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Article

Estimating the Price Elasticity of Residential Water Demand: The Case of Phoenix, Arizona

James Yoo*, Silvio Simonit, Ann P. Kinzig, and Charles Perrings

James Yoo is an assistant professor in the Department of Economics and Business, Bethany College. Silvio Simonit is a regional specialist with Sustainable Land Management, International Union for Conservation of Nature, Mexico City, Mexico. Ann P. Kinzig and Charles Perrings are professors in the School of Life Science, Arizona State University.

*Correspondence to be sent to: jyoo@bethanywv.edu.

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Abstract *Changes in water availability, and hence price, are expected to be amongst the most disruptive effects of climate change in many parts of the world. Understanding the capacity of society or consumers to adapt to such changes requires understanding the responsiveness of water demand to price changes. We estimate the price elasticity of residential water demand in Phoenix, Arizona, which is likely to be strongly impacted by climate change. Most existing approaches to the estimation of water demand functions have limited capacity to isolate the effect of price on water consumption where there is little variation in water price. A recent study by Klaiber et al. (2012) attempts to address this issue by using differences in consumption levels, and weather-related characteristics to isolate the price effect on water demand, and by using a constant term in a differenced regression model. We also estimate a differenced regression model, but include direct measures of changes in water prices. This inclusion successfully isolates the price effect on water demand, and enables us to distinguish between the short- and long-run price elasticity of water demand, and hence the short-and long-run adaptation to changes in water availability.*

Key words: Water demand function, marginal price, price elasticity.

JEL codes: Q21, Q25, Q28.

In many parts of the world, climate change is expected to have significant implications for water availability, and hence water prices. To understand the capacity to adapt to changes in water availability, we need to understand the consumer's response (demand) to change in water price. However, many utility companies around the world currently apply pricing structures that allow little variation from which to recover response measures. In this paper we apply a method for estimating the price elasticity of water demand under simple block pricing in Phoenix, Arizona, where climate change is expected to have particularly severe impacts on both water demand (through its effects on mean temperatures) and supply (through its effects on mean precipitation).

The City of Phoenix is located at the northern edge of the Sonoran Desert, and is projected to experience increased mean temperatures and decreased precipitation as a result of climate change (Natural Resources Defense Council 2011). This is expected to increase water demand, and to decrease freshwater supply over the next few decades. At the same time, many of the non-temperature drivers of water demand are expected to increase. In the 2000s, the population of the Phoenix Metropolitan Area grew by around 35%, and while the rate of growth slowed during the 2008 recession, it is expected to continue at similar rates in the 2010s (Census 2010). These trends are likely to affect water prices. Reduced supply is likely to induce substitution between surface water and groundwater withdrawal, thus increasing the cost of water. Continued population growth, all things being equal, will increase water demand. As a result, policy makers and water providers are both concerned with finding ways to assure the long-term sustainability of water use.

A variety of water conservation policies have already been tested in Phoenix, including the revision of pricing structures to manage demand (Campbell 2004; Balling and Gober 2006). The design of demand management policy does, however, depend on an understanding of how water use responds to changes in water price. The price elasticity of water demand may be obtained from water demand functions that describe water consumption as a function of price, climate, demographic and housing characteristics, and time. In this study we estimate a residential water demand function for the City of Phoenix between 2000 and 2008.

The City of Phoenix operates a simple two-block pricing structure in which the only variation in price is seasonal. This makes it difficult to isolate the impact of price on water demand. Recent efforts to counter this problem have estimated the effect of price on water demand via the constant term in a regression model of the effect of non-price variable on changes in water consumption between two periods (Klaiber et al. 2012). This is a reasonable approach where the model is complete except for price effects. If the model is not complete, however, the constant term may be expected to change with the inclusion of other variables. In our study we similarly use differences in consumption levels between two dates as a measure of demand, but we also control for weather and other factors affecting water demand, and we include direct measures of changes in water prices. We also consider a long enough time series of inter-annual differences in consumption to estimate the own-price elasticity of water demand both in the short run (over two years) and in the longer run (over eight years). To preview our results, we find that a demand function including a direct measure of price provides a better fit to the data than a model using the intercept as a price effect. Consistent with previous results, we also find that the long-run price elasticity of demand is larger than short-run elasticity, and that lower income households (typically low water users) are more responsive to changes in prices than higher income households.

The paper is structured as follows. The next section reviews recent studies of water demand. This is followed by a description of our first-difference model, and the data used to calibrate it. Section 4 presents our results, and we conclude with a summary and a discussion of the implications for policy.

Water Demand Models

Since the pioneering study by Gottlieb (1963), residential water demand has been extensively investigated by economists in many different contexts, including France (Nauges and Thomas 2000; Nauges and Thomas 2003), Germany (Schleich and Hillenbrand 2009), Italy (Mazzanti and Montini 2006), Spain (Martinez-Espineira 2002; Martinez-Espineira 2007), and the United States (Hewitt and Hanemann 1995; Olmsted, Hanemann, and Stavins 2007; Pint 1999; Gaudin 2006). Espey, Espey, and Shaw (1997), Worthington and Hoffman (2008), and Dalhuisan et al. (2003), in their surveys of residential water demand studies, explored the factors found to affect the price elasticity of demand. Espey and Shaw (1997) noted that price elasticity estimates ranged widely from -0.02 to -3.31, with an average of -0.51, and Worthington and Hoffman (2008) found that price elasticity estimates range from -0.5 to 0 in the short run, and -0.5 to -1 in the long run. Further, Dalhuisan et al. (2003) found that average price elasticity estimates are -0.41, with a standard deviation of 0.86. Among the studies these authors examined, approximately 90% of the price elasticity estimates fell between 0 and -0.75. A later review of the residential water demand literature by Arbues, Garcia-Valinas, and Martinez-Espineira (2003) considered differences in the specification of water demand models, and paid particular attention to the selection of variables, the choice of the functional form, types of data, and type of price specification. These authors found that the magnitude of price elasticity estimates varied both with the econometric techniques applied, and the type of data used (panel versus cross-section data, or aggregated versus individual-level water consumption data).

Although the price elasticity estimates vary case by case, there are two general conclusions that may be drawn from the existing literature. First, water demand is generally price inelastic. This is because water expenditure generally constitutes a relatively small proportion of a consumer's total expenditure, and there are few substitutes for residential water. Second, the long-run elasticity is larger than the short-run elasticity. Water consumers have fewer options for switching between high and low-use residential water use options in the short run. In the longer run, consumers have more options for substituting towards less water-intensive appliances, and for altering their landscaping from lawns to drought-tolerant plants (Omlstead and Stavins 2006). Another factor is that it takes time for consumers both to register changes in water costs, and to identify the factors in water use that determine costs (Martinez-Espineira 2007).

Both water demand model specification and the econometric techniques used to estimate demand functions have gone through several phases of development. Initially, concern was focused on whether to use marginal or average price as a price variable in estimated water demand functions, with some studies suggesting that price elasticity tended to be biased upwards when marginal price changes were used (Billing 1980). Later, following Nordin (1976) and Taylor (1975), researchers included both marginal price and a variable measuring the difference between the total water bill and what would have been paid if all units of water were charged at the marginal price. This difference variable was intended to capture the income effects of multiple block pricing structures. However, Arbues, Garcia-Valinas, and Martinez-Espineira (2003), in their broad survey of water demand literature, indicated that the choice of price variable had not significantly affected the price elasticity estimates.

Most studies have used conventional regression methods such as ordinary least squares, 2- and 3-stage least squares, and time series analysis to estimate the price elasticity of residential water demand. There are, however, aspects of water markets that complicate the choice of estimation method. About one-third of U.S. residential water users face increasing block prices (IBPs) where marginal prices of water increase with the quantity demanded. Under block pricing, consumers face a two-stage choice. First, they choose the block of consumption in a discrete choice fashion; they then choose the quantity of water consumed within the block. Most early studies omitted the first-stage choice from the estimation procedure, and modeled consumption within the block directly. Later studies employed a discrete continuous choice (DCC) model to handle block choice in the block pricing structure directly.

The DCC model was initially applied to the study of labor supply (Hausman 1985; Burtless and Hausman 1978), and was introduced to the study of residential water demand by Hewitt and Hanemann (1995), followed by Pint (1999). Initially, the elasticity estimates generated by these studies fell in the range of {-1,-2}, which is far beyond the upper bound of what had been found in previous studies. Later studies, using broadly representative and highly detailed individual level water consumption data, found the price elasticity obtained from the DCC model to be closer to estimates from previous studies (Olmsted, Hanemann and Stavins 2007). Nevertheless, there are limitations to the DCC model. Using the model to estimate the effect of price using data from a single water provider is problematic if the price schedule is stable over time, and there is insufficient variation from which to isolate the effect of a change in price. In addition, price changes under block pricing are often confounded with demand shocks, as consumers face higher prices because they consume more water.

Recently, Nataraj and Hanemann (2011) introduced an experimental approach called regression discontinuity design, to estimate the response to an increase in marginal price by exploiting the introduction of a third price block in Santa Cruz, California. These authors found the price elasticity of demand to be approximately -0.12, which falls at the low end of previous estimates. Building on their study, Klaiber et al. (2012) employed an experimental approach to estimate water demand in the Phoenix area by using the constant term in a first-differenced regression model of changes in water consumption between two periods as a proxy for the effect of price changes. This study used household-level water consumption data, and exploited the order statistics for these consumption data to estimate the price response for different levels of water use. These authors found that larger water users were less sensitive to price, and that all users were less sensitive to price in summer than in winter. While the study is an innovative attempt to isolate the price effect under a single water provider, it does potentially suffer from omitted variable bias. If the constant term in such a model varies with the addition or deletion of other variables, it is desirable to include a more direct measure of prices.

Data and Methods

Most water providers in the Phoenix Metropolitan Area operate a multiple block pricing structure (see table 1). The City of Phoenix itself operates a flat, two-block structure. This means that there is no variation in marginal price of water other than the variation across different seasons (low, medium, and high water use seasons) within a year. Since higher water users also face higher marginal prices, the possible endogeneity of the water price makes it hard to isolate the effect of price on demand. To address this problem, we constructed a first differenced regression model of the kind applied by Klaiber et al. (2012) to estimate water demand responses to inter-annual changes in marginal prices.

The basic residential water demand function takes the form:

$$Q_{ijt} = \alpha_0 + \alpha_1 P_{jtb} + F(Z_{it}) + W(R_{jt}) + u_{ijt} \qquad [1]$$

where Q_{ijt} is aggregate water consumption in census block (or household) i in the month j of year t. The variable P_{jtb} is the marginal price in the month j

Table 1. Water Rate for a Single-family Residence in Major Arizona Cities

Water Provider	Type of Rate Structure	Monthly service charge	Volume charge (Price per 1,000 Gallon)
Buckeye	Increasing block rate (5 Blocks)	\$12.70	\$2.2-0 to 6,000 gallon \$3.10-6,001 to 10,000 \$5.30-10,001 to 15,000 \$7.95-15,001 to 30,000 \$8.18-over 30,000
Chandler	Increasing block rate (3 Blocks)	\$8.21	\$1.00-0 to 3,000 gallon \$1.49-3,001 to 10,000 \$1.65- over 10,000
Mesa	Increasing block rate (3 Blocks)	\$11.48	\$2.30- 0 to 12,000 gallon \$3.45-12,001-24,000 3.86-over 24,000
Peoria	Increasing block rate (4 Blocks)	\$14.16	\$1.49-2,000 to 5,000 gallon \$2.69-6,000 to 10,000 \$3.24-11,000 to 25,000 \$3.85-over 26,000
Phoenix	Flat rate, high month season	\$4.64	\$3.51 – all use over 7,480
Scottsdale	Increasing block rate (3 Blocks)	\$11.25	\$1.80-0 to 7,500 gallon \$3.35-7,501 to 39,000 \$4.60-over 39,000
Tucson	Increasing block rate (4 Blocks)	\$5.62	\$1.39- -0 to 11,220 \$5.13-11,221 to 22, 440 \$7.25-22,441 to 33,660 \$9.90-over 33,660
Yuma	Increasing block rate (3 Blocks)	\$15.68	\$1.42-0-7,480 gallon \$1.52-7,481 to 22,440 \$1.75-over 22,441

Source: Water Resource Advocate, 2010.

of year t in the b^{th} block, $F(Z_{it})$ is a function describing the effect of demographic or housing characteristics Z_{it}, and $W(R_{jt})$ is a function describing the effect of temperature or precipitation in the month j of year t. Variable u_{ijt} are unobserved errors not captured by the model. We estimated two differenced versions of the basic water demand function. The first differenced version specified that the change in water consumption is a function of the change in prices, weather-related characteristics, and dummy variables to capture the impact of water-intensive features of residential properties, and treated the constant γ_0 as the price effect (proxy) on water demand:

$$Q_{ijt+T} - Q_{ijt} = \gamma_0 + \gamma_1(F(Z_{it+T}) - F(Z_{it})) + \gamma_2(W(R_{it+T}) - W(R_{it})) + \gamma_3 D_{pool} + \gamma_4 D_{value} + u_{ijt+T} - u_{ijt}. \quad [2]$$

The price elasticity of demand in this case was then calculated as:

$$\varepsilon_{cons} = \frac{\gamma_0}{(P_{jtb+T} - P_{jtb})} \frac{P_{jtb+T}}{Q_{ijt+T}} \quad [3]$$

where P_{jtb} is the marginal price at the base year, and P_{jtb+T} and Q_{ijt+T} are marginal price and water consumption at the year that the change was made. Since we found the constant term in equation (2) to be unstable and to vary significantly depending on which sets of explanatory variables were included, we estimated a second differenced version of the basic water demand function that included the change in prices, weather-related characteristics, and dummy variables related to water-intensive features of residential properties:

$$Q_{ijt+T} - Q_{ijt} = \beta_0 + \beta_1(P_{jtb+T} - P_{jtb}) + \beta_2(F(Z_{it+T}) - F(Z_{it})) + \beta_3(W(R_{it+T}) - W(R_{it})) + \beta_4 D_{pool} + \beta_5 D_{value} + u_{ijt+T} - u_{ijt} \quad [4]$$

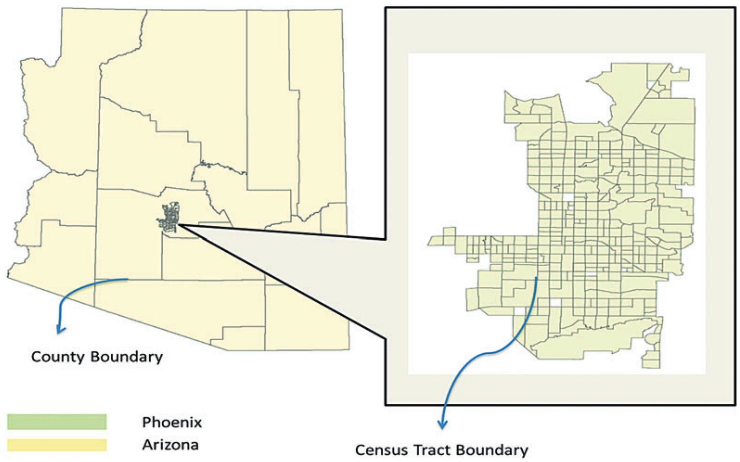
With this direct measure for the price effect, β_1, the price elasticity of demand was calculated as follows:

$$\varepsilon_{\mathrm{Pr}ice} = \beta_1 \frac{P_{jtb+T}}{Q_{ijt+T}}. \quad [5]$$

The data comprised water consumption records associated with 312 census tracts served by the Phoenix Water Services Department. To avoid the problems caused by changes between consumption blocks, we selected census tracts where there were no block switches in water consumption from second (high consumption) to first (low consumption) block, or vice versa, between two years. Since more than 95% of household water consumption falls in the second block, and since this did not change in our selected time period, the restriction had little effect on the sample size.

Figure 1 shows the boundary of census tracts within the City of Phoenix. Water data are provided in units of one-hundred cubic feet (CCF). In theory, estimating residential water demand using micro household-level data would be preferred (Schefter and David 1985; Saleth and Dinar 2000; Klaiber et al. 2012). However, this requires a great deal of private information that is not generally in the public domain (which is why micro-level

Figure 1. Census tract boundary within the City of Phoenix



Source: Author's calculation in geographic information system.

analyses are so sparse). It is quite common, however, to use data aggregated to census tract, water provider, or community levels (Dalhuisen et al. 2003; Gaudin 2006; Schleich and Hillenbrand 2009; Strong and Smith 2010).

Weather-related characteristics such as monthly temperature and precipitation were purchased from the PRISM database,[1] and used to calculate monthly mean temperature and precipitation at the census-tract level, which matched the water consumption data. Census data for 2000 and 2010 were used to calculate the median household income at the census-tract level. In addition, we identified single-family residential properties with pools from the Maricopa Assessor's Office, and calculated the proportion of residential properties with pools in each census tract, then averaged them from 2000 to 2008. The average proportion of houses with pools was approximately 21.5%. We created the dummy variable (D_{pool}) by assigning 1 for a census tract with more than 21.5% of properties with a pool, and 0 otherwise. We expect the coefficient on D_{pool} to be positive since pools substantially increase residential water use during the summer.

In the same way, we created a dummy variable for property value, since more highly-valued properties are expected to have more water-intensive features. The historical average property value from 2000 to 2008 on a census-tract level was approximately \$164,467 in Phoenix. Our dummy variable (D_{value}) was assigned 1 for a census tract with average property value with greater than \$164,467, and 0 otherwise.[2] Summary statistics of selected variables are reported in table 2. We note that the average residential water use per household was decreasing over this period, which reflected both the effectiveness of water conserving, as well as changes in landscaping and facilities in new properties (figure 2). Precipitation was significantly more

[1] *The PRISM Climate Group (http://prism.oregonstate.edu).*

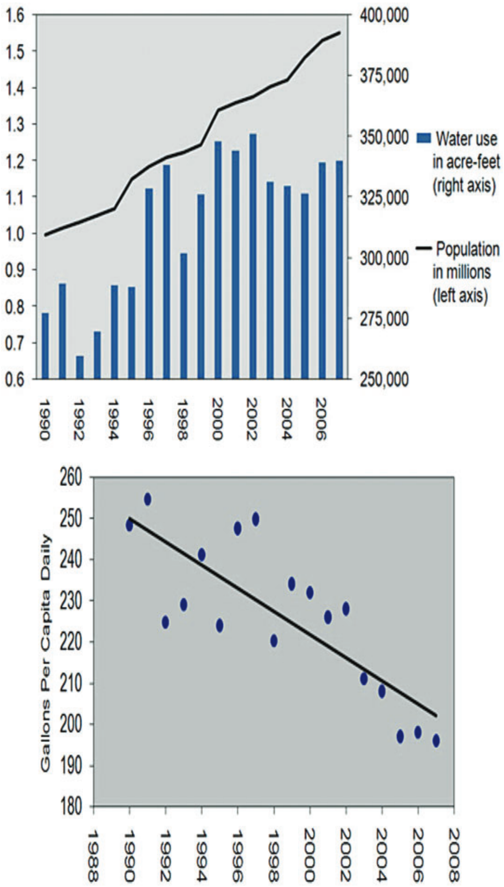
[2] *We also estimated the model with continuous variable (difference in total pool area, and difference in property values), but the model fit better with dummy variables.*

Table 2. Summary Statistics of Selected Variables, 3,744 Observations

Variable	**2000**	**2002**	**2004**	**2006**	**2008**
Average Water Use/Household (CCF)	17.43 (6.26-67.06)	17.09 (6.29-69.44)	15.51 (6.47-77.82)	15.31 (6.38-76.42)	13.97 (6.18-72.50)
Average Precipitation (mm)	16.07 (0-121.36)	8.52 (0-38.94)	19.86 (0-89.35)	14.36 (0-60.83)	20.70 (0-92.96)
Average Temperature (Celsius)	22.88 (11.45-34.74)	22.68 (10.18-34.74)	22.55 (11.17-34.02)	22.77 (10.73-35.55)	22.62 (10.26-34.24)
Median Household Income (dollar/ year)	$40,778 ($10,607-122,057)	-	-	-	$49,947 ($9,668-$231,500)
Dum_{Pool}	0.4046 (0-1)	0.4046 (0-1)	0.4046 (0-1)	0.4046 (0-1)	0.4046 (0-1)
Dum_{Res_Value}	0.2209 (0-1)	0.2209 (0-1)	0.2209 (0-1)	0.2209 (0-1)	0.2209 (0-1)
Historical % of property with a pool Historical average values of residential property			0.215 (0-1) $164,467 ($16,445-$8, 084,218)		

Note: Numbers inside parentheses represent maximum (upper bound) and minimum (lower bound) values.

Figure 2. Historical population and water use



Source: City of Phoenix: Water Resource & Conservation.

variable than temperature in the period. Mean monthly precipitation for the year 2002 was, for example, approximately 50% of mean monthly precipitation in the base year 2000. By comparison, mean monthly temperatures exhibited relatively little variation over the years.

Median income was calculated using census 2000 and 2010 demographic data. Since income for other years are not available at the census-tract level at the moment, we matched 2010 income with the closest year for which we have consumption data, which is 2008. We estimated the income elasticity of water demand for a model differenced between 2000 and 2008.

Price variation in the dataset is derived from the fact that the City of Phoenix adjusts the water rate every year to meet the increasing cost of delivering and maintaining residential water supplies. Table 3 shows the monthly fixed fee and marginal price schedule of water across different seasons of the year; the price schedule was obtained from the City of Phoenix's Water Resource Department. The water rate in Phoenix is characterized by a two-block pricing structure

Table 3. Water Rates in Phoenix

	2000	2002	2006	2007	2008
Monthly Fixed Rate	$5.16	$5.16	$4.64	$4.64	$4.64
Volume Charge					
Low water use season (Dec., Jan., Feb., March)	$1.12	$1.24	$1.50	$1.65	$1.83
Medium water use season (April, May, Oct., Nov.)	$1.32	$1.47	$1.77	$1.97	$2.20
High water use season (June, July, Aug., Sept.)	$1.68	$1.87	$2.24	$2.50	$2.81
Environmental Charge	$0.08	$0.08	$0.23	$0.25	$0.31

Source: Phoenix Water Resources Department.

that has two components: a monthly fixed charge and a volume charge. The monthly fixed charge covers the use of 4,488 gallons (6 CCF)[3] of water use for October through May, and 7,480 gallons (10 CCF) for June through September. A water user in the first block pays only the monthly fixed charge. The volume charge consists of a user charge and an environmental charge.

Water users in the second block face a marginal price (volume charge/CCF + environmental charge/CCF) associated with the additional amount of water use per unit. For example, during the summer (high water use season), the water user pays only the monthly fixed charge up to 10 CCF of water/month. However, consumers that use additional water beyond 10 CCF are subject to a volume charge on a CCF basis. During the fall and winter seasons (medium and low water use seasons), the threshold between the first and second blocks is 6 CCF of water use. Consumers using any extra water beyond that threshold also face a volume charge. Hence, water users in the second block pay both a monthly fixed charge and a volume charge. In this study, we focused on the sample that falls in the second block of water use.

Results and Discussion

We selected the following two-year intervals with which to estimate the short- and long-run price elasticity of residential water demand: 2000, 2002, 2004, 2006, and 2008. We note that the demand model estimated in this study is not a structural demand model, but does have a linear form. The resulting price elasticities are approximations based on limited variation in marginal prices in our data set.

Table 4 shows the estimated coefficients from the two differenced regression models estimated: the model that uses the constant as a price effect (MCP), and the model that includes a direct measure of price effect (MDP). As in most previous studies, higher temperatures and lower rainfall are expected to increase the quantity of water consumed. Table 4 shows that the coefficients on temperature and precipitation were all significant, and had the expected signs in both models (except for 2004 in the MDP model, where the coefficient on temperature was negative, but insignificant). The coefficients on our two dummy variables, D_{pool} and D_{value}, were both

[3] *One hundred cubic feet units equals 748 gallons.*

Table 4. Estimated Coefficients from MCP and MDP Models

Variable	MCP Model	MDP Model	Partial F-Statistics
2000 vs. 2002 (3,685 obs.)			
Constant	**-0.8878 (0.0444)*** **	-0.4345 (0.0941)***	
Difference in Temperature	0.1189 (0.0189)***	0.1249 (0.0188)***	
Difference in Precipitation	-0.0279 (0.0011)***	-0.0289 (0.0011)***	
Dum_{Pool}	0.5734 (0.0726)***	0.5748 (0.0723)***	
$\text{Dum}_{\text{Res\_Value}}$	0.5253 (0.0444)***	0.5243 (0.0875)***	
Difference in Price	-	**-7.4523 (1.365)*** **	
R^2	0.2021	0.2085	F (1,3,684) ~ 29.74***
2000 vs. 2004 (3,677 obs.)			
Constant	**-2.3068 (0.0497)*** **	1.3444 (0.3109)***	
Difference in Temperature	0.0645 (0.0092)***	-0.0107 (0.0110)	
Difference in Precipitation	-0.0249 (0.0014)***	-0.0304 (0.0015)***	
Dum_{Pool}	0.5811 (0.0817)***	0.5789 (0.0802)***	
$\text{Dum}_{\text{Res\_Value}}$	0.5159 (0.0991)***	0.5103 (0.0972)***	
Difference in Price	-	**-13.1450 (1.1058)*** **	
R^2	0.1168	0.1495	F (1,3676) ~ 141.10***
2000 vs. 2006 (3,662 obs.)			
Constant	**-2.6928 (0.0574)*** **	0.5359 (0.2221)***	
Difference in Temperature	0.2520 (0.0229)***	0.2455 (0.0223)***	
Difference in Precipitation	-0.0523 (0.0015)***	-0.0497 (0.0016)***	
Dum_{Pool}	0.7356 (0.0954)***	0.7357 (0.0926)***	
$\text{Dum}_{\text{Res\_Value}}$	0.5183 (0.1163)***	0.5251 (0.1129)***	
Difference in Price	-	**-8.4245 (0.5609)*** **	
R^2	0.3109	0.3509	F (1,3,661) ~ 225.23***
2000 vs. 2008 (3,657 obs.)			
Constant	**-3.7565 (0.0686)*** **	3.1981 (0.2273)***	
Difference in Temperature	0.2900 (0.0245)***	0.2503 (0.0217)***	
Difference in Precipitation	-0.0284 (0.0014)***	-0.0367 (0.0013)***	
Dum_{Pool}	0.8678 (0.1136)***	0.9081 (0.1006)***	
$\text{Dum}_{\text{Res\_Value}}$	0.6052 (0.1376)***	0.6018 (0.2274)***	
Difference in Price	**-**	**-10.0553 (0.3168)*** **	
R^2	0.2271	0.3943	F (1,3,656) ~ 1007.6***

*Note: Asterisks ***, **, and * denote significance at the 0.1%, 1%, and 5% levels, respectively. Numbers inside parentheses represent the robust standard error.*

positive and significant. Over the whole period, we found the magnitude of the coefficient on D_{pool} to be increasing, which reflects the fact that the number of properties with a swimming pool was also increasing (the average number of properties with a swimming pool at the census tract level increased from 260 in 2000, to 285 in 2008). The positive impact of D_{value} reflects the fact that more expensive houses tend to have more landscape areas, more bathrooms, and other water-using features.

The constant terms in the MCP model were negative and significant, but its value turned out to be vulnerable to adding variables. The coefficient on the direct price measures in the MDP model were also negative and significant, but turned out to be insensitive to the addition of variables.[4] A partial F-test to see whether the MDP model provides an improvement over the MCP model rejected the null hypothesis of equality between two models (P-value < 0.0001) for all samples, showing that including a direct price difference improves the model significantly.

Table 5 reports the price elasticities estimated from both models; there is a clear distinction between the two. Whereas the MCP models generated a decreasing price elasticity as the interval over which differences are taken lengthened, the MDP models generated an increasing elasticity. The results for one interval, 2002-2004, were out of line with the rest. The price elasticity in 2004 for the MDP model was significantly higher than for other years, and temperature turned out to be negative, although not significant. In addition, the adjusted R^2 was lowest for 2004 among all years, indicating that other factors could have influenced residential water use beyond the predictors used in this study. Other than that, we found the price elasticity to increase as the interval lengthened.

Our estimate of the "short run" price elasticity—over the interval 2000-2002—was -0.661. Our estimate of the "long run" price elasticity—over the interval 2000-2008— was -1.155. These estimates are consistent with previous findings. Pint (1999) and Hewitt and Hanemann (1995) both estimated residential water demand in a similar environment (California and Texas). The former study estimated the price elasticity of demand to fall in the range of -0.14 to -1.24, while the latter found it to fall in the range of -1.53 to -1.629. Our estimates fall in the range of the former study, and are below the range of the latter. All three estimates are, however, higher than many others reported in the literature. One reason for this may be that many earlier studies used regression methods in which either the block pricing structure was not directly modeled, or the absence of significant variation in prices was not correctly addressed.

We also used the MDP model to estimate income effects. However, we were unable to investigate how the income elasticity of water demand evolves over time because income data at the census tract level do not exist for the years 2002, 2004, and 2006. We matched the 2010 census-aggregated household median income with closest year data in our sample, which is 2008, and estimated the MDP model for the 2000-2008 interval only. Table 6 reports the resulting parameter estimates, and the corresponding price and income elasticities. A partial F-test again shows that including the income difference significantly improves the model. The magnitude of coefficients on the constant, the price effect, temperature, and precipitation do not change much relative to those from the MDP model without income effects. However, as might be expected, the magnitude of coefficients on the two income-related dummies both decreased (by 40% and 12%, respectively).

[4] *The results are available from the authors upon request.*

Table 5. Price Elasticity Estimates from MCP and MDP Models

Year	MCP Model	MDP Model
2000 vs. 2002	-1.276	-0.661
	(-1.154,-1.399)	(-0.427, -0.898)
2000 vs. 2004	-0.957	-1.494
	(-0.910, -1.003)	(-1.216, -1.776)
2000 vs. 2006	-0.931	-1.016
	(-0.892, -0.969)	(-0.885, -1.149)
2000 vs. 2008	-0.849	-1.553
	(-0.836-0.857)	(-1.457,-1.649)

Note: A 95% confidence interval for elasticity was constructed using the bootstrapping method.

Using estimated parameters for income and price effects, and the mean marginal price and mean water use for 2008, we calculated approximate price and income elasticities and their corresponding 95% confidence intervals, which are presented in the third column of table 6. The 95% confidence interval was constructed using the bootstrapping method. The estimate of price elasticity is close to that from the MDP model without the income effect. Our mean estimate of the income elasticity of water demand is about 0.036, showing that a 1% increase in median household income between 2000 and 2008 increased water use by 0.036% over that interval. The fact that consumers with higher income tend to use more water is consistent with previous findings. In fact, mean daily water use in Scottsdale (median household income of $71,816)[5], at 249 gallon/day was more than double that of Phoenix (median household income of $48,596), at 123 gallons/day in 2008 (Western Resource Advocates 2010). We note that our estimates of the income elasticity of demand for water are at the lower end of the range of income elasticities from previous studies.

Finally, we considered how the price elasticity of water demand changed at different levels of water use by estimating the price elasticity of water demand at different quantiles of water use in the sample. We used a quantile MDP regression model to obtain price estimates at the 0.1, 0.25, 0.5, 0.75, and 0.9 quantiles of water use. Table 7 presents the estimated coefficients, and the price and income elasticity estimates from the quantile regression model for the 2000-2008 interval, along with their 95% confidence intervals. The table shows that the impact of climate decreases as water use increases, indicating that higher water users in Phoenix are less responsive to a change in rainfall or temperature than low water users.[6] Furthermore, the price elasticity of demand is higher at lower levels of water use than at higher water use levels, indicating that low water users are more price-sensitive than high water users. This is consistent with findings on quantile energy demand studies, which show that electricity consumers' sensitivities to price are strongest at the lowest levels of electricity consumption (Fan and Hyndman 2011; Kaza 2013).

[5]*Statistics were taken from State & County Quick Facts (Census 2010).*
[6]*The coefficient on temperature at 10 percentile water use is 2.22 times bigger than that at the 90 percentile, while the coefficient on precipitation at 10 percentile water use is 1.11 times bigger than that at the 90 percentile.*

Table 6. MDP Model with both Price and Income Effect, 2000 vs. 2008

Variable	Estimated Coefficient	Elasticity
Constant	3.0496 (0.2276)***	-
Difference in Temperature	0.2515 (0.0216)***	-
Difference in Precipitation	-0.0366 (0.0012)***	-
Dum_{Pool}	0.7985 (0.1018)***	-
Dum_{Res_Value}	0.3638 (0.1274)***	-
Difference in Price	**-10.0513 (0.3153)*** **	-1.549 (-1.458, -1.639)
Difference in Income	**9.95e-06 (1.64e-06)*** **	0.036 (0.014, 0.058)
R^2	0.4003	-
Partial F-Statistics	F(1,3656) $\sim$ 36.51***	-

*Note: Asterisks ***, **, and * denote significance at the 0.1%, 1%, and 5% levels, respectively. Numbers inside parentheses represent the robust standard error. A 95% confidence interval for elasticity was constructed using the bootstrapping method based on 5,000 drawings.*

An inspection of the summary statistics for income and water uses by quantile confirms that water users in the higher quantiles have a higher income than water users in the lower quantiles, which indicates that high-income households were less sensitive to water price increases than lower income households. This is as expected, because the water bill is a much smaller proportion of monthly expenditure for high-income people than for low-income households. Not surprisingly, we found the income elasticity of demand to be higher amongst high water users than amongst low water users.

Summary and Discussion

The main goal of this study was to estimate the short- and long-run price elasticity of water demand in cases where the dataset is derive from a single water provider, and where there is limited price variation. We employed a differenced regression approach that includes a direct measure of price, and found that the price elasticity exhibits an increasing pattern over time, which is consistent with previous findings. We also found water use to be increasing in income, and that low water users (lower income users) were more sensitive to increasing prices than high water users (higher income users).

Our study does have its limitations; one is that the differenced regression method is not capable of addressing the block-switching behavior associated with a change in marginal price, which leads us to focus only on users in the second block. Another limitation stems from the fact that there is no price variation within seasons. This problem might be overcome if data on the City of Phoenix were combined with data from other providers. Moreover, since our estimates are somewhat higher than the historical average of price-elasticity estimates, it would be desirable to estimate this model using the data from other single providers in Phoenix Metropolitan areas such as Chandler, Mesa, Tempe, etc.

Nevertheless, the approach demonstrates that it is possible to recover the kind of elasticity estimates required to manage adaptation to climate change from rather unpromising data. These findings have implications for demand management as a strategy for adapting to the water implications of

Table 7. Estimated Coefficients and Price and Income Elasticity Estimated from Quantile Regression Method (2000 vs. 2008)

Variable	**10 Percentile**	**25 Percentile**	**50 Percentile**	**75 Percentile**	**90 Percentile**
Constant	2.8740 (0.2942)***	3.1890 (0.2023)***	3.1316 (0.2001)***	2.7824 (0.2308)***	3.1697 (0.2479)***
Difference in Temperature	0.3659 (0.0233)***	0.3093 (0.0148)***	0.2478 (0.0154)***	0.1977 (0.0161)***	0.1648 (0.0192)***
Difference in Precipitation	-0.0396 (0.0233)***	-0.0390 (0.0009)***	-0.03491 (0.0009)***	-0.0317 (0.0012)***	-0.0355 (0.0019)***
Dum_{Pool}	1.0868 (0.1349)***	0.6611 (0.0837)***	0.4047 (0.0904)***	0.2143 (0.0995)**	0.2192 (0.1463)
Dum_{Res_Value}	-1.5728 (0.3620)	0.0321 (0.1279)	0.5619 (0.1573)***	1.0185 (0.1565)***	1.7416 (0.2954)***
Difference in Price	-13.1453 (0.3720)***	-11.9699 (0.2871)***	-10.1473 (0.3157)***	-7.8476 (0.3720)***	-6.7451 (0.3766)***
Difference in Income	7.32e-07 (3.92e-06)	1.41e-05 (1.91e-06)***	1.85e-05 (1.59e-06)***	0.00002 (1.77e-06)***	1.80e-05 (2.28e-06)***
Price Elasticity	**-2.399 (-2.265, -2.532)**	**-2.116 (-2.017, -2.216)**	**-1.697 (-1.594, -1.801)**	**-1.314 (-1.192, -1.436)**	**-0.889 (-0.791, -0.986)**
Income Elasticity	0.002 (-0.021, 0.025)	**0.045 (0.033, 0.057)**	**0.067 (0.056, 0.078)**	**0.078 (0.064, 0.091)**	**0.075 (0.056,0.094)**

*Note: Asterisks ***, **, and * denote significance at the 0.1%, 1%, and 5% levels, respectively.*
Numbers inside parentheses represent the robust standard error. A 95% confidence interval for elasticity was constructed using the bootstrapping method based on 5,000 drawings.

climate change. Understanding differences in the price responsiveness of different groups helps target demand management to areas where it will be most effective, and understanding the evolution of price responsiveness over time helps target the sequencing of measures. Understanding the price elasticity of demand also helps clarify the revenue implications of different measures.

In Phoenix, for example, the greater price responsiveness of low-income/low water-users indicates that water conservation by demand management may require a different pricing structure than currently exists. At current prices, demand management through a proportionate increase would be more effective amongst low-income groups than amongst high-income/high water users. The lower price responsiveness of high-income users indicates that the effectiveness of demand management for those users might require a significantly steeper price structure than currently exists. The evidence suggests that most residential water use in Phoenix is accounted for by outdoor irrigation, and is associated with relatively high water-users/high-income households (Western Resource Advocates 2010). A steeper pricing structure implies that water bills might be substantially raised for those largely high-income groups in the upper consumption block. Since short-run elasticities are lower than long-run elasticities for high income groups, this would also affect the timing of both the revenue streams associated with a given measure, and the projected change in the level of water consumption.

With good estimates of the price and income elasticity of demand it is possible to develop price structures that are able to achieve targeted changes in consumption without being punitive to any particular groups. Given that climate change is likely to impact various income groups differently, this may be important. The fact that the price elasticity of demand is higher among low-income/low water-use groups does not imply that demand management measures should be targeted only at those groups. What it does imply is that price measures should be designed to be effective at all income levels.

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