TO WHAT WATER PRICE DO CONSUMERS RESPOND?
A STUDY OF INCREASING BLOCK RATES AND MANDATORY WATER RESTRICTIONS

By

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ABSTRACT

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The way consumers react to block pricing has important welfare implications for many economic policies. Standard economic theory assumes that households optimize with marginal price, yet there is no clear empirical evidence as to what water price they actually respond. If households are not responding to marginal price, increasing block rates for water may not be cost-effective or even successful at achieving its policy goals of conservation and equity. Using a detailed household-level panel dataset for 16,277 residential customers in Southern California, I shed light on complex pricing schedules and answer several questions about water consumption behavior.

I begin by examining a household's perceived price of water, where I am able to exploit price variation from several rate increases and a rate structure change from increasing block rates to "water budgets"—water budgets use block sizes that are determined by household and environmental factors. I find strong evidence that consumers respond to different alternative prices, rather than marginal price, depending on which block structure they face. I also find that the average consumer is able to predict their consumption with a standard error of 27%. Improvements in price signals and information provision may limit this type of suboptimizing behavior and uncertainty.

Water suppliers also use mandatory water restrictions to induce conservation, and I find that they reduced overall consumption by 5%—this effect was stronger for those with larger lawns. Lastly, I compare reduced-form and structural methods for estimating price elasticities of demand. As consumption and price are inextricably linked, I conclude that the method of instrumental variables may be fundamentally inappropriate for demand estimation under block rates. Covering many facets of water pricing and consumption behavior, this paper provides useful information to suppliers deciding how to balance their budgets, induce conservation, and provide reliable supply.

This thesis is dedicated to Karim, Hanaa, and Rasha Soliman.

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CHAPTER 1

INTRODUCTION

Meeting residential, industrial, and agricultural water needs has long been an issue in many parts of the world. An increase in the frequency of extreme weather events, a reduction in the reliability of current water supplies, and a growing concern about the environmental effects of new supply projects has increased the need to better understand both water consumption and conservation behavior. For these reasons, many residential water suppliers have focused on improved demand management.

While non-price conservation programs and command-and-control policies are relatively common in the Western United States, the principal tool that water suppliers have to induce conservation is price structure. To many economists, the ideal would be to use marginal-cost pricing to reflect the long-run marginal cost (LRMC). However, water pricing is aimed at pursuing not only greater allocative efficiency, but also objectives of equity, public health, financial stability, and public acceptability (Arbues et al. 2003).

Water prices are therefore administratively determined, and they typically lie below LRMC. This is in contrast to many natural resource markets, such as those for oil and coal, where prices are determined by a market equilibrium and reflect scarcity. Many see increasing block rates as a second-best attempt to reduce economic overuse, and Figure 1.1 provides an example of a 5-block structure from the supplier studied in this paper.[1] The notion that they induce conservation may be the reason for the shift away from decreasing block rates seen in Table A.1.

In order to estimate price elasticities of demand under traditional block rates for water, most researchers have used either reduced-form or structural methods, with the assumption that consumers optimize with marginal price. There is, however, a growing body of evidence in the residential elec-

[1] Increasing block rates charge higher marginal prices for higher quantities consumed. Under these rates, water suppliers can charge something close to LRMC for marginal uses, while meeting zero-profit constraints through the manipulation of block sizes and lower-block prices. At the household level, consumers pay lower rates for necessities like showering and cooking, and rates closer to marginal cost for outdoor irrigation. However, even if the highest block price reflects LRMC, some welfare losses occur due to the lower prices charged on earlier units of water.

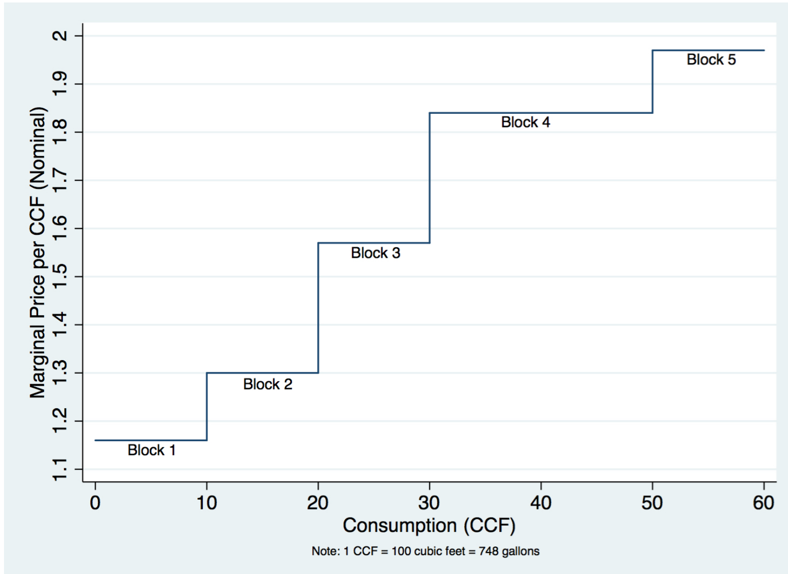


Figure 1.1 Increasing block rates for the Moulton Niguel Water District (CA) in 2011

tricity literature that shows that consumers respond to either expected marginal or average price when facing block rates. Given the complexity of the water budget rate structure[2] and the necessity to better understand consumption behavior in the face of climate change, a major focus of this paper is to analyze price perception and response.

Since it is not known what water price consumers actually respond to, I examine the topic with a unique household-level panel dataset that contains significant price variation and detailed consumption records for 16,277 single-family customers. I begin by examining a household's perceived price of water using bunching analysis and Shin's (1985) dynamic adjustment model. I find strong evidence that consumers respond to different alternative prices, rather than marginal price, depending on which block structure they face. I also find that the average consumer is able to predict their consumption with a standard error of approximately 27% using Borenstein's (2009) uncertainty model. These results imply that the perfectly-optimizing, perfectly-informed consumer is rare, and that it is quite difficult to infer price responsiveness of demand from changes around

[2] This rate structure utilizes block sizes that are based on household characteristics, environmental conditions, and a decision by the water supplier as to what constitutes efficient water use given those characteristics and conditions. As such, block sizes can differ across households at any given time, and over time for any given household. As of 2013, 3% of California's approximately 400 urban water suppliers had implemented water budgets—the remaining suppliers use traditional increasing block rates (65%), uniform rates (26%), seasonal or flat rates (5%), and decreasing block rates (1%) (American Water Works Association, 2013). See Beecher (2012) and Baerenklau et al. (2014) for an overview of the costs and benefits of water budgets, respectively.

discontinuities in marginal price.

Many water suppliers also use command-and-control policies to induce conservation, and I examine the impact of mandatory outdoor restrictions. I find that they decreased overall consumption by approximately 5% and that the effect was stronger for those with larger lawns. Lastly, reduced-form methods were utilized to compare price elasticities of demand with structural estimates generated in a previous study. The results were very sensitive to the choice of instrument, covariates, and specification.

These instrumental variables (IV) approaches were also seemingly unable to address the endogeneity present in increasing block rates. Since IV methods do not account for the discrete choice of block, these results may be due to the fact that households switched their marginal consumption block frequently. More fundamentally, water consumption and price are inextricably linked, and I conclude that reduced-form methods may be inappropriate for demand estimation under block rates. As this paper addresses several topics regarding water pricing and consumer behavior, it provides useful information to water suppliers who are deciding how to balance their budgets, induce conservation, and provide reliable supply.

The remainder of this paper proceeds as follows. Chapter 2 briefly summarizes the water demand literature. Chapter 3 introduces the theory behind the study of kinked budget constraints and price perception. Chapter 4 contains information about the study area and data. Chapter 5 provides the econometric analysis and discussion. Chapter 6 concludes.

CHAPTER 2

LITERATURE REVIEW

The literature on residential water demand is extensive, and economists have generally agreed on the variables to include in water demand functions. Since water has no close substitute, the only price entering the demand function should be that of water. Other variables that affect water consumption are income, household characteristics, home features, and weather variables. At the core of this literature, however, lies difficulties in theoretically and empirically modeling the block pricing used by many water suppliers (see Arbues et al. 2003 for an overview).

Consensus has been difficult to obtain on the best way to model demand under block pricing, as this type of rate structure leads to a kinked budget constraint, and a nonlinear and a non-differentiable demand function. Researchers also disagree on the proper specification of the price variable. Therefore, early work examined whether the price variable should be the average price or the marginal price, which clearly differ after the first consumption block in both increasing and decreasing block rates.

Following the work of Taylor (1975) and Nordin (1976) in the electricity literature, the marginal price specification was modified to include the "difference variable"—this is defined as the difference between what the consumer actually paid and what they would have paid if all consumption was charged at the marginal price. The motivation for this modification was that it is difficult to analyze the impact of changes in rates that do not correspond to the current level of consumption, which are known as intra-marginal rates. Given that a change in intra-marginal rates does not affect the marginal price, the former will only affect demand through an income effect. A theoretical argument was made that the difference variable should be of equal magnitude to income but opposite in effect in the case of increasing block rates (Corral et al. 1995).

The work of Taylor (1975) and Nordin (1976) gave rise to a number of papers that tried to empirically test this relation, such as Billings and Agthe (1980), Foster and Beattie (1981), and

Howe (1982). This set of papers used IV techniques to attempt to correct for the bias present in ordinary least squares (OLS) estimation due to the simultaneity or co-determination of quantity, price, and the difference variable. However, there has been relatively little empirical support for the hypothesis that the difference variable is equal in magnitude and opposite in sign to the income variable. Ruijs (2009) suggests that this may be due to consumers' lack of information about the rate structure, the difference variable being small relative to income, or estimation biases.

A general shortcoming of this literature, and another possible explanation for the lack of empirical support, has been the use of aggregate consumption data and proxies for household income. In their review of the water demand literature, Arbues et al. (2003) argue that the use of aggregate data has been the major source of incorrect specification. Their reasoning is that researchers are unable to determine the distribution of water use across households and how it varies as a function of the rate structure.

Others, such as Opaluch (1982), Chicoine and Ramamurthy (1986), and Nieswiadomy (1992), have argued that the price that consumers respond to is an empirical question and is context-specific. Their work shows that it can be difficult for consumers to determine true marginal prices because they may be unaware of the block nature of price or may not react until they receive their bill. Nieswiadomy and Molina (1991) and Nieswiadomy (1992) use a model developed by Shin (1985) to test whether consumers react to average price, marginal price, or a function of both—this model and other econometric techniques will be described in greater detail in Chapter 5.

Using decreasing block data for residential electricity, Shin (1985) finds that consumers react to average price. Nieswiadomy and Molina (1991) and Nieswiadomy (1992) find that consumers respond to marginal price when faced with increasing block rates for water. A more recent examination by Ito (2014) finds that residential electricity consumers respond to average price. Because of an increase in aggregate consumption compared to uniform rates, he concludes that this response makes block rates unsuccessful in achieving their goal of energy conservation.

There have been relatively few attempts to explicitly model the decision process of a consumer facing block rates for water, specifically the choice of which block to locate consumption. When water is sold under block rates, a serious issue for model specification and estimation is the aforementioned co-determination of price, quantity, and the difference variable (Corral et al. 1995; Hewitt and Hanmann 1995). Nauges and Thomas (2000) argue that the correct specification in such cases utilizes work by Burtless and Hausman (1978) from the labor supply literature. These authors proposed a two-stage model in which a consumer first selects the block (discrete choice), then maximizes their utility subject to a budget constraint (continuous choice).

Hewitt and Hanmann (1995), Pint (1999), Olmstead (2009), Baerenklau et al. (2014), and Szabo (2015) are among the only authors to use this kind of structural two-step or discrete-continuous choice (DCC) model in the study of water demand. However, due to the computational intensity of the DCC model and a lack of micro-data, many researchers have simplified the demand function by only considering the block where most consumers are located (selection bias) or by omitting the choice of block by the consumer (simultaneity bias) (Nauges and Thomas, 2000).

Despite the differences among econometric methods and the data utilized, economists generally agree that residential water demand is inelastic with respect to price, but not perfectly so. The vast majority of the literature have found price elasticities in the range of 0 and -1, and Table 2.1 presents results from some of these studies.

Authors	Data	Method	Price Specification	Price Elasticity
Howe and Linaweaver (1967)	CS	OLS	MP	-0.21 to -1.57
Foster and Beattie (1979)	CS	OLS	AP	-0.27 to -0.76
Billings and Agthe (1980)	LD	OLS	Nordin	-0.27 to -0.49
Billings (1982)	LD	IV	Nordin	-0.56 to -0.66
Chicoine and Ramamurthy (1986)	CS	OLS	MP	-0.60 to -0.61
Moncur (1987)	LD	OLS	MP	-0.03 to -0.68
Nieswiadomy and Molina (1989)	LD	IV	Nordin	-0.09 to -0.86
Nieswiadomy (1992)	CS	IV	MP, AP	-0.22 to -0.60
Hewitt and Hanemann (1995)	LD	IV, DCC	Nordin	-1.57 to -1.63
Corral et al. (1995)	LD	DCC	Nordin	-0.11 to -0.17
Pint (1999)	LD	DCC	MP	-0.04 to -1.24
Olmstead (2009)	LD	IV, DCC	MP	-0.28 to -0.64
Baerenklau et al. (2014)	LD	DCC	MP	-0.58 to -0.76

Notes: CS for cross sectional data. LD for longitudinal data. Nordin for MP plus difference variable.

Table 2.1 Summary of selected studies in residential water demand

Borenstein (2009) argues, however, that much of this literature has been based on the assumption that consumers are perfectly informed and constantly optimizing on the margin. Such an assumption is seemingly at odds with the way that almost everyone thinks about their water consumption. He goes on to examine price response in more detail than Opaluch (1982) and Shin (1985), and finds that residential electricity customers in California respond to expected marginal price in the presence of uncertainty about consumption. Consumers may alternatively use average price as an approximation of marginal price if the cognitive cost of understanding complex price schedules is significant (Ito 2014). This suboptimization behavior, which has its foundations in earlier work, is described as "schmeduling" by Liebman and Zeckhauser (2004).

Liebman and Zeckhauser (2004) state that utility pricing has several features that make it difficult for consumers to know their true marginal price: (1) pricing schedules are sometimes not published or presented clearly on the bill; (2) consumers vary their consumption seasonally; (3) pricing schedules can change relatively frequently or seasonally; (4) bills aggregate many disparate individual decisions and are typically presented in units that are not directly observable to the consumer; and (5) the link between a consumer's choices and consumption is difficult to reconcile, such as how many gallons are in a shower. These factors, "...a nonstationary economic environment, delayed payoff, and bundled consumption[,] combine to make it almost impossible to determine one's marginal price by observing how bills vary with behavior" (Liebman and Zeckhauser 2004, p.11).

There have been many improvements to water demand estimation under block rates. These include the correction for the endogeneity between price and quantity, the use of time series data, and the utilization of empirical techniques that are consistent with utility theory. However, the assumption implicit in much of this literature, that households optimize with marginal price, is now seen as too strong. There is a growing body of evidence in the residential electricity literature that finds suboptimizing behavior and significant uncertainty with regards to consumption. With rising marginal costs of new water supplies and climate change adding uncertainty to weather patterns, there is a need to better understand how households are responding to price.

CHAPTER 3

THEORETICAL DISCUSSION

Block rate pricing presents theoretical and empirical difficulties in the modeling and analysis of residential water demand. In contrast to traditional consumer demand analysis, the demand function for a good facing block rates is typically nonlinear and non-differentiable. Standard demand curves cannot accurately represent consumer behavior when facing a kinked budget constraint.[1] Empirical estimation can also be quite complex because price and quantity are simultaneously determined. Moreover, the discrete choice of block and the continuous choice of quantity should both be modeled. The econometric challenges are discussed in greater detail in Chapter 5.

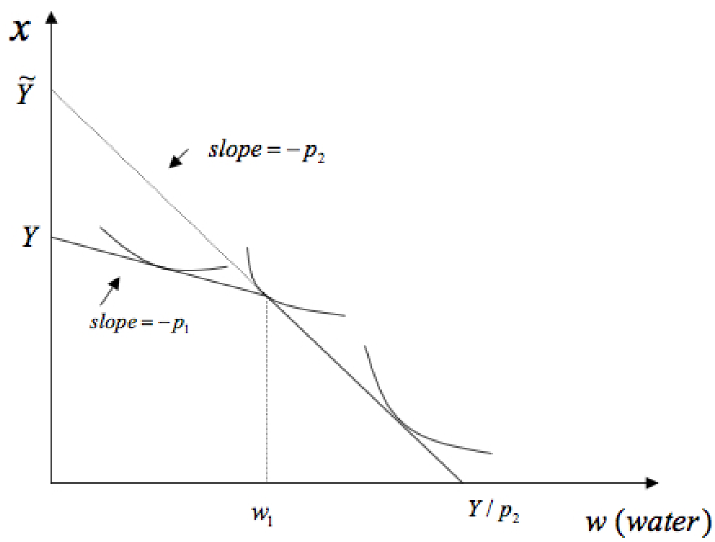


Figure 3.1 Utility maximization under a two-tier increasing block rate structure

Households are assumed to maximize utility, subject to a budget constraint, which is kinked under block rate pricing. An example of a simple two-tier increasing block rate structure is shown in Figure 3.1, where Y is income, $\widetilde{Y}$ is "virtual income" (defined below), w_1 is the level of consumption at which the price changes (the kink point), and p_1 and p_2 are the prices of water in

[1] See Moffitt (1986) for a general derivation of the demand function, and Hewitt and Hanemann (1995) for a careful derivation of it in the context of water demand.

block 1 and block 2, respectively. In such a framework, the consumer then faces three possible consumption choices: consume on the interior of segment one, on the interior of segment two, or at the kink point.

For households consuming anywhere on a kinked budget constraint other than in the first linear segment, the marginal price varies across units of consumption. This problem can be resolved in the example from Figure 3.1 by defining the budget constraint as follows:

$$Y = \begin{cases} p_1 w + \mathbf{x}, & \text{if } w \leq w_1 \\ p_1 w_1 + p_2(w - w_1) + \mathbf{x}, & \text{if } w > w_1 \end{cases}$$

or equivalently:

$$\begin{aligned} Y &= p_1 w + \mathbf{x}, \quad \text{if } w \leq w_1 \\ Y + (p_2 - p_1)w_1 &= p_2 w + \mathbf{x}, \quad \text{if } w > w_1, \end{aligned}$$

where w is the quantity of water consumed and $\mathbf{x}$ is a composite good with price normalized to 1. The term $\widetilde{Y} = Y + (p_2 - p_1)w_1$ is virtual income, which denotes the intercept of the second segment on the budget constraint extended to the vertical axis, whereas $\widetilde{D} = (p_2 - p_1)w_1$ is the difference variable. While the difference variable was commonly used in earlier literature, virtual income is now more prevalent, as it provides a convenient representation of the situation faced by consumers in blocks beyond the first. More specifically, virtual income refunds the implicit subsidy that a household receives from the block rate structure (Olmstead 2009).

However, Borenstein (2009) states that this traditional view of consumption behavior requires considerable effort from the consumer because:

> ...in the DCC models, consumers are assumed to calculate their preferred consumption if they were to face each of the possible marginal prices on the different steps and then choose on which of the steps to consume. These approaches, however, rely on discrete price changes at identifiable points and on the assumption that consumers respond to those abrupt price changes. That is, these papers assume that consumers chose their consumption quantity based on the marginal price that they are observed to have faced. Some research recognizes that consumers

> do not exactly hit their consumption target in every billing period due to variations in daily activities, weather, and other factors. This optimization error is argued to be part of the error term. In practice, this view of consumer behavior is quite demanding. First, it has the obvious information requirements that the customer knows the date his current billing period began and will end, and the prices and quantity break points in the increasing-block schedule. More importantly, if there are any exogenous shocks to his demand, this approach requires that the consumer knows (or, at least thinks he knows) those shocks with certainty for the entire billing period at the time the period begins. Otherwise, when the consumer is choosing consumption on day 1 of the billing period he will not know the marginal price on which he should base his decision (p.6).

There has recently been more examination into what price consumers actually respond to, specifically in the context of electricity consumption. An approach by Ito (2014) extends the discussion by stating that economic theory gives three predictions about consumers' perceived price under block pricing. To characterize the predictions, consider a price schedule $p(w)$, where the marginal price of w equals p_1 for $w \leq w_1$ and p_2 for $w > w_1$.

The standard model of kinked budget constraints mentioned above predicts that consumers optimize w based on the true marginal price schedule $p(w)$, or put differently, that the perceived price is equal to $p(w)$. Implicit in this response is two assumptions: (1) consumers have no uncertainty about w; and (2) they fully understand the structure of the block price schedule (Ito 2014). Borenstein (2009) and Saez (2010) relax the first assumption—they argue that it is unrealistic to assume that consumers both know w with certainty and respond to their true marginal price of w. In their models, consumers incorporate uncertainty about w and respond to their expected marginal price. They make decisions (behavioral rules) and can calculate their expected marginal price based on the distribution of predicted random shocks that will occur during a billing month; they do not necessarily need information about their daily consumption (Borenstein 2009; Ito 2014).

Liebman and Zeckhauser (2004) relax the second assumption by allowing inattention to the details of complex price schedules. Their model predicts that if the mental cost of understanding the price schedule is significant, consumers respond to the average price as an approximation for their marginal price. Compared to marginal price or expected marginal price, less information is required to calculate average price.

Ito (2014) considers a general form of perceived price that encompasses all three theoretical predictions, and his kink point analysis is motivated by the model presented in Saez (2010). Several of his empirical techniques require significant exogenous price variation and a well-identified control group. He is able to exploit price variation at spatial discontinuities in electricity service areas, where households in the same city experience vastly different block price schedules. These requirements are unfortunately not met in the data used for this paper, but components of his statistical methods are utilized in Chapter 5.

The examination that follows utilizes the approaches of Shin (1985), Liebman and Zeckhauser (2004), Borenstein (2009), and Ito (2014). These authors call into question the validity of a standard economic assumption, and studying the price consumers respond to is currently seen as an empirical investigation. Therefore, these authors' methods are more relevant for the subsequent analysis.

CHAPTER 4

CONTEXT AND DATA

The data for this study comes from the Moulton Niguel Water District (MNWD), located in Orange County, California. MNWD provides water, recycled water, and wastewater service to approximately 170,000 people in its service area, which includes the cities of Aliso Viejo, Laguna Niguel, Laguna Hills, Mission Viejo, and Dana Point. See Figure 4.1 for a map of their service area.

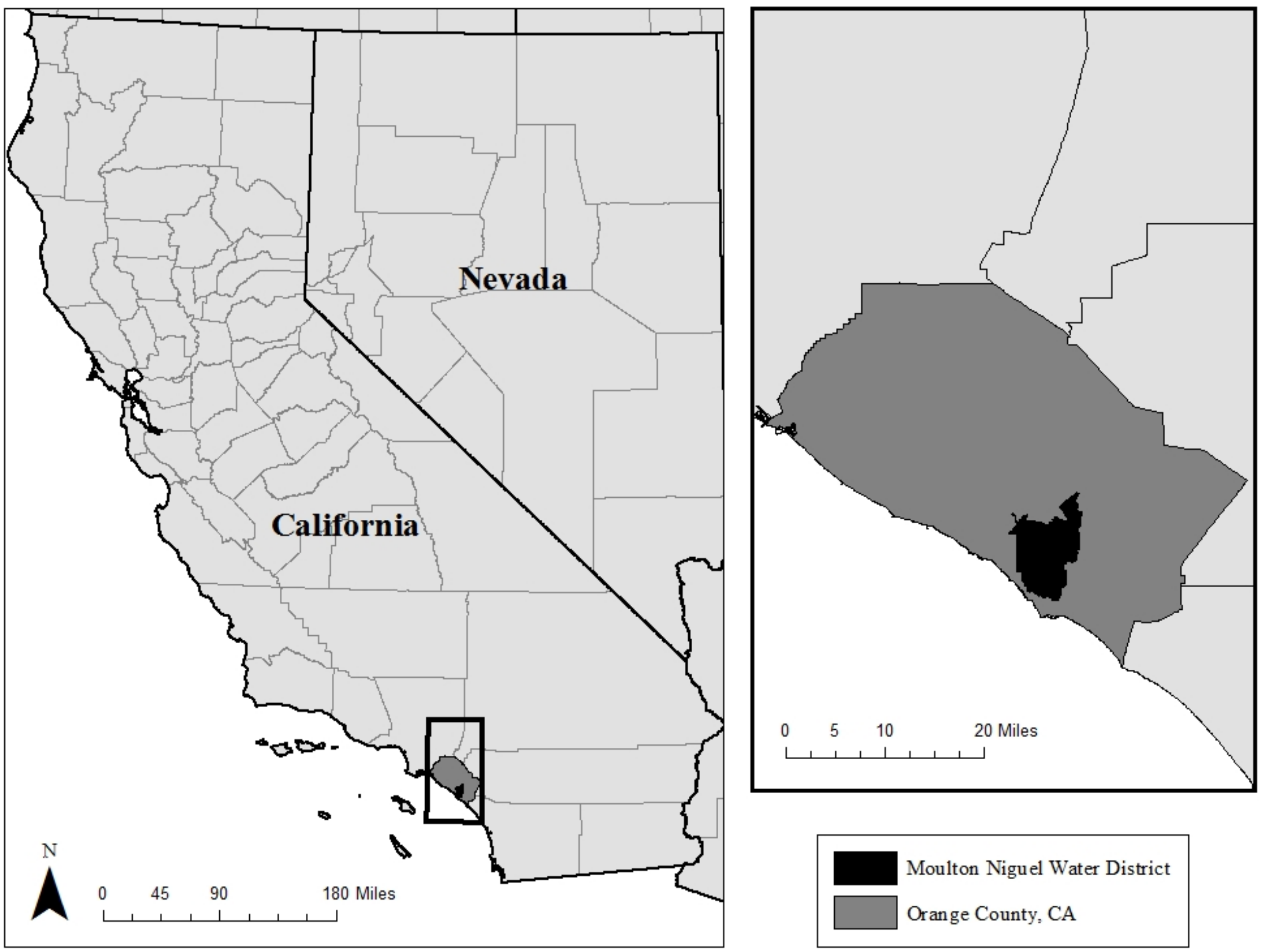


Figure 4.1 Map of Moulton Niguel Water District

Approximately 80% of MNWD's water is purchased from the Municipal Water District of Orange County, which purchases its water from the Metropolitan Water District of Southern California, a regional water wholesaler that delivers water from the Colorado River and Northern California (MNWD, 2015b). The demographic breakdown of the MNWD service area is shown in Table 4.1. It should be noted that residents are well-educated and live in relatively new and expensive homes.

Data Source	Variable	Mean	Std. Dev.
MNWD	Household size	4.05	0.76
	Irrigated area (feet^2)	3495	4654
ACS 5-Year, 2009-2013 (all values by census block group)	Median house value* (2013, $1000)	662.3	191.1
	Median year structure built*	1982.2	10.2
	Bachelors degree (%)	32.9	8.8
	Professional degree (%)	4.0	3.4
	Median age*	42.6	6.6
	Population density (people per square mile)	6286	3309
	Number of housing units	691	291

Note: Variables with a (*) represent the median value for a census block group.

Table 4.1 Household and census block characteristics of MNWD

Household size and irrigated area are confirmed on a household basis by MNWD. They are typically updated voluntarily by customers, who can either provide information about changes in their household composition or submit a petition for a larger monthly block allowance.[1] Large reported household sizes normally require verification, and large reported irrigated areas would trigger a follow-up, since MNWD has baseline values from parcel maps and assessor data. The remaining variables in Table 4.1 were gathered using the 2009-2013 American Community Survey (ACS) 5-Year census estimates and are by census block group. Other than adjustments for inflation, demographic variables are time-invariant.[2]

The dataset used for the analysis covers continuous monthly use records of 16,277 single-family households from October 2007 to March 2015. Two major changes occurred during this time period. First, MNWD implemented mandatory water restrictions from April 2009 until April

[1] These are typically given for medical need, livestock, or increases in irrigated area. [2] The water supplier merged the census data with the consumption and pricing data—they then removed all potentially identifiable information prior to my receipt of the full dataset.

Block	Under Increasing Block Rates	Under Water Budgets
Block 1	Up to 10 CCF	Up to indoor budget
Block 2	10 CCF up to 20 CCF	Up to outdoor budget
Block 3	20 CCF up to 30 CCF	Total water budget up to 125% of total budget
Block 4	30 CCF up to 50 CCF	125% of total budget up to 150% of total budget
Block 5	Over 50 CCF	Over 150% of total budget

Note: 1 CCF = 100 cubic feet = 748 gallons

Table 4.2 Block sizes under MNWD's two rate structures

2011. This limited outdoor water use to three days per week, with a daily maximum of 15 minutes. For the time periods before and after the mandate, there were no restrictions on outdoor use. Second, MNWD switched from increasing block rates to water budgets in July 2011—see Table 4.2 for the size of each consumption block under the two rate structures. Under water budgets, residential customers are given an indoor and an outdoor allocation based on household characteristics and environmental conditions, which can vary monthly. Figure A.1 shows the block sizes faced by typical households in the sample, and Figure A.2 provides a histogram of block size allocation under water budgets.

For customers located in MNWD's service area, indoor water budgets are calculated using three factors: (1) 60 gallons of water per person per day (deemed "efficient" by MNWD); (2) the number of people in the household; and (3) the number of days in the billing cycle. Outdoor water budgets are also calculated using three factors: (1) the amount of irrigated area; (2) actual daily plant water loss, captured by evapotranspiration; and (3) a plant factor that reflects the water needs of native plants. A more detailed description of these outdoor factors can be found in Section A.3.

Some summary statistics are provided in Table 4.3, and a graph of average monthly water consumption for the sample is included in the Appendix (Figure A.3). This figure shows that while seasonal shifts in consumption continue to occur, they are on average less extreme after the rate structure change. MNWD increased nominal volumetric charges twice under their traditional increasing block rate pricing schedule: once in July 2009 and again in July 2010. When MNWD switched from increasing block rates to water budgets in July 2011, which resulted in an additional rate increase, nominal prices for each block remained the same until the end of the study period.

Variable	2007	2008	2009	2010	2011	2012	2013	2014	2015
Consumption (CCF/month)	16.31	18.77	16.91	14.82	14.92	15.34	16.02	15.36	12.68
Evapotranspiration (inches/month)	2.38	4.07	4.17	3.81	4.11	4.60	4.29	4.21	3.97
Nominal price ($/CCF)	0.86	0.86	0.94	1.09	1.28	1.38	1.38	1.38	1.38
Block 2	0.96	0.96	1.05	1.23	1.43	1.54	1.54	1.54	1.54
Block 3	1.16	1.16	1.27	1.48	2.21	2.75	2.75	2.75	2.75
Block 4	1.36	1.36	1.49	1.73	3.84	5.51	5.51	5.51	5.51
Block 5	1.46	1.46	1.60	1.86	6.91	11.02	11.02	11.02	11.02
Nominal average price paid ($/CCF)	0.91	0.92	1.00	1.15	1.41	1.53	1.55	1.53	1.46
Real price (2013, $/CCF)	0.95	0.92	1.03	1.17	1.31	1.39	1.38	1.37	1.39
Block 2	1.06	1.03	1.15	1.31	1.47	1.55	1.54	1.53	1.56
Block 3	1.28	1.25	1.39	1.58	2.27	2.77	2.75	2.73	2.78
Block 4	1.50	1.46	1.62	1.85	3.94	5.54	5.51	5.47	5.57
Block 5	1.61	1.57	1.75	1.98	7.09	11.09	11.02	10.94	11.14
Real average price paid (2013, $/CCF)	1.00	0.99	1.09	1.22	1.45	1.53	1.55	1.52	1.48
Real budget (2013, $/month)	372.7	372.2	366.7	363.2	363.2	368.6	369.8	376.5	386.6

Notes: The study period is from October 2007 to March 2015. The rate structure changed in July 2011. Consumption is reported in integer values. 1 CCF = 100 cubic feet = 748 gallons.

Table 4.3 Summary statistics for the entire sample

It should be noted that when the rate structure changed in July 2011, the real price paid per CCF (100 cubic feet) of water increased by 25% and the highest-block price increased by approximately 450%. Figure A.4 shows how nominal rates changed over time.

The income variable, which is defined as "real budget" in Table 4.3, follows from the recommendation of Strong and Smith (2010) and Baerenklau et al. (2014). It is based on census block income and adjusted for the fraction of income typically spent on the census category of "utilities, fuels, and public services" (proportional to income). This was then adjusted for temporal changes in per-capita personal income for the Los Angeles-Long Beach-Santa Ana metropolitan statistical area using data from the Bureau of Labor Statistics in order to capture fluctuations around the time of the recession.

Summary statistics by marginal consumption block are found in Tables 4.4 and 4.5. Table 4.4 shows that under increasing block rates, marginal consumption was in block 1 or block 2 for 75% of the observations. Those consuming in blocks 3 through 5 had above average consumption, real budgets, evapotranspiration, household size, irrigated area, graduate education, median house value, and age, and lived in less dense areas—these trends are generally more pronounced as one increases marginal consumption block.

Variable	Full Sample	Block 1	Block 2	Block 3	Block 4	Block 5
Fraction of observations	1.00	0.39	0.36	0.14	0.08	0.03
Consumption (CCF/month)	16.45	6.56	14.86	24.68	37.77	73.66
Evapotranspiration (inches/month)	3.92	3.49	3.96	4.43	4.60	4.79
Household size	4.05	3.78	4.15	4.29	4.39	4.49
Irrigated area (feet^2)	3495	1929	3143	4534	7031	14725
Real budget (2013, $/month)	367.3	365.4	365.8	369.2	375.6	382.6
Bachelors degree (%)	32.9	33.9	32.5	31.5	32.1	34.7
Masters degree (%)	4.0	3.2	3.9	4.4	5.6	8.4
Median age	42.6	41.0	42.6	43.9	45.6	48.5
Median house value (2013, $1000)	662.3	603.1	663.1	702.6	778.6	945.8
Population density (people per sq. mile)	6286	7233	6232	5448	4532	2894
Housing units in census block	691	712	702	664	625	576

Note: Represents data from October 2007 until July 2011. Includes 716,188 observations.

Table 4.4 Summary statistics under increasing block rates by marginal consumption block

Under water budgets, block sizes vary across households at any given time, and over time for any given household. In order to facilitate comparisons between the marginal consumption blocks of each rate structure, the blocks in Table A.3 were generated using pre-rate change block sizes. However, block sizes under traditional increasing block rates are often determined using the concept of a "typical" household. For example, if the vast majority of customers in a district have a household size of four, the supplier could use this information to determine the size of the "necessities" block (block 1). As such, there is merit in looking at summary statistics by marginal consumption block under water budgets using the actual block size calculation. However, that Tables 4.4 and 4.5 should not be compared directly (only Tables 4.4 and A.3).

Table 4.5 (p.17) shows that 80% of the observations were within a household's water budget (block 1 or block 2). Consumption in Blocks 2 through 5 were above average, as was household size, irrigated area, master's degree attainment, and median house value. These same households live in areas that are less dense.

Variable	Full Sample	Block 1	Block 2	Block 3	Block 4	Block 5
Fraction of observations	1.00	0.44	0.36	0.12	0.05	0.03
Consumption (CCF/month)	15.42	6.93	18.91	24.03	29.93	40.62
Evapotranspiration (inches/month)	4.31	3.97	4.67	4.46	4.40	4.25
Household size	4.05	3.88	4.16	4.20	4.25	4.29
Irrigated area (feet^2)	3495	1945	5274	3531	3771	4174
Real budget (2013, $/month)	371.5	369.9	370.3	376.5	378.0	379.6
Bachelors degree (%)	32.9	33.8	31.3	33.8	34.1	34.1
Masters degree (%)	4.0	3.3	4.4	4.6	4.9	5.2
Median age	42.6	41.1	44.0	42.9	43.2	43.6
Median house value (2013, $1000)	619.0	568.3	653.6	656.8	677.0	696.8
Population density (people per sq. mile)	6286	7164	5541	5815	5557	5296
Housing units in census block	691	714	656	707	704	700

Note: Represents data from July 2011 until March 2015. Includes 732,465 observations.

Table 4.5 Summary statistics under water budgets by marginal consumption block

Summary statistics for non-price conservation programs can be found in the Appendix (Table A.4). This information is not included in the analysis because of very low participation rates.

CHAPTER 5

EMPIRICAL ANALYSIS AND DISCUSSION

In this chapter, I examine price response and the impacts of mandatory water restrictions on water consumption.

5.1 Perceived Price

Evidence from many recent studies suggests that consumers may not respond to block pricing as standard economic theory would predict (Ito 2014). A possible explanation is that information regarding actual marginal price is costly to obtain. An alternative hypothesis is that rational consumers will respond to average price if the net benefit of determining marginal price is negative (Shin 1985). Since it is not known what price consumers actually respond to, this is treated as an empirical issue to be investigated with MNWD data. I begin with three empirical tests adapted from the labor supply and residential electricity literature.

5.1.1 Bunching Analysis

Bunching or clustering at kink points should be observed if consumers are actually responding to marginal price (Ito 2014). However, many households cannot perfectly control their water consumption, or they may not be aware of the exact location of the kink points. There may also be measurement error in the consumption data. In these cases, bunching should be expected around the kinks instead of exactly at the kinks (Saez 2010). The amount of bunching should be greater when the discrete jump in marginal price is large, the price elasticity of demand is large, or the ability to precisely control consumption is strong (Ito 2014).

In order to examine the presence of bunching, Figures 5.1 and 5.2 present yearly histograms of consumption levels for the 16,277 households in the sample. Each bin corresponds to a 1 CCF

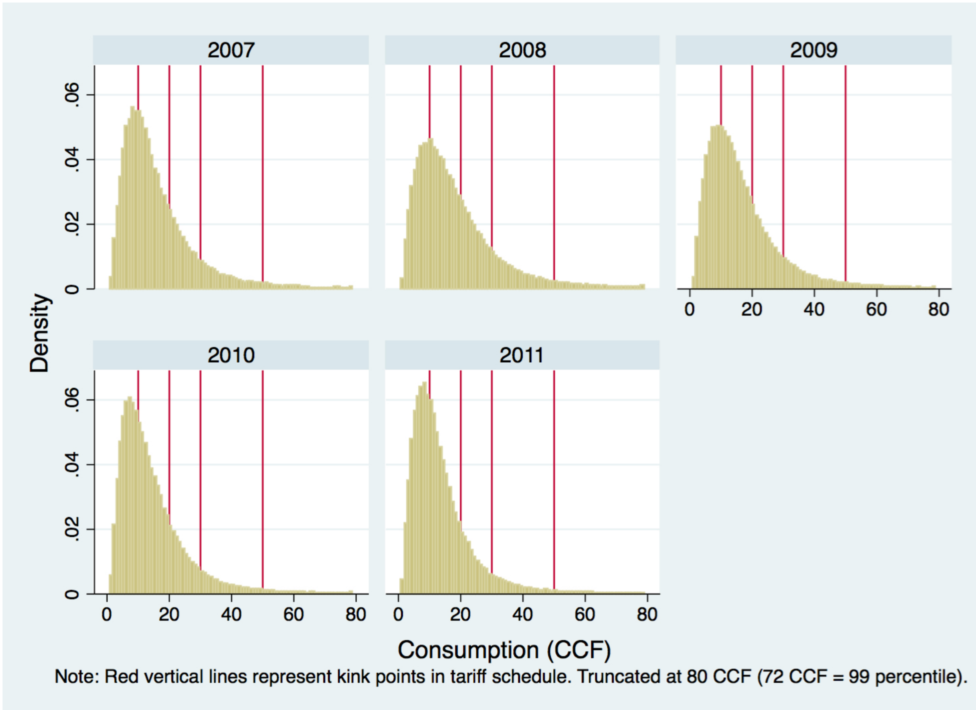


Figure 5.1 Consumption distribution under increasing block rates by year

increment in consumption, as usage is billed and reported by MNWD in integer values. The kink points in the increasing block rate schedule are indicated by vertical red lines in Figure 5.1—they are not included in Figure 5.2 because kink points under water budgets vary by household due to a large variation in lawn and household size. Even with significant marginal price increases between blocks, which are more pronounced under water budgets, all consumption distributions are quite smooth—the figures show no evidence of bunching under either pricing structure. Similarly, histograms of monthly consumption do not show any evidence of clustering at kink points (Figures A.5 and A.6 in the Appendix).

There is still a possibility that bunching is occurring under water budgets, but it is being masked by the continuous nature of irrigated area or different household sizes—either could smooth out bunching in the aggregate. Therefore, the sample was broken down into the most common household sizes—the mean and median block sizes that each group would face were then calculated. The histograms by household size are presented in Figure A.7, and again show no evidence of clustering. Approximately 78% of the sample have a household size of four, followed by 13%

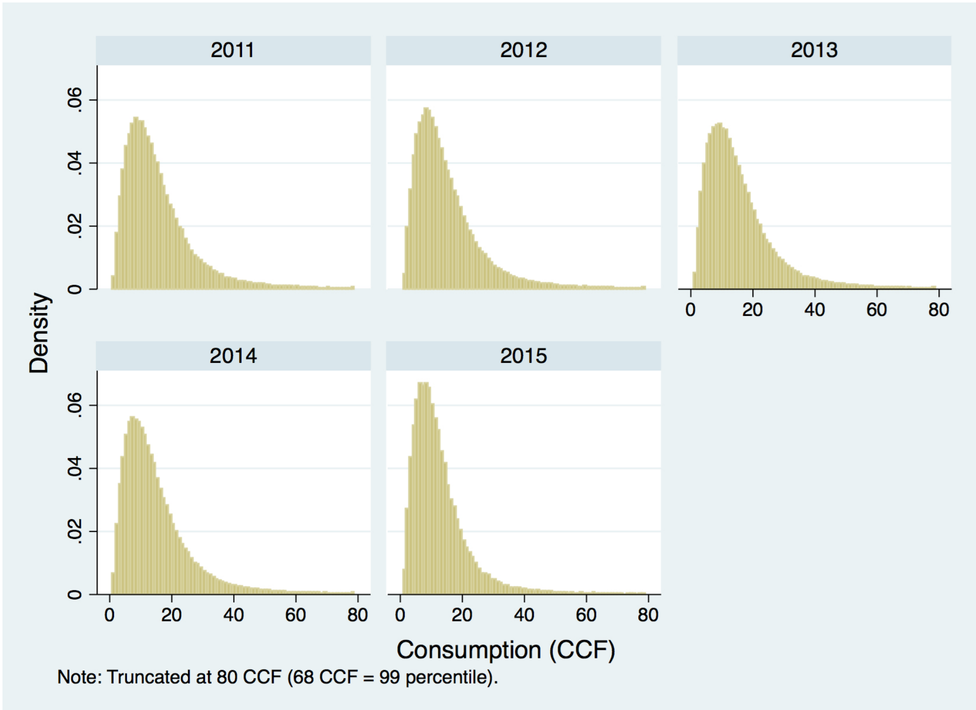


Figure 5.2 Consumption distribution under water budgets by year

with a household size of three, 5% with a household size of five, and 3% with a household size of six. The smoothest distributions are for households of size three and four, which can be attributed to the fact that they have the largest share of observations.

A final bunching examination involved the scaling of quantities in order to have a standard measure across time and households. The calculation involved dividing block usage by block allocation for the marginal consumption block in a given month—an integer factor was then added: 1 if marginal consumption was in block 2, 2 if in block 3, and so on. For example, if a household's marginal consumption was in block 4, and their usage and allocation were 3 and 12, respectively, their scaled quantity for that month would be 3.25. The results for this exercise can be found in Figures A.8 and A.9. They suggest that there is bunching under water budgets (Figure A.9), but only at the first and second kink points. Intuitively, it is unclear why there would be bunching at these kink points, especially since the discrete jumps in price are not very large.

A possible explanation for the bunching found in Figure A.9 is that MNWD rounded monthly consumption to integer values for billing purposes and simplicity. If households consume slightly below the kink point but are then rounded up, the bunching is artificial. This same practice may be a contributing factor to the lack of bunching found in previous exercises. Ignoring the errors that rounding can produce for a moment, the lack of a counterfactual or control group, such as the one created by Ito's (2014) spatial discontinuity or a switch from uniform rates (no kinks) to block rates, makes it quite difficult to further examine the presence of bunching.

Nevertheless, the vast majority of the evidence from these exercises suggests that there is no bunching under either increasing block rates or water budgets. According to Ito (2014), the absence of bunching implies two possibilities. First, consumers may be responding to marginal price with close to zero elasticity. Second, consumers may be responding to an alternative price—this possibility will be examined in Section 5.1.3.

5.1.2 How Predictable is Consumer Usage and Marginal Price?

The degree to which the standard estimation of residential water demand captures consumer behavior depends in part on the consumer's predictability of their own demand. This uncertainty can also affect how a constrained-optimizing consumer will respond to block rates (Borenstein 2009). In order to examine this uncertainty, Borenstein recommends the following regression to be estimated for each household separately:

$$ln(Monthly\_Use)_t = \sum_{j=1}^{12} \alpha_j Month_j + \beta ln(Monthly\_Use)_{t-1} + \gamma_1 t + \gamma_2 t^2 + \gamma_3 t^3 + \varepsilon, \quad (5.1)$$

where $Month_j$ are twelve month-of-year dummy variables. The root mean squared error (RMSE) of this regression is a measure of consumer price variability because price and quantity are simultaneously determined. It is in turn a component of predictive ability. The "RMSE could be an upward biased estimate of consumer uncertainty if consumers have better information about this month's consumption than is revealed by their typical seasonal pattern, last month's consumption, and a cubic function in time. It could be biased down because some consumers pay far less attention to consumption than this regression suggests" (Borenstein 2009, p.18).

The results from these regressions are in Table 5.1—for the sake of comparison, Borenstein finds a mean RMSE of 0.186 and a median of 0.159 for residential electricity consumers in California. The mean RMSE for the full sample suggests that the average consumer will be able to predict their consumption with a standard error of approximately 27%. This would imply that it is quite difficult to infer price responsiveness of demand from changes around discontinuities in marginal price. Moreover, it shows that even under the most vigilant optimizing behavior, households would be unable to choose consumption based on ex post marginal price because exogenous shocks to demand make it virtually impossible for consumers to know what marginal price they would face.

Statistic	Under Increasing Block Rates	Under Water Budgets	Full Sample
Mean RMSE	0.2697	0.2628	0.2694
(Std. Dev.)	(0.0934)	(0.0933)	(0.0926)
Median RMSE	0.2530	0.2463	0.2531

Note: The root mean squared error (RMSE) was estimated separately for each household.

Table 5.1 Estimates of consumer uncertainty

An area of further research will be to uncover what attributes are driving this uncertainty. Other than household size and irrigated area, the covariates in this dataset are by census block group and are therefore not specific enough to determine what types of households have the largest standard error or what affects predictive ability. This will be examined through primary data collection in this water district or by identifying another dataset with more detailed household characteristics.

5.1.3 Shin's Test of Price Perception

Opaluch (1982) was the first to provide a test to determine whether a marginal or average price model is more appropriate. Shin (1985) argued that the assumption inherent in previous water demand literature, that consumers are well-informed, is too strong. He extended the examination to include a component that captures imperfect information, defined as perceived price, which is a function of both average and marginal price. The specification of water use in this section follows from the conventional water demand analysis and utilizes Shin's (1985) perceived price modification. This results in:

$$w = f(p^*,\ \tilde{y},\ \mathbf{z}), \tag{5.2}$$

where the monthly demand for water (w) depends on the perceived real price of water (p^*), the household's budget for utilities and related expenditures (or virtual income, $\tilde{y}$), and household and environmental characteristics that are thought to affect water usage ($\mathbf{z}$).

Perceived price, p^*_{it}, for household (i) in month (t) is constructed as a function of marginal price, average price, and a price perception parameter, k, such that:

$$p^*_{it} = MP_{it}(AP_{i,t-1}/MP_{it})^k, \tag{5.3}$$

where MP is the marginal price of water per CCF, AP is the average price per CCF, and k is a fixed parameter designed to measure price perception. I will use average price from the previous month, which will be explained in greater detail below. If the consumer responds only to marginal price, then $k = 0$. If the consumer responds only to average price, then $k = 1$. If the consumer's perceived price lies between marginal and average price, which may be due to the fact that the consumer stops searching for information when expected marginal benefit equals expected marginal cost, then $0 < k < 1$. Nieswiadomy and Molina (1991) note that under increasing block rates, $k > 1$ implies that $P^* < AP < MP$ and $k < 0$ implies that $P^* > MP > AP$. While it is expected that k lies in the unit interval, no restrictions were placed on it because of how the model is estimated in (5.4).

I assume that water consumption (w) is a double logarithmic function of explanatory variables for household (i) in month (t), which is the most common form found in the literature; this is due to the extreme right skewness of water demand. When estimating the price perception parameter, Shin (1985) and Nieswiadomy and Molina (1991) use a partial adjustment model. In Nieswiadomy and Molina's model, the lagged values of average price and consumption from the previous month are included as right hand side variables. Their argument is that the previous month's average price is embedded in the perceived price that consumers are reacting to in the current month. Therefore, the estimating equation becomes:

$$
\begin{aligned}
ln(w_{it}) = \psi_1 ln(MP_{it}) + \psi_1 k ln(AP_{i,t-1}/MP_{it}) + \psi_2 ln(w_{i,t-1}) + \psi_3 ln(\tilde{y}_{it}) \\
+ \pi(seasonal) + \phi(timetrend) + \delta evap_{it} + \mathbf{z}_i + \eta_{it}
\end{aligned}
\tag{5.4}
$$

where (seasonal) are three season dummy variables, $evap_{it}$ is the weather faced by household (i) in time (t), $\mathbf{z}_i$ represents household fixed effects, and η_{it} is the idiosyncratic error term. Equation (5.4) is estimated for each rate structure separately with fixed effects and fixed effects-IV models.[1] The primary value of interest is the price perception parameter, k, and the results can be found in Tables A.5 and A.6.

Using only the fixed effects-IV models, k was estimated to be 0.10 under increasing block rates and -0.29 under water budgets.[2] The increasing block rate k value implies that consumers perceived price lies between marginal and average price, while under water budgets, it is larger than both marginal and average price. The k estimate that Nieswiadomy and Molina (1991) obtained for increasing block rates in Denton, Texas was -0.43. This test was never performed for households facing water budgets, so there is no baseline estimate to compare my results with. However, both estimated k values are consistent with the notion that under complex pricing structures, households often respond to an alternative price.

5.2 Mandatory Water Restrictions

MNWD implemented mandatory water restrictions from April 2009 until April 2011. During this time, they limited outdoor watering to three days per week, with a daily maximum of 15 minutes. In order to visualize the impact of these restrictions (Figure 5.3), households were grouped by

[1] Adapted from McFadden et al. (1977) and Nieswiadomy and Molina (1991), the first stage involves regressing observed water demand on the marginal prices at preset quantities, and using the predicted consumption to compute predicted marginal price and virtual income. In the second stage, these predicted values are used as right-hand-side variables in the demand equation. [2] 95% CI [0.068, 0.137] and [-0.296, -0.274] for k under increasing block rates and water budgets, respectively.

irrigated area quintiles. In the MNWD service area, the primary use of outdoor water is lawns, and the table below provides context for the distribution of lawn sizes:

	Mean	Std. Dev.	Min	10th	25th	Median	75th	90th	Max
Irrigated Area (sq.ft.)	3495	4654	0	300	977	2500	4300	10393	156351

Note: Irrigated area is time-invariant.

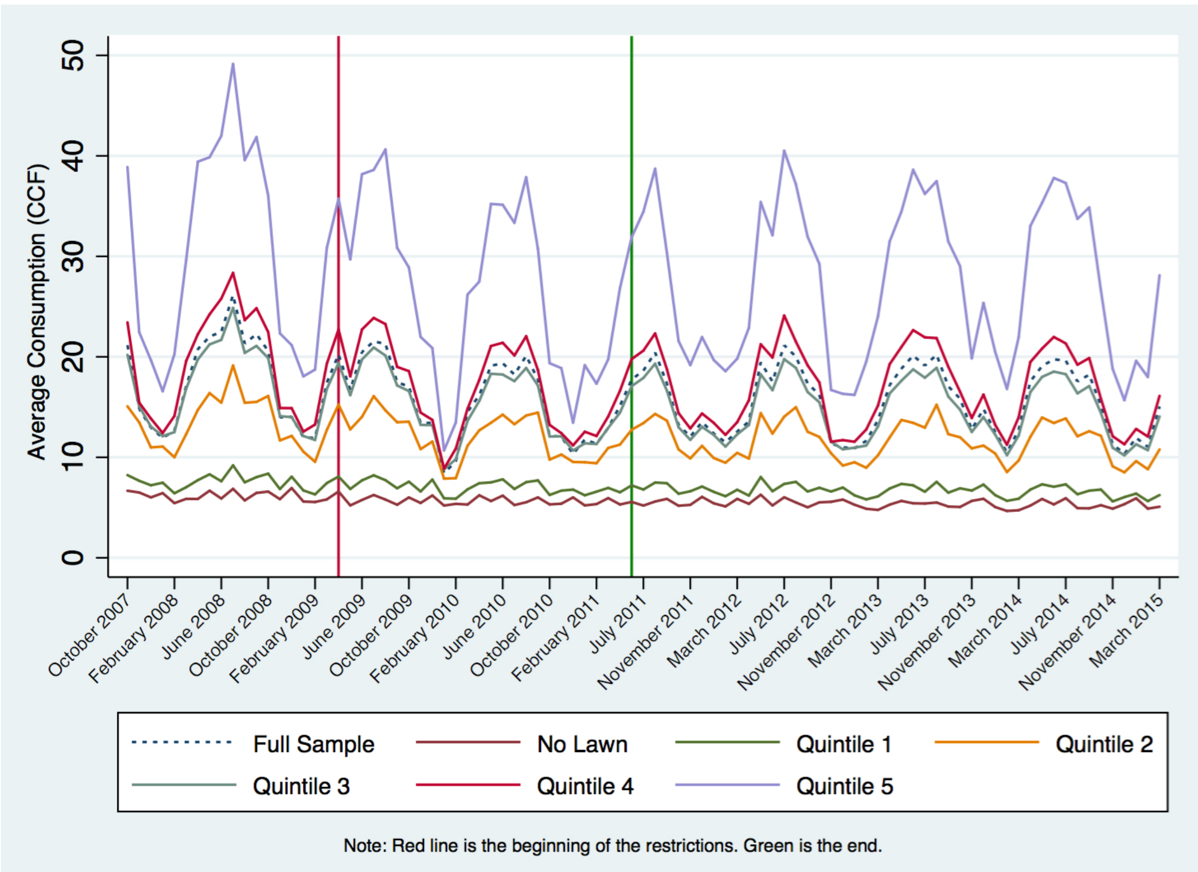


Figure 5.3 Average consumption by lawn size quintile

5.2.1 Impact of the Mandate

There were no water restrictions prior to the mandate, and the limitations on outdoor water usage were eased after a two year period. In order to examine their impact on water consumption, I split the sample into two groups: (1) households with lawns (the "treatment" group); and (2) those without lawns (the "control" group).[3] In order to see the differential impact by lawn size, the "treatment" group was again split into quintiles. The full specification for this estimation is:

$$
\begin{aligned}
ln(w_{it}) = \alpha lawn_{iq} + \beta_1 restrictions + \beta_2 postrestrictions + \gamma(lawn_{iq} * restrictions) \\
+ \xi(lawn_{iq} * postrestrictions) + \delta evap_{it} + \phi(timetrend) + \mathbf{z}_i + \nu_{it},
\end{aligned}
\tag{5.5}
$$

where $lawn_{iq}$ is the treatment dummy variable equal to 1 if household (i) has lawn size within quintile (q), *restrictions* is a dummy variable equal to 1 during the period of mandatory restrictions (April 2009 to April 2011), *postrestrictions* is a dummy variable equal to 1 for the period after the restrictions were eased (May 2011 to March 2015), $(lawn_{iq} * restrictions)$ and $(lawn_{iq} * postrestrictions)$ are the interaction terms, $\mathbf{z}_i$ represents household fixed effects, and ν_{it} is the idiosyncratic error term—γ and ξ are the parameters of interest.

The results can be found in Table 5.2 and they suggest that there was a 5-6% reduction in overall consumption following the mandate—this is based on the most basic specifications (models 1, 2, 5 and 6) where a household is classified as either having a lawn or not. Models 3, 4, 7, and 8 split up the basic treatment group (lawn) into quintiles. The coefficients on the interaction terms of restriction dummy and lawn size quintile show that households responded differently to the mandate. Those with larger lawns reduced their consumption more during the restrictions period relative to the reference group of quintile one. The results from a different grouping of lawn size can be found in Table A.7, and they provide for similar conclusions.

When analyzing these results, it is important to remember that California is currently in its fifth year of a severe drought. During the study period, several statewide informational campaigns and non-price conservation programs could have also affected usage. More specifically in the MNWD service area, a new pricing structure, the aforementioned water budgets, was implemented

[3] I first separated evapotranspiration into quintiles by year, as hotter months induce more (outdoor) consumption. I then produced scatterplots of water demand (y-axis) and irrigated area (x-axis) by the evapotranspiration quintiles for the pre-mandate, mandate, and post-mandate periods. I included a horizontal line to capture a threshold amount equivalent to watering three days per week, 15 minutes each day, for an entire month (several thresholds were calculated for different spigot/ sprinkler quantities). The motivation for this exercise is that there should be a binding amount of water in which certain households would have to change their behavior. I expected to see a flattening at the threshold amount during the mandate period, but unfortunately, this exercise did not produce any meaningful results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)
restrictions	0.0319**	-0.117***	0.0229***	-0.128***	-0.0367**	-0.0342**	-0.0460***	-0.0440***
	(0.0113)	(0.0131)	(0.00364)	(0.00436)	(0.0112)	(0.0132)	(0.00353)	(0.00455)
lawn*postrestrictions	-0.0508***	-0.0582***			-0.0488***	-0.0581***		
	(0.0114)	(0.0132)			(0.0114)	(0.0132)		
postrestrictions		-0.207***		-0.211***		-0.00156		-0.00179
		(0.0189)		(0.00588)		(0.0190)		(0.00622)
lawn*postrestrictions		-0.0100				-0.0128		
		(0.0190)				(0.0190)		
quint2*restrictions			-0.0315***	-0.0477***			-0.0245***	-0.0477***
			(0.00482)	(0.00566)			(0.00480)	(0.00566)
quint3*restrictions			-0.0376***	-0.0535***			-0.0345***	-0.0534***
			(0.00476)	(0.00571)			(0.00476)	(0.00571)
quint4*restrictions			-0.0566***	-0.0599***			-0.0547***	-0.0599***
			(0.00485)	(0.00581)			(0.00484)	(0.00581)
quint5*restrictions			-0.0774***	-0.0664***			-0.0776***	-0.0664***
			(0.00495)	(0.00595)			(0.00495)	(0.00595)
quint2*postrestrictions				-0.0213**				-0.0325***
				(0.00754)				(0.00753)
quint3*postrestrictions				-0.0219**				-0.0264***
				(0.00764)				(0.00762)
quint4*postrestrictions				-0.00474				-0.00729
				(0.00773)				(0.00772)
quint5*postrestrictions				0.0147				0.0155*
				(0.00782)				(0.00782)
evapotranspiration	0.137***	0.148***	0.137***	0.148***	0.146***	0.146***	0.146***	0.146***
	(0.000700)	(0.000710)	(0.000701)	(0.000711)	(0.000708)	(0.000709)	(0.000708)	(0.000709)
ln(income)	-0.233***	-0.296***	-0.224***	-0.269***	0.0845**	0.0640*	0.0980***	0.107***
	(0.0314)	(0.0281)	(0.0316)	(0.0285)	(0.0281)	(0.0294)	(0.0282)	(0.0298)
timetrend					-0.0440***	-0.0417***	-0.0440***	-0.0421***
					(0.000443)	(0.000640)	(0.000443)	(0.000639)
_cons	3.312***	3.797***	3.258***	3.635***	1.638***	1.756***	1.558***	1.501***
	(0.186)	(0.166)	(0.187)	(0.168)	(0.166)	(0.173)	(0.166)	(0.176)
N	1448653	1448653	1448653	1448653	1448653	1448653	1448653	1448653

Notes: All models include household fixed effects. All lawn dummy variables dropped due to collinearity and are not reported. Quintile 1 (quint1) is reference category. Standard errors are clustered at household level and in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.2 Estimates of the impact of mandatory water restrictions

two months after the restrictions were eased (in July 2011). This potentially contaminates the post restriction results, and therefore it cannot be determined whether habit formation due to the mandate actually occurred. In order to minimize this potential confounding and be more confident in the results, a time trend term was added to models 1 through 4 (which generated 5 through 8). The coefficient on this term shows that consumption decreased by about 4% per year. The results from these two sets of models are quite similar, which suggests that the mandate actually changed the consumption behavior of households with larger lawns more than those with smaller lawns.

5.3 Structural vs. Reduced-Form Estimation

The price elasticity of demand is a key variable of interest in the water demand literature, as water suppliers use price to induce conservation and generate revenue. As mentioned in Chapter 2, researchers have utilized DCC models and IV techniques to address the endogeneity present in block pricing. In general, the DCC approach is considered to be better than IV methods because of their large-sample properties of consistency, asymptotic normality, and asymptotic efficiency (Moffitt 1986). They are also able to model both the discrete and continuous choice inherent in block rates, and are consistent with utility theory. Additionally, IV methods do not account for the potential bunching around kink points. However, Olmstead (2009) points out that "cheaper" models, such as these reduced-form methods, may be appropriate for certain purposes. The downside to both techniques is that they assume consumers know and are responding to the marginal price signals.

Structural estimation using the DCC model and the same dataset has been conducted by Kenneth Baerenklau and Kurt Schwabe for an internal MNWD report. Their maximum likelihood estimation results can be found in Table A.8. Because structural estimation has already been carried out, traditional IV techniques are explored instead. Very few previous studies have had the opportunity to make such a methodological comparison, and the DCC results will be used as baseline estimates for the exercise that follows.

The idea behind these IV methods is to instrument the marginal or average price with various summary statistics of the nonlinear price schedule. "This amounts to approximating the nonlinear price schedule with a linear function of the marginal prices. This procedure is valid to the extent that this linear approximation holds (so that the observed marginal prices are strongly correlated with the instruments) and to the extent that the error term is uncorrelated with the characteristics of the tariff structure used as instruments (so that the exclusion restriction is satisfied)" (Szabo 2015, p.16).

Four instruments were examined, and they include two of the most common found in the literature (1 & 2) and two more recent ones (3 & 4):

(1) Wilder and Willenborg (1975): the first stage involves regressing observed marginal price on the characteristics of the price structure (fixed charges and the full set of marginal prices), as well as all of the exogenous covariates. The predicted values of price and the exogenous covariates are used in the second stage.

(2) McFadden, Puig, and Kirschner (1977): the first stage involves regressing observed water demand on the marginal prices at preset quantities, and using the predicted consumption to compute predicted marginal price and virtual income. In the second stage, these predicted values are used as right-hand-side variables in the demand equation.

(3) Olmstead (2009): the observed marginal price and virtual income are instrumented by the marginal prices at preset quantities (the kink points).

(4) Szabo (2015): the average price is instrumented by the marginal prices of consuming at preset quantities (the most common kink points).

The basic analytical model used to describe household water demand in this section is:

$$ln(w_{it}) = \alpha ln(p_{it}) + \beta ln(\tilde{y}_{it}) + \mathbf{z}_{it}\gamma + \varepsilon_{it} \tag{5.6}$$

where w_{it} is the monthly water use of household (i), p_{it} is the price of water faced by the household (either marginal or the instrument), $\tilde{y}_{it}$ is virtual income, $\mathbf{z}_{it}$ is a vector of household, economic and environmental characteristics that are thought to affect usage, and ε_{it} is the idiosyncratic error term.

For ease of comparison with Table A.8, the same exogenous variables used in the DCC models were included in the IV models. Baerenklau and Schwabe considered a different approach for each rate structure: (1) the pre-rate change model utilized household fixed effects; and (2) the post-rate change model used time-invariant socio-demographic characteristics. The pre- and post-rate change results can be found in Table 5.3 and 5.4, respectively.[4] The results are quite sensitive to the choice of instrument, exogenous variables, and specification.

What is immediately startling is the fact that all significant price parameter estimates, 6 of the 8 elasticities, are positive. Moreover, under a given price structure, the models produce relatively similar estimates for price. For the sake of comparison, the DCC model in Table A.8 generates a price elasticity of -0.009 under increasing block rates and -3.073 under water budgets.

[4] The first stage estimates and results from testing for weak instruments are available upon request. All four instruments produced F-statistics greater than 10 under both rate structures.

	(OLS)	(Szabo IV)	(Olmstead IV)	(McFadden IV)	(Wilder IV)
	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)
spring	0.0653***	0.140***	0.114***	0.0963***	0.148***
	(0.00109)	(0.00124)	(0.00141)	(0.00155)	(0.00131)
summer	0.0139***	0.236***	0.191***	0.163***	0.260***
	(0.00146)	(0.00171)	(0.00208)	(0.00197)	(0.00169)
fall	-0.00473***	0.236***	0.204***	0.191***	0.257***
	(0.00139)	(0.00159)	(0.00189)	(0.00153)	(0.00157)
restrictions	-0.0713***	0.0513***	-0.0166***	-0.0796***	0.0724***
	(0.00119)	(0.00139)	(0.00151)	(0.00172)	(0.00146)
evapotranspiration	0.0954***	0.127***	0.140***	0.161***	0.113***
	(0.000519)	(0.000568)	(0.000666)	(0.000666)	(0.000702)
timetrend	-0.137***	0.0451***	-0.00593***	-0.0528***	0.0609***
	(0.00103)	(0.00120)	(0.00145)	(0.000972)	(0.00120)
ln(income)	7.165***	18.88***	9.101***		20.95***
	(0.0663)	(0.0828)	(0.144)		(0.0924)
ln(predicted_income)				-3.633	
				(2.849)	
lnap		0.543***			
		(0.00860)			
ln(mp)	1.896***		0.287***		
	(0.00747)		(0.0100)		
ln(predicted_mpM)				-0.599	
				(0.412)	
ln(predicted_mpW)					0.540***
					(0.0107)
_cons	-40.06***			23.59	-122.3***
	(0.394)			(16.93)	(0.548)
N	716188	716188	716188	716188	666864

Note: All models include household fixed effects.
ap is for average price. mp is for marginal price. M is for McFadden. W is for Wilder.
Standard errors are clustered at the household level and in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.3 Pre-rate change models

One relatively simple explanation for this apparent contradiction with economic theory and the DCC model is that these instruments may not be correcting for the endogeneity present in increasing block rates. A more fundamental explanation is that this is a different type of endogenetiy than that found in say the education literature. Water usage and price are intrinsically connected variables, and an instrument correlated with price is by necessity correlated with usage. Therefore, I conclude that IV techniques may not be appropriate for water demand estimation under block rates.

	(OLS)	(Szabo IV)	(Olmstead IV)	(McFadden IV)	(Wilder IV)
	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)
spring	0.0215***	0.110***	-0.0633***	0.116***	0.101***
	(0.00122)	(0.00191)	(0.0139)	(0.00200)	(0.00207)
summer	-0.148***	0.178***	0.0338**	0.182***	0.130***
	(0.00166)	(0.00237)	(0.0126)	(0.00226)	(0.00396)
fall	-0.198***	0.188***	0.284***	0.189***	0.126***
	(0.00175)	(0.00194)	(0.00610)	(0.00158)	(0.00465)
restrictions	-0.158***	-0.0800***	0.0593***	-0.0745***	-0.0987***
	(0.00110)	(0.00167)	(0.00560)	(0.00179)	(0.00218)
evapotranspiration	0.0663***	0.158***	0.217***	0.153***	0.134***
	(0.000621)	(0.000905)	(0.00593)	(0.000982)	(0.00188)
timetrend	-0.280***	-0.0523***	0.0538***	-0.0540***	-0.111***
	(0.00113)	(0.00128)	(0.00452)	(0.000981)	(0.00402)
education	0.215***	0.580***	-9.207***	0.834***	0.501***
	(0.0265)	(0.0455)	(0.478)	(0.0436)	(0.0467)
householdsize	0.0839***	0.158***	0.110***	0.160***	0.163***
	(0.00325)	(0.00517)	(0.0270)	(0.00530)	(0.00543)
ln(lawn)	0.135***	0.334***	-0.0819***	0.345***	0.289***
	(0.00272)	(0.00389)	(0.0247)	(0.00387)	(0.00493)
ln(income)	0.0621***	0.536***	21.01***		0.360***
	(0.0160)	(0.0286)	(0.870)		(0.0309)
ln(predicted_income)				2.478	
				(2.904)	
ln(ap)		0.0333**			
		(0.0115)			
ln(mp)	3.126***		0.733***		
	(0.0118)		(0.0344)		
ln(predicted_mpM)				0.158	
				(0.419)	
ln(predicted_mpW)					0.787***
					(0.0510)
_cons	0.949***	-4.532***	-119.5***	-16.21	-2.971***
	(0.0966)	(0.166)	(4.908)	(17.26)	(0.193)
N	701932	701932	701932	701932	653752

Note: ap is for average price. mp is for marginal price. M is for McFadden. W is for Wilder.
Standard errors are clustered at the household level and in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.4 Post-rate change models

CHAPTER 6

CONCLUSION

One of the principal tools that water suppliers have to induce conservation is price structure. With an increase in the frequency of extreme weather events, a reduction in the reliability of current water supplies, a growing concern about the environmental effects of new supply projects, and legal constraints with regards to pricing, these suppliers are turning to more complex rate structures and non-price conservation initiatives to achieve reductions in demand, maintain fiscal stability, and promote equity. The Moulton Niguel Water District utilized both of these strategies, implementing increasing block rate water budgets and mandatory outdoor water restrictions between 2007 and 2015.

In order to examine price responsiveness under block rates, much of the residential water demand literature assumes that consumers are perfectly informed and perfectly optimizing on the margin. However, there is a growing body of evidence that finds that consumers often do not respond to their true marginal price. In fact, many consumers are inattentive to the details of a given pricing schedule and are quite uncertain about their consumption patterns. There are many possible reasons for this type of behavior, such as a lack of information about the pricing schedule and the fact that bills aggregate many disparate individual decisions yet represent a small share of total income. As many economic policies utilize block rates, understanding how consumers actually respond to them is critical.

To the best of my knowledge, this is one of the only papers to examine price perception when facing block rates for water, and I find strong evidence that households are not responding to marginal price. These consumers instead respond to a function of marginal and average price. Additionally, the average household in my sample predicts their consumption with a standard error of approximately 27%. This implies that it is quite difficult to infer price responsiveness of demand from changes around discontinuities in marginal price. Given the cost of implementing increasing block rates, specifically water budgets, this suboptimization behavior suggests that there may be more cost-effective price structures and ways to induce conservation. One alternative that several suppliers use is command-and-control policies, which can still introduce cost and efficiency concerns. I find that mandatory outdoor water restrictions decreased overall consumption in the district by approximately 5%. When households were then grouped by lawn size, those with larger lawns reduced their consumption more during the restrictions period.

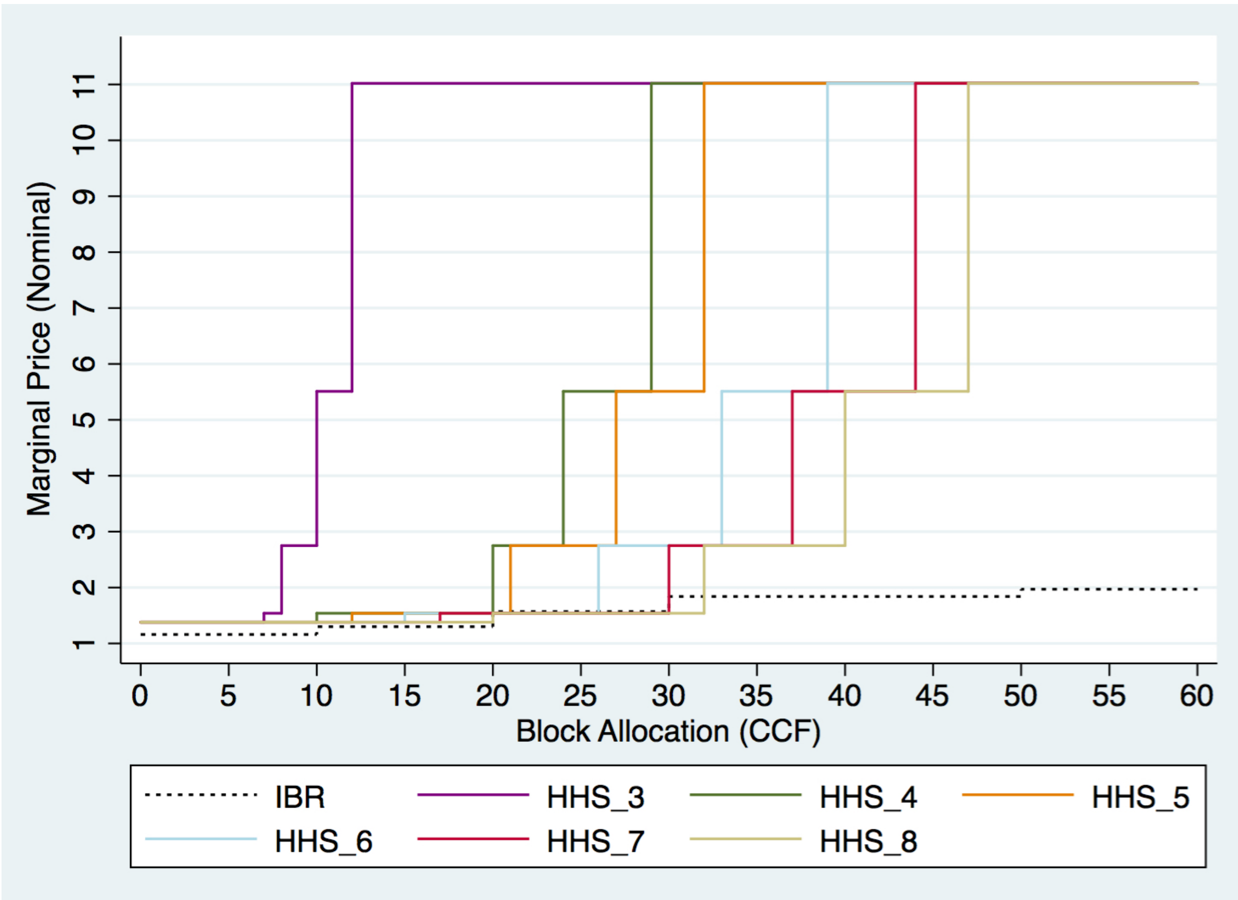
The last exercise conducted in this paper was the use of traditional IV methods to address the endogeneity present under block pricing. I find that the parameter estimates are very sensitive to the choice of instrument, exogenous variables, and specification. Moreover, positive elasticities were obtained. Two possible reasons for this apparent contradiction with economic theory and the DCC model is that either the instruments did not correct for the endogeneity, or that the intrinsic connection between water usage and price may imply that IV techniques are inappropriate for water demand estimation under block rates.

Several components of this paper will be researched further in the near future. They include: (1) determining how and which types of consumers are able to minimize the error in their predictive ability; (2) examining clustering under water budgets with alternative approaches; (3) investigating the effectiveness of non-price conservation programs, and how knowledge or information is spread in participating communities; (4) comparing structural and reduced-form approaches in other water districts; (5) studying the non-convexities present in the water budget rate structure; (6) determining if information provision helps consumers respond to marginal price; and (7) examining various formulations of an optimal pricing problem.

APPENDIX

APPENDIX

A.1 Figures



Note: IBR represents block sizes under increasing block rates, which were the same for every household, while HHS_# is the typical water budget allocation for a given household size in 2011. Under water budgets, I calculated Block 1 using 30 days for a billing cycle; the Block 2 calculation used mean irrigated area for each household size and mean evapotranspiration for the sample; Blocks 3 and 4 are 125% and 150%, respectively, of the sum of Blocks 1 and 2.

Figure A.1 Typical block allocation by household size

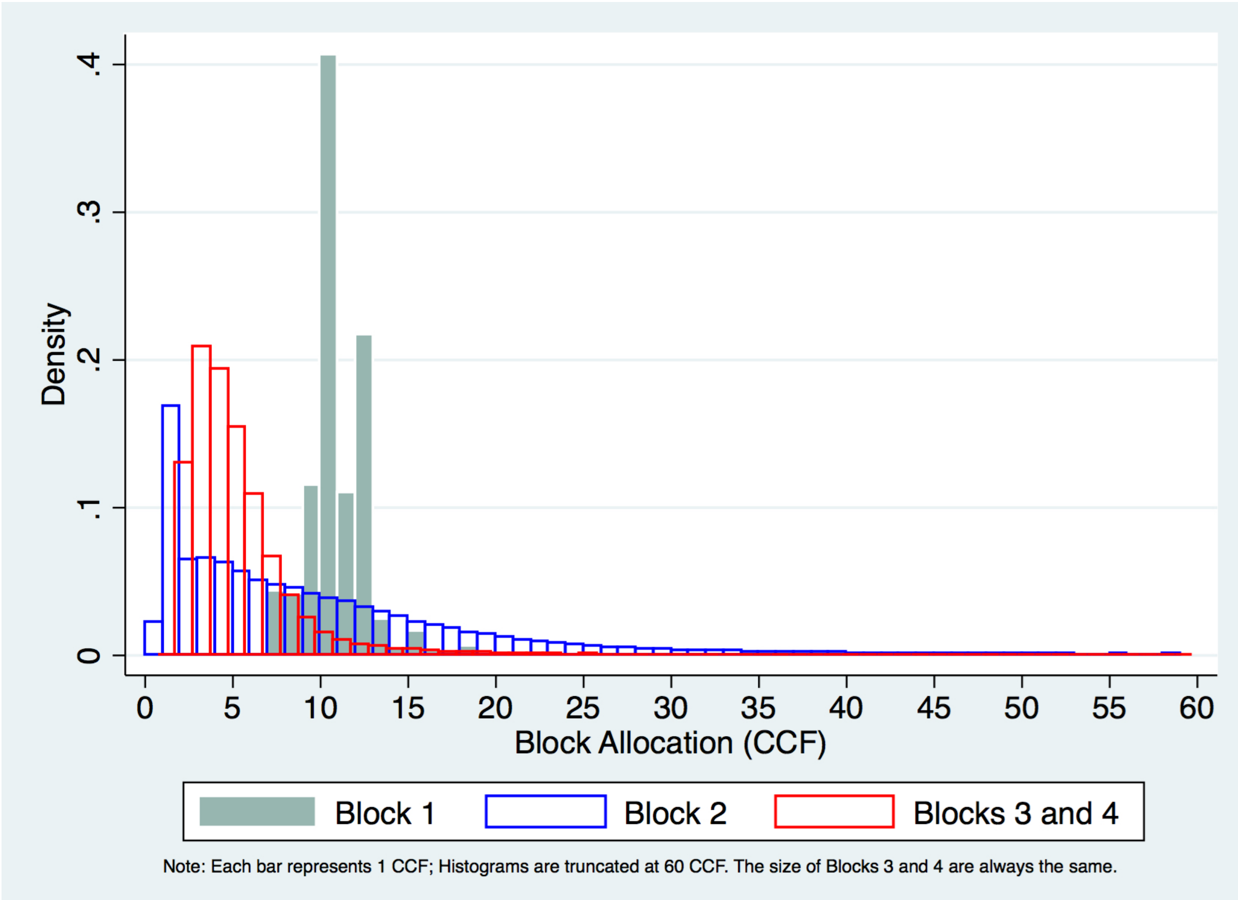


Figure A.2 Histogram of block sizes under water budgets in 2012

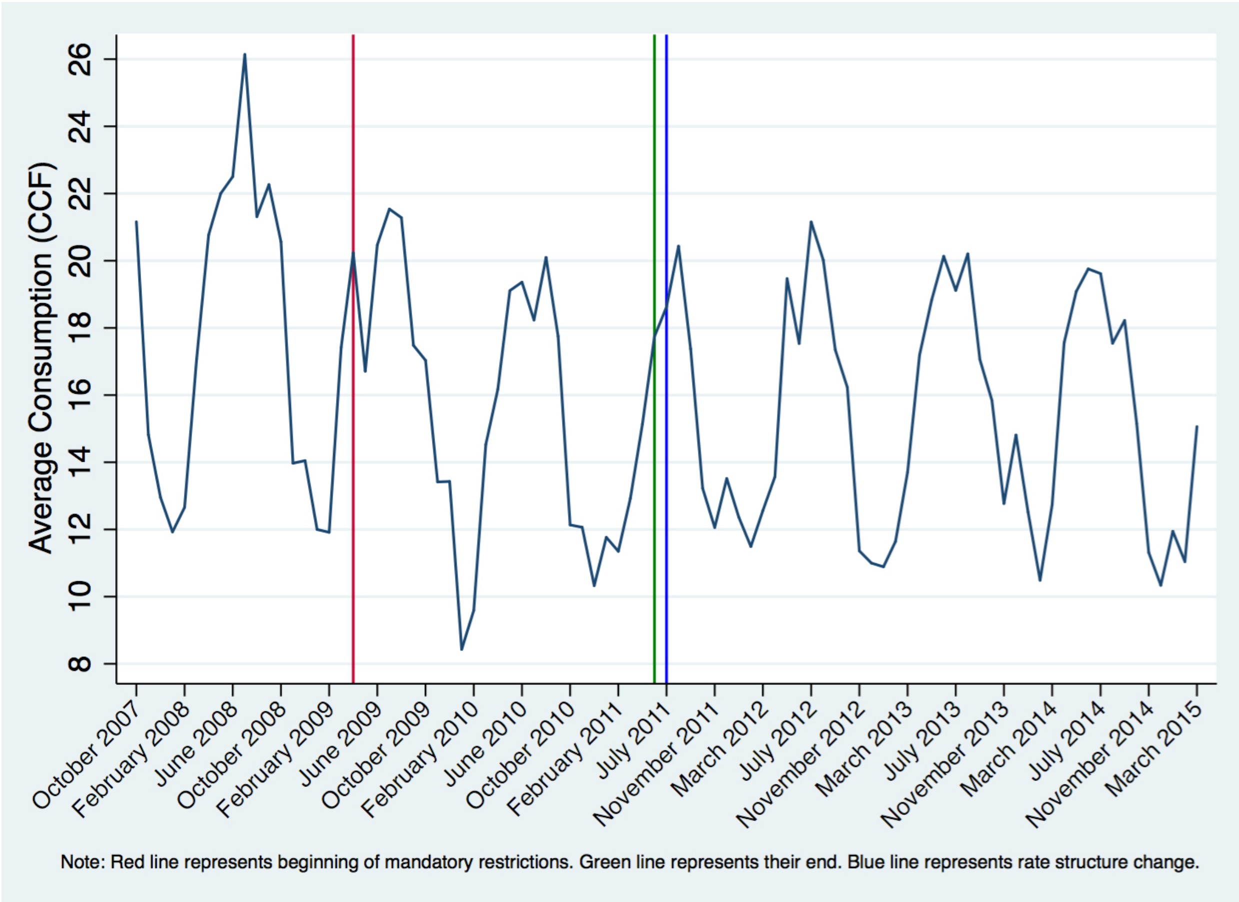


Figure A.3 Average consumption by month

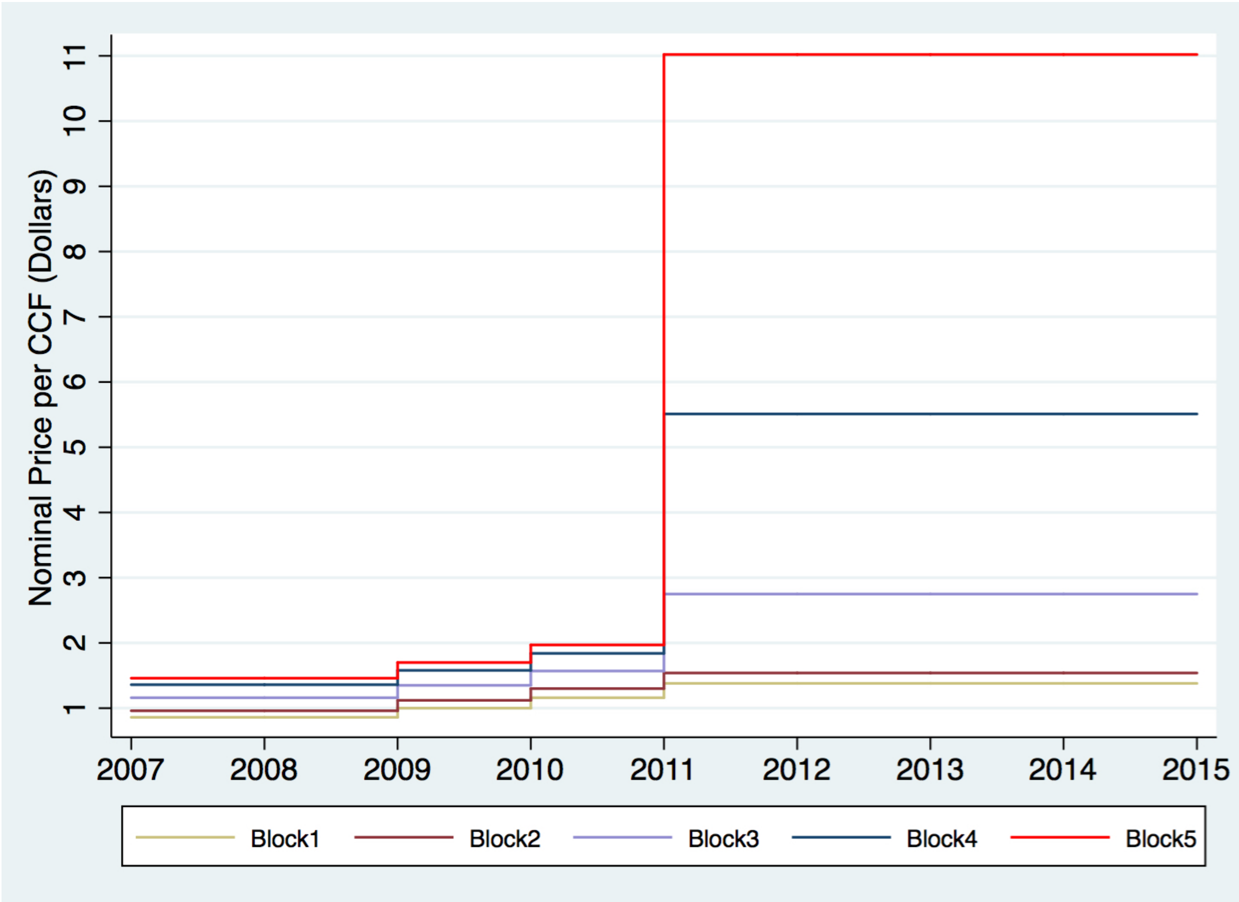


Figure A.4 Nominal rate changes

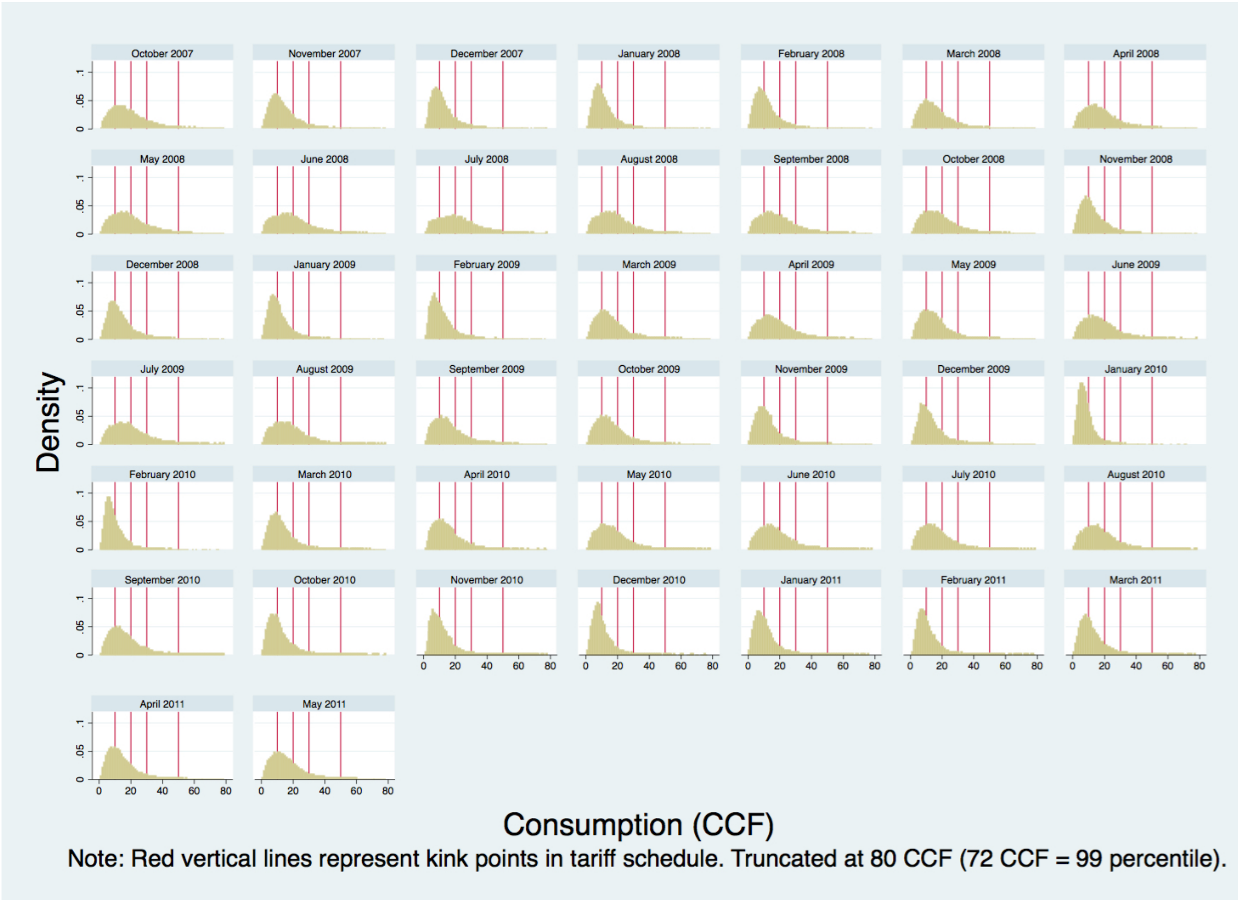


Figure A.5 Consumption distribution under increasing block rates by month

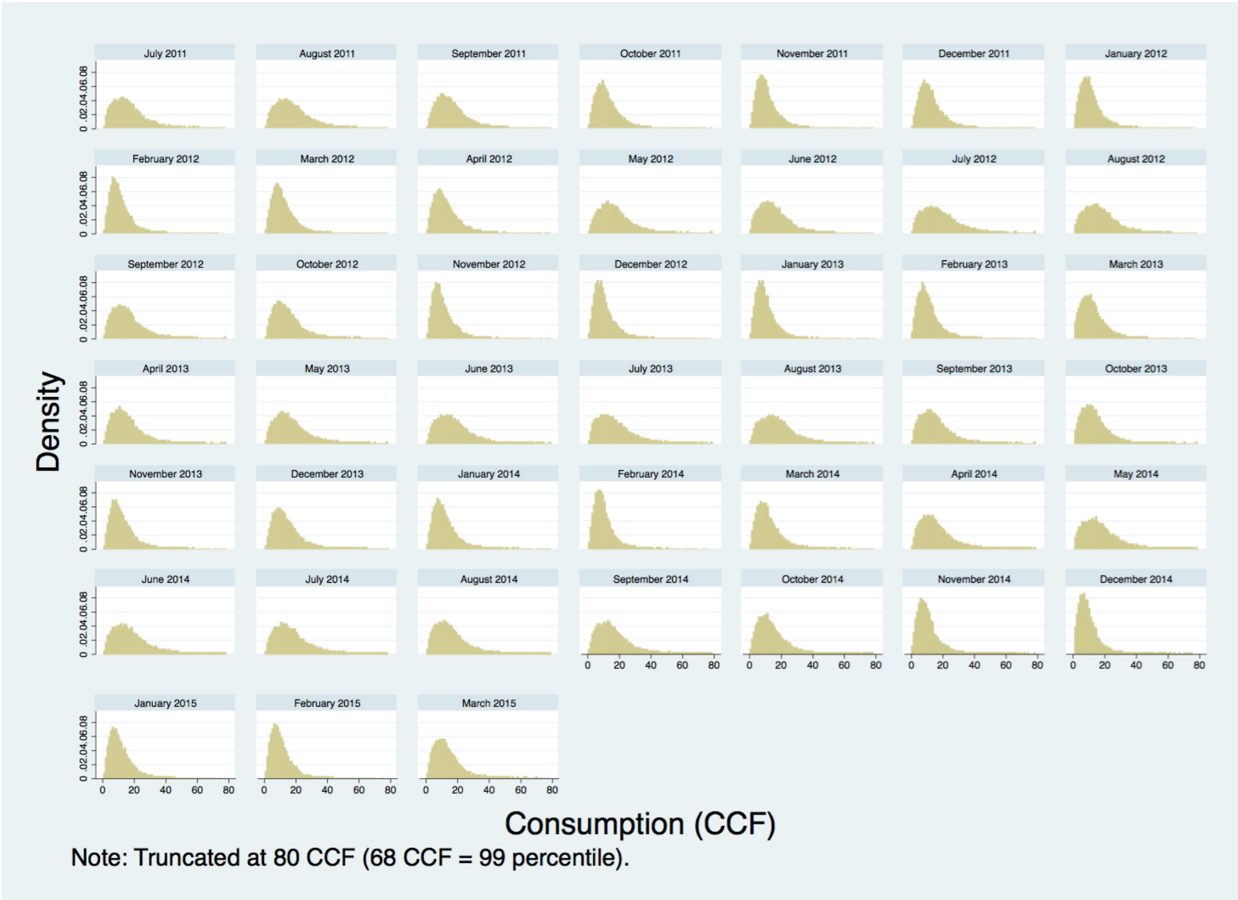
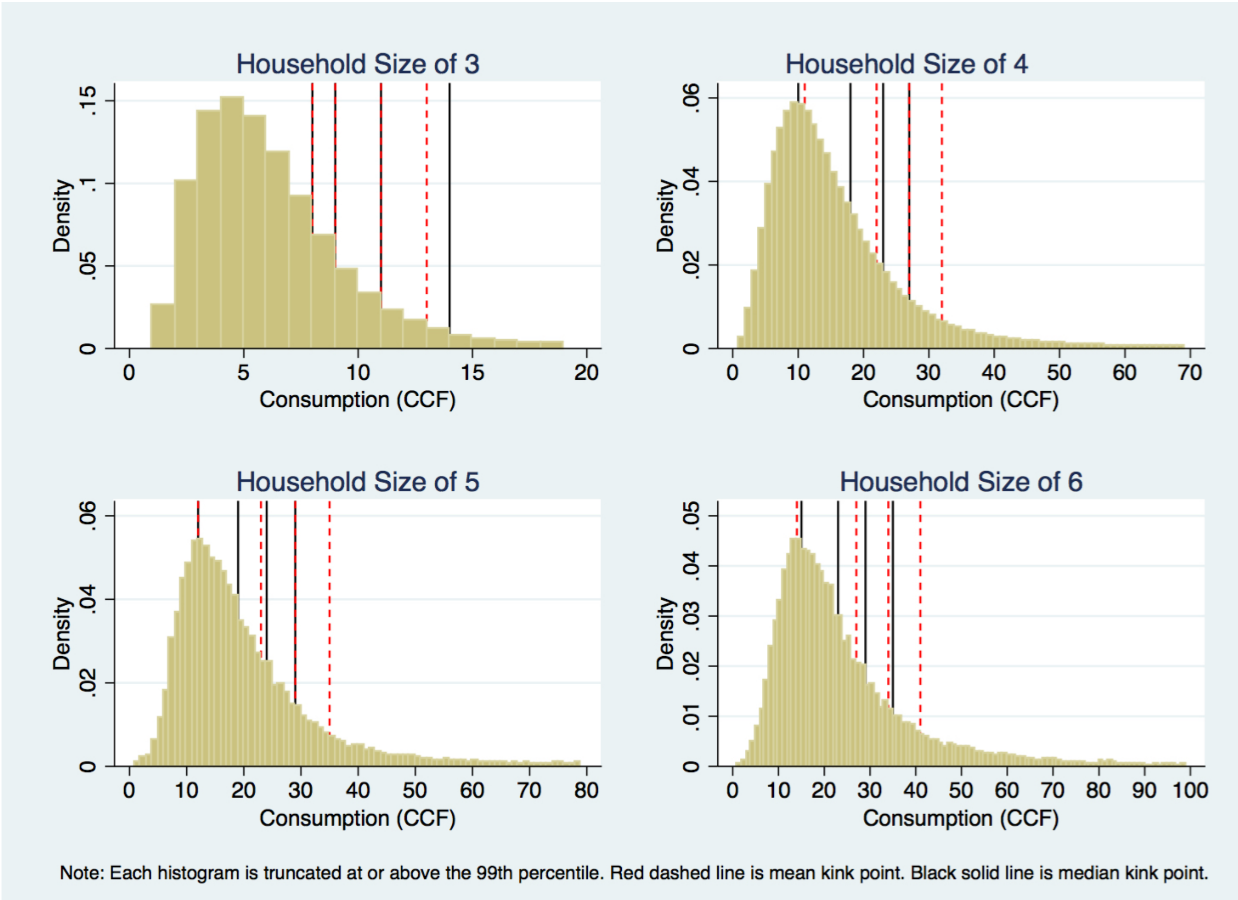


Figure A.6 Consumption distribution under water budgets by month



Note: Recall from Chapter 5 that only 5% and 3% of the sample have a household size of 5 and 6, respectively.

Figure A.7 Consumption distribution under water budgets by household size

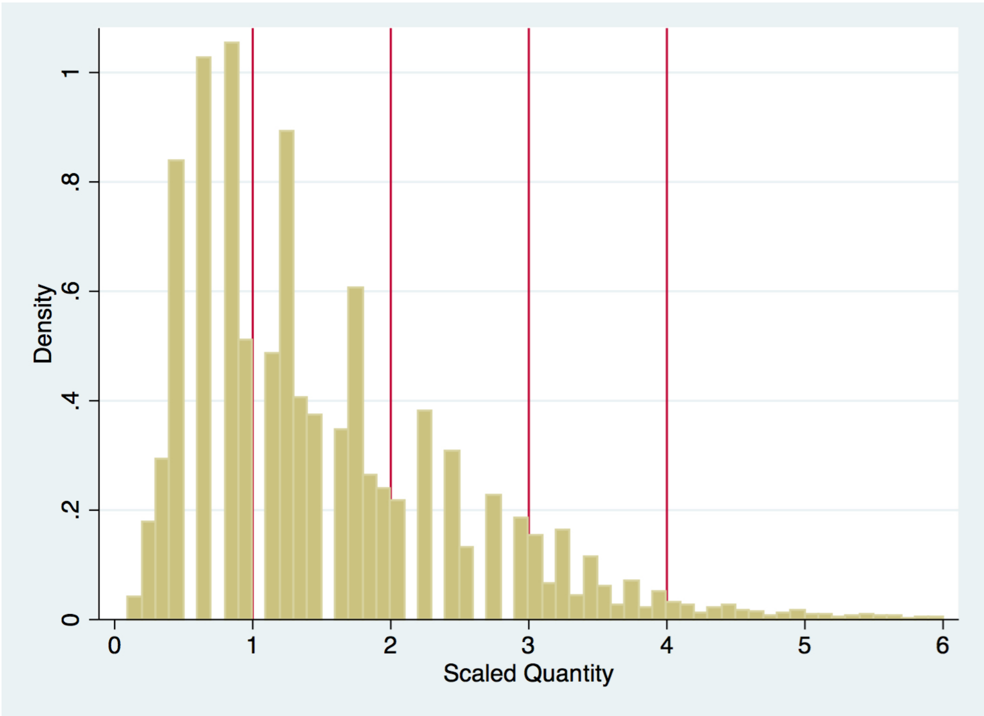


Figure A.8   Scaled quantities under increasing block rates

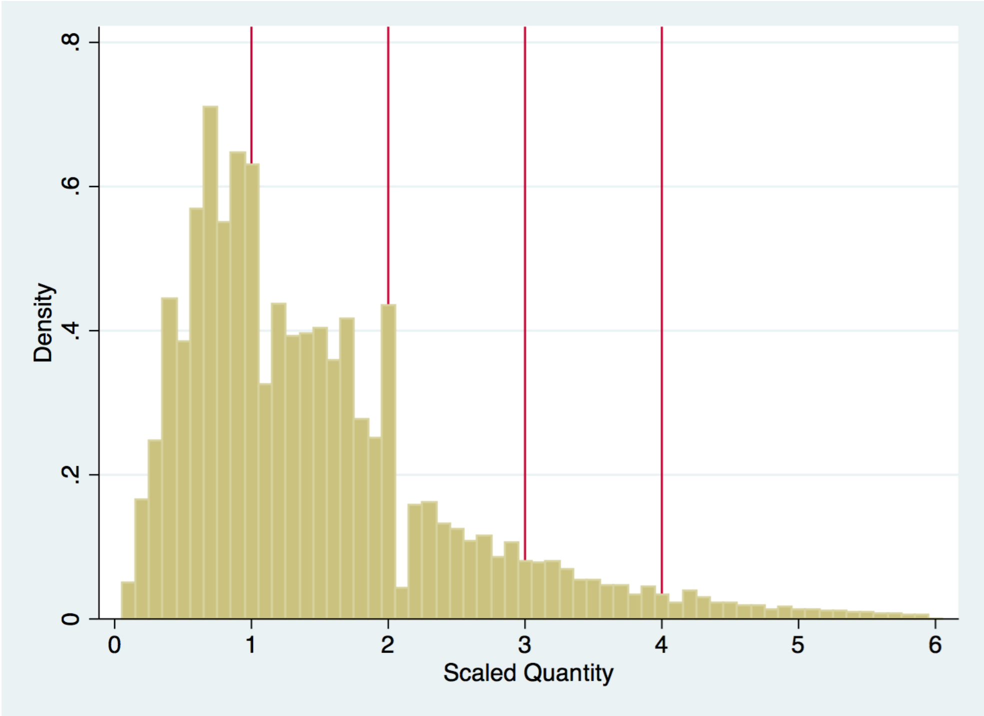
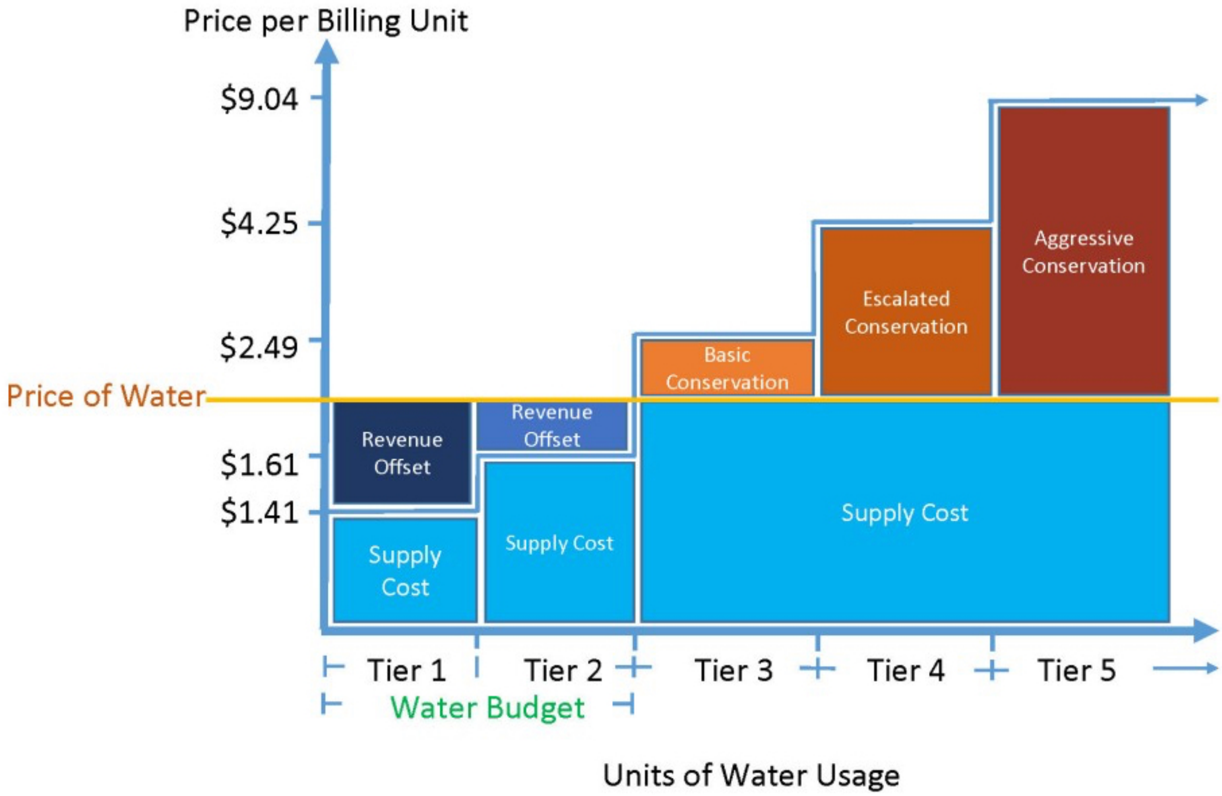


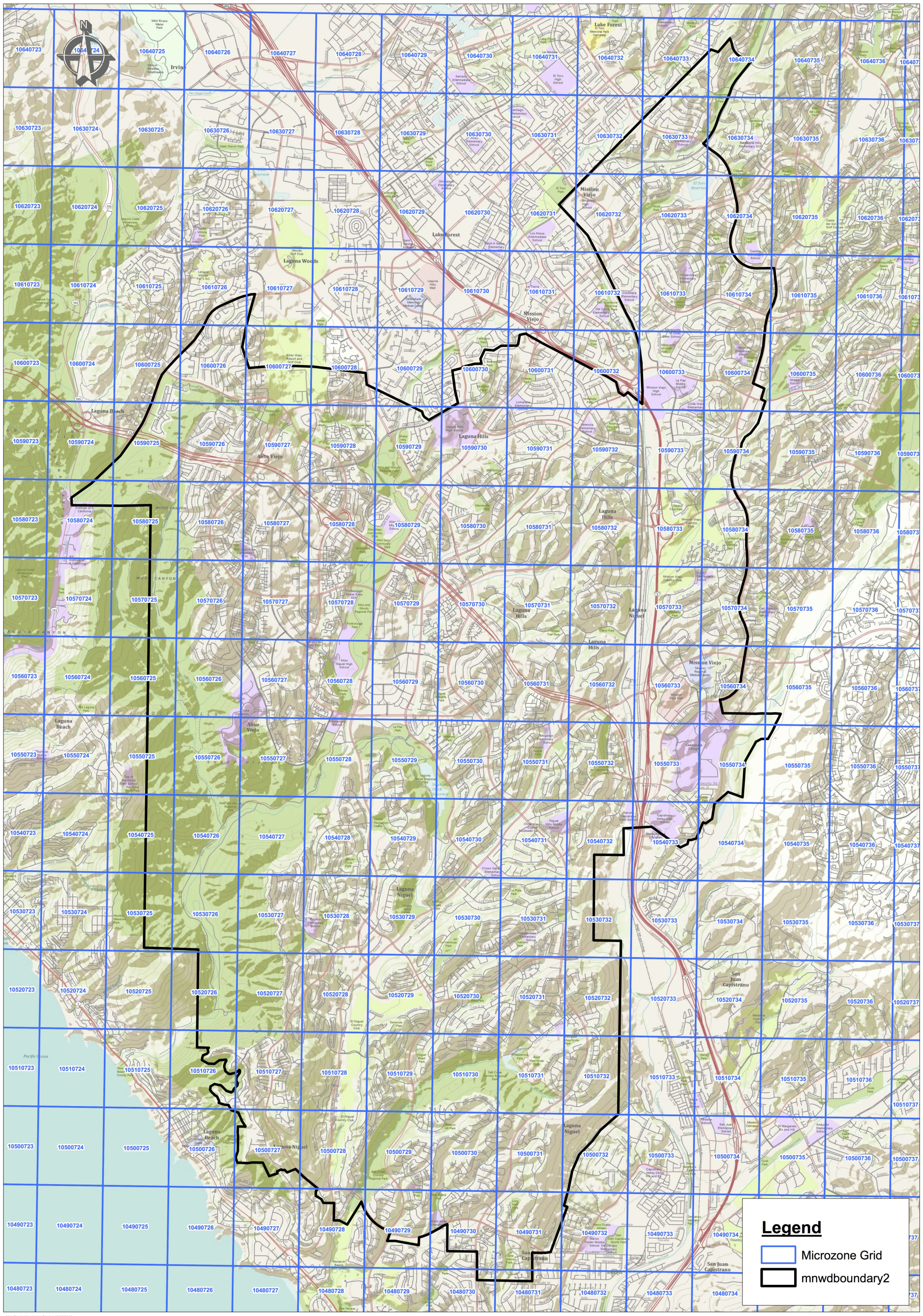
Figure A.9   Scaled quantities under water budgets

Note: Vertical red lines represent kink points. Truncated at scaled quantity of 6 (5.4 is 99th percentile).
Scaled quantity = ((block usage)/(block allocation)) + 1 for block 2; 2 for block 3; 3 for block 4; 4 for block 5.



Source: Moulton Niguel Water District, 2015a

Figure A.10 Cost allocations for the Moulton Niguel Water District



Source: Moulton Niguel Water District, 2015b

Figure A.11 Microzones in the Moulton Niguel Water District

A.2 Tables

Rate	2000	2002	2004	2006	2008	2010	2012	2014
Decreasing block %	35	31	25	24	28	19	18	16
Uniform %	36	37	39	40	32	31	30	30
Increasing block %	29	32	36	36	40	49	52	54

Source: 2014 Water and Wastewater Rate Survey, American Water Works Association, 2015

Table A.1 Residential water rate structure distribution in North America by water supplier

	Traditional IBR	(May)	Water Budgets	(July)
Block	Nominal	Real	Nominal	Real
Block 1	1.16	1.18	1.38	1.42
Block 2	1.30	1.32	1.54	1.59
Block 3	1.57	1.60	2.75	2.84
Block 4	1.84	1.87	5.51	5.69
Above Block 4	1.97	2.00	11.02	11.38

Table A.2 Water price per CCF in 2011

Variable	Full Sample	Block 1	Block 2	Block 3	Block 4	Block 5
Fraction of observations	1.00	0.42	0.37	0.13	0.06	0.02
Consumption (CCF/month)	15.42	6.49	14.79	24.60	37.72	73.80
Evapotranspiration (inches/month)	4.31	3.93	4.38	4.81	5.00	5.14
Household size	4.05	3.78	4.17	4.32	4.45	4.53
Irrigated area (feet^2)	3495	1858	3232	4918	7916	17050
Real budget (2013, $/month)	371.5	369.5	371.7	373.3	376.8	378.4
Bachelors degree (%)	32.9	33.9	32.3	31.4	32.2	35.0
Masters degree (%)	4.0	3.2	4.0	4.6	6.0	8.9
Median age	42.6	41.0	42.6	44.2	46.2	49.1
Median house value (2013, $1000)	619.0	563.3	623.5	666.5	751.9	914.4
Population density (people per sq. mile)	6286	7237	6134	5302	4275	2581
Housing units in census block	691	711	702	657	607	568

Note: Represents data from July 2011 until March 2015. Includes 732,465 observations.
Block sizes were calculated using pre-rate change cutoffs.

Table A.3 Summary statistics under water budgets by marginal consumption block

Variable	Mean	Std. Dev.	Households
High efficiency washers rebated	0.097	0.326	2053 (12.6%)
High efficiency toilets rebated	0.097	0.465	1688 (10.4%)
High efficiency nozzles received	0	0	0
Drip irrigation installed (linear feet)	0.465	24.952	142 (0.87%)
Turf grass removed & replaced with natives (sq. feet)	2.033	52.288	149 (0.92%)
Turf grass removed & replaced with synthetic (sq. feet)	2.978	51.896	202 (1.2%)

Table A.4 Summary statistics of non-price conservation programs

	Increasing Block Rates		Water Budgets	
	(OLS)	(McFadden IV)	(OLS)	(McFadden IV)
	ln(usage)	ln(usage)	ln(usage)	ln(usage)
ln(mp)	0.874***		0.124***	
	(0.00960)		(0.00333)	
ln(lagap/mp)	-1.391***		-0.320***	
	(0.00915)		(0.00333)	
ln(pred_mp)		0.605***		1.029***
		(0.0283)		(0.0119)
ln(pred_lagap/mp)		0.0621***		-0.293***
		(0.00991)		(0.00495)
ln(lagusage)	0.373***	0.383***	0.400***	0.145***
	(0.00197)	(0.00383)	(0.00234)	(0.00482)
spring	-0.0806***	-0.0779***	-0.0942***	-0.0946***
	(0.00116)	(0.00147)	(0.00136)	(0.00153)
summer	-0.100***	-0.0846***	-0.0502***	-0.0525***
	(0.00140)	(0.00190)	(0.00139)	(0.00155)
fall	-0.0361***	0.0744***	0.116***	0.129***
	(0.00115)	(0.00146)	(0.00104)	(0.00116)
evapotranspiration	0.0923***	0.161***	0.152***	0.0728***
	(0.000498)	(0.000877)	(0.000525)	(0.00111)
timetrend	-0.0758***	-0.0197***	0.0154***	0.00602***
	(0.000953)	(0.00107)	(0.000436)	(0.000506)
restrictions	-0.0969***	-0.0694***		
	(0.000840)	(0.00111)		
_cons	1.289***	0.930***	0.591***	0.957***
	(0.00656)	(0.00772)	(0.00673)	(0.00956)
N	699911	699911	716188	716188
k		0.10		-0.28

Note: All models include household fixed effects.
mp for marginal price. ap for average price. pred for predicted value.
Standard errors are clustered at household level and in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.5 Estimates from Shin's partial adjustment price perception model

	Increasing Block Rates		Water Budgets	
	(1)	(2)	(3)	(4)
	usage	mp	usage	mp
laggedusage	0.710***		0.606***	
	(0.000749)		(0.000738)	
block1p	14687.6***		6199.7***	
	(384.0)		(455.9)	
block2p	-4264.0***		9905.3***	
	(188.7)		(406.7)	
block3p	5454.4***		3929.4***	
	(352.9)		(347.8)	
fixedsewer	1618.6***		-3106.2***	
	(167.0)		(176.8)	
irrigatedarea	0.000468***		0.000602***	
	(0.00000231)		(0.00000196)	
evapotranspiration	2.048***		1.742***	
	(0.00718)		(0.00533)	
income	0.0157***		0.0398***	
	(0.000206)		(0.000100)	
predicted_usage		0.0113***		0.0699***
		(0.0000181)		(0.000162)
_cons	-15.43***	1.031***	-32.31***	1.029***
	(0.546)	(0.000372)	(0.616)	(0.00316)
N	699911	699911	716188	716188

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.6 First stage results for Shin's partial adjustment price perception model

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)	ln(usage)
restrictions	0.0319**	-0.117***	0.0321**	-0.117***	-0.0367**	-0.0342**	-0.0365**	-0.0326*
	(0.0113)	(0.0131)	(0.0113)	(0.0131)	(0.0112)	(0.0132)	(0.0112)	(0.0132)
lawn*restrictions	-0.0508***	-0.0582***			-0.0488***	-0.0581***		
	(0.0114)	(0.0132)			(0.0114)	(0.0132)		
postrestrictions		-0.207***		-0.207***		-0.00156		0.000790
		(0.0189)		(0.0189)		(0.0190)		(0.0190)
lawn*postrestrictions		-0.0100				-0.0128		
		(0.0190)				(0.0190)		
verysmallinteraction			-0.00485	0.00155			-0.00375	0.00177
			(0.0139)	(0.0165)			(0.0139)	(0.0165)
smallinteraction			-0.0149	-0.0255			-0.0143	-0.0254
			(0.0119)	(0.0138)			(0.0118)	(0.0138)
mediuminteraction			-0.0450***	-0.0614***			-0.0390***	-0.0613***
			(0.0116)	(0.0135)			(0.0116)	(0.0135)
largeinteraction			-0.0588***	-0.0698***			-0.0572***	-0.0696***
			(0.0117)	(0.0136)			(0.0116)	(0.0136)
extrainteraction			-0.0799***	-0.0773***			-0.0798***	-0.0772***
			(0.0117)	(0.0136)			(0.0117)	(0.0136)
superinteraction			-0.149***	-0.0782**			-0.154***	-0.0782**
			(0.0214)	(0.0248)			(0.0214)	(0.0248)
verysmallpostinter				0.00922				0.00766
				(0.0230)				(0.0230)
smallpostinter				-0.0146				-0.0154
				(0.0197)				(0.0197)
mediumpostinter				-0.0217				-0.0311
				(0.0193)				(0.0194)
largepostinter				-0.0154				-0.0172
				(0.0194)				(0.0194)
verylargepostinter				0.00322				0.00360
				(0.0194)				(0.0195)
extremelypostinter				0.0959**				0.106**
				(0.0328)				(0.0328)
timetrend					-0.0440***	-0.0417***	-0.0440***	-0.0421***
					(0.000443)	(0.000640)	(0.000443)	(0.000640)
evapotranspiration	0.137***	0.148***	0.137***	0.148***	0.146***	0.146***	0.146***	0.146***
	(0.000700)	(0.000710)	(0.000701)	(0.000711)	(0.000708)	(0.000709)	(0.000708)	(0.000709)
ln(income)	-0.233***	-0.296***	-0.221***	-0.269***	0.0845**	0.0640*	0.100***	0.105***
	(0.0314)	(0.0281)	(0.0315)	(0.0284)	(0.0281)	(0.0294)	(0.0282)	(0.0298)
_cons	3.312***	3.797***	3.242***	3.636***	1.638***	1.756***	1.545***	1.512***
	(0.186)	(0.166)	(0.186)	(0.168)	(0.166)	(0.173)	(0.166)	(0.176)
N	1448653	1448653	1448653	1448653	1448653	1448653	1448653	1448653

Note: Lawn sizes binned by percentiles. 0 < Very Small < 10th; 10th ≤ Small < 25th;
25th ≤ Medium < 50th; 50th ≤ Large < 75th; 75th ≤ Very Large < 99th; Extremely Large ≥ 99th.
All models include household fixed effects. All lawn dummy variables dropped due to collinearity and are not reported.
nolawn is reference category. Standard errors are clustered at household level and in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.7 Estimates of the impact of mandatory water restrictions

	(Pre-Rate Change) ln(usage)	(Post-Rate Change) ln(usage)
spring	0.0958***	0.213
	(0.0021)	(0.1721)
summer	0.1639***	0.4518***
	(0.0021)	(0.1118)
fall	0.1914***	0.2505***
	(0.0011)	(0.0217)
restrictions	-0.0821***	
	(0.0009)	
evapotranspiration	-0.0821***	0.1433***
	(0.0004)	(0.038)
timetrend	-0.052***	-0.0104
	(0.0005)	(0.0169)
ln(mp)	-0.009***	-3.0732***
	(0.0009)	(0.2183)
ln(income)	-0.0001	-0.0765
	(0.0006)	(0.1111)
education		0.2181
		(0.139)
household size		0.6258***
		(0.0411)
lawn size		0.0812***
		(0.0017)
_cons		0.6858
		(0.6004)
N	716188	716188

Note: (Pre-Rate Change) includes household fixed effects,
while (Post-Rate Change) only includes time-invariant demographic variables.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.8 Estimates from the DCC model

A.3 Description of Outdoor Factors for Water Budgets

The source for this section is MNWD (2015a).

(1) Irrigable area is the amount of landscaped area on the property that receives regular watering, and this includes pools and spas. GIS and County Assessor parcel data were used to determine the irrigable area for each home.

(2) Evapotranspiration (ET) is the amount of water lost due to evaporation and plant transpiration. Evaporation will vary due to factors such as wind, humidity, and temperature. Plant transpiration is the amount of water that plants lose from their leaves and plant tissues. The ET rate is measured daily by 110 virtual weather stations in MNWD's service area. Each weather station is associated with a microzone (see Figure A.11 for a map of the microzones), with the actual ET corresponding to a microzone added up for each day in the billing cycle. There is higher monthly ET during summer months.

(3) The plant factor measures the specific amount of irrigation water required by each type of plant. For example, turf grass has a plant factor between 0.6 and 0.8, while water-efficient plants can have a plant factor of only 0.3. Residential water budgets are calculated using a plant factor of 0.7.

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