Residential water demand, climate change and exogenous economic trends

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Abstract: This study develops a model of municipal demand for residential landscaping designed to estimate sensitivity of water use to changes in weather conditions. We apply the model to a panel of monthly water utility billing data for single family residential users in northern Nevada, for nine years from 2003 to 2011. Furthermore we estimate the change in demand for residential water use that results under various climate change scenarios. We find that residential single family water demand for our study area may increase by between 42 and 176 million gallons per year by the end of this century.

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Introduction

Outdoor water use is the largest and most variable component of residential water use in the western United States, where almost all annual precipitation occurs during the winter months and arid conditions require irrigation to maintain most types of residential landscaping (Sovocool et al. 2006; Hilaire et al. 2008; Kenney et al. 2008). Short run increases in the use of irrigation water cost households relatively little in comparison to the expense of replacing vegetative landscaping materials.[1] Even for landscape vegetation selected for drought tolerance, some degree of irrigation is necessary. In addition, homeowners are observed to water more heavily than is minimally required through periods of high heat (Hilaire et al. 2008). This may be the case for several reasons including: the time to adjust automated irrigation systems is not worth the savings to homeowners; landscape vegetation appears wilted during the day, even when healthy during higher than normal temperatures; and the perception that the cost of repairing inefficient irrigations systems is not compensated by water bill savings.

Residents in the Southwestern United States have already experienced an increase in average temperature of 1.5 degrees Fahrenheit over the last half century and future climate change predictions for this region suggest temperatures increasing by as much as 2.5 to 8.5 degrees Fahrenheit in the next century with more severe and frequent droughts and decreases in springtime precipitation (Global Climate Change Impacts in the United States 2009).

Climate change poses a further challenge for regions where irrigation is necessary to maintain non-native landscape vegetation (as well as some native desert vegetation in extreme conditions) during the summer months, but generally unnecessary during the winter. In addition to using more water during hotter summers, customers in areas with strong seasonality will also be irrigating for an increasing number of days each year. For the western United States the IPCC predicts that climate change has and will continue to cause temperature increases throughout the year, but that these increases will be more substantial during the summer months (Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007)

Models projecting municipal water use for resource and infrastructure planning in areas affected by climate change would ideally include the relationship between changes in weather events and the behavioral response of households. We develop and estimate a model of water demand for single-family homes, using a unique panel of 9-years of monthly household-level water usage from 2003 through 2011, for the greater Reno metropolitan area in northern Nevada.

The study area is an example of a semi-arid climate with less than eight inches of precipitation per year on average (National Weather Service Forecast Office 2012). The model uses variation in temperature, days of precipitation, and wind speed to explain changes in water consumption at the household level, based on observed monthly water use during the decade. We control for household size, irrigable area, price, income, and other house characteristics along with time fixed effects.

The resulting estimated model is used with IPCC climate change predictions of seasonal changes in weather variables, including temperature increases of up to 1.5 degrees Fahrenheit by 2020 and 2.5 to 8.5 degrees Fahrenheit by the end of this century. Because the period that our data cover span the boom, bust, and recovery that heavily affected the residential housing market in the study region, we are able to control for structural economic conditions that can indirectly affect irrigation water use by single family homes. In particular municipal water utilities observe that capital expenses associated with changing landscaping tends to occur when homes change hands. One would expect that during the recent housing crisis, the added value of water-intensive landscaping would be lower than during the preceding housing boom.

In the following section we motivate our modelling approach in the context of previous research related to the municipal residential water demand and climate change. Following that we develop a model of household water demand in section 3 and discuss the limitations of our approach. In section 4 we discuss our data and estimation technique and in section 5 we present our results. We use our model results along with IPCC projections of temperature and precipitation changes for the Western United States to determine the range of possible changes in residential water demand in Section 6. Finally, section 7 discusses the implications of this study.

Modeling water demand response to weather and climate change

Dell et al. (forthcoming) review empirical studies that estimate the impact of climate change on economic outcomes such as agricultural output and energy demand. These studies causatively identify the economic effects of climate change by employing panel data methodologies that exploit high-frequency exogenous changes in temperature, precipitation, and other climatic variables over time within a given spatial area. There are no studies analyzing the impact of climate change on residential water demand reported in this review.

Polebitski et al. (2011) and Balling and Cubaque (2009) are the only published studies we are aware of that forecast the effects of climate change on water use. The authors use forecasts from downscaled Global Climate Models (GCM) to estimate the change in urban water demand that will result from climate change. Both studies build on water demand models that are estimated using bimonthly (Polebitski and Palmer 2010) or monthly (Balling and Cubaque 2009) billing data aggregated at the census tract level. The obvious drawback of both studies is the use of aggregated data to estimate the water demand model. Our disaggregated data allows us to build a behavioral model so that we can focus on how heterogeneous residential water consumers make landscape irrigation decisions under varying weather conditions that are similar to those predicted by climate change models.

Although few water demand studies focus explicitly on climate change, most do include one or more weather variables such as average temperature or total precipitation that describe the influence of weather on seasonality of residential water use. Other studies use indices of weather effects to control for seasonality including the evapotranspiration (ET) rate (Billings and Agthe 1980; Agthe et al. 1986; Nieswiadomy and Molina 1988; Hewitt and Hanemann 1995; Bamezai 1997); the number of days without a significant rainfall times the average monthly temperature (Griffin and Chan 1990; Gaudin et al. 2001); lagged precipitation and average temperature (Pint 1999); relative humidity (Al-Quanibet and Johnston 1985); and growing and cooling degree days (Lyman 1992). A criticism with the use of indices of weather effects is that these variables mask the weather conditions as they are observable to decision makers. Indices capture and aggregate weather information, but the decision-maker observes weather events directly, and therefore reacts directly (adjusts irrigation timing before heading out to work or before turning in for the evening in response to weather reports or expectation of heat and precipitation events).

Most previous empirical models of water demand with weather effects specify the effect of precipitation as linear; however Maidment and Miaou (1986) and Miaou (1990) argue that precipitation events initially reduce water demand with a diminishing effect over time. This approach makes sense for areas that obtain frequent and considerable quantities of precipitation, however rainfall is generally infrequent and of short duration during the irrigation season for our study area. A single spring or summer precipitation event may cause residents to skip a day of outdoor irrigation, but will not impact cumulative irrigation days. Therefore following Martínez-

Espiñeira (2002) and Hoffman et al. (2006) we model monthly precipitation as a count variable rather than using the quantity of precipitation.

Price structure and block rates

A focus of the water demand literature has been the specification of price and estimation techniques that accommodate the block pricing schemes commonly used by water utilities today. Early studies determined that marginal price should be used when pricing is done according to a block rate scheme; furthermore, when using marginal price a difference variable should be included (Taylor 1975; Nordin 1976; Billings and Agthe 1980). The difference variable measures the income effect of the rate structure; it the difference between what a household would pay if all units were charged at the marginal price and what they actually pay. OLS estimates of the marginal price and difference variables will be biased as result of the endogeneity of marginal price, difference, and quantity of water used (Griffin and Martin 1981). Many water demand studies use two-stage least squares (2SLS) and instrumental variables (IV) techniques to control for this endogeneity (Jones and Morris 1984; Deller et al. 1986; Agthe et al. 1986; Agthe and Billings 1987; Nieswiadomy and Molina 1989; Höglund 1999; Nauges and Thomas 2000; Hewitt and Hanemann 1995). Structural estimation techniques are also used to estimate water demand under block rates and are especially useful for data that are limited in either cross-sectional or time series observations (Hewitt 1993; Hewitt and Hanemann 1995; Olmstead et al. 2007; Olmstead 2009). Strong and Smith (2010) propose preference-based methods for estimating consumer responses to price changes.

Moeltner and Stoddard (2004) estimate firm-level monthly water use as a function of marginal price, climate variables, individual firm characteristics, and time effects. They show that by using monthly observations of water use and marginal prices for individual customers as opposed to time-aggregated data commercial water demand can be found to exhibit strong seasonal patterns which can aggravate simultaneity problems associated with block pricing if unaccounted for in demand specifications. This result is applicable to our case of residential water demand estimation; we build on their model which is described in the following section.

Data

Empirical studies of residential water demand differ primarily in the quality of water use data. A large body of studies use data aggregated to the city or community level, the utility level in large metropolitan areas, or by census tracts (Agthe et al. 1986; Griffin and Chang 1990; Höglund 1999; Nauges and Thomas 2000; Strong and Smith 2010; Polebitski and Palmer 2010). Using aggregate data makes it difficult to account for household and property heterogeneity. Various studies employ household billing data (Hanke and de Maré 1982; Jones and Morris 1984; Deller et al. 1986; Nieswiadomy and Molina 1988, 1989, and 1991; Lyman 1992; Renwick and Archibald 1998; Pint 1999; Olmstead et al. 2007). The majority of recent studies utilize panel data where the time observations are annual, semi-annual, bimonthly, or monthly (Lyman 1992; Höglund 1999; Nauges and Thomas 2000). The less frequent time observations make it difficult to isolate the relationship between seasonal variation in weather conditions and water use. Overall, monthly or daily household-level panel data is desirable for studying the effect of weather conditions on household water consumption.

Another problem encountered in previous studies is obtaining information about relevant household and property characteristics including family size and income, the use of water efficient appliances, the irrigable area, vegetation characteristics, and irrigation technology used. Several studies obtain information through homeowner surveys; however this limits the sample size and may force researchers to generalize characteristics across neighborhoods (Jones and Morris 1984; Chicoine and Ramamurthy 1986; Lyman 1992; Renwick and Archibald 1998; Olmstead et al. 2007; Miyawaki et al. 2011). Still other studies have used census block or tract data and generalized this information across households within each unit, which has the advantage of using actual demographic and economic data rather than proxies, but limits the ability of the researcher to model water use differences within a neighborhood (Balling et al. 2008; Polebitski and Palmer 2010; Strong and Smith 2010). Some studies use household-level tax assessor information or income tax information to proxy these variables (Hanke and de Maré 1982; Jones and Morris 1984; Nieswiadomy and Molina 1988, 1989, and 1991; Pint 1999). The number of bedrooms may be used as a proxy for household size, the property value as a proxy for household income, and the yard size (total acreage minus the house footprint) as a proxy for irrigable area. The advantage of the later approach to our work is that it maintains household-level variation.

Empirical Model Formulation

We consider water as an input to the household production function for landscape maintenance. The decision-maker chooses the type and quality of landscape to produce, which determines the water intensity of production. There is no direct substitute for water in this production process; however the household can change production to a less water intensive landscape type (e.g. xeriscaping). Therefore the demand function should ideally include marginal price of water, income, and prices of landscape alternatives. Modeling how water intensiveness of landscape alternatives influences water use would require landscape information at the household level as well as prices of other inputs to alternative types of landscaping. Such landscape production specific information is complex, requiring assumptions about production functions and cross-price information that are not easily incorporated into an empirical model. Consequently we abstract from direct modeling of water as an input into landscaping decisions.

For a given household *i*, water demand in month *t* can be expressed as

$$y_{it} = p_{it}\beta_p + d_{it}\beta_d + x_i'\beta_x + c_t'\beta_c + m_t'\beta_m + \varepsilon_{it}$$

where

$$\varepsilon_{it} = \mu_i + e_{it},$$

p_{it} is the observed marginal price of water associated with household *i* and month *t*, d_{it} is the observed difference between what the household would pay if the total quantity of water consumed was charged at the marginal price and what they actually pay, x_i is a k by 1 vector of household characteristics, c_t is a m by 1 vector of climate indicators, m_t is a n by 1 vector of period indicator variables corresponding to time period t, the β-terms are parameters corresponding to their associated regressors, and ε_{it} is and error term which is decomposed into a household-specific constant μ_i and an normally distributed random error term e_{it} with mean zero and variance ${\sigma_e}^2$. We assume the distribution of μ_i to be multivariate normal with $E[\mu_i] = 0, E\left[\mu_i\mu_j'\right] = {\sigma_\mu}^2 \cdot I_{T_i}$ if $i = j$ and $E[\mu_i] = 0, E\left[\mu_i\mu_j'\right] = 0$ if $i \neq j$, where I_{T_i} is a $T_i \times T_i$ identity matrix, and T_i is the total number of time periods included in the sample for household *i*. As stated we assume the household specific effect is uncorrelated across households and we further assume that μ_i, e_{it}, and all covariates are uncorrelated within and between water utilities. We use instrumental variables to control for the endogeneity of price, difference, and quantity; random effects to control for unobserved heterogeneity; and period indicator variables to control for unobserved time effects that may result from market activities, regional economic conditions, and the timing of exogenous price changes.[2]

Data

Our data consists of monthly water use for single family residential customers for two utilities in the greater Reno metropolitan area from February 2003 to December 2011. A selection of the total single family residential data was made based on several criteria: 1) regular monthly data was considered to be billing periods of 23 to 37 days [3] 2) uninterrupted consumption history from February 2003 to December 2011, 3) availability of property and building characteristics from the county assessor dataset.[4] Our knowledge our final group of customers is representative of the population of single family residences in the region. The final sample includes 5,109 single family residential customers. Tables 1a and 1b describe monthly water use characteristics. The data include comes from two water utilities that operate in the same region: Truckee Meadows Water Authority (TMWA) serves the cities of Reno and Sparks and has a much larger customer base than Washoe County Department of Water Resources (DWR), which serves the remaining households in Washoe County, Nevada. In our data a greater proportion of observations were eliminated from the DWR dataset due to the filter procedures outlined above, and the variation within the DWR subsample is greater than the TMWA subsample.

We account for seasonal and inter-annual variation in weather conditions by including the average temperature, days of rainfall, and average wind speed for each billing period. Billing periods vary over the sample due to the fact that different homes are on billing cycles that start and end on different days of the same month. We calculate monthly averages from daily weather measurements obtained from the nearest weather station in NOAA's Global Historical Climate Network database during each day of each monthly billing period and we exploit this variation in weather conditions within and among seasons and over the years in the data to produce highly significant household responses to weather conditions.[5] Despite the availability of a variety of weather indicators we base our model heavily on average temperature due to the fact that it is a very strong predictor of total water use.[6] Figures 1-2 illustrate how total water use relates to average monthly temperature; figures 3-4 illustrate how total water use relates to days of precipitation; and figures 5-6 illustrate how total water use relates to average monthly wind speed. There is a clear positive relationship between average water use and average temperature and wind speed and a negative relationship between average water use and days of precipitation, although precipitation and wind speed are much noisier time series. Table 2 describes weather average characteristics over the sample as well as for each billing month.

We use data from two water utilities that operate in roughly the same study area in order to exploit differences in the rate structures to obtain sufficient variation in marginal price. A summary of water charges for our data are provided in tables 3-4. Water charges are comprised of a monthly fixed fee (tables 3a and 3b) and variable rates (tables 4a and 4b) according to an increasing block pricing scheme. The fixed fee is based on the diameter of the pipe that services the household and the tier rates are charged based on 1,000's of gallons of water consumption in each tier. The number of tiers in the block pricing system varies over time within each utility as well as between utilities. DWR customers face as many as six tiers, while TMWA customers face up to three tiers. Furthermore DWR charges different service regions different fixed fees and/or block prices, and has implemented changes in its blocks and rates over the study period. Therefore the combined data has considerable variation in marginal price and difference. We use real prices in our model, which we derive using the appropriate urban consumers CPI.

Lastly we obtain household and property data from the Washoe County assessor's tax roll database. We use the number of bedrooms as a proxy for household size and the house value as a proxy for income, which we convert to a monthly income proxy following Nieswiadomy and Molina (1988). To control for property characteristics we subtract the house footprint from the total land area to calculate the yard size; we also include a squared term to allow for a non-linear relationship; and we use age of the house as well as age squared as a proxy for the technology of indoor water-intensive appliances. Table 5 displays descriptive statistics for the household data.[7] DWR customers have higher average monthly income, average yard size, and average family size and higher variance for all of these variables, while TMWA has a higher average house age and variance in house age. The differences in the two utilities' customer bases result from the fact that TMWA's customers primarily reside in the central and older regions of the Reno-Sparks metropolitan area while DWR's customers tend to live in more suburban regions where newer and larger houses are predominant. As a result of these differences we would expect customers in these two regions to respond differently to climate change, which we test in our model.

Results

We estimate our model using two-stage least squares (2SLS), with predicted values for marginal price and difference estimated in the first stage based on all exogenous variables from the final model as well as instruments that capture the utilities' billing structures including fixed charges, tier thresholds, and tier rates. In addition we estimate separate seasonal slope coefficients for temperature and precipitation to allow for different behavioral responses as well as to fit with the climate change predictions which vary by season. We also estimate separate slope coefficients for TMWA and DWR customers for the household and weather variables. In cases where the slopes are not significantly different for the two utilities we have estimated one overall coefficient.

Tables 6 and 11 present the second stage estimation results. The weather variables are all significant and robust to a variety of specifications with the exception of the winter precipitation variable. Since customers generally do not water during the winter in this region we would not expect an increase in winter precipitation to affect water use. Our results indicate that a one degree increase in average monthly temperature during the spring leads to a 3.8% and 3.4% increase in water use, while a one degree temperature increase during the fall leads to a 4.3% and a 3.8% increase in water use for DWR and TMWA customers respectively. These effects dwarf the response during the summer and winter, during which a one degree increase in average monthly temperature leads to a 1.1% (DWR) and 0.7% (TMWA) increase in summer water use and a 0.5% (DWR) and 0.2% (TMWA) increase in winter water use. The small effect during the winter is expected because residents do not generally irrigate during the winter. However the small effect during the summer is more surprising, although considering the fact that households are already irrigating during these months an increase in temperature will only require a marginal increase in irrigation water. We also include a one month lag of average temperature to account for a 'dry-out' effect which results from persistent high temperatures that deplete the vegetation of moisture.[8] As expected this effect is significant albeit relatively small; a one degree increase in the previous month's average temperature leads to a 0.6% (DWR) and a 0.4% (TMWA) increase in water use. Overall DWR customers are more responsive to weather conditions than TMWA customers likely due to the larger average yard sizes for this group, which we assume is correlated with a larger irrigated area. Days of precipitation has a negative and significant coefficient for all four seasons, suggesting that households water less when it rains. However an additional day of rain matters the most during the summer and results in a 1.6% decrease in water use. Finally an increase in average wind speed of one knot leads to a 5% (DWR) and 2.7% (TMWA) increase in water use suggesting that irrigation increases substantially in response to windy days. This implies that instead of turning off irrigation on windy days, customers increase irrigation to make up for the lost sprinkler water.

This model produces negative and significant parameter estimates for marginal price and the associated difference variable and positive and significant parameter estimates for monthly income. According to Nordin (1976), the difference coefficient should be approximately equal in magnitude and opposite in sign from the income coefficient.[9] Although we obtain the correct sign the magnitude of the difference variable is larger than the income effect for DWR and smaller than the income effect for TMWA. The difference in income effects for the two utilities is consistent with the higher average property values for DWR customers; household water utility expenses make up a smaller share of monthly income. All other signs are as expected: longer billing periods are correlated with higher water use, larger families use more water, older houses are less efficient and we observe higher water use but at a decreasing rate, and larger yards require more water at a decreasing rate. Our results are robust to different specifications considered and the parameters of interest are robust to the set of regressors specified.[10]

Table 7 summarizes estimated average elasticities from our model. Our inelastic price and income elasticity findings are consistent with other residential water studies. Dalhuisen et al. (2003) in a meta-analysis of 64 residential water studies found an average and median price elasticity of -0.41 and -0.35 respectively, and an average and median income elasticity of 0.43 and 0.24. Our price elasticity of -0.20 and income elasticities of 0.04 (DWR) and 0.16 (TMWA), while low, are well within the range of elasticities cited by Dalhuisen et al. (2003). More interestingly we find that residential water users are elastic with respect to changes in temperature during the spring and fall. While households are inelastic with respect to changes in temperature during the winter and summer and precipitation and wind in general, our results in general suggest that weather conditions play a larger role in residential water demand than price or income.

Investigation of period indicator variables, included to control for seasonality and unobserved time effects provides a glimpse of the effects of how exogenous impacts of the economic boom, bust and recovery affected water demand patterns. The recession, which began in December of 2007, hit Nevada particularly hard in terms of housing prices. Figure 7 shows the housing sales activity beginning to pick up in 2009 for Washoe County, where Reno is located. The indicator variables represent the difference in water use with respect to the base period, March 2003. Figure 8 shows that the indicator variables have a slight downward trend, which suggests that the average household used less water over the study period. Consistent with the timeline of the recession the indicator variables are above average in pre-recession years (2003 and 2004) and below average after the recovery began (2009, 2010, and 2011). We suggest that this trend is evidence of the effect the high foreclosure rates during the recession. Foreclosure often results in property neglect, including permanent losses in landscape vegetation. New owners are presented with a property that must be re-landscaped, and an ideal opportunity to install more water-resistant native vegetation. We argue that this may in part explains the slight drop in average water use experienced by the water utilities in our study over this period.

Impact of Climate Change on Residential Water Demand

We use predictions for increasing temperatures from the Fourth Assessment of the Intergovernmental Panel on Climate Change. There are some drawbacks to using IPCC estimates. First the timescale used for these forecasts is almost a century, which is far longer than is useful for economic forecasting. We also consider the shorter 10 year and 40 year time windows during which the average temperature is expected to increase by as much as 1.5 degrees Fahrenheit and 1 to 4 degrees Fahrenheit respectively. Second these estimates are based on results from GCM's, which make predictions for expansive geographic areas—the whole western U.S. in this case. The predictions are imprecise for our study area as a result. We use these predictions as an example of how our model can be used to predict changing water demand. Using downscaled climate change predictions would yield better predictions for example.

These predictions assume that others factors are held constant which does not allow for changing landscapes that are likely to occur for some households or inevitable price increases. Therefore our predictions serve as an upper bound for the climate change impacts on single family residential water demand.

Table 8 summarizes our predictions for 2020. We predict that water use will increase during the fall by as much as 7.4 and 6.3 percent for DWR and TWMA customers respectively, which is the largest seasonal increase in water use for our sample. This translates to an additional 8 thousand and 5 thousand gallons respectively used per year by the average household and 7 thousand and 4 thousand gallons per year respectively for the median household; the total increase in annual water use amounts to 31 million gallons. Tables 9-11 summarize our predictions for 2050, which include a 5 to 20 percent increase in household water use for DWR customers during the fall, a 4 to 17 percent increase in household water use for TMWA customers during the fall, and a total predicted increase of water use for our sample of 21 to 83 million gallons.

We use information from the regional predictions table 11-1 that is published by Working Group I to make our predictions for 2090-2100.[11] The predictions for the Western U.S. region are provided by season and annually; table 12 summarizes these predictions which indicate that between a 3.8 and 10.3 degree Fahrenheit increase is expected per year by the end of this century. This increase is in reference to the base period used. Since temperatures have already increased by 1.5 degrees Fahrenheit we subtract this amount from the predictions. Table 13 and 14 summarize our predictions at the household level. We find that the largest changes in residential water demand will occur in the spring and fall with a 6 to 41 percent increase for DWR customers and a 5 to 35 percent increase for TMWA customers in spring water use and a 10 to 40 percent increase for DWR customers and a 9 to 34 percent increase for TMWA customers in fall water use. Extrapolating these results to the households in our sample we estimate that there will be between a 42 and 176 million gallon per year increase for the households in our sample, holding other factors constant.

Our model also predicts the impact of changing precipitation and drought on household water use. However there is little consensus about the direction of the change in precipitation for the western U.S.; some models predict an increase in precipitation, while others a decrease. This is due to the fact that in some parts of the West there is expected to be a large increase in precipitation while others will experience severe drought. We would need downscaled predictions to resolve this uncertainty and there we do not make predictions for precipitation.

These results indicate that there will be a considerable impact of climate change on residential single family water demand in our study area unless landscaping changes are made. Price instruments can be used to encourage customers to both conserve water and invest in water efficient landscaping and irrigation technology. We estimate the necessary percentage increase in marginal price needed to mitigate the climate change impacts that we estimated by 2020. Based on our estimated elasticity for marginal price in order to mitigate a the increases in water demand for 2020 a 33 percent increase in real marginal price will be needed for DWR customers and a 28 percent increase in real marginal price for TMWA customers in the spring and a 37 percent and 31 percent increase in real marginal price will be needed in the fall. These estimates are assuming that no landscaping changes are being made, which likely overestimates the necessary price increase. Some households will decide to convert their landscape before these full price increases are even reached, which would indicate that a majority of the climate change effect might be mitigated without too substantial of a price increase.

Discussion

Our modeling approach relies on data for water use at the household and monthly billing level, over several years. The panel and a random effects specification allow us to control for unobserved individual data that is correlated with responses to weather change, as well as to capture seasonal variation. Time indicators capture unobserved effects correlated with time periods and appear to capture the boom, bust, and recovery effects of recent economic trends. This approach assumed that within the data set, individual households are not making structural changes to their landscaping type, but rather responding to economic and weather events over time. Our data includes substantial variation in pricing within the block rate pricing system within as well as across years which likely contributes to the robustness of the results. Similarly, we are able to exploit different timing of customer billing cycles along with daily weather data to produce considerable variation in average monthly levels for weather variables within a year. The high elasticity of demand for temperature is not surprising given current values for home landscaping; however, this result indicates that water utilities should be aware that climate change will likely have a significant impact on water use. While not used in our study region, other jurisdictions, including the Las Vega area, use incentive-based programs to encourage homeowners to change landscape vegetation for water conservation, as well as mandated zoning laws that limit use of turf grass as landscaping. Given the elasticity of demand for temperature, these policies may be of high value to reduce the expected increase in water demand from increased temperatures. With respect to price elasticity of demand, the fact that elasticity changes along a demand curve, increasing with price, coupled with low water prices (relative to other items in household budgets) is consistent with our (and others') resulting inelastic demand. However, as price is increased (and/or block rate stricture was modified at the upper end), elasticity increases, making it an effective water conservation tool. An ideal package of demand management tools might include both price and non-price incentive-based programs.

We assume that response to weather events over the ten year period can be used to simulate responses to future weather events. In the very long run, one would assume that demand response to weather events would change as water prices increase; homeowners replace current landscaping with high drought tolerant landscaping; and the housing market trends toward higher density housing with less irrigated area per individual. In this case, our estimates would tend to over-estimate the response of water demand to climate change.

Tables

Table 1a: Average Water Use (1,000 gallons)

TMWA					
Observations: 356952			Households: 3336		
Variable	**Mean**	**Median**	**Standard Deviation**	**Minimum**	**Maximum**
Total Use	10.68	7.00	9.22	0	79
Tier 1 Use	4.94	6.00	1.55	0	7
Tier 2 Use	5.30	1.00	7.16	0	61
Tier 3 Use	0.44	0.00	2.37	0	52

Table 1b: Average Water Use (1,000 gallons)

DWR					
Observations: 189711			Households: 1773		
Variable	**Mean**	**Median**	**Standard Deviation**	**Minimum**	**Maximum**
Total Use	15.40	9.00	14.98	0	159
Tier 1 Use	4.65	5.00	1.27	0	14
Tier 2 Use	4.45	4.00	4.66	0	62
Tier 3 Use	4.35	0.00	7.14	0	77
Tier 4 Use	1.44	0.00	4.33	0	59
Tier 5 Use	0.39	0.00	2.17	0	23
Tier 6 Use	0.12	0.00	1.50	0	85

Table 2: Weather characteristics for overall sample and by billing month

Variable	Mean	Median	Standard Deviation	Min	Max
Average Daily Temperature, Degrees F	54.42	52	15.17	26	81
January	34.22	34	3.40	26	42
February	35.60	36	3.66	29	43
March	39.63	40	2.60	35	48
April	46.65	46	3.70	38	56
May	52.10	51	3.71	45	62
June	61.82	62	4.92	51	74
July	71.69	72	4.05	61	79
August	78.15	78	1.60	74	81
September	73.94	74	2.20	67	78
October	64.17	65	4.08	52	72
November	52.23	52	3.48	42	63
December	40.60	41	3.39	31	49
Total Days of Precipitation	4.47	4	3.65	0	17
January	8.62	8	2.82	2	15
February	6.95	6	3.80	1	16
March	8.62	9	2.29	3	17
April	5.43	5	3.58	0	15
May	5.40	5	3.48	0	14
June	3.98	3	2.92	0	15
July	2.18	1	3.12	0	14
August	1.88	1	2.00	0	7
September	1.52	1	1.68	0	7
October	1.94	1	2.16	0	7
November	3.51	3	1.94	0	9
December	4.09	4	1.99	0	11
Average Daily Wind Speed, Knots	5.23	5.30	1.47	1.70	8.70
January	3.94	4.10	0.95	1.70	5.80
February	3.37	3.00	1.01	1.80	5.70
March	4.80	4.70	0.98	2.50	7.00
April	6.69	6.80	0.89	4.60	8.70
May	7.12	7.20	0.55	5.10	8.40
June	6.91	7.00	0.61	5.40	8.30
July	6.35	6.30	0.49	5.10	7.30
August	5.84	5.90	0.34	4.90	6.70
September	5.27	5.30	0.38	4.20	6.40
October	4.54	4.50	0.61	2.80	5.90
November	3.89	3.70	0.60	2.40	5.60
December	3.93	4.00	0.98	1.70	5.60

Table 3a: Nominal Fixed Monthly Charges by Service Size: TMWA

Service Size	01/03-09/03	10/03-02/05	03/05-05/09	06/09-05/10	06/10-12/12
3/4"	$10.02	$14.80	$15.70	$15.70	$15.70
1"	$10.61	$16.30	$17.20	$17.30	$17.30
1 1/2"	$12.24	$18.50	$19.60	$19.60	$19.60
2"	$14.34	$21.50	$22.80	$22.80	$22.80

Table 3b: Nominal Fixed Monthly Charges by Service Size: DWR

Service Size	01/03-02/06	03/06-02/07	03/07-02/08	03/08-07/09	08/09-01/10	02/10-01/11	02/11-12/11
3/4"	$7.91	$10.93	$11.48	$12.05	$11.78	$12.79	$13.43
1"	$8.36	$12.69	$13.32	$13.99	$15.18	$16.72	$17.56
1 1/2"	$10.76	$16.78	$17.29	$18.04	$20.84	$23.27	$24.44

Table 4a: Nominal Block Pricing and Rate Structure: TMWA

All Service Sizes					
Tier Threshold (gallons)	**01/03-09/03**	**10/03-02/05**	**03/05-05/09**	**06/09-05/10**	**06/10-12/12**
Tier 1	6,000	6,000	6,000	6,000	6,000
Tier 2	N/A	28,000	28,000	25,000	25,000
Rate per 1,000 gallons	**01/03-09/03**	**10/03-02/05**	**03/05-05/09**	**06/09-05/10**	**06/10-12/12**
Tier 1	$1.56	$1.56	$1.58	$1.63	$1.72
Tier 2	$2.43	$2.43	$2.50	$2.64	$2.78
Tier 3	N/A	$2.90	$2.91	$3.05	$3.25

Table 4b: Nominal Block Pricing and Rate Structure: DWR

Tier Threshold (gallons)	Service Size	01/03-02/06	03/06-02/07	03/07-02/08	03/08-07/09	08/09-01/10	02/10-01/11	02/11-12/11
Tier 1	3/4", 1"	5,000	5,000	5,000	5,000	6,000	6,000	6,000
	1 1/2"	27,000	27,000	27,000	27,000	28,000	28,000	28,000
Tier 2	3/4", 1"	12,000	12,000	12,000	12,000	20,000	20,000	20,000
	1 1/2"	86,000	86,000	86,000	86,000	150,000	150,000	150,000
Tier 3	3/4", 1"	37,000	24,000	24,000	24,000	40,000	40,000	40,000
	1 1/2"	375,000	375,000	375,000	375,000	600,000	600,000	600,000
Tier 4	3/4", 1"	62,000	37,000	37,000	37,000	N/A	N/A	N/A
	1 1/2"	775,000	775,000	775,000	775,000			
Tier 5	3/4", 1"	85,000	52,000	52,000	52,000	N/A	N/A	N/A
	1 1/2"	N/A	N/A	N/A	N/A			
Rate per 1,000 gallons	**Service Size**	**01/03-02/06**	**03/06-02/07**	**03/07-02/08**	**03/08-07/09**	**08/09-01/10**	**02/10-01/11**	**02/11-12/11**
Tier 1	3/4", 1"	$1.48	$1.56	$1.64	$1.74	$2.02	$2.23	$2.34
	1 1/2"	$1.76	$1.96	$2.02	$2.11			
Tier 2	3/4", 1"	$1.76	$1.85	$1.95	$2.07	$2.53	$2.78	$2.92
	1 1/2"	$1.89	$2.21	$2.28	$2.38			
Tier 3	3/4", 1"	$2.14	$2.25	$2.40	$2.52	$3.04	$3.34	$3.51
	1 1/2"	$2.09	$2.25	$2.32	$2.42			
Tier 4	3/4", 1"	$2.58	$2.72	$2.87	$3.04	$4.05	$4.46	$4.68
	1 1/2"	$2.24	$2.67	$2.75	$2.87			
Tier 5	3/4", 1"	$2.84	$2.99	$3.16	$3.34	N/A	N/A	N/A
	1 1/2"	$2.64	$2.97	$3.06	$3.19			
Tier 6	3/4", 1"	$3.05	$3.21	$3.39	$3.59	N/A	N/A	N/A
	1 1/2"	N/A	N/A	N/A	N/A			

* These rates represent those faced by the majority of DWR residential single family customers. Customers in certain service areas are charged according to different rate schedules.

Table 5: Household Characteristics for overall sample and by utility

Variable	Observations	Mean	Median	SD	Min	Max
Monthly Income in $1,000's	546663	4.06	3.50	2.96	0.41	77.15
DWR	189711	5.99	5.42	3.84	0.47	77.15
TMWA	356952	3.03	2.80	1.60	0.41	21.61
Yard Size in Acres	546663	0.26	0.15	0.30	0	4.97
DWR	189711	0.47	0.38	0.40	0	4.97
TMWA	356952	0.15	0.13	0.14	0	2.85
Age of House	546663	19.86	16	14.16	0	101
DWR	189711	15.29	12	10.92	0	73
TMWA	356952	22.29	18	15.06	0	101
Family Size	546663	3.27	3	0.73	0	7
DWR	189711	3.32	3	0.76	0	7
TMWA	356952	3.25	3	0.72	0	7

Table 6: Second Stage Regression Results

Variable	Coefficient	Robust S.E.
Avg. Temp Dec.-Feb. (DWR)* **	0.0054	0.0011
Avg. Temp Mar.-May (DWR)* **	0.0377	0.0014
Avg. Temp Jun.-Aug. (DWR)* **	0.0111	0.0013
Avg. Temp Sep.-Nov. (DWR)* **	0.0432	0.0014
Avg. Temp Dec.-Feb. (TMWA) **	0.0022	0.0010
Avg. Temp Mar.-May (TMWA)* **	0.0340	0.0011
Avg. Temp Jun.-Aug. (TMWA)* **	0.0071	0.0010
Avg. Temp Sep.-Nov. (TMWA)* **	0.0382	0.0009
One Month Lag Avg. Temp. (DWR)* **	0.0063	0.0006
One Month Lag Avg. Temp. (TMWA)* **	0.0037	0.0005
Days of Precip. Dec.-Feb.	-0.0015	0.0011
Days of Precip. Mar.-May **	-0.0029	0.0014
Days of Precip. Jun.-Aug.* **	-0.0162	0.0015
Days of Precip. Sep.-Nov.* **	-0.0054	0.0017
Avg. Windspeed (DWR)* **	0.0494	0.0030
Avg. Windspeed (TMWA)* **	0.0265	0.0029
Marginal Price* **	-0.1036	0.0147
Difference* **	-0.0204	0.0029
Monthly Income (DWR) **	0.0059	0.0029
Monthly Income (TMWA)* **	0.0513	0.0065
Days (DWR)* **	0.0329	0.0009
Days (TMWA)* **	0.0377	0.0009
Bedrooms (DWR)* **	0.1719	0.0109
Bedrooms (TMWA)* **	0.1346	0.0100
Age of House* **	0.0119	0.0009
Age of House Squared (DWR)* **	-0.0003	0.0000
Age of House Squared (TMWA)* **	-0.0002	0.0000
Yardsize in acres (DWR)* **	0.2200	0.0481

Yardsize in acres (TMWA)* **	1.2371	0.0965
Yardsize squared (DWR)* **	-0.0706	0.0164
Yardsize squared (TMWA)* **	-0.6596	0.0542
Constant* **	-2.2232	0.0797
R-squared Within: 0.5442	**ρ = 0.2384**	
Between: 0.2522	**σ_u = 0.3762**	
Overall: 0.4802	**σ_e = 0.6724**	

Table 7: Selected Elasticities

Variable	**Elasticity at Mean**	**Elasticity at Median**
Avg. Temp Dec.-Feb. (DWR)	0.1969	0.1989
Avg. Temp Mar.-May (DWR)	1.7570	1.7327
Avg. Temp Jun.-Aug. (DWR)	0.7906	0.7994
Avg. Temp Sep.-Nov. (DWR)	2.7040	2.7193
Avg. Temp Dec.-Feb. (TMWA)	0.0826	0.0825
Avg. Temp Mar.-May (TMWA)	1.5612	1.5661
Avg. Temp Jun.-Aug. (TMWA)	0.4984	0.5112
Avg. Temp Sep.-Nov. (TMWA)	2.4395	2.4828
One Month Lag Avg. Temp. (DWR)	0.3404	0.3251
One Month Lag Avg. Temp. (TMWA)	0.1998	0.1910
Days of Precip. Dec.-Feb.	-0.0100	-0.0092
Days of Precip. Mar.-May	-0.0191	-0.0177
Days of Precip. Jun.-Aug.	-0.0433	-0.0324
Days of Precip. Sep.-Nov.	-0.0125	-0.0108
Avg. Windspeed (DWR)	0.2582	0.2616
Avg. Windspeed (TMWA)	0.1389	0.1406
Marginal Price	-0.2014	-0.2145
Monthly Income (DWR)	0.0356	0.0322
Monthly Income (TMWA)	0.1556	0.1437

Table 8: Maximum increase in household water use (gallons) from increasing temperatures for 2020

	Percentage increase		Increase for Average Household (Gallons)		Increase for Median Household (Gallons)	
Season	**DWR**	**TMWA**	**DWR**	**TMWA**	**DWR**	**TMWA**
Dec.-Feb.	1.74	0.89	79.06	38.45	69.76	35.41
Mar.-May	6.59	5.66	559.38	361.46	395.28	282.90
Jun.-Aug.	2.60	1.62	719.17	284.08	650.79	258.54
Sep.-Nov.	7.41	6.28	1,523.72	889.42	1,260.08	753.65
Annual	--	--	8,643.98	4,720.22	7,127.74	3,991.49
Sum across all households in sample	**DWR**		15,325,781.92		12,637,486.03	
	TMWA		15,746,645.85		13,315,625.99	
	Total Sample		31,072,427.77		25,953,112.02	

Table 9: Increase in household water use from increasing temperatures for DWR customers for 2050

	Percentage increase		Increase for Average Household (Gallons)		Increase for Median Household (Gallons)	
Season	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Dec.-Feb.	1.16	4.65	52.71	210.84	46.51	186.03
Mar.-May	4.39	17.57	372.92	1491.68	263.52	1054.08
Jun.-Aug.	1.74	6.94	479.44	1917.77	433.86	1735.45
Sep.-Nov.	4.94	19.77	1015.81	4063.25	840.05	3360.21
Annual	--	--	5762.66	23050.62	4751.83	19007.31

Table 10: Increase in household water use from increasing temperatures for TMWA customers for 2050

	Percentage increase		Increase for Average Household (Gallons)		Increase for Median Household (Gallons)	
Season	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Dec.-Feb.	0.59	2.36	25.63	102.54	23.61	94.43
Mar.-May	3.77	15.09	240.97	963.89	188.60	754.39
Jun.-Aug.	1.08	4.31	189.39	757.54	172.36	689.43
Sep.-Nov.	4.19	16.75	592.95	2371.78	502.44	2009.74
Annual	--	--	3146.81	12587.25	2661.00	10643.99

Table 11: Predicted Annual Water Use Increase for 2050 (1000's of Gallons)

Evaluated for Mean and Median Household	**Mean**		**Median**	
Predictions	**Minimum**	**Maximum**	**Minimum**	**Maximum**
DWR	10217	40869	8425	33700
TMWA	10498	41991	8877	35508
Total	20715	82860	17302	69208

Table 12: Exerpt from Table 11.1 from the IPCC Fourth Assessment Report

		Temperature Response (°F)						**Precipitation Response**						**Extreme Seasons (%)**		
Region	**Season**	**Min**	**25**	**50**	**75**	**Max**	**T yrs**	**Min**	**25**	**50**	**75**	**Max**	**T yrs**	**Warm**	**Wet**	**Dry**
NORTH AMERICA (continued)																
Western North	DJF	2.9	5.6	6.5	7.9	10.4	25	-4	2	7	11	36	>100	80	18	3
America	MAM	2.7	4.3	5.6	6.1	10.8	20	-7	2	5	8	14	>100	87	14	
	JJA	4.1	5.8	6.8	8.5	10.3	10	-18	-10	-1	2	10		100	3	
30N,50E to	SON	3.6	5.0	5.6	8.1	9.5	20	-3	3	6	12	18	>100	95	17	2
75N,100E	Annual	3.8	5.2	6.1	7.4	10.3	15	-3	0	5	9	14	70	100	21	2.0

Table 13: Increase in household water use from increasing temperatures for DWR customers for 2090-2100

	Percentage increase		Increase for Average Household (Gallons)		Increase for Median Household (Gallons)	
Season	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Dec.-Feb.	2.17	10.28	98.25	466.12	86.69	411.28
Mar.-May	5.95	40.51	504.84	3439.48	356.74	2430.47
Jun.-Aug.	4.36	15.20	1203.55	4199.93	1089.13	3800.64
Sep.-Nov.	10.49	40.18	2156.34	8259.68	1783.24	6830.56
Annual	--	--	11888.93	49095.60	9947.39	40418.82

Table 14: Increase in household water use from increasing temperatures for TMWA customers for 2090-2100

	Percentage increase		Increase for Average Household (Gallons)		Increase for Median Household (Gallons)	
Season	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Dec.-Feb.	1.15	5.21	49.73	226.30	45.80	208.40
Mar.-May	4.92	34.88	314.51	2228.37	246.15	1744.04
Jun.-Aug.	2.71	9.44	476.73	1659.02	433.87	1509.86
Sep.-Nov.	8.86	33.93	1254.55	4804.73	1063.05	4071.31
Annual	--	--	6286.56	26755.25	5366.61	22600.86

Table 15: Predicted Annual Water Use Increase for 2090-2100 (1000's of Gallons)

Evaluated for Mean and Median Household	**Mean**		**Median**	
Predictions	**Minimum**	**Maximum**	**Minimum**	**Maximum**
DWR	21079	87047	17637	71663
TMWA	20972	89256	17903	75396
Total	42051	176302	35540	147059

Table 16: Price Increase Calculations

Utility	DWR	TMWA	DWR	TMWA
Season	Percentage increase in household water use by 2020		Percentage marginal price increase need to negate the effect	
Dec.-Feb.	1.74	0.89	8.66	4.40
Mar.-May	6.59	5.66	32.71	28.09
Jun.-Aug.	2.60	1.62	12.93	8.02
Sep.-Nov.	7.41	6.28	36.80	31.18

Figures

Figure 1:

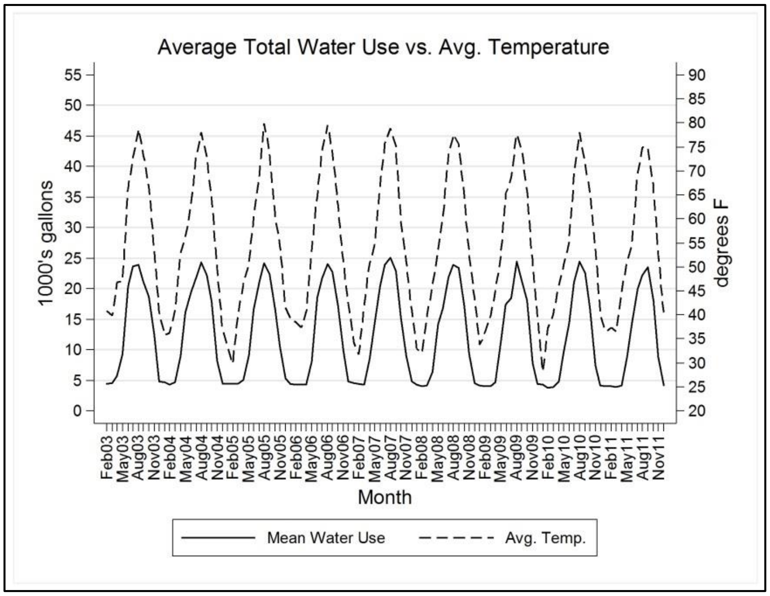


Figure 2:

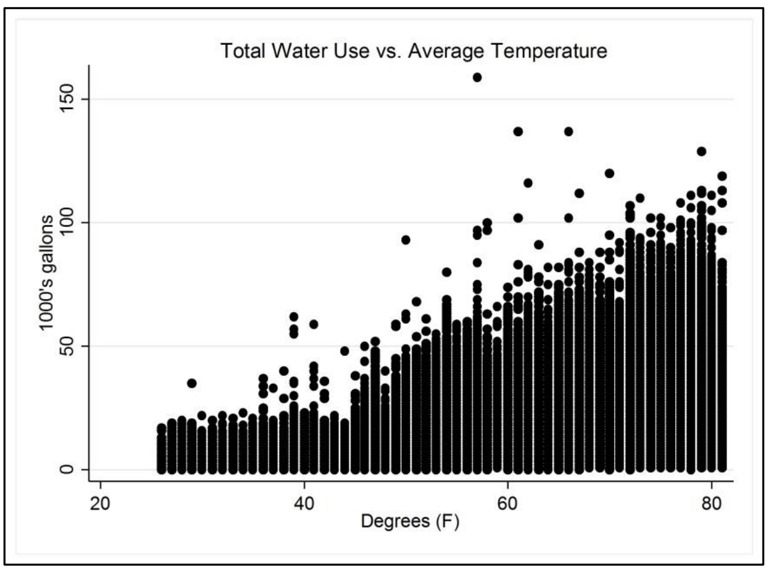


Figure 3:

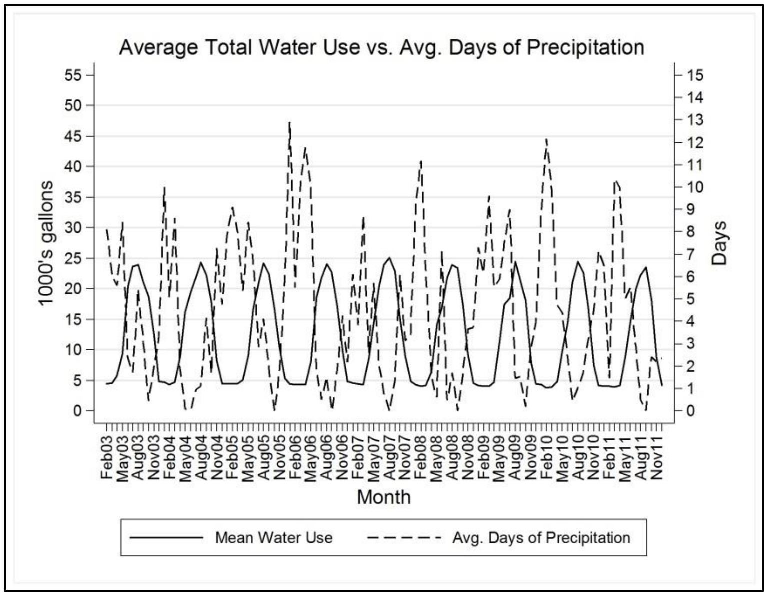


Figure 4:

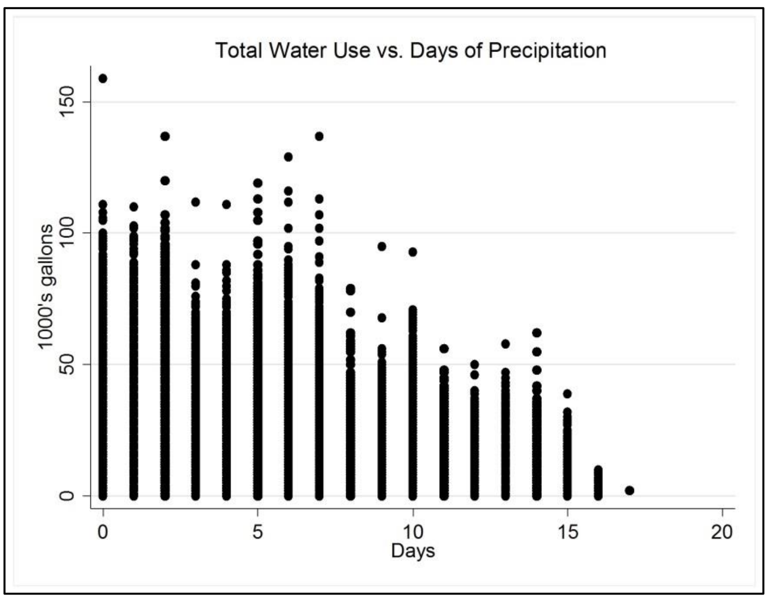
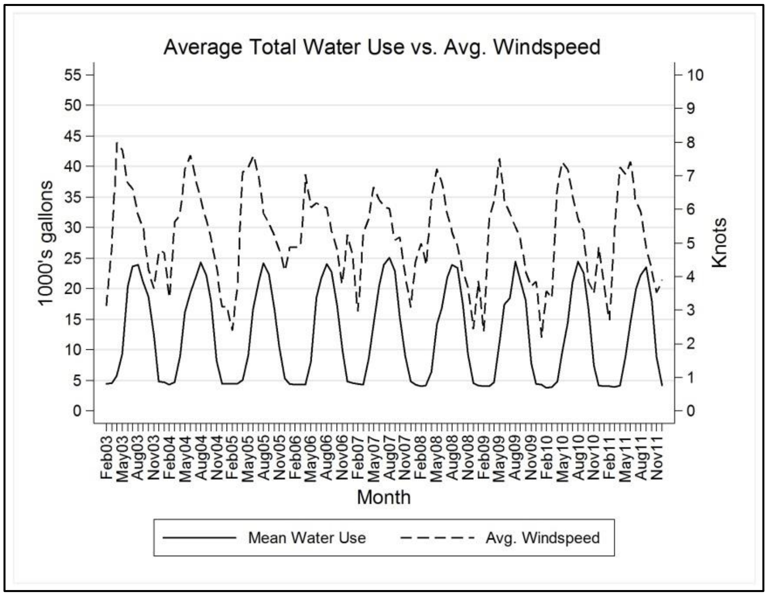


Figure 5:



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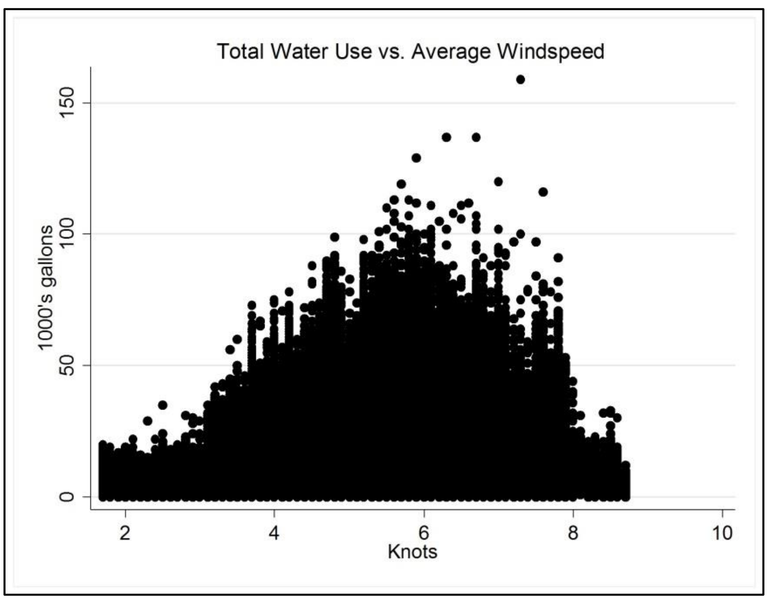

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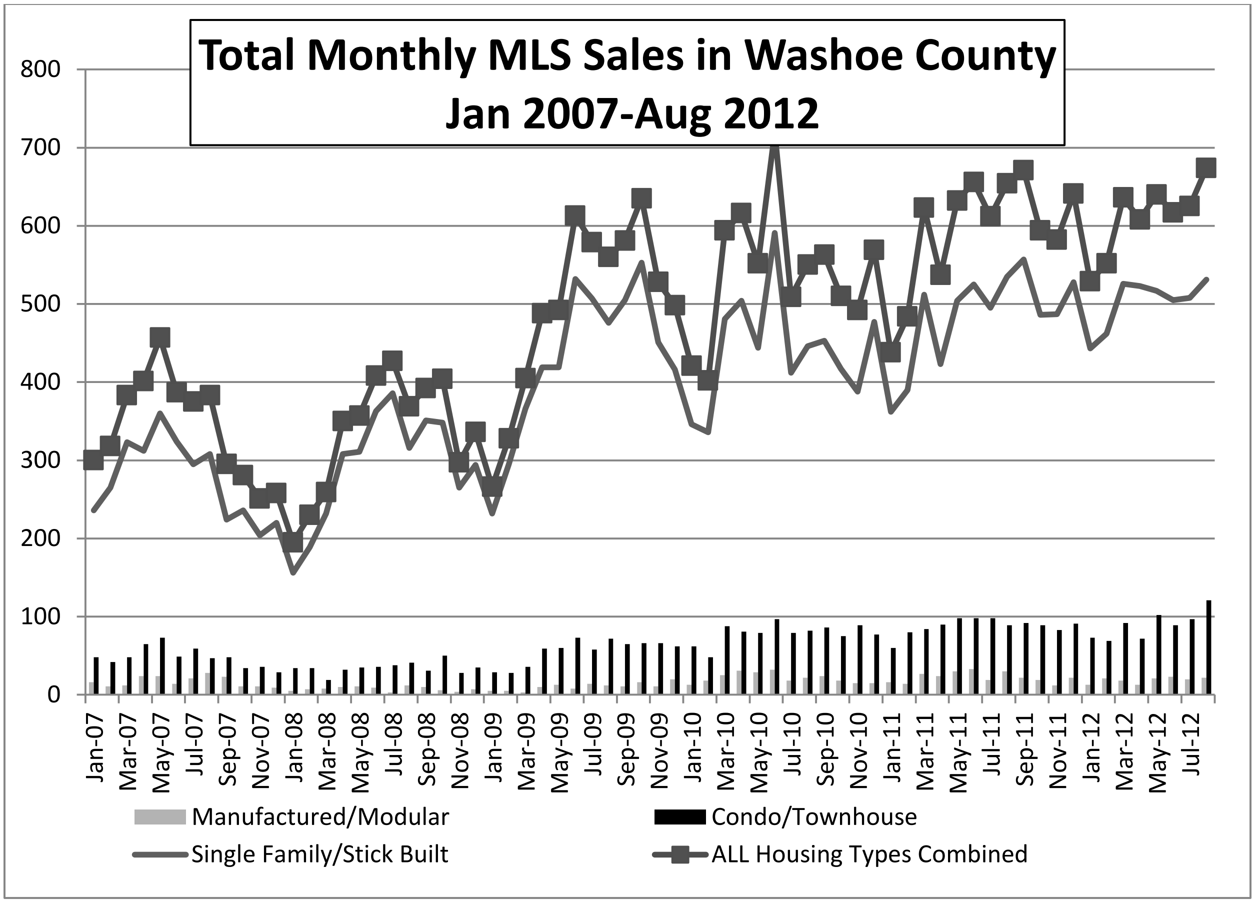
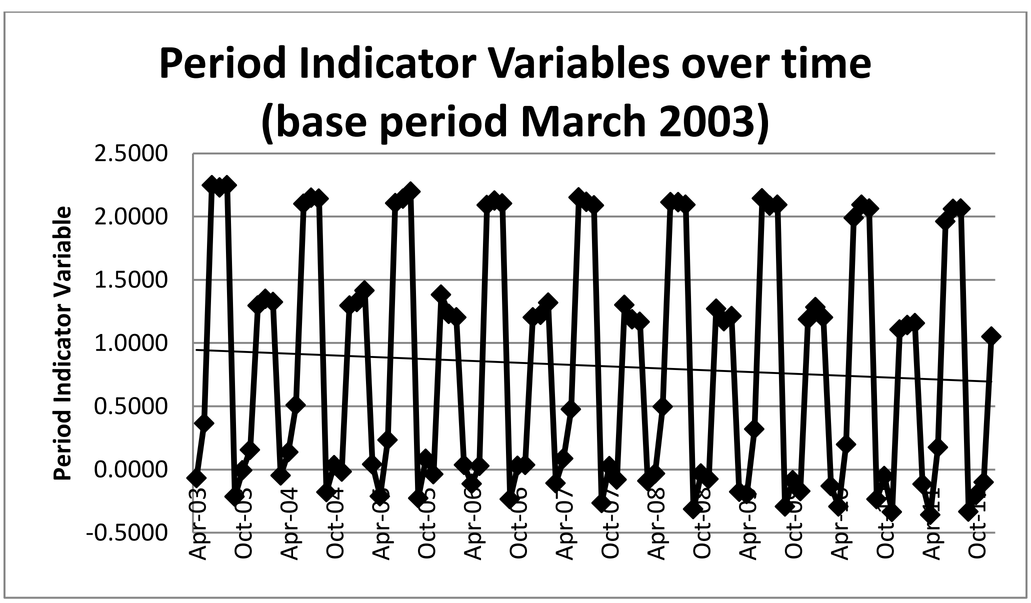


Figure 8:



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Footnotes

[1] The authors recognize that homeowners may also adapt in the long run by using better irrigation practices, but regardless of this choice climate change necessitates an increase in the quantity of water used for irrigation to maintain the same quality of landscape.

[2] See Moeltner and Stoddard (2004) for a detailed description of the econometric issues that arise in the context of water demand estimation and how this model handles these issues.

[3] Many observations fall short or exceed this measure due to inconsistencies in the utility's meter reading service or can occur during the first or last month service, which we deem to be irregular monthly data. We determined the limits of 23 and 37 days so as to maximize the quantity of data retained while eliminating considerable inconsistency. See Lott, Tchigriaeva, and Rollins (2013) for more details.

[4] For more information on the specifics of our data cleaning and elimination as well as a complete description of our data sources please see our technical report (Lott, Tchigriaeva, and Rollins, 2013).

[5] In the case of precipitation we count the total days of precipitation during each billing period.

[6] Weather data includes average, minimum, and maximum daily temperature, relative humidity, and reference evapotranspiration rate; daily precipitation in inches; average daily wind speed and maximum gust; and cooling, heating, and growing degree days.

[7] The inclusion of house age and yard size observations that take on a value of zero correspond respectively to new houses and condominiums for which the owner has no irrigable area for which they are responsible.

[8] This hypothesis is based on the fact that the 99th percentile of average monthly relative humidity over this period was only 63%. Therefore it can be assumed that persistent high temperatures are not offset by high humidity, which is an important consideration for vegetation. A lag of precipitation was also considered, but was not significant.

[9] For a complete discussion of this issue see Nieswiadomy and Molina (1989).

[10] A Hausman test was used to verify our use of a random effects model as well as inclusion of the full set of month indicator variables over month and year indicators.

[11] See http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch11s11-1-2.html#table-11-1 for more details of climate scenario descriptions and discussion of global climate models used.