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1 2	Rate Structure Change and Residential Water Consumption: Spillover and Asymmetric Effects
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Rate Structure Change and Residential Water Consumption: Spillover and Asymmetric Effects

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- 32

33 Abstract

34 California's demand-side water management policies, such as changing water rate structures,

35 have gained significant attention in dealing with more frequent, longer droughts, and an

36 increasing population. We quantify the effectiveness of rate structure change using a novel

37 survey dataset of 189 water agencies from 1994 to 2019 in California. Results indicate that

38 single-family residential per capita per day water consumption was reduced by an average of

39 3.2% when switching from non-conservation-based to a conservation-based water rate structure.

40 Results indicate heterogeneity in the estimated effect, depending on the base rate structure and

41 length of time the base rate structure was in place.

- 42 Keywords: California, water rate structures, water conservation, asymmetric effects, spillover
- 43 effects
- 44 **JEL Codes:** L95, Q21, Q25, Q50,
- 45

46 **1. Introduction**

47 California has been facing water management challenges from its ever-increasing population 48 growth and expanding urban development, as well as severe and long-lasting droughts. 49 California droughts are getting more intense, lasting longer, and are more frequent (Diffenbaugh, 50 et al., 2015). From 1970 to 2021 California experienced seven significant droughts (1976-1977; 51 1987-1992; 1987-1992; 2007-2009; 2012-2016; 2012-2016, and 2020-2021). The combination 52 of low precipitation and high temperatures made the 2012-2016 drought very intense, and the 53 same pattern is unfolding in the current (2021) drought (Escriva-Bou, et al., 2021, Lee, et al., 54 2021). 55 For many years California has enacted conservation measures to address growing water 56 demands and insecure water supply levels driven by drought conditions. To date state and local 57 demand-side water management policies have collectively reduced gallons per capita per day of 58 water use by 34% compared to 1994 (Lee, et al., 2021). However, effects of the state's expected 59 population increase (Dieter and Maupin, 2017) and future climate change will pose substantial 60 challenges for future water management (Dieter and Maupin, 2017, Escriva-Bou, et al., 2017, 61 Hanak and Lund, 2012, Langridge, 2018, Schwarz, et al., 2018, Vicuna, et al., 2007, Wang, et 62 al., 2018), highlighting the need for continued water conservation in general, and use for urban 63 landscapes in particular. 64 In an effort to meet these conservation targets, water agencies have relied on diverse

demand-side management strategies, such as conservation-water price rates, price adjustments,
subsidies and water-saving rebates as economic incentives, and outdoor water use restrictions.
These measures are regarded as cost-effective means to reduce water use, compared to the
development of new supply sources, such as recycled water, desalination, or reuse of wastewater

(Escriva-Bou and Sencan, 2021, Kenney, 2014, Kenney, et al., 2010, Kenney, et al., 2011, Marie
and Zafar, 2016). Among these means, price adjustments—both rate levels and structures—are
common tools to reduce household water demand, which can likely result in increased
uncertainty in revenue streams for agencies while encouraging water conservation (Ali, et al.,

73 <u>2021</u>, <u>Beecher and Chesnutt, 2012</u>, <u>Tiger, et al., 2014</u>).

74 While the popularity and prominence of alternative pricing structures have grown 75 substantially over time, policymakers need to understand how the change in rate structures 76 impact water consumption and how this affects California conservation efforts and behavioral 77 responses by households. While such aspects are critically important for policy considerations, 78 no past literature has assessed the effectiveness of structural changes. The majority of the 79 economic literature focuses on the effects of water rate structures on household consumption 80 (Baerenklau, et al., 2014, Dalhuisen, et al., 2003, Marzano, et al., 2018, Olmstead, et al., 2007, Zhang, et al., 2017)¹, but not on asymmetry or persistence of such effects over time, and 81 82 especially the impacts on water consumption following a switch from one rate structure to 83 another.

84 Excluding small water agencies, California has 409 urban water suppliers, and each 85 serves more than 3,000 customers. Based on the characteristics of the service area and supply 86 sources, each of these agencies employs different water rate structures, such as flat, uniform, 87 tiered, or budget-based. Agencies move across structures and adjust prices based on agency 88 financing requirements, weather conditions in a region, and conservation goals. As an example, 89 California's many agencies have changed rate structures in response to both short-term supply 90 shocks (e.g., the recent California droughts) as well as the governor's long-term water use policy 91 targets, such as "Make Water Conservation a California Way of Life" standards (California

¹ See in the Literature Review section for detailed information on the previous studies.

92 Department of Water Resources and State Water Resources Control Board, 2018).

93 This study addresses policy-relevant questions: (i) How are pricing structures and water consumption changing within agencies in California? (ii) How do residential households respond 94 95 to different rate structure changes? And (iii) how long does the effect of the pricing structure 96 change persist? Our study builds on the existing literature related to water rate structures. 97 However, rather than investigating and comparing parameter estimates across different rate 98 structures, we answer those questions by estimating whether, to what extent, and under which 99 circumstances residential households respond to changes in the rate structures, especially with 100 regard to water conservation.

101 To our knowledge, this is the first study to estimate the long-term effects of rate structure 102 changes on residential water consumption in California, in terms of *spillover and asymmetry* 103 *effects* of policy intervention on water conservation-based rate structures. Quantifying the effect 104 of rate structure transitions on water demand has direct implications for water agencies, many of 105 which consider pricing strategies to encourage conservation. Given this importance, our study 106 will not only broaden the spectrum of existing water price levels and price structure studies, but 107 it also will provide policymakers and water agencies with new information to help mitigate 108 future water shortages.

109 2. Literature Review

Since the pioneering studies by <u>Gottlieb (1963)</u>, and <u>Howe and Linaweaver Jr (1967)</u>, residential water demand has been extensively studied. The main objective of all this research is to estimate a residential water demand function wherein individual or aggregate residential consumption is expressed as a function of water price and other factors, such as income, household and housing composition, local community characteristics, regional environmental conditions, policy

115 objectives, or other socioeconomic variables. By expanding the scope² of the study, the literature

analyzed pricing structure endogeneity between water consumption and welfare effects (Gaudin,

117 <u>2006</u>, <u>Hewitt and Hanemann</u>, 1995).

118 2.1. Residential water demand function with water price

119 The large body of literature analyzing the effect of water pricing has focused on the 120 responsiveness of water demand to higher prices by estimating price elasticities under different 121 water rate structures and comparing these estimates. Water demand in most cases is estimated as 122 relatively inelastic, albeit it is not perfectly inelastic. Statistically, such price elasticities of 123 demand are negative across all models. The possible reasons are that water is irreplaceable for 124 essential use, and water bills are treated as a necessary expense for goods that make up a portion 125 of a customer's total expenditure (Arbués, et al., 2003, Yoo, et al., 2014). In addition, customers 126 are not always aware of the rate structures, and even less so under more complex rate structures. Previous studies identify the effect of rate structures on residential water demand using 127 128 estimated elasticities, in that each rate structure produces a different elasticity of demand. Most 129 of the previous studies in this area show that increasing block structure (IBS) (e.g., tiered or 130 budget based) tends to produce higher estimates of price elasticity than other structures (e.g., 131 uniform) to be compared (Baerenklau, et al., 2014, Dalhuisen, et al., 2003, Marzano, et al., 2018, 132 Olmstead, et al., 2007). IBS tends to be conservation-oriented. The structure imposes a low 133 marginal price for the first few units, and incrementally increases the price for any household consuming outside of the first block. Higher marginal price than average price³ promotes the 134 135 reduction of water consumption by signaling a water scarcity to high-use consumers who

 $^{^{2}}$ In the context of the same research, the scope of the research was expanded by diverse methodologies for analyzing water demand, but the section of literature in our paper does not focus on the methodology.

³ Exceptionally, Nieswiadomy and Cobb. (1993) identifies cases in which customers are more sensitive to average prices than to marginal prices, showing that the IBS conservation effect is not as great as expected.

presumably will respond in keeping consumption low, while also offering low-cost water for essential uses such as drinking, cooking, cleaning, and bathing (Zhang, et al., 2017). This reason allowed IBS to give a strong incentive for water-saving and for policymakers to use prices to achieve water savings.

140 2.2. Residential water demand function with other factors

141 Greater sensitivity of demand to price and more significant conservation in IBS is supported 142 through several meta-analyses. In a meta-analysis of 124 estimates generated during 1967-1993 143 Espey, et al. (1997) reported that a mean price elasticity estimate for the short-run median is -144 0.38 and the long-run median is -0.64, with a mean value of -0.51. After examining 296 145 estimates during 1963-2001, Dalhuisen, et al. (2003) noted that a mean price elasticity is -0.41, 146 with a standard deviation of 0.86. In a more recent study, Sebri (2014) analyzed 100 estimates 147 during 2002-2012 and obtained a mean price elasticity of -0.365. Approximately 90% of these 148 price elasticity estimates fell between 0 and -0.75.

149 Differences in elasticity estimates across rate structures may arise from many other 150 factors. Several academic works of literature lend support for these factors: Hajispyrou, et al. 151 (2002) found that large families are likely to have a disadvantage under IBS, compared to small 152 families at the same level of agency, due to a higher marginal price of water; Hoffmann, et al. 153 (2006) discovered that price elasticity is higher in owner-occupied households than in renter 154 households; (Hewitt, 2000), Hewitt and Hanemann (1995) verified that agencies in the regions 155 with sunnier, warmer, drier weather, and longer growing seasons are likely to implement IBS; 156 and Nieswiadomy and Cobb (1993) found agency managers in cities whose residents have a 157 stronger interest in conservation may be more willing to adopt IBT. Likewise, a meta-analysis on 158 the price elasticity of demand by Worthington and Hoffman (2008) and Arbués, et al. (2003)

159 well documented elasticities while considering other factors.

160 **2.3.** Water rate structure changes

161 The extensive empirical literature has emphasized how price and other factors influence 162 residential water demand by estimating the effect of water prices on water consumption. Still, 163 fewer relevant studies explore the different water pricing structure changes and water demand in 164 terms of water conservation. Limited evidence is available on the effectiveness of pricing in 165 structural change; however, initial research (Table 1) suggests significant potential. 166 In particular, Nauges and Whittington (2017) and Zhang, et al. (2017) authored some of 167 the few empirical papers investigating the issue of rate structure change by water agencies. Using 168 household-level monthly water use data for Organisation for Economic Co-operation and 169 Development (OECD) countries and developing countries in 2008, Nauges and Whittington 170 argue that different IBR designs perform poorly in targeting subsidies to low-income households 171 by analyzing the effect of the shift from a uniform volumetric structure to an IBR structure on 172 water use and water bills of households in the light of measures of equity and economic 173 efficiency. Zhang, et al. investigated the effectiveness of this national policy reform comparing 174 household-level monthly water use data in 28 cities that adopted IBR pricing structures during 175 2002–2009, with that of 110 cities that had not yet done so. The authors found that the policy 176 reform to IBR adoption reduces annual water consumption by 3.3%, on average. 177 Given the potential of water structure change that affects water conservation 178 effectiveness and the lack of enough information on water rate structure change, the efficacy of 179 any part of a holistic water conservation program will diminish. Our study can empower both the 180 water agency and the household with new and essential information they need to improve 181 efficiency.

3. Conceptual framework

183 We derive relationships that inform our hypotheses to be inferred in the empirical analysis. We 184 apply a multi-period setting to determine the effect of rate structure changes on the mean water 185 consumption of municipal customers. We analyze this framework based on the following 186 concept: rational households maximize their expected lifetime utility by deciding on current 187 consumption and future consumption under a given budget constraint. The household is 188 characterized by a time preference factor that refers to the relative preference of current 189 consumption for future consumption. Such relative preference is explained by intertemporal 190 substitution—the decision to forego current consumption for future consumption. Considering 191 market-clearing conditions-the quantity supplied is the quantity demanded-even though the 192 water agency is the supplier, the quantity supplied is the sum of each household demand. Thus, 193 our conceptual framework uses the approach of the household's utility maximization problem, 194 assuming that this is a representative household (or a residential customer).

195 Considering a simple two-period economy, the household utility function is $U = U(C_t) + \beta U(C_{t+1})$ where β is the household's time discount factor on intertemporal utility, reflecting a 197 weight on the expected utility that households will get through future consumption.

198 Correspondingly, household utility maximization is⁴:

199 (1)
$$\underbrace{Max}_{C_t,C_{t+1}} U(C_t) + \beta U(C_{t+1})$$

200

$$C_{t}, C_{t+1}$$

s.t. $C_{t} + \frac{C_{t+1}}{1+r} = y_{t} + \frac{y_{t+1}}{1+r}$

201 We denote the terms C_t and C_{t+1} as water consumption during period *t* and period t+1, 202 respectively. The parameter *r* is the real interest rate. The term y_t and y_{t+1} represent real income. 203 We assume that the composition of residential customers within a single agency does not change

⁴ See Appendix (B): Mathematical Derivation for details

204 over time. In other words, within a water agency, the demographics and socioeconomic factors 205 of the households, such as household size and income, would be identical either at the period *t* or 206 at period t+1. Otherwise, the question could be raised whether this change in water consumption 207 was due to a change in the characteristics of the households. For example, one may doubt 208 whether the household income within an agency during the period t+1 changes relative to that 209 during period *t*, thereby water consumption changes even without rate structure changes.

Additionally, we assume that the only thing consumed by the household is water. In general, households spend their income on several goods other than water, yet we assume for simplicity that only water use affects a household's total budget. Otherwise, to consider their consumption of other goods a complexity arises, and we must also consider information about the relative price of other goods and the resulting substitution effects.

215 The intertemporal water consumption relationship derived from equation (1) is:

216 (2)
$$U'(C_t) - \beta(1+r)U'\{(C_{t+1})\} = 0$$

217 Consider the first-order conditions (FOC) of optimal consumption level with constant relative 218 risk averse (CRRA) utility function (i.e., $U(C_t) = \frac{C_t^{1-\gamma}}{1-\gamma}$)),

219 (3)
$$1 = \beta (1+r) \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma}$$

220 Where γ is a parameter that affects the price elasticity of water demand. The parameter γ 221 represents the household's response that partly depends on the length of time the previous rate 222 structure was in place, which ultimately affects changes in water consumption. It can be regarded 223 as a subjective preference.

The policy intervention effect is captured as the change in water consumption caused by the change in the price structure. This means that in the two-period problem under different price structures due to intervention, water price during *t* and t+1 is different. Hence, our study derives the equilibrium water consumption path with CRRA under the assumption of different unit prices on water consumption between the time point *t* and the time point t+1. Accordingly, the objective function is written as:

230 (4)
$$\underbrace{Max}_{C_t,C_{t+1}} \quad U(C_t) + \beta U(C_{t+1})$$

231
$$s.t. \quad C_t + \frac{A_{t+1}C_{t+1}}{(1+r)} = y_t + \frac{y_{t+1}}{1+r}$$

232 Consequently, derived the equilibrium water consumption path is:

233 (5)
$$1 = \beta (1+r) \frac{1}{A_{t+1}} \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma}$$

The variable A_{t+1} indicates a relative water unit price ratio, namely, $A_{t+1} = \frac{P_{t+1}}{P_t}$. Note that we assume in our analytical framework that, $P_{t+1} > P_t$ or relative price $A_{t+1} = \frac{P_{t+1}}{P_t} > 1$ since the mean unit price of water consumption under conservation-based structures is likely more expensive than non-conservation-based structures. Generally, it is known that conservation-based structures can be complex, require metering infrastructure and cost-tracking methodologies, leading it to be more costly to administer (<u>Raftelis, 2005</u>).

240 As β and *r* are constant across periods, the following periodical optimal consumption 241 path is:

242 (6)
$$\left(\frac{C_{t+1}}{C_t}\right) \propto (A_{t+1})^{\frac{-1}{\gamma}}$$

Figure A1 in the appendix displays the relationship between $\left(\frac{C_{t+1}}{C_t}\right)$ and γ at any given A_{t+1} (where $A_{t+1} > 1$). Through the parameter γ , which varies depending on how long the household stays with the previous price structure, we can see how the term $\frac{C_{t+1}}{C_t}$ changes (i.e., what percentage of the water consumption decreases more, or what percentage of the water

247 consumption decreases less?). Based on Figure A1,
$$\left(\frac{c_{t+1}}{c_t}\right)$$
 increases over γ ; thus, $\left(\frac{c_{t+1}}{c_t}\right)_A < 1$

 $\left(\frac{C_{t+1}}{C_t}\right)_{p}$ at $\gamma_A < \gamma_B$. This implies that a household that experienced a given rate structure for a 248 249 longer time has a lower γ than a household that stayed for a shorter time period (i.e., $\gamma_{lonr} <$ 250 γ_{short}), the degree of reduction in water consumption in a long period is greater than that in a short period (i.e., $\left(\frac{C_{t+1}}{C_t}\right)_{long} < \left(\frac{C_{t+1}}{C_t}\right)_{short}$). 251 252 What happens to water consumption when one agency switches one price structure to 253 another structure? We try to answer this main question through the change of γ , which is 254 represented by the household's response. Thus, the testable hypothesis under this relationship is 255 that the agency's price structure change due to intervention affects the household's water 256 consumption. Our conceptual framework shows that the impact of such structure change on 257 household consumption depends on the length of time spent in the existing rate structure before 258 changing to another structure. We infer this hypothesis by applying an empirical investigation on 259 our dataset's different lengths of time and structures.

260 **4. Data**

In California, water suppliers with more than 3,000 customers or suppliers offering over 3,000
acre-feet of water annually (409 water agencies) are subject to the state water use policies and
conservation targets, such as the 2015 water mandate or Conservation a Way of Life in
California regulations (Buck, et al., 2016, California Department of Water Resources and State
<u>Water Resources Control Board, 2018, Lee, et al., 2021, Nemati, et al., 2018</u>). Focusing on these
409 water agencies, we collected data for this study through an extensive survey of water

agencies on their residential water rates, rate structures, and billing cycles from 1994 to 2019.
The survey was conducted through an extensive review of the agency's website (e.g., relevant
financial information, water plans), follow-up emails, and phone interviews. Some agencies
could only provide the most recent rate structure data, and some provided data for the entire
sample period. We completed the survey for only 189 agencies out of the 409 indicated above
with at least one year of pricing (level and structure) information.

273 Next, we merged these datasets with other data sources from the California Department 274 of Water Resources (DWR) and State Water Resources Control Board (water board) on monthly 275 water consumption, water agency characteristics (e.g., ownership type, and agency service area 276 population), and service area boundaries. After combining all the information, we created a long-277 term and comprehensive dataset covering rate structure, rate levels, and monthly water 278 consumption from 1994 to 2019 for 189 agencies in California. These water suppliers account 279 for roughly 80% of California's water consumption (serving more than 23 million people in 280 California). The unique dataset on water agencies' choice of rate structure over time for 25 years 281 will provide us the opportunity to investigate the effects of changes in the structure of average 282 monthly water use.

Table 2 suggests yearly aggregated overall counts of agencies by each rate structure, and annual water use measured by residential gallons per day per capita (GPCD) over the entire sample. On average, Table 2 illustrates the rate structure California's water agencies adopt the most is increasing tiered rates (tiered), followed by uniform, budget-based, and flat-rate structures. As indicated in the table, water agencies are replacing non-conservation-based rate structures (uniform and flat) with conservation-based ones (tiered and budget). As a result, the average per capita water use of the agencies surveyed have been reduced dramatically since 1994

(Figure A2 in appendix). The total number of observations is 20,614 from all rate structures that189 agencies adopted.

292 Interestingly, since 2009, flat-rate structures have been seen in some cases. Given the 293 nature of the flat rate, this form is not popular in California. Even though the flat-rate structure 294 has been captured, too few cases say that California is considering a transition to this rate 295 structure. However, some institutions have used this structure in some cases, depending on their 296 specific circumstances and necessity. Specifically, flat-rate customers will be charged 297 conservation rates when their meters are installed, as required by section 527 of the water code. 298 Their water bill could go up or down, depending on how much water households use. The flat 299 rate is determined by the household's lot size and the average lot size. If a household uses more 300 water than the average metered customer, the water bill will be higher because the metered bill 301 will reflect how much water the household uses. Due to this characteristic, some agencies seem 302 to charge a flat rate for water supply planning purposes, especially when the state government 303 and water agencies need a stable and fixed budget and revenues. Since 2009, some agencies in 304 California might have suffered from budget limitations. Under the circumstance, the flat-rate 305 structure might be necessary for a certain period, because it has to quickly implement and 306 provide a great deal of financial stability since revenue depends on factors that are easy to predict 307 and less variable than future water demand.

308 Figure A2 shows the mean GPCD in the study agencies with a downward trend. The 309 average total GPCD from 1996 to 2019 is about 118.24. This trend reflects the state and local 310 efforts to encourage conservation and improve efficiency through various tools, such as pricing 311 mechanisms.

312

2 Table 3 explains the overall change count in rate structures. Most of the agencies in our

dataset have adopted a tiered rate structure (i.e., a total of 35 changes). The next most dominant
rate choice is the uniform rate structure (i.e., a total of 14 changes), followed by switching from
any type. That said, any type focusing on switching from uniform to budget and any type
focusing on switching from tiered to budget has a total of five changes and six changes,
respectively. This is generally in agreement with the aggregated counts presented in Table 2
above as well.

319 Switching from non-conservation-based water rate structures to conservation-based rate 320 structures—generally referred to as tiered and budget structures—were most often made with a 321 total of 42 changes. In the opposite case, switching from conservation-based water rate structures 322 to non-conservation-based rate structures had fewer changes (a total of 18). Due to climate 323 changes and population growth, it is not surprising that California's water agencies working 324 toward water-savings are switching to conservation-based rate structures to secure sustainable 325 water resources. Table 3 provides an insight into how water agencies have changed their pricing 326 structure over time; specifically, it allows us to gauge in which direction the agencies prefer to 327 change. Estimating the effectiveness of the protection policy through changes in the rate 328 structure can be verified in the results section of this study.

5. Empirical Methods

Our conceptual framework shows a relationship between the change in water price structures and resultant water consumption by households. We empirically test this relationship through the following questions: (i) What is the effect of changing rate structures on water use? (ii) What is the asymmetrical effect when agencies change from non-conservation-based to conservationbased rate structures, and vice versa? (iii) What is the effect on water use by remaining in a specific rate structure for a length of time.

336 In this estimation, we seek to explore household responses and interpret the temporal 337 effects of changes in the pricing structure on water consumption. We study aspects of the effects 338 of structural changes in reducing water consumption using agency-level sequent temporal data. 339 Additionally, a temporal design of the interventions allows us to study the persistence and 340 durability of the effects of price structure changes in reducing water use. That is because the 341 effects of policy intervention appear through both short-term behavioral adjustments and 342 relatively long-term physical capital adjustments (Bernedo, et al., 2014). As a result, we can 343 provide a more in-depth analysis and policy insights.

Following <u>Autor (2003)</u>, we explore these dynamics on the basic residential water
demand function using equation (7):

346 (7)
$$ln(q_{iym}) = \sum_{i=-m}^{i=m} \alpha_i \cdot Rate \ Structure_{iym} + \beta_i \cdot Length_{iym} + \delta_i + \gamma_m + \mu_y + \varepsilon_{iym}$$

347 where the outcome of interest is the log of aggregate water consumption for agency *i* in year *y*, and month m, $ln(q_{ivm})$. In this specification, we include indicators for months before and after a 348 change in the pricing structure. The variable of interest is $Rate Structure_{iym}$ which denotes the 349 type of rate structure an agency is using. We consider flat, uniform, tiered, and budget. α_i 350 351 captures the average change in the different water consumption measured in GPCD under certain 352 rate structures relative to the reference rate structures. By considering the length of time staying 353 in the same rate structures, β_i captures the specific change in the different water consumption 354 measured in GPCD under certain rate structures relative to the reference rate structures, and the average change without considering time. δ_i is agency fixed effects, γ_m indicates agency 355 calendar month fixed effects, and μ_{γ} refers to agency calendar year fixed effects. Lastly, $\varepsilon_{i\gamma m}$ 356 357 captures all remaining unobservable effects that affect the dependent variable. 358 As mentioned earlier, $Length_{ivm}$, as the temporal design of the interventions represents

the length of time remaining in the existing rate structure before changing to the new rate
structure. Therefore, in addition to estimating the cumulative effects of rate structure changes on
water use, we also study the effects over time.

362 For this, we divided the length of time the agency kept an existing rate structure into 363 three cut-offs for the case of switching from non-conservation-based to conservation-based rate 364 structures, respectively (i.e., less than or equal to two years; between two and five years; and 365 more than five years). We then examined two cut-offs for the case of switching from 366 conservation-based to non-conservation-based rate structures (i.e., less than or equal to two 367 years, and more than two years). We defined these cut-offs for the length of time based on the number of unique agencies spent in the same rate structure. The former case contained 42 unique 368 369 agencies, and the latter contained 18 unique agencies. We describe the estimation of the effects 370 reflecting these cut-offs separately from the estimation of the average treatment effects that do 371 not consider the length of time at all in the results section.

372 6. Empirical Results

373 First, to estimate changes over time in GPCD by rate structures, we used an ordinary least 374 squares (OLS) estimator, followed by a fixed-effects estimator after controlling for agency and 375 month fixed effects, and then a fixed-effects estimator after considering year fixed effects 376 beyond controlling for agency and monthly fixed effects. We found more water savings under a 377 conservation-based structure, such as budget and tiered-rate structures (Table 4). This finding is 378 robust to various modeling approaches. As shown in column 3 of Table 4, average water use 379 measured in GPCD decreases by 8.4% under a tiered-rate structure and by 11.9% under the 380 budget-rate structure, compared to the flat-rate structure. These results provide evidence that 381 conservation-based rate structures are effective in reducing water use.

382 Table 5 shows the estimated coefficients from the fixed-effect model after controlling 383 agency, month, and year fixed effects estimation for the change from one rate structure to 384 another structure. For this, we performed a separate regression on each structure change. As we 385 expected, column 1 shows a negative coefficient sign. When the agency switched its rate 386 structure from uniform to tiered, average water use is decreased by 2.9%. However, we did not 387 find a statistically significant effect for all other switches, which could be due to the low number 388 of observations in these cases. We combined conservation-based rate structure and non-389 conservation-based rate structures and re-estimated the models (Table 6). 390 Column 1 in Table 6 reports the estimated average treatment effects of policy 391 intervention—switching to the conservation-based rate structures from non-conservation-based 392 rate structures. We found evidence that when an agency switches its rate structure from non-393 conservation-based to conservation-based, the average GPCD decreases by 3.2%. This clearly 394 indicates that water-saving policy interventions result in water consumption reductions. 395 Unlike column 1, which did not consider the duration of the policy intervention, columns 396 2 and 3 show the results of adding the duration of policy intervention into the formula. In other 397 words, it shows how the degree of water consumption reduction varies according to the length of 398 time remaining in the existing rate structure before changing to the new structure. Specifically, 399 column 2 shows a water-saving effect of about 1.7% when the length of time spent in the 400 previous non-conservation-based rate structure was less than two years. On the other hand, when 401 staying in the previous non-conservation-based rate structure was between two and five years, 402 the water consumption decreased by 4.7%. Finally, when the time remaining in the same rate 403 structure was longer than five years, water consumption decreased by 6.0%. 404 Regression results of switching from a conservation-based rate structure to a non-

405 conservation-based rate structure are shown in Table 7. Column 1 indicates no statistically 406 significant effect on water use when an agency switches from conservation-based rate structures 407 to a non-conservation-based rate structure. However, the results changes when we break down 408 the sample by the length of time stayed in conservation-based rate structures. As shown in 409 column 2, when an agency had a conservation-based rate structure for less than two years before 410 switching to a non-conservation-based structure, we observed a positive and statistically 411 significant effect on GPCD—average GPCD increased by 9.8%. In contrast, column 3 presents a 412 negative coefficient sign with no statistical significance. In other words, we did not find a statistically significant effect on water use for an agency retaining a conservation-based structure 413 414 for longer than two years before switching to a non-conservation-based structure.

These results provide two important insights into the asymmetry and duration of the effect. First, we observed that changing from a non-conservation-based to a conservation-based water rate structure reduces water use regardless of duration of non-conservation-based rates. However, switching from a conservation- to a non-conservation-based rate structure increases consumption only for those with less than two years on conservation-based rates before the switch. Second, we observed that more water use reductions occur the longer agencies stayed on non-conservation-based rates before switching to conservation-based rates.

In addition, results from Table 6 provide three crucial policy implications. First, when the time spent in a non-conservation-based rate structure is short (i.e., less than or equal to two years in column 2), households tend to be less involved in water conservation-related policies. That is, households have little or no knowledge of how to make behavioral adjustments for water conservation. They haven't received education or promotion that encourages pro-conservation

427 knowledge, awareness or perceptions, and consequential habits.

428 Second, households have made fewer water-saving investments for relatively long-term 429 water conservation, such as installing water-saving products or gadgets, and following water-430 saving techniques in their homes. These home upgrades or techniques may include a water-431 saving shower or flow restrictor, taking shorter showers or fewer baths, checking for faucets and 432 pipe leaks, and turning off the water while shaving or brushing teeth. Water-saving capital 433 investments involve monetary costs for purchasing and applying certain devices, which can incur 434 significant personal and social costs (Suárez-Varela and Dinar, 2020, Neidell, 2009). Third, 435 regardless of water-saving capital investments, these adjustments also involve a time commitment for households. Besides being practical adjustments with monetary costs from an 436 economic point of view, these costs become sunk costs. 437

Our dataset indicates that at least two types of utilities would have relatively long periods 438 439 with a non-conservation rate structure. First would be utilities that are slow to adopt new 440 policies. These utilities might have delayed water-conservation practices (e.g., Sacramento and 441 Fresno avoiding universal metering), which might mean they have not made much progress on 442 conservation. Thus, large water savings occur once utilities switch to conservation-based rates. 443 Second, utilities that previously adopted a conservation rate but then switched back to non-444 conservation rates. Customers at these utilities might already have made investments in capital 445 and behavioral changes. Thus, relatively small savings might be expected once the utility 446 changes to conservation-based rates. Therefore, a shorter time in a non-conservation-based rate 447 structure can result in fewer sunk costs. However, less water savings is achieved when 448 households don't make water-saving adjustments, albeit it is not statistically significant. We 449 found that water consumption was reduced less under the conservation-based structure when no 450 forced or non-coercive incentives were offered to make households feel the need to save water.

451 The households that remained in the non-conservation-based rate structure for a long 452 period of time (i.e., more than two years or five years in columns 3 and 4 of Table 6), did not 453 have the incentives to conserve water like households with conservation-based rate structures. 454 First, under the non-conservation-based structure, households could use water at a relatively low 455 price for a long period of time; they did not need to adjust their behaviors. Second, households 456 had no incentives to purchase and install water-saving features or change water-use behaviors. 457 Third, households had little need to entail sunk costs with monetary or time aspects. 458 Accordingly, when households with lower water prices from long-term non-conservation-based 459 rate structures experience policy changes to a conservation-based rate structure because of 460 droughts, their reduction in water consumption appeared much greater. 461 Table 7 shows three insights according to different durations of policy intervention. First, 462 when the time spent in the conservation-based rate structure is two years or less (column 2), 463 households made no short-term behavioral adjustments for conservation policies. Second, 464 households made fewer water-saving capital investments for relatively long-term physical capital 465 adjustments. For instance, households might make investments in water-efficient devices (e.g., 466 appliances, fixtures, garden irrigation), or perhaps a long-term behavior change (e.g., fully 467 loading the dishwasher, taking shorter showers), and third, less sunk costs. Hence, when the 468 policy was changed to a non-conservation-based rate structure, and the policy intervention for 469 conservation disappears, households increased water consumption again. 470 The cases in which the water agency stayed in the conservation-based rate structure for a long period of time (i.e., more than two years in column 3), the smaller their rebound 471 472 consumption after the agency returns to non-conservation pricing. This result suggests that the 473 effects of policy interventions on rate structure changes are not necessarily symmetric. In other

words, the change in rate structures on residential water conservation can have asymmetriceffects depending on which structure is changed to which structure.

476 The possible reasons for this are that some households experienced higher rates from 477 conservation pricing for a much longer period of time, which resulted in behavioral adjustments. 478 They also had time to make water-saving capital investments for relatively long-term physical 479 capital adjustments. These households tend to continue to reduce water use because of invested 480 behavioral and capital adjustments, and either monetary or time sunk costs. These consistencies 481 can be seen as positive spillover effects from the policy intervention on water conservation. This 482 implies that interventions can yield long-term behavioral changes or additive policy effects when strict policies are continued and persist after the policies are discontinued. 483

484 **7. Conclusions**

Greater reliance on demand-side management as a tool to moderate urban water use has increased the need to understand the effectiveness of pricing structures on household water use. This issue is relevant for water agencies, policymakers, and academics. Past literature suggests that consumers respond differently to marginal prices, depending on whether water rate schedules are increasing, decreasing, or uniform. Yet, it remains unclear whether consumers respond to changes in the rate structure itself, particularly when they face a rate change from non-conservation-based rates to conservation-based ones and vice versa.

With surveyed rate structure data for 189 water agencies (serving more than 23 million people) across California from 1994-2020, we examined the effects of change in water rate structure on single-family residential water consumption. We found several key results. First, the average GPCD water consumption declines when water agencies switch from non-conservationbased (i.e., flat and uniform) to conservation-based rate structures (i.e., budget-based and tiered).

497 Second, regardless of the form of the change in the rate structure (i.e., non-conservation-498 based structures to conservation-based structures and vice versa), the length of time spent on the 499 previous structure affects the level of change in water use. Notably, the longer an agency 500 maintains a non-conservation-based rate structure before switching to conservation-based 501 structure, the more significant the observed reductions in average GPCD water consumption. In 502 addition, the longer agencies remain on conservation-based rates before switching to non-503 conservation-based rates, the smaller the increase in water consumption.

504 It is likely that as the period of involvement in the conservation-based rate structure was 505 long, households have more positive spillover effects of policy interventions. These effects are 506 driven by the length of time households experienced conservation-based rates—longer exposure 507 leads to behavioral adjustments and water-saving capital investments. These adjustments yield 508 long-term behavioral changes by households even after water conservation is discontinued by 509 reminding households of invested behavioral and capital adjustments and monetary or time sunk 510 costs. However, these *spillover effects* are *asymmetric*. Specifically, when households with a 511 long-term non-conservation-based rate structure are switched to conservation-based rates larger 512 reductions in water use occurs.

513 Our work adds to the literature in several ways: first, we provide new information on rate 514 structure changes to water agencies, regulators, and policymakers, who are stakeholders first and 515 fundamentally involved in the price structure. Regulators may exploit this information to reduce 516 demand during periods of scarcity, and agencies often facing zero-profit constraints may use this 517 information to estimate the impact of rate changes on total revenues. Second, California appears 518 to have a particularly proactive set of urban water management policies, compared to other states 519 with water scarcity. Given the current and anticipated water scarcity situation and broader

520 i	interest in using	g management tool	s for water	conservation in	n other states,	California's studies	s on
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521 water management issues hold potentially important lessons for other jurisdictions that face

522 similar conditions. More broadly, it can play a role as a harbinger in water issues that can

523 similarly arise anywhere in the world, wherever population and industries are growing.

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560 **References**

- Ali, M., J. Wang, H. Himmelberger, and J. Thacher. 2021. "An economic perspective on fiscal
 sustainability of US water utilities: what we know and think we know." *Water Economics and Policy* 7:2150001.
- Arbués, F., M.Á. Garcıa-Valiñas, and R. Martınez-Espiñeira. 2003. "Estimation of residential
 water demand: a state-of-the-art review." *The Journal of Socio-Economics* 32:81-102.
- Autor, D.H. 2003. "Outsourcing at will: the contribution of unjust dismissal doctrine to the
 growth of employment outsourcing." *Journal of Labor Economics* 21:1-42.
- Baerenklau, K.A., K.A. Schwabe, and A. Dinar. 2014. "The residential water demand effect of
 increasing block rate water budgets." *Land Economics* 90:683-699.
- Beecher, J.A., and T.W. Chesnutt. 2012. "Declining water sales and utility revenues: a
 framework for understanding and adapting." A white paper for the Alliance for Water *Efficiency*. <u>http://www</u>. allianceforwaterefficiency.
 org/uploadedFiles/Resource_Center/Library/rates/Summit-Summary-and-Declining-
- 574 Water-Sales-and-Utility-Revenues-2012-12-16. pdf.
- Bernedo, M., P.J. Ferraro, and M. Price. 2014. "The persistent impacts of norm-based messaging
 and their implications for water conservation." *Journal of Consumer Policy* 37:437-452.
- Buck, S., M. Nemati, and D.L. Sunding. 2016. "The welfare consequences of the 2015 California drought mandate: evidence from new results on monthly water demand."
- 579 California Department of Water Resources, and State Water Resources Control Board. "Making
 580 water conservation a california way of life." <u>https://water.ca.gov/-/media/DWR-</u>
 581 <u>Website/Web-Pages/Programs/Water-Use-And-Efficiency/Make-Water-Conservation-A-</u>
 582 <u>California-Way-of-Life/Files/Publications/Final-Primer-2018-Water-Conservation-</u>
 583 Drought-Planning-Legislation-1152018.pdf.
- 584 California Public Utilities Commission.
 585 <u>https://www.cpuc.ca.gov/#gsc.tab=0&gsc.q=California%20in%202050%3A%20Some%</u>
 586 20Sizzling%20Predictions&gsc.page=1.
- 587 Dalhuisen, J.M., R.J. Florax, H.L. De Groot, and P. Nijkamp. 2003. "Price and income
 588 elasticities of residential water demand: a meta-analysis." *Land Economics* 79:292-308.
- 589 Dieter, C.A., and M.A. Maupin. "Public supply and domestic water use in the United States,
 590 2015." US Geological Survey.
- 591 Diffenbaugh, N.S., D.L. Swain, and D. Touma. 2015. "Anthropogenic warming has increased
 592 drought risk in California." *Proceedings of the National Academy of Sciences* 112:3931 593 3936.
- 594 Escriva-Bou, A., B. Gray, E. Hanak, and J. Mount. 2017. "California's future: climate change."
- Escriva-Bou, A., J. Mount, and M. Dettinger (2021) "California's Latest Drought in 4 Charts." In
 California's Latest Drought in 4 Charts.
- Escriva-Bou, A., and G. Sencan. 2021. "Water partnerships between cities and farms in Southern
 California and the San Joaquin Valley."
- Espey, M., J. Espey, and W.D. Shaw. 1997. "Price elasticity of residential demand for water: a
 meta-analysis." *Water Resources Research* 33:1369-1374.
- Gaudin, S. 2006. "Effect of price information on residential water demand." *Applied Economics* 38:383-393.
- Gottlieb, M. 1963. "Urban domestic demand for water: a Kansas case study." *Land Economics* 39:204-210.
- Hajispyrou, S., P. Koundouri, and P. Pashardes. 2002. "Household demand and welfare:

- 606 implications of water pricing in Cyprus." *Environment and Development Economics*:659-607 685.
- Hanak, E., and J.R. Lund. 2012. "Adapting California's water management to climate change."
 Climatic change 111:17-44.
- Hewitt, J.A. 2000. "A discrete/continuous choice approach to residential water demand under
 block rate pricing: reply." *Land Economics* 76:324-330.
- Hewitt, J.A., and W.M. Hanemann. 1995. "A discrete/continuous choice approach to residential
 water demand under block rate pricing." *Land Economics*:173-192.
- Hoffmann, M., A. Worthington, and H. Higgs. 2006. "Urban water demand with fixed
 volumetric charging in a large municipality: the case of Brisbane, Australia." *Australian Journal of Agricultural and Resource Economics* 50:347-359.
- Howe, C.W., and F.P. Linaweaver Jr. 1967. "The impact of price on residential water demand
 and its relation to system design and price structure." *Water Resources Research* 3:13-32.
- Kenney, D.S. 2014. "Understanding utility disincentives to water conservation as a means of
 adapting to climate change pressures." *Journal of the American Water Works Association*106:36-46.
- Kenney, D.S., M. Mazzone, and J. Bedingfield. 2010. "Relative costs of new water supply
 options for Front Range cities." *The Water Center of Colorado State University, September/October.*
- Kenney, D.S., M. Mazzone, J. Bedingfield, C. Bergemann, L. Jensen, and C.W.C. Board. 2011.
 "Relative costs of new water supply options for Front Range cities: Phase 2 Report."
- Langridge, R. 2018. "Management of groundwater and drought under climate change."
 California's Fourth Climate Assessment 10.
- Lee, J., M. Nemati, and A. Dinar. 2021. "Historical trends of residential water use in California:
 effects of droughts and conservation policies." *Applied Economic Perspectives and Policy*.
- Marie, S., and M. Zafar. 2016. "What will be the cost of future sources of water for California?"
 Relatório à CPUC. EUA, CA, 16p.
- Marzano, R., C. Rouge, P. Garrone, L. Grilli, J.J. Harou, and M. Pulido-Velazquez. 2018.
 "Determinants of the price response to residential water tariffs: meta-analysis and beyond." *Environmental Modelling & Software* 101:236-248.
- Mount, J., and E. Hanak. 2014. "Water use in California." *Public Policy Institute of California* (*PPIC*).
- 639 ---. 2016. "Water use in California." In *PPIC Water Policy Center*, PPIC Water Policy Center.
- Nataraj, S., and W.M. Hanemann. 2011. "Does marginal price matter? A regression discontinuity
 approach to estimating water demand." *Journal of Environmental Economics and Management* 61:198-212.
- Nauges, C., and D. Whittington. 2017. "Evaluating the performance of alternative municipal
 water tariff designs: quantifying the tradeoffs between equity, economic efficiency, and
 cost recovery." *World Development* 91:125-143.
- Neidell, Matthew. 2009. "Information, avoidance behavior, and health: the effect of ozone on
 asthma hospitalizations." *Journal of Human Resources*, 44(2).
- Nemati, M., S. Buck, and D. Sunding. 2018. "Cost of California's 2015 Drought Water
 Conservation Mandate." *ARE Update* 21:9-11.
- Nieswiadomy, M., and S.L. Cobb. 1993. "Impact of pricing structure selectivity on urban water
 demand." *Contemporary Economic Policy* 11:101-113.

652 Olmstead, S.M., W.M. Hanemann, and R.N. Stavins. 2003. "Does price structure matter? 653 Household water demand under increasing-block and uniform prices." New Haven: 654 School of Forestry and Environmental Studies, Yale University, Working Paper. 655 ---. 2007. "Water demand under alternative price structures." Journal of environmental 656 economics and management 54:181-198. 657 Raftelis, G.A. ed., 2005. Water and Wastewater Finance and Pricing: A Comprehensive Guide. 658 CRC Press. 659 Reynaud, A. "Assessing the impact of public regulation and private participation on water 660 affordability for poor households: an empirical investigation of the French case." LERNA, 661 University of Toulouse. Schwarz, A., P. Ray, S. Wi, C. Brown, M. He, and M. Correa. 2018. "Climate change risks faced 662 663 by the California Central Valley water resource system." California's Fourth Climate 664 Change Assessment. Publication number: CCCA4-EXT-2018-001 https://www.energy. 665 ca. gov/sites/default/files/2019-07/Water_CCCA4-EXT-2018-001. pdf. Sebri, M. 2014. "A meta-analysis of residential water demand studies." Environment, 666 667 Development and Sustainability 16:499-520. Suárez-Varela, M., and A. Dinar. 2020. "The role of curtailment versus efficiency on spillovers 668 669 among pro-environmental behaviors: evidence from two towns in Granada, Spain." 670 Sustainability 12:769. 671 Tiger, M., J. Hughes, and S. Eskaf. 2014. "Designing water rate structures for conservation & 672 revenue stability." University of North Carolina Environmental Finance Center and 673 Sierra Club, Lone Star Chapter: Chapel Hill, NC, USA. 674 Vicuna, S., E.P. Maurer, B. Joyce, J.A. Dracup, and D. Purkey. 2007. "The sensitivity of 675 California water resources to climate change scenarios 1." JAWRA Journal of the 676 American Water Resources Association 43:482-498. 677 Wang, J., H. Yin, E. Reyes, T. Smith, and F. Chung. 2018. "Mean and extreme climate change 678 impacts on the State Water Project." California's Fourth Climate Change Assessment. 679 Publication number: CCCA4-EXT-2018-004. 680 Worthington, A.C., and M. Hoffman. 2008. "An empirical survey of residential water demand modelling." Journal of Economic Surveys 22:842-871. 681 682 Yoo, J., S. Simonit, A.P. Kinzig, and C. Perrings. 2014. "Estimating the price elasticity of 683 residential water demand: the case of Phoenix, Arizona." Applied Economic Perspectives 684 and Policy 36:333-350. 685 Zerrenner, K., and J. Rambarran. 2017. "Examining conservation-oriented water pricing and 686 programs through an energy lens: an analysis of the energy savings associated with water demand reductions." Environmental Defense Fund: New York, NY, USA. 687 Zhang, B., K.H. Fang, and K.A. Baerenklau. 2017. "Have Chinese water pricing reforms reduced 688 689 urban residential water demand?" Water Resources Research 53:5057-5069. 690 691

Author & Year	Rate (Price) Structures Analyzed*	Findings	Data Description
<u>Olmstead, et al.</u> (2007)	Uniform IBP	The price elasticity of water demand differs between uniform and block rate price structures, and IBP tends to yield a higher price elasticity than a uniform rate price structure.	Household-level data: Total 1,082 households in 11 urban areas in the United States and Canada, served by 16 public water agencies with daily water use records, by separately estimating with the following home age: pre-1960; 1960-1969; 1970-1979; 1980-1989; and 1990-1996
Baerenklau, et al. (2014)	Uniform IBR	Under IBR (a fiscally neutral water budget rate structure), water demand was approximately 17% lower where it would have been under a similar uniform price rate structure. Additional demand reductions could be achieved by increasing certain block prices, decreasing certain block volumes, or removing, splitting, or adding additional blocks.	Household-level data: Over 13,000 single-family households in Southern California with continuous monthly water use records from 2003 to 2012
<u>Reynaud (2006)</u>	Flat CUR IBR DBR	Specific pricing structure impacts specific residential water demands. Noticeably, local communities' observable and unobservable characteristics lead to such pricing choices, thereby influencing residential water consumption levels. IBR has the strongest price sensitivity by showing that a 10% price increase results in a 2.5% decrease in water consumption. In contrast, rate structures of CUR and DBR are only half as sensitive to water prices by showing that a 10% price increase results in water consumption reduction by around 1%.	Local communities-level data: 899 local communities in Canada with monthly residential water demand records considering the number of days with restriction in use in 1993, 1995 and 1998
<u>Gaudin (2006)</u>	Uniform IBR DBR	Marginal price information on the residential water bill potentially affects water use (in terms of per capita residential consumption); the agency can reduce water use for conservation with a 30 to 40% lower rate increase. For example, a 10% decrease in water quantity requires a price increase of approximately 20% if price information on the bill is given, but otherwise, 29% is required.	Agency-level data: Across the USA, 501 agencies with monthly residential water demand records in 1996; 495 agencies in the summer of 2003; and 383 agencies in December 1995
<u>Olmstead, et al.</u> (2003)	Uniform IBR	Price elasticity and water demand under block prices are lower than those under uniform prices. As a result, the impact of the price structure on water demand is greater than the impact of the marginal price itself.	Household-level data:1,082 households in 11 urban areas in the United States and Canada, served by 16 water agencies with daily water use records.
<u>Nataraj and</u> <u>Hanemann</u> (2011)	IBR	Residential water demand is sensitive to an increase in marginal price; doubling marginal price leads to a 12% reduction in water use (500 cubic feet per bill) among high-use households.	Household-level data: Bi-monthly water use data for all households served by the Santa Cruz Water Department from 1990 to 2000

Table 1. Overview of the literature on water rate structure and demand.

Note: *The existing literature used Increasing Block Price (IBP) and Increasing Block Rate (IBR) interchangeably, and Constant Unit Rate (CUR) and uniform rate are interchangeable.

Year	Mean of GPCD	Number of Agencies	Number of agencies by rate type			type
			Tiered	Uniform	Budget	Flat
1994	141.77	24	8	17	0	0
1995	144.95	24	9	16	0	0
1996	121.99	28	14	17	0	0
1997	122.83	34	21	16	0	0
1998	144.73	34	15	19	0	0
1999	100.37	32	17	16	0	0
2000	131.35	30	15	16	0	0
2001	126.88	39	21	19	0	0
2002	130.25	42	25	18	0	0
2003	120.74	44	28	18	0	0
2004	121.58	42	29	15	0	0
2005	116.43	42	28	15	0	0
2006	113.21	41	27	15	0	0
2007	137.80	48	33	17	0	0
2008	124.62	62	36	29	0	0
2009	123.14	101	69	35	1	2
2010	113.25	110	76	34	4	2
2011	112.23	110	79	29	6	2
2012	117.91	95	64	24	7	1
2013	120.44	97	64	25	7	2
2014	123.25	105	68	27	8	2
2015	92.59	119	85	31	8	2
2016	91.37	128	86	39	10	1
2017	96.78	134	85	38	11	1
2018	97.68	162	111	39	12	2
2019	85.97	125	85	31	9	1

Table 2. Summary statistics of the data used in the analysis.

Structure	Uniform	Tier	Any	Any	Budget	Non-	Conser
Structure			(Uniform)	(Tier)		conservation	vation
Uniform	-	35					
Tiered	14	-					
Any (Uniform)			-		5		
Any (Tiered)			0	-	6		
Budget			0	0	-		
Non-conservation						_	42
Conservation						18	-

Table 3. Matrix for total change count in rate structures.

Note: Total 120 treatments; Any types indicate Uniform, Tier, or Flat, but Flat was excluded since only one unique agency used in our sample; and dash (-) denotes no change between the same rate structures; thus, the diagonal elements are meaningless.

Model	(1)	(2)	(3)
Structure	OLS	Fixed effects	Fixed effects
Uniform	-0.100**	-0.153***	-0.047^{*}
	(0.044)	(0.042)	(0.027)
Tiered	-0.244***	-0.254***	-0.084***
	(0.044)	(0.001)	(0.014)
Budget	-0.102**	-0.407***	-0.119**
	(0.046)	(0.060)	(0.060)
Agency FEs	Ν	Y	Y
Month FEs	Ν	Y	Y
Year FEs	Ν	Ν	Y
No. Obs.	20643	20643	20643
R^2	0.023	0.369	0.483

Table 4. Parameter estimates for changes in GPCD by rate structure. (Reference structure: Flat; Dependent variable: log of GPCD of water)

Standard errors in parentheses * p < 0.10, ** p < 0.05, *** p < 0.01

(Reference structure: Trevious fuic structure, Dependent variable: log of Greb of water)							
Structure changes	(1)	(2)	(3)	(4)			
	Uniform	Tiered	Uniform	Tiered			
	To Uniform	to	to	to			
Reference structure		Uniform	Budget	Budget			
	to		-	-			
	Tiered						
Uniform	-0.029**						
	(0.012)						
Tiered		-0.032					
		(0.021)					
Uniform			0.007				
			(0.036)				
Tiered				0.038			
				(0.026)			
Agency FEs	Yes	Yes	Yes	Yes			
Month FEs	Yes	Yes	Yes	Yes			
Year FEs	Yes	Yes	Yes	Yes			
Observations	4611	1606	600	1023			
R-squared	0.521	0.690	0.714	0.652			
F-test	133.285	93.557	38.693	49.581			

Table 5. Parameter estimates for changes in GPCD by switching rate structures (Reference structure: Previous rate structure; Dependent variable: log of GPCD of water)

Table 6. Parameter estimates for changes in GPCD by switching from non-conservation-based rate to conservation-based rate structures (Dependent variable: log of GPCD)

Length of time stayed in	(1)	(2)	(3)	(4)
non-conservation	No length	Less than or	Between two	More than
Structure		equal to two	and five years	five years
		years	(i.e., >2 & 5)	(i.e., >5)
		(i.e., ≤2)		
Non-conservation to conservation	-0.032***	-0.017	-0.047**	-0.060***
(Reference rate structure: non-conservation)	(0.010)	(0.018)	(0.019)	(0.017)
Observations	5,427	1,071	1,368	2,988
R-squared	0.537	0.708	0.652	0.532
Agency FEs	Yes	Yes	Yes	Yes
Month FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
F	167.849	68.816	66.780	90.099

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 7. Parameter estimates for changes in GPCD by switching from conservation-based rate to non-conservation-based rate structures (Dependent variable: log of GPCD of water)

Length of time stayed in	(1)	(2)	(3)
conservation	No length	Less than or equal	More than
Structure		to two years	two years
		(i.e., ≤2)	(i.e., >2)
Conservation to non-conservation	-0.014	0.098***	-0.027
(Reference rate structure: Conservation)	(0.021)	(0.034)	(0.026)
Observations	1,725	473	1,252
R-squared	0.680	0.609	0.716
Agency FEs	Yes	Yes	Yes
Month FEs	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes
F	95.916	20.509	101.788

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

Appendix Appendix (A): Figures



Figure A1. Relationship between intertemporal consumption and subjective preference rate.



Figure A2. The average water use in the surveyed water agencies measured in gallons per capita per day (GPCD) over time.

Appendix (B): Mathematical Derivation

The utility function is given by $U(C_t) = \frac{C_t^{1-\gamma}}{1-\gamma}$ at time $t \iff U'(C_t) = C_t^{-\gamma}$. Considering the

two-period model, $U = U(C_t) + \beta U(C_{t+1})$, the objective function is:

(A1)

$$\underbrace{Max}_{C_t,C_{t+1}} \quad U(C_t) + \beta U(C_{t+1})$$
s.t. $C_t + \frac{C_{t+1}}{1+r} = y_t + \frac{y_{t+1}}{1+r}$
 $\Rightarrow \frac{C_{t+1}}{1+r} = y_t - C_t + \frac{y_{t+1}}{1+r}$
 $\Rightarrow C_{t+1} = (1+r)(y_t - C_t) + y_{t-1}$

Substituting C_{t+1} into the objective function yields as:

(A2)

$$\underbrace{Max}_{C_{t}} \quad U(C_{t}) + \beta U\{(1+r)(y_{t} - C_{t}) + y_{t-1}\}$$

$$FOC: \quad U'(C_{t}) - \beta U'\{(1+r)(y_{t} - C_{t}) + y_{t-1}\}(1+r) = 0$$

$$\Rightarrow \quad U'(C_{t}) - \beta(1+r)U'\{(C_{t+1})\} = 0 \quad (\because C_{t+1} = (1+r)(y_{t} - C_{t}) + y_{t-1})$$

$$\Rightarrow \quad U'(C_{t}) = \beta(1+r)U'\{(C_{t+1})\}$$

$$\Rightarrow \quad C_{t}^{-\gamma} = \beta(1+r)C_{t+1}^{-\gamma} \quad (\because U'(C_{t}) = C_{t}^{-\gamma})$$

Applying constant relative risk-averse (CRRA) utility function, $C_t^{-\gamma} = \beta (1 + r)C_{t+1}^{-\gamma}$, the Euler equation is:

(A3)
$$1 = \beta (1+r) \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma} = \beta R \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma} \text{ such that } (1+r) = R$$

Let us assume $P_{t+1} > P_t$ or relative price $A_{t+1} = \frac{P_{t+1}}{P_t} > 1$ since the unit price of water consumption under conservation-based structures tends to be more expensive than that of nonconservation-based structures. Using the relative price, the objective function is written as:

(A4)
$$\underbrace{Max}_{C_t,C_{t+1}} \quad U(C_t) + \beta U(C_{t+1})$$

s.t.
$$P_t C_t + \frac{P_{t+1}C_{t+1}}{(1+r)} = y_t + \frac{y_{t+1}}{1+r}$$

or, $C_t + \frac{A_{t+1}C_{t+1}}{(1+r)} = y_t + \frac{y_{t+1}}{1+r} \Leftrightarrow C_{t+1} = \frac{(1+r)}{A_{t+1}}(y_t - C_t) + \frac{y_{t+1}}{A_{t+1}}$

 C_{t+1} can then be substituted into the objective function (A4) to get a maximization in a single variable C_t which taking the derivative yields the first-order conditions (FOC) such as equation (A5):

(A5)
$$\underbrace{Max}_{C_t} \quad U(C_t) + \beta U\left\{\frac{(1+r)}{A_{t+1}}(y_t - C_t) + \frac{y_{t+1}}{A_{t+1}}\right\}$$

FOC:
$$U'(C_t) - \beta(1+r) \frac{U'(C_{t+1})}{A_{t+1}} = 0$$

 $\Leftrightarrow U'(C_t) = \beta R \frac{U'(C_{t+1})}{A_{t+1}}$ such that $(1+r) = R$

$$\Leftrightarrow 1 = \beta R \frac{1}{A_{t+1}} \left(\frac{(C_{t+1})}{(C_t)} \right)^{-\gamma} \left(\because U'(C_t) = C_t^{-\gamma}; U'(C_{t+1}) = C_{t+1}^{-\gamma} \right)$$

At $\beta R = 1$ and at $A_{t+1} = \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma}$, we get the following dynamic optimal consumption path:

(A6)
$$\underbrace{C_{t+1}}_{future} = \underbrace{C_t}_{current} \times \underbrace{(A_{t+1})^{\frac{-1}{\gamma}}}_{retlavie \ price}$$

The exchange rate between today's consumption and tomorrow's consumption is proportional to $1/\gamma$. The parameter γ varies depending on how long the household stays with the previous price structure.