 1983 were provided by the city. Current Tucson Water rates are applied to the consumption data, and monthly and annual water bill revenue computed. The goal is to design an alternate rate structure which has as its objective improved conservation incentives, subject to the following constraints:

1) Annual revenue is to remain unchanged.
2) The new rate structure must be simpler and easier to understand than the current structure.
3) Households using less than average amounts of outdoor water must have lower summer bills.
4) Households using more than average amounts of outdoor water must have higher summer bills.
5) Average and marginal price curves must be closer together for most (i.e., > 95%) customers.
6) The average price curve must not decline for most (i.e., > 95%) customers.
7) Monthly revenue flow is not to be more skewed than it currently is.
8) Monthly bills for typical consumers will not change dramatically (i.e., < 10%).

The new rate structure is composed of three parts; a rate which is applied to all metered ccf of water, a surcharge applied to outdoor water from May through October, and a minimum bill equal to the rate applied to 3 ccf. Less than 5 percent of the customers are affected by the minimum bill. Its purpose is to cover meter-reading costs and provide an incentive to shut off water in vacant homes.

Indoor water is defined as a weighted average of consumption from December through February:

$$Q_{\text{indoor}} = (Q_{\text{DEC}} + Q_{\text{JAN}} + (31/28)Q_{\text{FEB}})/3$$

Outdoor water is then defined as the non-negative difference between total water consumption and indoor water:

$$Q_{\text{outdoor}} = \begin{cases} Q_{\text{total}} - Q_{\text{indoor}} & \\ 0 & \end{cases} \quad \text{whichever is greater}$$

This results in a rate structure where the price of water used indoors is the rate, while the price of water used outdoors is the rate plus the surcharge (see figure 5).

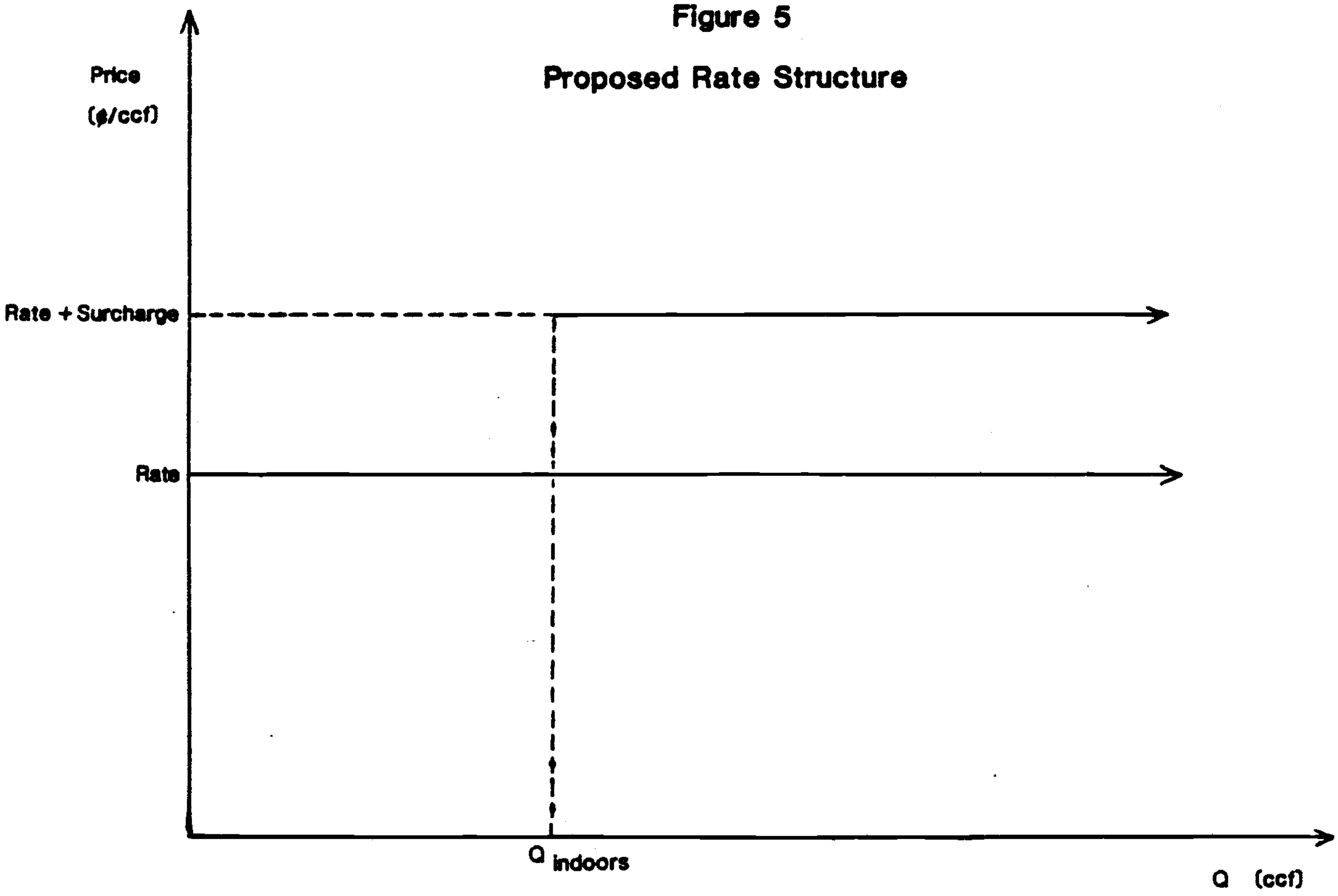


Figure 5

Proposed Rate Structure

The constraint that annual revenues remain constant reduces the possible rate-surcharge combinations to a simple function (see figure 6). If the surcharge is 0, the rate would be $1.14 per ccf. For every 3¢ increase in the surcharge, the rate falls about 1¢. Any rate-surcharge combination that satisfies this relation will automatically satisfy constraints 1) through 6). The greater the surcharge, the more effective the rate structure will be at reducing peak demand and groundwater overdraft. However, constraints 7) and 8) limit the magnitude of the surcharge. With a surcharge of 15¢ and a rate of $1.09 per ccf, typical monthly bills are changed very little. As the surcharge increases, typical bills for the summer months rise while winter bills fall, with yearly expenditures remaining constant. When the surcharge reaches 55¢ per ccf and the rate is 96¢ per ccf, the typical summer bills are about ten percent higher.

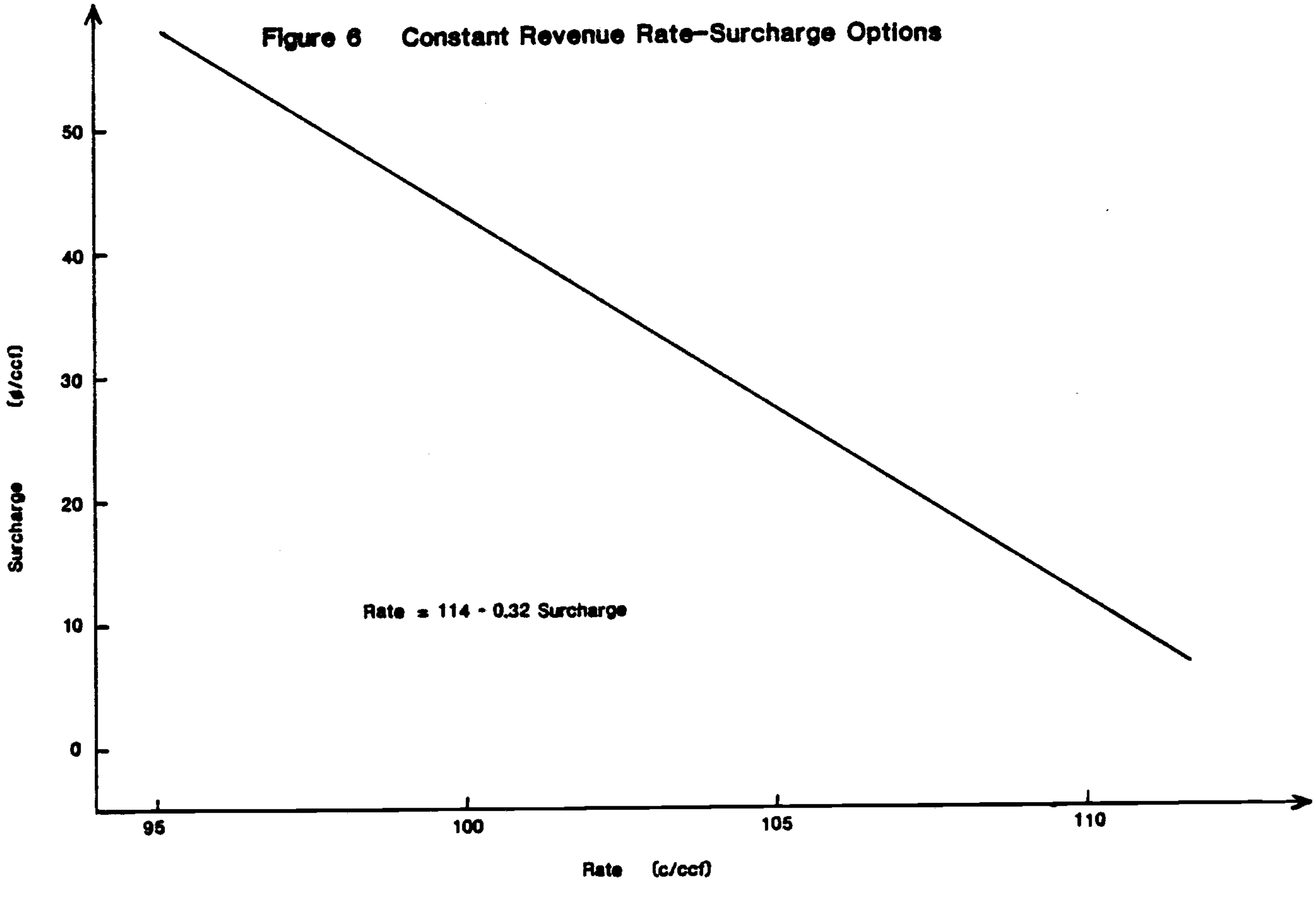


Figure 6 Constant Revenue Rate–Surcharge Options

While the surcharge tends to shift water expenditures from winter months to summer, its greatest impact is among those consuming varying amounts of water indoors and outdoors. Referring to our two hypothetical households under the 55 ¢ per ccf surcharge, the six-person household would now pay $24 per month for 25 ccf per water regardless of the season, while the household with thirsty landscaping and pool will pay $32.05 for 25 ccf in the summer.

Not only is the new rate structure more equitable, it is more efficient at encouraging conservation. A ten percent reduction in demand by the typical consumer results in a ten percent reduction in the February water bill, and a 12 percent reduction in the July bill. Therefore, even if consumers continue to react to average prices, they will perceive positive incentives to conserve.

Finally, note that the proposed structure offers the opportunity for some savings in administrative costs. Unlike the current structure, meter readings could occur every other month without introducing computational problems or significantly reducing water utility revenues.

Conclusion

Water rates designed to further multiple resource allocation goals may become complex pricing structures where the price of water is a function of quantity purchased, season of year, location of user, and other factors. It is shown that when this pricing complexity is compounded by frequent changes in the rate structure and insufficient billing information, water consumers react to lagged average prices rather than marginal prices. This can result in rate features intended to promote water conservation being ineffective or even counter-productive. Problems of equity among consumers with different consumption patterns also may result.

Tucson Water is examined as a case study, and an alternate rate structure based on distinguishing indoor and outdoor water demand is developed. The current structure is defined by five quantities, ten prices, and a service charge, while the proposed rate structure consists of one quantity, two prices, and a minimum bill. The simplicity of the proposed rate structure increases the likelihood that consumers will react to marginal price, but even if they continue to react to average price, the structure provides positive incentives for water conservation.

The initial size of the surcharge on outdoor water is determined by its political acceptability, with a 15-20¢ surcharge having minimal impact on typical water bills. The economically efficient surcharge is probably considerably higher. If effluent is recycled or recharged, then the proper level of the base rate is one that covers the "costs of capture," or the costs associated with pumping, treating and delivering water. The outdoor surcharge should cover the difference between "replacement costs" and capture costs, or those additional costs associated with augmenting and increasing the basin's water supplies. This would include all costs borne by the city associated with the Central Arizona Project.

The search for an optimal water pricing system involves balancing economic efficiency with social equity, within the bounds of political acceptability. This paper demonstrates methods of evaluating water rate structures, categorizing their shortcomings, and developing rate structure alternatives.