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Evidence for the effectiveness of progressive urban water demand management

Kim J. Zietlow and
Harald von Witzke

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Kim J. Zietlow and Harald von Witzke
Humboldt University of Berlin

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Abstract

Based on panel data from the City of Davis, California, comprising more than 15,000 urban water consumption units and 81 billing periods over 13 years, this study investigates residential water demand and the effectiveness of three structural water conservation measures. The city switched from a uniform to an increasing block pricing scheme, introduced a second tariff block for single-family residential households, and changed the calculation logic for the household sewer rate. An instrumental fixed effects regression analysis results in a price elasticity of -0.19 for residential consumers. The data also suggests that all structural tariff adjustments were effective, even under consideration of the general economic situation. This is the first study which demonstrates the effectiveness of coupling the sewer rate with a proxy for indoor water consumption on a household level.

Keywords: residential water demand; water pricing; price elasticity; panel data

JEL: C23; C36; Q21; Q25

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1 Introduction

Driven by population and income growth, many communities have to cope with increasing urban water demand in the presence of ever scarcer resource availability. Adjusting the price of water is the most common approach to curtail urban water demand. Among other factors, the price elasticity of demand determines the effectiveness of tariff changes. The greater the responsiveness to price increases, the higher the anticipated reduction in demand.

An effective policy lever is to adjust the tariff structure. Volumetric pricing bears greater water saving incentives than a flat tariff. In addition, implementing an increasing block pricing (IBP) scheme offers further incentives to avoid over-consumption, as households are stepwise charged an increasing price per liter according to the amount of consumption. In practice, it is rare to find structural changes to the water pricing scheme. Hence, most empirical studies only investigate the impact of price changes and socioeconomic characteristics such as income, age, or household composition on water demand. The study by Nataraj and Hanemann (2008) is an exception. It outlines the impact of introducing an additional block to an existing IBP system in Santa Cruz, California.

This study utilizes a rich data set from the City of Davis, California comprising more than 15,000 individual water consumption units and 81 billing periods. Between 1996 and 2009 the city excessively raised water tariffs and conducted several structural water conservation efforts. Employing an in-depth micro-econometric approach yields rare insights including the price elasticity of residential consumers based on longitudinal data and the effectiveness of three policy changes. This is the first study which empirically tests, whether coupling the sewer rate with winter water consumption on a household level has an impact on water demand.

The paper starts with a brief literature review highlighting the key economic and econometric aspects when dealing with demand estimation. Section 3 provides an overview of the data and structural water tariff changes, while section 4 explains the steps to specify the model for the given context. Section 5 presents the main results including a novel approach to employ robustness checks. Section 6 concludes with policy implications, literature contributions, and a proposal for future research.

2 Literature review

2.1 Economic considerations

Water in its consumptive form is considered an economic good. Hence increases in price should yield reductions in consumption. Several studies suggest that consumers are rather price insensitive, as water has limited substitutes for many purposes and the water bill makes up only a small fraction of disposable household income (Cavanagh et al. 2002). Empirical evidence is shown by Espey et al. (1997) who find a price elasticity of -0.51 with only 10%

lying above 0 and below -0.75. Agthe and Billings (1980), Nieswiadomy and Molina (1989), Pint (1999), Martínez-Espiñeira (2003) find a value between -0.25 and -0.75.

Several studies attempt to determine, whether consumers react to average or marginal prices. Applying the Taylor-Nordin difference variable Nieswiadomy and Molina (1989) find that consumers react to marginal prices. However, the literature offers several other price specifications, yet none proofs to be superior in terms of capturing consumer sensitivity. Martínez-Espiñeira (2003) uses average marginal price, Gaudin (2006) average price, Chicoine et al. (1986) and Griffin and Chang (1990) the difference of both.

2.2 Econometric considerations

The most common water tariff structure is increasing block pricing (IBP). It is characterized by marginal prices, which increase stepwise with rising consumption. Since the consumer pays the volumetric rate for each respective block, consumption within a lower block comes at a discount. This particular feature of an IBP system can be treated as an implicit income subsidy. Nordin (1976) incorporates this concept into an econometric context by creating a difference variable (D) which captures the size of the effect. Nieswiadomy and Molina (1991) finds that in water demand estimation *D* has a similar size than income on a household level, yet appears opposite in sign. The Taylor-Nordin difference variable becomes meaningful in water demand estimation, when data on income is not available or unreliable. However, the literature shows great controversy about D, since the strong assumption that consumers are aware of their water tariff in detail and adjust consumption accordingly is oftentimes not fulfilled. Shin (1985) introduces a "price-perception variable" which is added to the general demand estimation equation to reveal, whether consumers react to average or marginal prices.

The literature on water demand estimation exhibits a range of different estimation approaches. For cross-sectional and panel data, ordinary least squares (OLS), two and three-stage least squares (2SLS and 3SLS), logit and instrumental variables (IV) can be used (Worthington and Hoffman 2006). Maximum likelihood techniques such as discrete/continuous choice or regression discontinuity approaches require more detailed data. OLS estimation has been widely applied, especially in earlier studies (Agthe and Billings 1980, Chicoine et al. 1986, Thomas and Syme 1998, Nieswiadomy 1992, Dandy et al. 1997). However, the problem of simultaneous choice remains and thus leads to biased estimates unless accounted for. Pint (1999) uses a fixed-effects model, but also obtains an upward-sloping demand curve.

In standard 2SLS estimation the observed marginal price is regressed on a set of explanatory variables and then uses the predicted price as regressor to explain demand for water. Even though this model yields unbiased results, it does not account for the characteristics of block pricing (Cavanagh et al. 2002). Nieswiadomy and Molina (1991) propose an approach in which observed water consumption is regressed on marginal prices at fixed consumption levels. Then marginal price is predicted by the actual rate schedule and the quantity predicted in the first stage. This approach is successfully applied by Hewitt and Hanemann (1995) as well as Higgs and Worthington (2001). Cavanagh et al. (2002) applies a two-stage GLS random-effects model with instrumental variables. In addition to treating block cut-offs by using marginal prices at certain consumption points, this approach accounts for potential correlation between observations across households.

The discrete/continuous choice model was introduced by Hewitt and Hanemann (1995) and further applied to water demand estimation by Rietveld et al. (1997), Corral et al. (1998), Pint (1999), and Olmstead et al. (2007). Nataraj and Hanemann (2008) develop a regression discontinuity model in order to test the responsiveness of consumers when faced with an additional block.

The underlying theoretical assumption in water demand estimation is the utility maximizing consumer who either tries to maximize consumption for a given budget or minimize costs for an anticipated demand level (Espey et al. 1997). Hence, the functional form of a water demand model needs to be evaluated according to its degree of realistically depicting actual behavior. Yet this aspect receives little attention compared to other issues (Renzetti 1992). Applied specifications include linear, double-log (Cobb-Douglas), and semilogarithmic (Stone-Geary).

Despite apparent estimation advantages the linear functional form implies that consumers react proportionally to price changes along the whole demand function. This behavioral pattern contradicts reality, as consumers tend to become rather price-insensitive for very low and high consumption levels, since urban tap water has no substitutes for many usages and there is a maximum water need. A widely applied specification is the double-log, or Cobb-Douglas functional form (e.g. Foster and Beatie 1981, Hewitt and Hanemann 1995, Olmstead et al. 2007, Mansur and Olmstead 2012). However, its major drawback with respect to modeling human behavior is that it unrealistically assumes a constant elasticity regardless of the price level. The log-linear specification is the most realistic depiction of human behavior, as it allows for changes in the elasticity along the price curve. The log-linear form has been applied in recent studies which test the effects of different water conservation approaches (Gaudin 2006) or estimating the price impact on urban water demand (Arbues et al. 2004). Monteiro (2010) provides a thorough overview of the different functional forms and their implications on water demand estimation. Testing which type of rate structure suits best in achieving pricing for scarcity and budget balancing, Roseta-Palma and Monteiro (2008) conclude that linear and semilogarithmic specification justify IBP, whereas a Cobb-Douglas type would point towards a uniform volumetric rate structure.

3 Data

Facing increasing groundwater depletion, rising infrastructure costs, and insecure climate conditions, the City of Davis has implemented several demand-side measures to ensure sustainable water availability since 1998. This includes water tariff structure changes as well as adjustments to the price level for all customer groups. Structural adjustments started in July 1998, when the city switched from a fixed tariff system based on lot size to a two-part tariff schedule. Under the new system, the water bill consists of a base rate depending on meter size and a volumetric pricing element. Single-family residential customers (SFR) started with a single block, i.e. the same marginal price for all units of water used, whereas all other consumer groups faced a two-tier IBP scheme from the beginning. In 2002, the city introduced an IBP structure also for SFR households. In the beginning of 2008, the sewer rate was coupled to household water consumption, i.e. bimonthly fees for the upcoming year are calculated based on actual winter water consumption of the previous year for the respective household. Water managers attempted to correct for the inequality arising from average citywide sewer rates which allowed high-end consumers to free ride on low-consumption water users.

Regarding changes in the price level, there have been three base rate adjustments (four for SFR) leading to an absolute increase of 192% between 1998 and 2009. During the same period, the consumption rate increased four times (five times for SFR) resulting in an absolute increase of 271% on average over all consumer groups (see Table 1).

The data was collected between March and June 2010 and comes from three different sources. First, the City of Davis Public Works Department provided consumption data and background information on the citywide conservation programs. Second, the city's Finance Department contributed information on historical water rates and rate structure changes. Since the data does not exist electronically, they granted access to their books. Third, climatic and economic variables are drawn from the websites of the Western Regional Climate Center[1] and the Bureau of Labor Statistics[2].

The whole data set ranges from period 1996/4 (Jul/Aug 1996) until 2009/6 (Nov/Dec 2009) and counts 81 bimonthly billing and consumption periods. In total, there are 15,712 households resulting in approximately 1.2 million individual observations. Even though small and large customers can be distinguished based on meter size, the focus of this study is on the four major user groups (see Table 2). The data comprises different variables which differ in terms of their purpose and nature. Table 3 provides an overview and descriptive statistics of all variables used in the estimation procedure.

The explained variable is bimonthly water consumption which is measured on a household level and assumed to be derived. This means that water demand is driven directly by price variables as well as economic, environmental, and household factors. Average price (AP) is calculated as the total water bill divided by consumption. Marginal price (MP) is the highest marginal price paid by the consumer in a certain period. Whereas some households switch between tier 1 and tier 2, others stay within one block regardless of the season or other factors. The same applies to the Taylor-Nordin difference variable (D) which quantifies the actual size of the implicit income subsidy of the consumer.

1 http://www.wrcc.dri.edu/cgi-bin/cliMONtpre.pl?ca2294 (June 9, 2010)

2 http://www.bls.gov/lau/#tables (June 9, 2010)

Following one of the most common choices for instrumental variables in water demand analysis, institutionally determined rates at certain quantities serve as exogenous variables to explain actual marginal price. The choice of instruments follows estimation approaches by Nieswiadomy and Molina (1989), Renwick and Green (2000), Reynaud et al. (2005), or Ruijs et al. (2008). However, annual inflation may be another useful instrument, since it is highly correlated with water rates, but is assumed to be uncorrelated with consumption. Here, marginal price and inflation show a correlation of 0.928, even though no causal relationship can be determined.

4 Model specification

Based on traditional water demand analysis (e.g. Chesnutt and McSpadden 1991, Lyman 1992, Renwick and Green 2000, Olmstead et al. 2007) a standard two-error model is employed (see Equation 1). The usual income term is replaced by the Taylor-Nordin difference variable (D).

Even though many studies employ a log-log specification and the advantage of directly deriving elasticity values are known to the author, the linear function form remains as a placeholder for the three possible versions at this point, i.e. linear (lin-lin), log-linear (log-lin), and double-log (log-log). Since there is no empirically proven advantage of any of these specifications and they differ regarding assumptions on the price elasticity over the price range (Monteiro 2010), all versions are estimated initially to determine the impact of functional form on the price coefficient.

Equation 1:

$$w_{it} = \alpha\, price_{it} + \beta\, D_{it} + Z_t\gamma + X_{it}\delta + \mu_i + \varepsilon_{it}$$

Besides a minimum of water consumption used for drinking and daily hygiene purposes, demand is derived. Thus, water demand per consumer i in period t (w_{it}) can be treated as a function of the following variables. The price variable ($price_{it}$), which for now should stay a placeholder for either marginal or average price, and the Taylor-Nordin difference variable (D_{it}) have a direct and indirect monetary effect on the consumer's choice. Despite the controversy about the interpretation and validity of the rate structure premium (D), the variable is included here to account for the gain in consumer surplus from consuming in the second block (Nordin 1976). Matrix Z_t contains covariates which affect water use in the whole city in the same way and only vary over time such as precipitation and temperature. The conservation policy tools (X_{it}) are added as dummy variables and differ between user groups, hence the subscript i. The model comprises two error terms of which μ accounts for time-invariant heterogeneous unobservable household characteristics such as water use preferences, use of water efficient technology or physical absence of occupants. ε represents the standard residual for random unknown factors and measurement errors (Olmstead et al. 2007). Both error terms are assumed to be independent and identically distributed with zero means and constant variances, i.e. $\mu \sim N(0, \sigma^2_\mu)$, $\varepsilon \sim N(0, \sigma^2_\varepsilon)$.

In response to the consumer's simultaneous choice of consumption and price, an instrumental variables approach is applied. In addition to a widely used instrument, a valid alternative is tested as well. The standard instrumental variable used in the literature is a set of marginal prices for certain consumption levels enforced by water management authorities. They are considered exogenous, since they are established independent of current resource use and for a fixed period of time beyond the length of the current consumption period. Here, thresholds of 10, 25, 50, 200, and 400 CCF are found to be useful. 100 CCF was dropped as rates for all user groups are the same as for 200 CCF, hence creating perfect multicollinearity. As an alternative instrument, we present the annual inflation rate. Its strength comes from the fact that its determination is completely independent of household level water consumption.

Estimating the goodness of the instruments yields satisfying results for both options. The p-value for the group of conditional marginal prices and for inflation is both sufficiently small (see Table 4). These results show that inflation is a valid alternative, when there is doubt that water prices are set exogenously of consumption. In order to be consistent with previous research, conditional marginal prices are used as instruments for further estimations.

Equation 2:

$$price = MP\ x\ \left(\frac{AP}{MP}\right)^{k} \quad with \quad \left(\frac{AP}{MP}\right) = perception$$

Equation 3:

$$\ln w_{it} = \varphi\ \ln(MP_{it}) + \varphi k \ln(perception_{it}) + \beta D_{it} + Z_t \gamma + \mu_i + \varepsilon_{it}$$

According to Espey et al. (1997) and Dalhuisen et al. (2003), consumers react either to marginal or average prices. Shin (1985) was the first to develop a method to test for the respective price variable by including a price perception variable (see Equation 2). The two extreme cases are k=0, i.e. the true indicator is marginal price, and k=1, the true indicator is average price. By integrating this concept into the regression equation (see Equation 3), testing the respective coefficients φ and φk yields evidence for the consumers' actual perception. In order to extract knowledge about k, the two hypotheses in Equations 4 and 5 are tested. Estimating both equations results in p-values of 0.07 and 0.00 respectively. Hence, Davis water consumers react to marginal and not average prices. This result is in line with Nieswiadomy and Molina (1991) who show that consumers under an increasing-block price system follow marginal prices.

Equation 4:

$$H_0:\ \frac{\varphi k}{\varphi} = 0$$

Equation 5:

$$H_0 : \frac{\varphi k}{\varphi} = 1$$

Given the panel nature of the dataset, both a fixed- and random-effects model could be applied. Results for a Hausman test suggest that a fixed-effects model is appropriate (see Table 5). Equation 6 shows the final model applied for further analyses.

Equation 6:

$$\ln(w_{it} - \overline{w_i}) = \alpha \ln(MP_{it} - \overline{MP_i}) + \beta(D_{it} - \overline{D_i}) + (Z_t - \bar{Z})\gamma + (X_{it} - \overline{X_i})\delta + (\mu_i - \overline{\mu_i}) + (\varepsilon_{it} - \overline{\varepsilon_i})$$

5 Estimation and results

This chapter comprises estimation results for several models in order to shed light on the water consumption pattern of Davis inhabitants. The first part uses the base model to elucidate differences in the price coefficient deriving from different estimation techniques. The second part evaluates differences in the estimation results between functional forms of the regression model. The third part focuses on the effectiveness of the three structural water conservation measures including robustness checks, whether the previous results are not confounded by the general economic trends.

5.1 Base model results for different estimation techniques

The first set of estimations demonstrates the need for instrumentation resulting from the simultaneous choice of consumption and marginal price. As expected, results for the OLS and FE model show positive price coefficients, 0.02 and 0.74 respectively (see Table 6). This shows that consumers rather allocate their consumption level based on price differences between blocks than adjust consumption in response to overall tariff increases. Applying an instrumental variable approach within the fixed effects framework yields a price coefficient of -0.19. This value is statistically significant and confirms that consumers treat water as a normal good. Also coefficients for the two instruments used, the marginal prices at consumption levels of 10 CCF and 50 CCF, prove to be significant at the 99% confidence level.

The overall R^2 value for each model ranges between 0.19 for the FE and 0.27 for the OLS specification. These values seem appropriate for the full sample and base model calculations, even though they are relatively small compared to other literature results (e.g. Pint 1999, Renwick and Green 2000, Monteiro 2010). Despite the focus on within-household variation, it is likely that the relatively low R^2 values result from disregarding changes of household factors over time such as income, number of residents, possession of water use appliances, or attitude towards water saving. As housing in Davis is dominated by students, the population structure within single-family houses changes frequently. Hence, even consumption records over the whole time period might not necessarily represent the consumption pattern of the same tenants.

All models have in common that coefficients for the covariates are all significant at the 99% confidence level and show the expected sign. The data confirms that consumers react negatively to greater rainfall and use more water, when temperatures rise. These results hold true albeit accounting for seasonal adjustments. A dummy variable for capturing the effect of the four summer months May-August was included and shows coefficients between 0.09 and 0.14 depending on the model.

5.2 Structural water conservation

The following section deals with the three structural water policy measures introduced during the time span of this analysis, i.e. the introduction of volumetric pricing, the introduction of IBP for an existing two-part tariff system, and coupling of the sewage bill to a proxy for indoor water consumption. All programs enter the estimation equation as dichotomous variables with a value of "1", when the program is effective, and "0" else.

In addition to general water demand estimation, this paper offers unique findings on the success of structural water conservation efforts. Motivated by the claim that consumers in Davis respond more to the general economic situation than to specific water conservation measures, the three conservation measure variables *IBP*, *tier*, and *sewer* are tested with respect to their robustness against county level annual per capita income (*incomepc*) and unemployment rate (*unemployment*). These two variables serve as a proxy, since one can assume that households are better off, when per capita income increases and the unemployment rate decreases. If reductions in household water use may not only be attributed to price changes, rebate programs, or other intentional efforts, but are rather indirectly induced, water policies need to be seen from a different perspective. Results are summarized in Table 7.

The first analysis focuses on the introduction of volumetric pricing with a uniform structure for single-family households in the second half of 1998. All other user groups are excluded, since they started with a two-tier block pricing structure from the beginning. The time period covered ranges from 4.1996 to 3.2002, as in 4.2002 a second block was introduced for SFR customers as well. These conditions reduce the sample to 443,262 observations and 13,822 individual households. The overall R^2 value is 0.27 for both models with a within-R^2 value of 0.46. The estimation of the model results in a statistically significant coefficient for IBP which takes a value of -0.11. Hence, the introduction of volumetric pricing was effective in reducing household water demand for single families. Coefficients for the covariates b*aserate, temperature, precipitation,* and *summer* are statistically significant and show the expected signs.

Adding per capita income and the countywide unemployment rate to the model does not change the results considerably. The coefficient for IBP remains statistically significant and negative (-0.04). Hence, this robustness check demonstrates that the effect of the tariff structure change for single families holds true albeit external macroeconomic effects.

The second analysis focuses on the introduction of a second block for single-family households. Between 4.1998 and 3.2002 the tariff structure for this user group used to be a combination of a fixed charge based on meter size and a volumetric rate for each cubic meter consumed. In 4.2002 the city introduced an IBP schedule with a threshold level of 36 CCF. The tariff structure change enters as a dichotomous variable ("tier") showing a value of "0" for the time periods with one block and "1" after the introduction of IBP. Thus, the time period for this analysis ranges from 4.1998 to 6.2009 including 933,826 observations for 14,648 individual households. The overall R^2 value is 0.73. Each of the models yields similar results for the usual regressors *D, baserate, temperature, precipitation*, and *summer*, which are statistically significant and show the expected sign. Estimation yields a statistically significant coefficient for *tier* with a value of -0.06. Hence, the policy change proves to be effective in reducing water consumption for SFR customers.

However, families with a historic consumption level below the threshold are unlikely to adjust their water use. Their consumption pattern might not be affected by the introduction of the second block. Thus, the interaction term *highcons_tier* is introduced. It captures the effect of *tier* separately for high and low consuming households. Low is defined as a historic consumption level of less than one standard deviation below the mean (16.18 CCF) and high for bimonthly consumption greater than one standard deviation above the mean (55.76 CCF). The estimation yields a coefficient of -0.33 for *highcons_tier*. The policy change had the expected effect for the anticipated target group of high consuming households, yet the positive coefficient for *tier* suggests an ambiguous effect on low consuming families.

The applied robustness checks yield similar results for all variables. The coefficient for the program variable remains negative for high consuming households (-0.32). In total, single family households respond effectively to the introduction of a second block independent of the overall economic situation.

The variable for the third policy change represents the modification of the household sewer rate structure. As of 2008 households pay a sewage charge which depends on individual winter water consumption and, thus, reflecting consumers' own contribution to the local sewage purification plant and infrastructure maintenance cost. This stands in contrast to the previous system, which was based on average citywide consumption. The data includes all user groups, as the tariff modification was valid for the whole city resulting in 1.037.198 observations. The estimation yields an overall R^2 value of 0.31 and all variables turn out statistically significant and show the expected sign. As expected, the coefficient for the tariff structure change sewer has a value of -0.12. Hence, the data reveals that the change in the sewer rate structure effectively reduced household water consumption.

Again, the robustness check involved an addition of data on county level per capita income and unemployment rate. Estimation results show a statistically significant negative consumption effect, yet the value is smaller than without the economic proxy variables

(-0.04). Nevertheless, households effectively adjusted water consumption in response to the tariff structure change despite marginal consideration of average income and unemployment levels in Yolo County.

6 Conclusion

This study employs a rich panel data set from the City of Davis, California covering 15,712 households over 81 consumption periods between 1996 and 2009. In addition to sharp increases in the water rates, the city switched from a uniform to an increasing block pricing structure, introduced a second tariff block (IBP scheme) for single-family residential households, and changed the sewer rate structure in a way that the volumetric charge is based on past individual winter water consumption. Applying an instrumental variable fixed effects approach yields a price elasticity of -0.19 for single-family residential households.

A policy analysis of the structural water conservation measures reveals that the adjustments prove to be effective in Davis. Single-family residential customers significantly reduced consumption, when moving from flat rate pricing to a two-part tariff with a uniform pricing element. Being faced with a second tier of an IBP scheme reduced water demand among this user group further. The adjustment of the sewer charge for the whole city also resulted in significant reductions in water consumption. Even though average consumption tends to decline in times of poorer overall economic conditions, water demand fluctuations due to these effects cannot be identified for consumers in Davis.

The change of the sewage tariff system displays an innovative approach to provide incentives for yearlong and forward-looking water savings. It shows that the more accurate billing and the direct discretion over their sewer charge made consumers reduce their water demand. This finding is unique and of utmost importance for water managers who aim to employ an additional water conservation policy instrument beyond standard price increases, restrictions, or rebate programs.

Despite water rate increases of about 271% between 1998 and 2009, the average water bill for Davis residents remained fairly constant. In the light of cost recovery for the utility provider, this indicates that there is sufficient room for further price increases in the future. The data suggests that the objectives of water conservation and sufficient revenue generation are likely to be achieved in Davis. Even if bound by revenue constraints for the utility provider, there is sufficient room to adjust the tariff structure towards more efficient pricing and increased equity. For instance, introducing a third block or raising the marginal price for the highest tier would lead to a more equitable scheme, in which the monetary burden on households would be more balanced and public utility revenues remain stable. As incomes are relatively high in comparison to the average water bill, high-consuming households could still afford extensive water consumption.

Adding to the rich body of water demand management literature, this study contributes in four ways to managing scarce water resources in the Southwest of the US. First, determining the price elasticity based on a longitudinal data set, which covers 14 years and more than 80 billing periods, has never been done before and, thus, may provide credibility and reliability to other study results. The value of residential price elasticity (-0.18) lies within the range of findings from other studies (Espey et al. 1997, Dalhuisen et al. 2003). Estimating elasticities for each user group indicates that water consumers in this geographic area seem to be rather insensitive to price changes. Differences between user groups are marginal.

Second, the only published study which addresses the introduction of an additional tier within an increasing block pricing scheme is Nataraj & Hanemann (2008). They use a regression discontinuity approach, whereas a fixed-effects approach is chosen here. However, both studies use a panel data set over a considerable number of years and find that adding another block yields a significant reduction in household water consumption for residential customers.

Third, this is the first study known to the authors which tests the effect of a sewer rate structure change on household water consumption. Making the sewer rate dependent on winter water consumption provides water managers with an additional instrument to shape consumers' water saving incentives. The present data suggests that this policy change significantly reduced household water demand.

Forth, this study incorporates the unique analysis, whether observed changes in consumption are rather due to variation in the overall economic environment or conventional water demand factors (household characteristics, prices, conservation programs, or climate). Employing data for monthly per capita income and level of unemployment does not support this hypothesis.

Drawn from the limitations of this study, future research should address the complexities of estimating urban water demand in a multidisciplinary fashion. Estimation results clearly indicate that households in the City of Davis effectively respond to monetary incentives in the form of tariff increases. However, as the rich literature on water economics suggests, water saving behavior is determined by a range of internal and external factors (Millock and Nauges 2010, Grafton et al. 2011). As this data set lacks information on environmental attitude and beliefs, inferences on the degree of influence of those internal factors on the present estimation results cannot be drawn. In the quest for a more differentiated picture, accounting for the influence of psychological components may reflect differences in the degree of responsiveness to monetary incentives between households with high and low environmental attitudes and beliefs. Hence, the literature on water demand management will benefit greatly, if future studies take psychological components into account in addition to standard socio-demographic characteristics, when estimating the effectiveness of water conservation programs.

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Table 1: Water pricing schedule for Davis, CA between 4.1998 and 6.2009

Base rates

Meter size	Meter size code	4.1998 - 3.2002	4.2002 - 1.2004	2.2004 - 3.2006	4.2006 - 3.2008	4.2008 - 3.2009	4.2009 - 6.2009
5/8" or 3/4"	01	5.66	6.22	6.22	8.40	10.00	10.10
1 - inch	02	7.70	8.83	8.83	11.80	14.10	14.10
1 1/2 - inch	03	12.78	15.31	15.31	20.30	24.30	24.30
2 - inch	04	18.89	23.11	23.11	30.50	36.50	36.50
3 - inch	06	35.21	43.94	43.94	57.80	69.10	69.10
4 - inch	07	53.54	67.34	67.34	88.40	105.70	105.70
6 - inch	08	104.46	132.32	132.32	173.60	207.60	207.60
8 - inch	09	165.58	210.33	210.33	275.80	329.80	329.80

Consumption rates

User group		4.1998 - 3.2002	4.2002 - 1.2004	2.2004 - 3.2006	4.2006 - 3.2008	4.2008 - 3.2009	4.2009 - 6.2009
Single-family residential	SFR	0.49	0.63	0.77	1.09	1.30	1.48
		0.49	0.68	0.86	1.41	1.69	1.87
Multi-family residential	MFR	0.52	0.69	0.69	0.96	1.15	1.40
		0.72	0.86	0.86	1.41	1.69	1.87
Small commercial/industrial	COMM	0.58	0.72	0.72	0.99	1.26	1.39
		0.72	0.86	0.86	1.41	1.69	1.87
Large commercial/industrial	COMM	0.58	0.79	0.79	1.06	1.53	1.49
		0.72	0.86	0.86	1.41	1.69	1.87
Irrigation	IRR	0.63	0.77	0.77	1.28	1.30	1.39
		0.72	0.86	0.86	1.41	1.69	1.87

The block thresholds changed in 4.2002: for SFR from 0 to 36 CCF, for MFR from 18 to 14 CCF, for small COMM from 111 to 115 CCF, for large COMM from 589 to 619 CCF, IRR remains at 363 CCF

Source: City of Davis Finance Department (2010)

Table 2: Water consumption per user group between 1996 and 2009

User group	house-holds	Mean (in CCF)	Std. Dev.	Min (in CCF)	Max (in CCF)	Total water demand p.a. (in tsd. CCF)	in%
SFR	14,593	36.55	47.20	0	9,999	533	*66*
MFR	392	393.03	682.41	0	9,570	154	*19*
COMM	589	180.19	467.01	0	13,170	106	*13*
IRR	138	63.66	221.78	0	9,999	9	*1*
Total	**15,712**	**55.51**	**182.47**	**./.**	**./.**	**802**	***100***

Source: Own calculations based on data provided by City of Davis Public Works Department

Table 3: Descriptive statistics

Variable	Unit	Description	Mean	Std. Dev.	Min.	Max.
Independent variable						
consumption	in CCF	bimonthly household water consumption	55.52	182.48	0	13170
Price variables						
MP	in $ per CCF	actual marginal price of water	0.75	0.44	0.00	1.87
AP	in $ per CCF	calculated average price of water	1.03	1.02	0.00	70.63
D	in $	theoretical Taylor-Nordin difference variable	19.40	30.60	0.00	947.07
baserate	in $	fixed bimonthly charge	7.87	5.81	5.00	329.80
Instrumental variables						
MP10	in $ per CCF	established marginal price at 10 CCF after 4.1998	0.70	0.39	0.00	1.87
MP25	in $ per CCF	established marginal price at 25 CCF after 4.1998	0.71	0.39	0.00	1.87
MP50	in $ per CCF	established marginal price at 50 CCF after 4.1998	0.82	0.52	0.00	1.87
MP200	in $ per CCF	established marginal price at 200 CCF after 4.1998	0.82	0.52	0.00	1.87
MP400	in $ per CCF	established marginal price at 400 CCF after 4.1998	0.83	0.52	0.00	1.87
inflation	1.00 = 4.1996	average bimonthly CPI in the US	1.19	0.12	1.00	1.40
Other variables						
temperature	in °F	average bimonthly temperature	61.63	10.19	42.79	76.59
precipitation	in inches	average bimonthly precipitation	1.45	1.79	0.00	8.09
summer	0 / 1	summer periods: 1 if 3-4; 0 else	0.33	0.47	0	1
residential	0 / 1	customer group: 1 if residential; 0 else	0.93	0.25	0	1
incomepc	in k$	average annual incomeper capita	29.94	4.20	23.32	37.13
unemploymentrate	in %	average annual unemployment rate	6.17	1.67	4.40	11.30
uniform	0 / 1	increasing block pricing: 1 after 4.1998; 0 else	0.88	0.33	0	1
tier	0 / 1	2nd tier for SFR: 1 after 4.2002; 0 else	0.58	0.49	0	1
sewer	0 / 1	new sewer rate system: 1 after 1.2008; 0 else	0.16	0.37	0	1

Source: Own calculations

Table 4: Strength of selected instrumental variables for marginal price variable

```
. xtreg MP MP10 MP25 MP50 MP100 MP200 MP400 baserate precipitation temperature summer, i (locationid) fe

Fixed-effects (within) regression               Number of obs      =   1195546
Group variable: locationid                      Number of groups   =     15713

R-sq:  within  = 0.9661                         Obs per group: min =         1
       between = 0.9486                                        avg =      76.1
       overall = 0.9623                                        max =     15937

                                                F(9,1179824)       =  3.73e+06
corr(u_i, Xb)  = 0.0355                         Prob > F           =    0.0000

------------------------------------------------------------------------------
          MP |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        MP10 |   .0944141   .0027633    34.17   0.000     .0889982      .09983
        MP25 |   .5669512   .0025627   221.23   0.000     .5619284     .571974
        MP50 |   .0641735   .0026414    24.30   0.000     .0589964    .0693506
       MP100 |  (dropped)
       MP200 |   .2435766   .0044353    54.92   0.000     .2348835    .2522697
       MP400 |   .0292555   .0037082     7.89   0.000     .0219875    .0365235
    baserate |  -.0001388   .0000244    -5.70   0.000    -.0001865   -.000091
precipitat~n |   .0021174   .0000598    35.38   0.000     .0020001    .0022347
 temperature |    .002573   .0000136   189.82   0.000     .0025464    .0025995
      summer |   .0056572   .0002359    23.98   0.000     .0051949    .0061196
       _cons |  -.1599216   .0008849  -180.73   0.000    -.1616559   -.1581873
-------------+----------------------------------------------------------------
     sigma_u |  .04118454
     sigma_e |  .07952317
         rho |  .21148941   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(15712, 1179824) =    13.49      Prob > F = 0.0000

.
. test MP10 MP25 MP50 MP100 MP200 MP400 baserate precipitation temperature summer

 ( 1)  MP10 = 0
 ( 2)  MP25 = 0
 ( 3)  MP50 = 0
 ( 4)  MP100 = 0
 ( 5)  MP200 = 0
 ( 6)  MP400 = 0
 ( 7)  baserate = 0
 ( 8)  precipitation = 0
 ( 9)  temperature = 0
 (10)  summer = 0
       Constraint 4 dropped

       F(  9,1179824) = 3.7e+06
            Prob > F =    0.0000

.
. xtreg MP inflation, i (locationid) fe

Fixed-effects (within) regression               Number of obs      =   1195546
Group variable: locationid                      Number of groups   =     15713

R-sq:  within  = 0.8629                         Obs per group: min =         1
       between = 0.9114                                        avg =      76.1
       overall = 0.8604                                        max =     15937

                                                F(1,1179832)       =  7.43e+06
corr(u_i, Xb)  = 0.0362                         Prob > F           =    0.0000

------------------------------------------------------------------------------
          MP |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
   inflation |   3.456325   .0012683  2725.26   0.000     3.453839    3.458811
       _cons |  -3.364952   .0015163 -2219.15   0.000    -3.367924    -3.36198
-------------+----------------------------------------------------------------
     sigma_u |  .05444172
     sigma_e |  .15985426
         rho |  .10393349   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(15712, 1179832) =     6.30      Prob > F = 0.0000
```

Table 5: Results for Hausman test for random or fixed effects model

```
. xtreg consumption MP D baserate precipitation temperature summer, i (locationid) re

Random-effects GLS regression                   Number of obs      =   1195546
Group variable: locationid                      Number of groups   =     15713

R-sq:  within  = 0.0833                         Obs per group: min =         1
       between = 0.0556                                        avg =      76.1
       overall = 0.0777                                        max =     15937

Random effects u_i ~ Gaussian                   Wald chi2(6)       = 107847.28
corr(u_i, X)       = 0 (assumed)                Prob > chi2        =    0.0000

------------------------------------------------------------------------------
 consumption |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          MP |  -32.84739   .3072364  -106.91   0.000    -33.44956   -32.24521
           D |   1.444471   .0054995   262.65   0.000     1.433692     1.45525
    baserate |  -.7974256   .0328905   -24.24   0.000    -.8618897   -.7329615
precipitat~n |  -.9430398   .0843911   -11.17   0.000    -1.108443   -.7776362
 temperature |    .892898   .0192574    46.37   0.000     .8551542    .9306418
      summer |   10.27224   .3330998    30.84   0.000     9.619378    10.92511
       _cons |  -1.401193   1.499802    -0.93   0.350    -4.340751    1.538365
-------------+----------------------------------------------------------------
     sigma_u |  105.51195
     sigma_e |  111.89183
         rho |  .47067952   (fraction of variance due to u_i)
------------------------------------------------------------------------------

.
. estimates store b_re


.
. xtreg consumption MP D baserate precipitation temperature summer, i (locationid) fe

Fixed-effects (within) regression               Number of obs      =   1195546
Group variable: locationid                      Number of groups   =     15713

R-sq:  within  = 0.0835                         Obs per group: min =         1
       between = 0.0361                                        avg =      76.1
       overall = 0.0633                                        max =     15937

                                                F(6,1179827)       =  17905.18
corr(u_i, Xb)  = 0.0132                         Prob > F           =    0.0000

------------------------------------------------------------------------------
 consumption |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          MP |  -30.71617   .3074406   -99.91   0.000    -31.31875    -30.1136
           D |   1.438298   .0055191   260.60   0.000     1.427481    1.449116
    baserate |  -1.312229   .0331106   -39.63   0.000    -1.377125   -1.247334
precipitat~n |  -.9638202   .0840655   -11.47   0.000    -1.128586   -.7990548
 temperature |   .8885115   .0191845    46.31   0.000     .8509105    .9261125
      summer |   10.21537   .3318051    30.79   0.000     9.565042     10.8657
       _cons |   4.163722   1.232842     3.38   0.001     1.747393    6.580051
-------------+----------------------------------------------------------------
     sigma_u |  142.79107
     sigma_e |  111.89183
         rho |  .61956445   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(15712, 1179827) =    76.03      Prob > F = 0.0000

.
. estimates store b_fe


.
. hausman b_fe b_re

                 ---- Coefficients ----
             |      (b)          (B)            (b-B)     sqrt(diag(V_b-V_B))
             |      b_fe         b_re        Difference          S.E.
-------------+----------------------------------------------------------------
          MP |   -30.71617    -32.84739        2.131211        .0112042
           D |    1.438298     1.444471        -.006173        .0004645
    baserate |   -1.312229    -.7974256       -.5148038        .0038117
precipitat~n |   -.9638202    -.9430398       -.0207805               .
 temperature |    .8885115      .892898       -.0043865               .
      summer |    10.21537     10.27224       -.0568732               .
------------------------------------------------------------------------------
                           b = consistent under Ho and Ha; obtained from xtreg
            B = inconsistent under Ha, efficient under Ho; obtained from xtreg

    Test:  Ho:  difference in coefficients not systematic

                  chi2(6) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                          =    22216.70
                Prob>chi2 =      0.0000
                (V_b-V_B is not positive definite)
```

Table 6: Base model results for different estimation techniques

Log-lin functional form	OLS	FE	FE - First stage	IV-FE
MP	0.02***	0.74***		-0.19***
	(0.00)	(0.00)		(0.01)
MP10			0.67***	
			(0.01)	
MP50			0.33***	
			(0.00)	
baserate	0.03***	-0.17***		0.02***
	(0.00)	(0.00)		(0.00)
temperature	0.04***	0.03***		0.04***
	(0.00)	(0.00)		(0.00)
precipitation	-0.03***	-0.04***		-0.04***
	(0.00)	(0.00)		(0.00)
summer	0.14***	0.09***		0.12***
	(0.00)	(0.00)		(0.00)
constant	0.84***	1.95***	0.00***	1.14***
	(0.01)	(0.01)	(0.00)	(0.01)
R^2 overall	0.27	0.19	0.93	0.26
# of observations	933,826	933,826	941,832	933,826
# of groups	n.a.	14,648	14,660	14,648
Consumption period	4.98-6.09	4.98-6.09	4.98-6.09	4.98-6.09

* Significance at the 90% percentile
** Significance at the 95% percentile
*** Significance at the 99% percentile

Table 7: Estimation results for structural water conservation measures

IV-FE estimation	Introduction of IBP		Introduction of a second block			Change of sewer rate structure	
ln (MP)			-1.26***	-1.27***	-1.31***	-0.17***	0.48***
			(0.00)	(0.00)	(0.01)	(0.00)	(0.01)
D			0.07***	0.07***	0.08***	0.01***	0.01***
			(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
baserate	0.01**	0.01**	-0.03***	-0.03***	-0.03***	-0.00***	-0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
temperature	0.03***	0.03***	0.01***	0.01***	0.01***	0.03***	0.03***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
precipitation	-0.06***	-0.05***	-0.01***	-0.01***	-0.00***	-0.03***	-0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
summer	0.21***	0.22***	0.13***	0.13***	0.13***	0.11***	0.14***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
IBP	-0.11***	-0.04***					
	(0.00)	(0.00)					
tier			-0.06***	0.24***	0.24***		
			(0.00)	(0.00)	(0.00)		
highcons_tier				-0.33***	-0.32***		
				(0.00)	(0.00)		
sewer						-0.12***	-0.04***
						(0.00)	(0.00)
incomepc		-0.00***			-0.00***		-0.00***
		(0.00)			(0.00)		(0.00)
unemployment		1.65***			0.00		-0.02***
		(0.01)			(0.00)		(0.00)
constant	1.65***	2.11***	2.61***	2.64***	2.95***	1.55***	3.11***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
R^2 overall	0.27	0.27	0.75	0.73	0.76	0.31	0.36
# of observations	443,262	443,262	933,826	933,826	849,201	1,037,198	942,442
# of groups	13,822	13,822	14,648	14,648	14,633	15,698	15,679
Sample	SFR	SFR	SFR	SFR	SFR	all	all
Cons. period	4.96-3.02	4.96-3.02	4.98-6.09	4.98-6.09	4.98-6.09	4.98-6.09	4.98-6.09

* Significance at the 90% percentile
** Significance at the 95% percentile
*** Significance at the 99% percentile

About the authors

Kim J. Zietlow is a Ph.D. candidate at the Chair for International Agricultural Trade and Development at Humboldt-Universität zu Berlin. His work focuses on water conservation behaviour and water demand management in Jordan and Germany.

Prof. Dr. Dr. h. c. Harald von Witzke holds the Chair for International Agricultural Trade and Development at Humboldt-Universität zu Berlin. He is president of the Humboldt Forum for Food and Agriculture (HFFA) e.V.

Anschrift:
Humboldt-Universität zu Berlin
Lebenswissenschaftliche Fakultät
Department für Agrarökonomie
Unter den Linden 6
10099 Berlin
e-mail: kim.zietlow@gmail.com