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Which Pricing Tools Are Effective to Promote Resource Conservation Behavior? Implications from Residential Water Consumption

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Using a discrete/continuous choice approach, we compare the effectiveness of increasing block rate and uniform rate structures on residential water conservation. Our findings show that residential water demand is more price elastic under increasing block rates, suggesting its potential as a tool for water conservation. However, its effectiveness may be limited if people do not fully understand the structure and instead rely on the average price when making water consumption decisions. Effective communication of the rate structure to consumers is essential to ensure it actively influences water consumption behavior.

Key words: discrete/continuous choice model, increasing block rate, price elasticity

Introduction

Increased population and public demand for water resources have raised public concerns about water scarcity (Dieter et al., 2018). The increasing prevalence of droughts in recent years further poses a serious challenge to sustainability of water resources (University of Nebraska-Lincoln, 2021). A variety of nonprice approaches to water conservation have been shown to be effective in the United States and other countries, including rebates and subsidies for water-efficient appliances (Lai et al., 2023), education campaigns that raise public awareness of water scarcity (Syme, Nancarrow, and Seligman, 2000; Yue et al., 2022), and short-term water restrictions (Kong et al., 2023); however, public authorities consider water pricing to be the most direct economic strategy to promote water conservation practices (Inman and Jeffrey, 2006; Olmstead and Stavins, 2009).

Residential water rates usually take one or a combination of these five forms:

i. *flat rate*, in which all customers pay the same fee regardless of the amount of water used;
ii. *uniform rate*, in which the per unit price for all metered units of water consumed is constant year round;
iii. *increasing block rate* (IBR), in which unit prices change as consumption exceeds certain thresholds, a method designed to promote conservation and most often found in urban areas and areas with limited water supplies;

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iv. *seasonal rate*, which covers a specific period and is established to encourage conservation during peak water use periods; and
v. *water budget rate*, in which a household is allocated a "water budget" based on both the anticipated need of the household, either by the number of people living in the house or property size and the prevailing drought conditions (Baerenklau, Schwabe, and Dinar, 2014).

Moreover, many rate structures include a fixed fee for water services regardless of the quantity consumed.

There is an ongoing debate regarding the effectiveness of different rate structures in reducing water consumption. Although IBR is designed to encourage conservation, uncertainties remain due to the perceived price inelasticity of residential water demand (Espey, Espey, and Shaw, 1997; Dalhuisen et al., 2003; Sebri, 2014). A recent meta-analysis of 100 studies with 638 price elasticity estimates found a left-skewed distribution ranging from −3.054 to −0.002, with a mean of −0.365 and a median of −0.291 (Sebri, 2014). Earlier meta-analyses suggested higher price elasticities under IBR compared to linear price structures (e.g., uniform rate) (Espey, Espey, and Shaw, 1997; Dalhuisen et al., 2003), while Sebri (2014) found mixed evidence regarding the effectiveness of IBR structures. Differences in elasticity estimates may result from different sources. First, price elasticity estimates under IBR structure capture additional effects from uniform price structure, which includes the elasticities of the probabilities that water consumption is in a particular price block and an indirect income effect in response to price changes when consumption exceeds a certain threshold (Olmstead, Hanemann, and Stavins, 2007). Second, since consumption exceeding a certain threshold causes an increase in the marginal price under IBR, the price under IBR structure is more salient to residents. Additionally, Dalhuisen et al. (2003) and Sebri (2014) suggested that proper estimation techniques to address the piecewise linearity of the budget constraint under IBR structures are crucial for unbiased price elasticity estimates.

Another major concern in the literature is whether consumers respond to the marginal or average price of water consumption (Borenstein, 2009; Binet, Carlevaro, and Paul, 2014; Ito, 2014; Cook and Brent, 2021). The neoclassical demand model suggests that informed consumers evaluate prices at the margin, using water until the marginal benefit of consuming an additional unit of water equals its marginal cost (Howe, 1998). However, Ito (2014) noted that this assumes that consumers are perfectly informed and fully understand the rate structure (e.g., the nonlinear pricing in IBR structure) and have no uncertainty in water consumption (i.e., there is no demand shock such as weather or income fluctuations). Consumers rarely meet both conditions, instead often exhibiting inattention toward complex rate structures. Cook and Brent (2021) also emphasized that rational behavior requires awareness of water usage, knowing where it fits in the rate structure, and having a sense of the water usage intensity of different activities.

Nieswiadomy and Molina (1991) found evidence that residential water demand responded to marginal prices under IBR structures. More recently, Nataraj and Hanemann (2011) observed a similar response in a natural experiment of introducing a third price block in an IBR structure for residential water, where the changes in rate structure were salient to consumers. However, more evidence has suggested that consumers are generally unaware of the marginal price (Brent and Ward, 2019), cannot identify quantity thresholds (McRae and Meeks, 2016), and apply higher marginal prices to all consumption under IBR structures (Shaffer, 2020). Poor knowledge of the water usage intensity of common household activities (Brent and Ward, 2019)—such as flushing the toilet, taking a shower, or watering the lawn—combined with a lack of incentives to understand water rate structures—especially when water bills are a small share of income (Foster and Beattie, 1981; Shin, 1985; Binet, Carlevaro, and Paul, 2014)—leads consumers to rely on expected marginal prices (Borenstein, 2009) or average prices as proxies (Ito, 2014).

Fixed charges in water rate structures also pose estimation challenges. While theory suggests that well-informed consumers base consumption on marginal prices rather than fixed charges (Borenstein, 2016), inattentive consumers might fail to distinguish between the two, similar to the information failure observed in complex rate structures. To address this, Foster and Beattie (1981) suggested that the fixed charge might be perceived as a marginal cost, but results were mixed across rate structures. Inspired by Taylor, McKean, and Young (2004), we extend the analysis to explore how residential water demand responds to marginal price versus average price, including fixed charge and excluding the fixed charge (i.e., the average total price and average volumetric price) under IBR structures. Although some studies have found evidence of consumers responding to average volumetric prices (Ito, 2014; Clarke, Colby, and Thompson, 2017) and average total price (Ito and Zhang, 2020), no study has compared consumers' responsiveness to average total price and average volumetric price.

In this paper, we (i) compare the effectiveness of uniform and IBR structure in promoting residential water conservation by estimating price elasticities, (ii) investigate whether residential water demand responds to marginal prices or average prices (average total price and average volumetric price) under IBR structures, and (iii) explore alternative IBR structures that could enhance water conservation. This paper also enriches the literature by exploring water demand under IBR structures in a relatively water-rich region. Unsustainable water consumption poses a significant challenge, and even regions with abundant water resources face concerns about their present and future water usage (Takacs, 2018). However, little research has been conducted to validate the effectiveness of water conservation measures in areas located outside of traditionally water-scarce regions.

Methods

The Discrete/Continuous Model

Estimating water demand under IBR structures is challenging due to the simultaneity between consumption levels and price choice, as unit prices change when consumption exceeds certain thresholds. This nonlinear budget constraint requires econometric techniques that address endogeneity. In IBR structures, consumers face a piecewise-linear budget, where marginal prices increase at kink points, applying higher rates to units consumed beyond the threshold of each block. As a result, the marginal price is conditional on water consumed. To model household water demand, both the choice of a price block and water consumption conditional on the given price block, this paper uses a two-error discrete/continuous choice (DCC) model.

The structural DCC model was originally developed to analyze piecewise-linear income taxes (Burtless and Hausman, 1978; Hausman, 1985). Hewitt (1993) and Hewitt and Hanemann (1995) first applied the DCC model to water demand under increasing block pricing structure. More recently, Olmstead, Hanemann, and Stavins (2007) and Vásquez Lavín et al. (2017) provided analytical expressions for log-log and semi-log demand functional forms, respectively. To make this paper self-contained, we illustrate the DCC model and estimation by starting with the linear demand function in the log-log form, a common representation of household water demand.

$$\ln w_{itc} = Z_{it}\delta + \alpha \ln p_{tc} + \gamma \ln y_{it} + \eta_i + \varepsilon_{itc}, \tag{1}$$

where the dependent variable is the log of water consumption for household i in month t from city c. Each city sets its own prices and adapts them over time, and the marginal price of water is p_{tc}. The variable y_{it} stands for household income. In addition to water price and household income, the demand models also include average monthly temperature and adoption of water-saving appliances, represented by Z_{it}. This model has two error terms. The first, η_i, represents heterogeneous water consumption preferences among households within the same city to address the unobservable household characteristics. The second, ε_{itc}, reflects random error unobservable to both the households and the researchers. This study assumed that the two errors are independent and normally distributed with mean 0 and variances σ_η^2 and σ_ε^2, respectively.

If a household faces uniform price for water, the demand function yields a conventional log-likelihood function for a log-normal regression (Olmstead, Hanemann, and Stavins, 2007):

$$\ln L = \sum \ln\left(\frac{1}{\sqrt{2\pi}} \frac{\exp(-(s)^2/2)}{\sigma_v}\right), \tag{2}$$

where $v = \eta + \varepsilon$ and $s = (\ln w - \ln w^*)/\sigma_v$, w is observed consumption, and $w^* = \exp(Z\delta)p^{\alpha}y^{\gamma}$ is the estimated optimal consumption. For the uniform rate structure, we follow Baerenklau, Schwabe, and Dinar (2014) by accounting for unobserved preference heterogeneity using fixed effects. We then derived parameter estimates through ordinary least squares (OLS) regression.

In an IBR structure with K blocks, each block has a unit price p_k and the blocks are separated by $K-1$ switching points or "kinks," denoted by w_k. The conditional demand is the quantity consumed within the kth price block. The conditional demand can be estimated using the demand function (1) evaluated at the unit price p_k after adjusting the virtual income; for households whose water consumption exceeds the upper threshold of block 1, there is an implicit subsidy resulting from the difference between what a household would pay if all consumptions were charged at the marginal price in block k and what they actually pay.

A household's unconditional demand is a function of conditional demands and kink points. Following Olmstead, Hanemann, and Stavins (2007), the unconditional demand function (where there are three blocks, i.e., $K = 3$) is given by

$$\ln w = \begin{cases} \ln w^*(p_1,y_1) + \eta + \varepsilon & \text{if } -\infty < \eta < \ln w_1 - \ln w^*(p_1,y_1) \\ \ln w_1 + \varepsilon & \text{if } \ln w_1 - \ln w^*(p_1,y_1) < \eta < \ln w_1 - \ln w^*(p_2,y_2) \\ \ln w^*(p_2,y_2) + \eta + \varepsilon & \text{if } \ln w_1 - \ln w^*(p_2,y_2) < \eta < \ln w_2 - \ln w^*(p_2,y_2) \\ \ln w_2 + \varepsilon & \text{if } \ln w_2 - \ln w^*(p_2,y_2) < \eta < \ln w_2 - \ln w^*(p_3,y_3) \\ \ln w^*(p_3,y_3) + \eta + \varepsilon & \text{if } \ln w_2 - \ln w^*(p_3,y_3) < \eta < \infty \end{cases}. \tag{3}$$

This structural approach captures unconditional demand as follows:

i If a household's demand for water is less than the kink point, w_1, then the unconditional demand is the same as the conditional demand.

ii If a household's water demand associated with block 2 exceed w_1, then the unconditional demand coincides with the conditional demand for block 2.

iii If a household consumes at the kink point, which happens when both the conditional demand associated with block 1 exceeds w_1, and the conditional demand associates with block 2 is less than w_1. In this case, the unconditional demand is w_1, adjusting for random error ε.

The log-likelihood function is given by Olmstead, Hanemann, and Stavins (2007):

$$\ln L = \ln\left[\begin{array}{c} \sum_{k=1}^{k} \frac{1}{\sqrt{2\pi}} \frac{\exp\left(\frac{-s_k^2}{2}\right)}{\sigma_v} \left(\Phi(r_k) - \Phi(n_k)\right) \\ + \sum_{k=1}^{k-1} \frac{1}{\sqrt{2\pi}} \frac{\exp\left(-u_k^2/2\right)}{\sigma_\varepsilon} \left(\Phi(m_k) - \Phi(t_k)\right) \end{array}\right], \tag{4}$$

where $v = \eta + \varepsilon; \rho = \text{corr}(v,\eta)$; $s_k = (\ln w - \ln w^*(p_k,y_k))/\sigma_v$; $u_k = (\ln w - \ln w_k)/\sigma_\varepsilon$; $t_k = (\ln w_k - \ln w^*(p_k,y_k))/\sigma_\eta$; $r_k = (t_k - \rho s_k)/\sqrt{1-\rho^2}$; $m_k = (\ln w_k - \ln w^*(p_{k+1},y_{k+1}))/\sigma_\eta$; and $n_k = (m_{k-1} - \rho s_k)/\sqrt{1-\rho^2}$.

By maximizing the log-likelihood function, we estimate the parameters of price elasticity, income elasticity, and the variances of the two error terms. Empirically, the coefficients estimated in the DCC model reflect conditional demand. To obtain the price and income elasticities for unconditional demand, we simulate a 1% increase in all marginal prices or 1% increase in income and then predict the expected water consumption.

Functional form selection can impact the price elasticity estimation. The log-log functional form is commonly used due to its direct interpretation of coefficients as elasticities, while other functional forms pose challenges in deriving likelihood functions and calculating elasticities in DCC model (Olmstead, Hanemann, and Stavins, 2007). Vásquez Lavín et al. (2017) found the log-log form has the best goodness-of-fit and prediction power. Since empirical results are sensitive to data sources and estimation strategies, it is useful to estimate different functional forms and report range values of price elasticities. Following Vásquez Lavín et al. (2017), we further employed a semi-log demand function to estimate residential water demand under IBR. The semi-log form, unlike the log-log form with constant elasticity, shows varying price elasticity across price levels and is larger at higher prices. To make the price elasticity estimations comparable, we provide elasticity estimates at specific price points.

Residential Water Demand Responses to Marginal Price and Average Price Under IBR

When consumers are charged under IBR structures, they may use average price as a proxy for their water costs if they are not fully informed. We estimate price elasticities using both average total price and average volumetric price specifications, which differ based on whether the fixed charge is excluded or included. Average price is *ex post* as the ratio of total expenditures of quantity consumed, allowing for linear demand estimation using equation (2). It is worth noting that water consumption and average prices are also determined simultaneously under IBR; therefore, we address endogeneity by using lagged average prices in the model estimation to account for the fact that people may base their water consumption decisions on past water bills rather than the bill they will get by the end of the current billing cycle.

To explore whether households respond to marginal prices or average prices under IBR structures, we employ two approaches. First, we compare the Akaike information criterion (AIC) statistics between marginal and average price specifications to evaluate model fit, with a smaller AIC value indicating better fit. Second, inspired by Ito (2014) and Binet, Carlevaro, and Paul (2014), we conduct a bunching analysis to examine whether households exhibit rational behavior by clustering at the kink points under the IBR structure.

Simulations for Alternative Rate Structures

This paper further uses the DCC model to derive alternative IBR structures that could reduce water consumption. We focus on relatively simple modifications to the current rate structure by adjusting the rate structure parameters (e.g., marginal prices, block quantity threshold, and number of blocks) (Baerenklau, Schwabe, and Dinar, 2014). We then use a new set of rate structure parameters and the log-log DCC model to predict water demand for each scenario and calculate the percentage change from observed demand. In addition, we provide estimates on financial self-sufficiency for alternative IBR structures. Specifically, we compare predicted revenue under new IBR structures to the current structure, providing insights into how structure change impacts both potential water savings and revenue.

Data

Data Description

Unlike many previous water demand studies that focus on arid and semi-arid regions, this study examines residential water demand in Minnesota, a relatively water-abundant state facing growing water stress due to rapid population growth, particularly in the Minneapolis–St. Paul metropolitan area (Minnesota Department of Natural Resources, 2021). We analyze water consumption data of 56,019 households across three cities in the Minneapolis–St. Paul metropolitan area from 2013 to

2019, considering both indoor and outdoor water usage. Each city set its own water rates, which are disclosed on their official website: City A adopted a three-tier IBR structure (IBR structure with three blocks) with annual price increases; city B had a four-tier IBR structure in 2019, and city C implemented a five-tier IBR structure from 2013 to 2015 before shifting to a combination of uniform rate and seasonal rate (the unit price was higher during nonwinter seasons), with annual price increasing from 2016 to 2017. Since water bills were issued bimonthly or quarterly in three cities, we compute the equivalent monthly water consumption in units of 1,000 gallons to pool the data. After excluding outliers where water consumption exceeds the 99th percentile, we observe that no household in cities B or C consumed water beyond the second tier of their respective IBR structures (i.e., blocks 3–5 were not utilized), allowing for a simplified two-tier assumption. Overall, our dataset includes 13 rate structures: seven three-tier IBR, two two-tier IBR, and four uniform rate structures.

Other variables used in model estimation include the average monthly temperature obtained from the National Climatic Data Center's Global Surface Summary of the Day (https://www.ncei.noaa.gov), and adoption of water-saving appliances by households. This paper excludes the irrigation season indicator and average monthly precipitation due to collinearity with temperature data in our research area. Given that each city had a unique rate structure that was updated annually, we omit city fixed effects and year fixed effects to avoid collinearity. With data spanning 7 years, households had enough time to adjust their water use. We include data on water-saving appliances adoption through a municipally subsidized program (for faucets, toilets, dishwashers, washing machines, and irrigation systems) in 2016 and 2017. We standardize water savings estimates and develop indicators for low, medium, and high savings. The base group consists of households without adopting water-saving appliances.

One limitation is the lack of information on household sociodemographic background, particularly household income. Nonetheless, the two-error DCC model accounts for constant characteristics and preference heterogeneity. A meta-analysis showed demographic variables do not significantly affect price elasticity estimation (Espey, Espey, and Shaw, 1997). To address the lack of household income information, we use annual residential water expenditure as a proxy for household income, following Baerenklau, Schwabe, and Dinar (2014). We estimate the relationship between annual water bill and household income using Consumer Expenditure Survey data conducted from 2013 to 2019 (US Bureau of Labor Statistics, 2024) and limit observations to Minnesota. The result suggests the following relationship of $b = 64.07y^{0.1509}$, where b is water bill and y is household income.

Summary Statistics of Water Consumption and Price

Table 1 reports summary statistics of the water consumption data. All monetary values, including prices in units of US dollars per 1,000 gallons and annual water bills in units of US dollars per year, were adjusted for inflation based on the 2013 Consumer Price Index. Panel A presents the mean values and standard derivations of water consumption and the uniform rate structure for 7,399 households in city C during 2016–2017. City C implemented a rate structure that combined uniform rate and seasonal rate, where households were charged higher prices during nonwinter seasons. The winter quarter was set as a 3-month period beginning in January. Due to the higher need for outdoor activities such as landscape watering, water demand often increases during nonwinter seasons: Average monthly water consumption was 3.72 thousand gallons during the winter season and 4.25 thousand gallons during nonwinter seasons. The mean of marginal price was $1.63 per thousand gallons, and households paid an average of $111.47 annually for their water bill. A relatively small proportion of households had adopted water-saving appliances.

The summary statistics under the IBR structure are shown in Panel B of Table 1, drawing data from 55,989 households in three cities during 2013 to 2019. On average, households consumed 5.47 thousand gallons of water per month, with 73% of the observations falling within block 1,

Table 1. Summary Statistics of Water Consumption and Price

Panel A: Uniform rate structures (2016–2017)	**Mean**	**Std. Dev.**
Average monthly water consumption (1,000 gallons)	4.141	2.508
Average monthly water consumption, winter season (1,000 gallons)	3.717	2.100
Average monthly water consumption, non-winter season (1,000 gallons)	4.249	2.619
Marginal price ($)	1.634	0.146
Annual water bill ($)	111.474	39.746
Adoption of water-saving appliances (1 = low)	0.004	0.060
Adoption of water-saving appliances (1 = medium)	0.008	0.089
Adoption of water saving appliances (1 = high)	0.004	0.062
Average monthly temperature (°F)	48.836	16.947
Panel B: Increasing block rate structures (2013–2019)	**Mean**	**Std. Dev.**
Average monthly water consumption (1,000 gallons)	5.473	4.177
Percentage of observations in block 1 (%)	73.384	–
Percentage of observations in block 2 (%)	23.826	–
Percentage of observations in block 3 (%)	2.790	–
Block 1 upper threshold (1,000 gallons)	6.450	0.565
Block 2 upper threshold (1,000 gallons)	17.525	0.408
Marginal price in block 1 ($/1,000 gallons)	1.391	0.147
Marginal price in block 2 ($/1,000 gallons)	1.783	0.280
Marginal price in block 3 ($/1,000 gallons)	2.968	0.543
Marginal price ($)	1.454	0.327
Average volumetric price, exclude fixed charge ($)	1.362	0.152
Average total price, include fixed charge ($)	2.497	1.218
Annual water bill ($)	133.863	64.752
Adoption of water-saving appliances (1 = low)	0.002	0.045
Adoption of water-saving appliances (1 = medium)	0.002	0.041
Adoption of water-saving appliances (1 = high)	0.001	0.037
Average monthly temperature (°F)	46.686	20.778

Notes: 1,000 gallons = 3.785 cubic meters.

24% in block 2, and 3% in block 3. It is not surprising that most households consumed water in block 1. The upper threshold of block 1 (6.45 thousand gallons on average) was higher than the average monthly water consumption. The upper threshold for block 2 was around 17.53 thousand gallons. Average marginal prices for IBR ranged from $1.39 to $2.97 per thousand gallons, while the average price excluding fixed charge was $1.36 per thousand gallons and the average price including the fixed charge was $2.50 per thousand gallons. On average, households being charged under the IBR structures in our research area pay $133.86 annually for their water bill. Like the uniform rate structure data example above, we found that only a small number of households had adopted water-saving appliances.

Results

Water Demand Under Uniform Rate Structures

Table 2 presents two sets of results for water demand estimation under the uniform rate structures using data from city C from 2016 to 2017. Column 1 shows the results using the log-log functional form, and column 2 shows the results using the semi-log functional form. In column 1, the estimated price elasticity is −0.232 ($p < 0.01$), indicating that a 1% price increase is associated with an expected reduction in water consumption of 0.232%. Results in column 2 show a similar price elasticity estimation of −0.238. In contrast to the log-log functional form, which assumes the price

Table 2. Results of Residential Water Demand Estimation Under Uniform Rate Structures (*N* = 59,953)

	Log-Log	Semi-Log
Price ($/1,000 gallons)	−0.232***	−0.146***
	(0.021)	(0.014)
Annual water bill ($)	0.958***	0.085***
	(0.011)	(0.000)
Average monthly temperature (°F)	0.006***	0.06***
	(0.000)	(0.000)
Adoption of water-saving appliances (1 = low)	0.026	0.033
	(0.064)	(0.065)
Adoption of water-saving appliances (2 = medium)	−0.025	−0.023
	(0.035)	(0.035)
Adoption of water-saving appliances (3 = high)	−0.053	−0.056
	(0.055)	(0.055)
Price elasticity at mean	−0.232	−0.238
Price elasticity at price = $1.3		−0.189
Price elasticity at price = $1.8		−0.262
Income elasticity	0.145	0.144

Notes: Values in parentheses are standard errors. Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% level.

elasticity is constant at every price point, the semi-log functional form enables us to compute price elasticity at specific price points. Specifically, we compute the price elasticity at $1.3 and $1.8, corresponding to around the 25th and 75th percentile of marginal price in the full dataset. The resulting price elasticities are −0.189 and −0.262, respectively. Water consumption behavior at different price points suggests that households are less responsive to price changes when prices are at lower levels but become more responsive when prices rise. Overall, the estimation of uniform rate structure indicates that residential water consumption is price inelastic in the research area, consistent with previous studies reviewed by Sebri (2014). To estimate the income elasticity, we substitute the annual water bill elasticity into the empirical relationship between water bills and household income. Additionally, water consumption is shown to be positively associated with temperature, and the adoption of water-saving appliances do not lead to a significant reduction in water usage.

Water Demand Under IBR Structures

The DCC Model Estimation Results Using Marginal Prices

The water demand estimation using the DCC model under IBR, including both the log-log and simi-log function form estimation, is presented in columns 1 and 2 of Table 3. The estimated parameters for price and water bill of the DCC model represent the effect of price and water bill changes on conditional water demand. To estimate price and income elasticity for unconditional demand, we simulated the water demand response to a 1% increase in all prices and 1% increase in water bills. As with the linear demand model under uniform rate structure, the parameter estimates generally have the expected signs and most are significantly different from 0 at the 1% significance level. The results of the DCC model estimation results suggest price elasticities are higher than these under the uniform-rate structures, regardless of the functional form used. The price elasticity estimations at the mean price are −1.150 in the log-log functional form and −1.379 in the semi-log functional form. Price elasticity estimates at the 25th and 75th percentile of prices in the semi-log

Table 3. Residential Water Demand Estimation Under Increasing Block Price Structures: The Comparison of the Discrete/Continuous Choice (DCC) Model Results Using Marginal Prices and Linear Demand Model Results Using Average Prices

	Marginal Price (N = 1,061,069)		Average Volumetric Price (N = 1,005,080)		Average Total Price (N = 1,005,080)	
	Log-Log	Semi-Log	Log-Log	Semi-Log	Log-Log	Semi-Log
	1	2	3	4	5	6
Marginal price ($/1,000 gallons)	−1.419***	−1.250***				
	(0.005)	(0.004)				
Lag average volumetric price, exclude fixed charge ($/1,000 gallons)			−1.207***	−0.580***		
			(0.006)	(0.005)		
Lag average total price, include fixed charge ($/1,000 gallons)					−0.918***	−0.251***
					(0.001)	(0.000)
Annual water bill ($)	1.369***	0.010***	1.279***	0.008***	0.852***	0.006***
	(0.002)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Average monthly temperature (°F)	0.006***	0.007***	0.006***	0.006***	0.006***	0.006***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Adoption of water-saving appliances (1 = low)	−0.034***	0.041***	−0.053***	−0.037***	−0.024**	−0.035***
	(0.013)	(0.014)	(0.011)	(0.012)	(0.010)	(0.011)
Adoption of water-saving appliances (2 = medium)	0.012	0.099***	−0.021*	0.015	−0.012	−0.006
	(0.015)	(0.016)	(0.013)	(0.014)	(0.011)	(0.012)
Adoption of water-saving appliances (3 = high)	0.084***	0.190***	0.030**	0.097***	0.018	0.051***
	(0.016)	(0.018)	(0.014)	(0.015)	(0.012)	(0.013)
Sigma(η)	0.532***	0.576***				
	(0.001)	(0.001)				
Sigma(ε)	0.245***	0.269***				
	(0.001)	(0.001)				
Akaike information criterion	1,621,475	1,730,854	1,567,228	1,733,867	1,292,535	1,451,998
Price elasticity at mean	−1.150	−1.379	−1.207	−0.792	−0.918	−0.629
Price elasticity at price = $1.3		−1.242		−0.754		−0.326
Price elasticity at price = $1.8		−1.984		−1.044		−0.451
Income elasticity	0.169	0.168	0.193	0.155	0.129	0.114

Notes: The marginal price specifications were estimated using the DCC model by maximum likelihood estimation, and the average price specifications were estimated using the linear demand model by maximum likelihood estimation. Values in parentheses are standard errors. Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% level.

functional form (−1.242 at a price of $1.3 and −1.984 at a price of $1.8) are also found to be higher than these estimated under the uniform rate structure. Similarly, these elasticities at different price points are obtained by simulating a 1% increase in all marginal prices and predicting the expected water consumption. In addition, the AIC statistics suggest that the log-log functional forms outperformed the semi-log functional forms. Our results are consistent with results using structural approaches that account for piecewise-linear budget constraints created by block rates (Olmstead, Hanemann, and Stavins, 2007; Baerenklau, Schwabe, and Dinar, 2014; Vásquez Lavín et al., 2017). The findings also align with previous studies showing that water demand is more elastic under IBR structure compared to uniform rate structure (Espey, Espey, and Shaw, 1997; Dalhuisen et al., 2003). Specifically, we find higher price elasticity estimates under IBR structure compared to the uniform rate structure, suggesting that the specific features of the rate structure have an impact on demand.

Regarding the elastic demand of residential water consumption, first, it is worth noting that our residential data on water consumption include both indoor and outdoor water consumption. Outdoor water use is more elastic than indoor water consumption as it is easier to adjust outdoor water use (Sebri, 2014; US Environmental Protection Agency, 2016). About 30% of U.S. households' water use is for outdoor purposes, overwhelmingly dominated by watering lawns and gardens (Cole and Stewart, 2013). Bakhtavoryan and Hovhannisyan (2022) found that substantial precommitments are established in residential water demand; the demand becomes price-elastic once the precommitted level is reached. This suggests that outdoor water consumption may have a lower precommitted ratio and that rate structures aimed at conservation could be designed to target outdoor water usage more effectively.

Second, water consumption in the research areas is lower than the average amount of water used by US households, which is about 320 gallons/day and 9.6 thousand gallons per month on average (US Environmental Protection Agency, 2013). At a low quantity demanded, a small change in absolute value will cause a big change in the percentage of water consumption, which is reflected as a larger elasticity estimation.

Third, we would expect the elasticity to vary between the long run and the short run (Espey, Espey, and Shaw, 1997; Sebri, 2014). As our data for the IBR structures spans 7 years, while the observed data with the uniform rate spans 2 years, long-run substitutes for water include installing water-saving appliances, smart irrigation systems, and adapting landscaping (Taylor, McKean, and Young, 2004). With expectations of increasing rates every year, households make long-run adjustments to conserve water. This tracks with Dalhuisen et al. (2003), who showed that households appear more responsive to price changes when they have had more time to adapt.

Regarding other factors that affect water demand, we find that income elasticities are comparable to these estimates obtained under uniform rate structures, and temperature is significantly associated with increased water consumption. Additionally, we obtain mixed results regarding the effect of adopting low- and medium- efficiency water-saving appliances across different price specifications and functional forms. Interestingly, the adoption of high-efficiency water-saving appliances appears to lead to higher water consumption, which is commonly referred to as the rebound effect in conservation and energy economics (Thiesen et al., 2008), implying that the expected gains from new technologies maybe partially offset by an increase in consumption.

The Linear Demand Model Estimation Results Using Average Prices

Table 3 further presents the estimation results of the linear demand model for average price specifications (i.e., average total price and average volumetric price) under IBR structure. Columns 3 and 5 show the results using the log-log functional form, and columns 4 and 6 show the results using the semi-log functional form. The price elasticity estimations using average volumetric price (excluding fixed charge) specification ranged from −0.754 to −1.207 for two different functional forms. However, when using the specification of average total price (including fixed charge), the price elasticity ranged from −0.326 to −0.918.

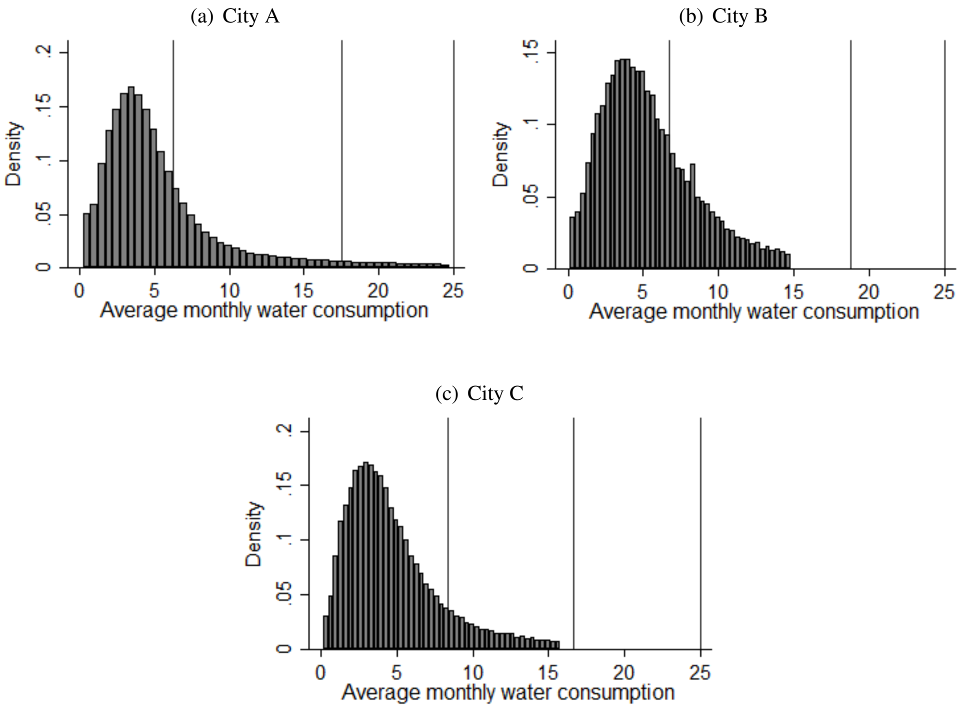

Figure 1. Residential Monthly Water Consumption Distribution and Blocks in Increasing Block Price Structures
Notes: x-axis unit is 1,000 gallons.

Whether Households Respond to Marginal Price or Average Price

The price elasticity estimations using the marginal specifications are higher than those using average price specifications, suggesting that people are more responsive to marginal price under IBR structure if they are aware of it. However, a higher price elasticity estimation for marginal price under IBR structure does not necessarily mean that people respond to it. To address the question of whether households react to marginal price or average price under IBR structure, we provide two types of evidence.

First, we compare the AIC between marginal price specifications and average price specifications, finding that AIC statistics are generally smaller for average price specifications. Moreover, the average total price specifications have even smaller AIC statistics compared to the average volumetric price specifications, indicating that the average total price specification better fits the data. This suggests that people may not only have imperfect understanding of the IBR structure but also limited understanding of the specific features of the fixed charge, leading them to include the fixed charge in their consumption decision. The lower price elasticities estimated for the average total price specifications indicate that if people do not differentiate fixed costs, it would further decrease the effectiveness of the IBR structure. Moreover, the fixed cost generates a distortion to average price, especially at lower levels of consumption. As consumption increases, the influence of fixed costs on the total average cost diminishes because the fixed costs are spread over more units of consumption, leading to a lower average cost per unit. When people use average total costs to make consumption decisions, a higher fixed cost inadvertently encourages water consumption, which needs to be avoided.

Second, inspired by Binet, Carlevaro, and Paul (2014) and Ito (2014), we conduct the bunching analysis to examine whether households exhibit rational behavior by clustering at the kink points under the IBR structure. Figure 1 shows the density plot of water consumption in each city, with the vertical lines representing the upper thresholds of each block. However, the plots do not show clear clustering of residential water consumption at the kink points. This suggests that households might not be fully

Table 4. Prediction of Water Consumption Under Alternative Price Structures

Alternative Price Structures	Percentage Change in Predicted Demand (%)	Percentage Change in Predicted Revenue (%)
Panel A. Increase prices		
3.5% increase in block 1 price	−2.83	−1.87
5% increase in block 1 price	−4.02	−2.66
3.5% increase in block 2 price	−1.21	−0.80
5% increase in block 2 price	−1.66	−1.10
3.5% increase in both block 1 and block 2 prices	−4.03	−2.66
5% increase in both block 1 and block 2 prices	−5.67	−3.75
Panel B. Decrease quantity upper thresholds		
Decrease block 1 upper threshold by 20%	−4.37	−2.89
Decrease block 1 upper threshold by 30%	−6.92	−4.57
Decrease block 2 upper threshold by 20%	0.26	0.17
Decrease block 2 upper threshold by 30%	0.17	0.11
Decrease both block 1 and block 2 upper thresholds by 20%	−4.11	−2.72
Decrease both block 1 and block 2 upper thresholds by 30%	−6.75	−4.46
Panel C. Add additional blocks		
Divide block 1 into two blocks by setting block 1 upper threshold to 70% of its original and price for new block to 50% of the sum of original block 1 and block 2 prices	−3.93	−2.60
Divide block 2 into two blocks by setting new block upper threshold to 70% of original block 2 upper threshold and price for new block to 50% of the sum of original block 2 and block 3 prices	−0.14	−0.09
Panel D. Equity design of rate structures		
3.5% decrease in block 1 price while 3.5% increase in both block 2 and block 3 prices	1.75	1.16
5% decrease in block 1 price while 5% increase in both block 2 and block 3 prices	2.57	1.70

informed and, as a result, may not respond rationally to the marginal prices under the IBR structure; they could be using average prices instead. As previous literature has suggested, people may not fully understand nonlinear rate structures and thus use the average price as an approximation of the marginal price, which results in less responsiveness to price changes in IBR structure (Ito, 2014; Cook and Brent, 2021).

However, the lack of household response to marginal prices under IBR structure does not mean that the structure itself is ineffective; instead, it suggests that it has not yet achieved its full potential for conserving water. Therefore, our main takeaway is that although IBR structure exhibits higher price elasticity and is more effective in encouraging water conservation, it should be accompanied by informing customers about the rate structure to ensure it actively influences water consumption behavior.

Alternative Rate Structures for IBR

Table 4 summarizes the predicted water demand estimation for each alternative rate structure designed to promote water conservation. For example, in the first scenario, increasing the price in block 1 by 3.5% was associated with a 2.83% reduction in predicted demand. Except for changes to the block 2 upper threshold, modifications in Panels A, B, and C (e.g., price increases, lower quantity thresholds, additional blocks) are generally associated with reduction in water demand.

The most effective strategy is reducing the block 1 upper threshold by 30%, which predicts a 6.92% reduction in water use. In contrast, lowering the block 2 upper threshold has a negative but minimal effect on reducing water consumption. Decreasing block 2 upper thresholds in addition to decreasing block 1 upper threshold will not lead to any improvement because as prices or thresholds in the simulated price structure change, so do the virtual incomes. If we decrease the block 2 upper threshold, the predicted demand increases due to the income effect. Similarly, an increase in block 2 price has a limited effect compared to an increase in block 1 price. This is not surprising because most households consumed water within block 1. Thus, reducing the size of block 1 and raising its price is more effective for conservation. In addition to how much water can be saved, we also provide estimates on financial self-sufficiency for alternative IBR structures.

One could argue that these alternative price structures will significantly impact consumers at lower levels and might be socially and politically undesirable. In response, we simulate household consumption with lower prices in block 1 and higher prices in blocks 2 and 3. The results shown in Panel D suggest that households would use more water under these scenarios. To achieve socially and politically desirable outcomes, multiple measures could be adopted in addition to the design of the rate structure, including offering additional subsidies to economically poor households.

Conclusion, Policy Recommendation and Suggestions for Future Research

Using longitudinal household water consumption data from the Minneapolis–St. Paul metropolitan area in Minnesota and applying a DCC approach to address the simultaneity between water consumption and price choice under IBR structures, our results suggest that residential water demand is more sensitive to price changes under IBR compared to a uniform rate structure, highlighting the potential effectiveness of IBR structure as a tool for water conservation. However, multiple evidence suggests that households may not respond to marginal price under IBR structure, potentially relying on average price instead; they may also have difficulty distinguishing fixed charge. Nonetheless, the fact that households do not respond to marginal prices under IBR structure does not imply that IBR structure itself is ineffective; rather, it means it has not reached its full potential for effectiveness. Through simulations, we propose alternative IBR structures that might promote greater water conservation, with smaller blocks and higher prices showing larger effects on reducing water consumption.

This study emphasizes that while IBR structure demonstrates higher price elasticity and greater effectiveness in promoting water conservation, its effect hinges on thorough consumer understanding. Effective communication of IBR structures is crucial to ensure households make informed water consumption decisions based on marginal rather than average prices, thereby maximizing the IBR structure's effectiveness. Our research is of interest not only to municipalities that have already adopted IBR structures but also to municipalities that are interested in or in the process of designing such approaches. Municipalities and policy makers might consider adopting IBR structures, in combination with effective communication, to encourage conservation or in response to drought conditions or water supply shortages (Baerenklau, Schwabe, and Dinar, 2014).

This study has several limitations, and future studies can take the following directions. First, it lacks households' sociodemographics and is unable to estimate heterogeneous effects. Flores Arévalo et al. (2021) addressed a similar issue by using census block data to approximate households' sociodemographics, which assumed that households within the same district have similar socioeconomic profiles. However, we believe the price elasticity estimates in our study are not significantly biased, as the fixed effects model (for uniform rate structures) and the two-error DCC model account for constant household characteristics and preference heterogeneity.

Second, there might be other factors that could influence water demand, such as changes in the broader economy, weather and climate, landscaping choices, and water-conserving technologies (Baerenklau, Schwabe, and Dinar, 2014). To account for such effects, we adjust for inflation based on the 2013 Consumer Price Index, control for temperature variations, and include a subsidized water-saving program.

Third, we cannot conclusively determine whether price elasticity varies with different pricing structures due to confounding factors. For example, an environmentally conscious municipality may be more likely to adopt IBR structure as a conservation tool (Olmstead, Hanemann, and Stavins, 2007), and any lawn irrigation restriction policy might directly decrease residential water consumption due to the increasing prevalence of droughts. Future research could use datasets that capture rate structure changes before and after for the same set of customers to improve understanding (Chovar Vera, Vásquez-Lavín, and Ponce Oliva, 2024).

Finally, water conservation is not the sole objective of a rate structure. Tariff design needs to reconcile several conflicting goals, including economic efficiency, financial sustainability, equity, affordability, and conservation (Nauges and Whittington, 2017; Leflaive and Hjort, 2020; Whittington and Nauges, 2020). A crucial step toward achieving these challenges involves quantifying the responses of tariff objectives to changes in the tariff structure. Future studies should consider these factors when designing tariff structures that effectively balance these objectives.

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