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

Juhee Lee, School of Public Policy, University of California, Riverside, Email: juheel@ucr.edu

Mehdi Nemati, Cooperative Extension in Water Resource Economics and Policy, School of Public Policy, University of California, Riverside, Email: mehdin@ucr.edu

Maura Allaire, Urban Planning and Public Policy, School of Social Ecology, University of California, Irvine, Email: maura.allaire@uci.edu

Ariel Dinar, Environmental Economics and Policy, School of Public Policy, University of California, Riverside, Email: adinar@ucr.edu

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Abstract

California's demand-side water management policies, such as changing water rate structures, have gained significant attention in dealing with more frequent, longer droughts, and an increasing population. We quantify the effectiveness of rate structure change using a novel survey dataset of 189 water agencies from 1994 to 2019 in California. Results indicate that single-family residential per capita per day water consumption was reduced by an average of 3.2% when switching from non-conservation-based to a conservation-based water rate structure. Results indicate heterogeneity in the estimated effect, depending on the base rate structure and length of time the base rate structure was in place.

Keywords: California, water rate structures, water conservation, asymmetric effects, spillover effects

JEL Codes: L95, Q21, Q25, Q50,

1. Introduction

California has been facing water management challenges from its ever-increasing population growth and expanding urban development, as well as severe and long-lasting droughts. California droughts are getting more intense, lasting longer, and are more frequent (Diffenbaugh, et al., 2015). From 1970 to 2021 California experienced seven significant droughts (1976-1977; 1987-1992; 1987-1992; 2007-2009; 2012-2016; 2012-2016, and 2020-2021). The combination of low precipitation and high temperatures made the 2012-2016 drought very intense, and the same pattern is unfolding in the current (2021) drought (Escriva-Bou, et al., 2021, Lee, et al., 2021).

For many years California has enacted conservation measures to address growing water demands and insecure water supply levels driven by drought conditions. To date state and local demand-side water management policies have collectively reduced gallons per capita per day of water use by 34% compared to 1994 (Lee, et al., 2021). However, effects of the state's expected population increase (Dieter and Maupin, 2017) and future climate change will pose substantial challenges for future water management (Dieter and Maupin, 2017, Escriva-Bou, et al., 2017, Hanak and Lund, 2012, Langridge, 2018, Schwarz, et al., 2018, Vicuna, et al., 2007, Wang, et al., 2018), highlighting the need for continued water conservation in general, and use for urban landscapes in particular.

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., 2021, Beecher and Chesnutt, 2012, Tiger, et al., 2014).

While the popularity and prominence of alternative pricing structures have grown substantially over time, policymakers need to understand how the change in rate structures impact water consumption and how this affects California conservation efforts and behavioral responses by households. While such aspects are critically important for policy considerations, no past literature has assessed the effectiveness of structural changes. The majority of the economic literature focuses on the effects of water rate structures on household consumption (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 especially the impacts on water consumption following a switch from one rate structure to another.

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

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

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

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 to different rate structure changes? And (iii) how long does the effect of the pricing structure change persist? Our study builds on the existing literature related to water rate structures. However, rather than investigating and comparing parameter estimates across different rate structures, we answer those questions by estimating whether, to what extent, and under which circumstances residential households respond to changes in the rate structures, especially with regard to water conservation.

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

2. Literature Review

Since the pioneering studies by Gottlieb (1963), and Howe and Linaweaver Jr (1967), 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 objectives, or other socioeconomic variables. By expanding the scope[2] of the study, the literature analyzed pricing structure endogeneity between water consumption and welfare effects (Gaudin, 2006, Hewitt and Hanemann, 1995).

2.1. Residential water demand function with water price

The large body of literature analyzing the effect of water pricing has focused on the responsiveness of water demand to higher prices by estimating price elasticities under different water rate structures and comparing these estimates. Water demand in most cases is estimated as relatively inelastic, albeit it is not perfectly inelastic. Statistically, such price elasticities of demand are negative across all models. The possible reasons are that water is irreplaceable for essential use, and water bills are treated as a necessary expense for goods that make up a portion of a customer's total expenditure (Arbués, et al., 2003, Yoo, et al., 2014). In addition, customers 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 estimated elasticities, in that each rate structure produces a different elasticity of demand. Most of the previous studies in this area show that increasing block structure (IBS) (e.g., tiered or budget based) tends to produce higher estimates of price elasticity than other structures (e.g., uniform) to be compared (Baerenklau, et al., 2014, Dalhuisen, et al., 2003, Marzano, et al., 2018, Olmstead, et al., 2007). IBS tends to be conservation-oriented. The structure imposes a low 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 price[3] promotes the reduction of water consumption by signaling a water scarcity to high-use consumers who

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[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.

2.2. Residential water demand function with other factors

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

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

well documented elasticities while considering other factors.

2.3. Water rate structure changes

The extensive empirical literature has emphasized how price and other factors influence residential water demand by estimating the effect of water prices on water consumption. Still, fewer relevant studies explore the different water pricing structure changes and water demand in terms of water conservation. Limited evidence is available on the effectiveness of pricing in structural change; however, initial research (Table 1) suggests significant potential.

In particular, Nauges and Whittington (2017) and Zhang, et al. (2017) authored some of the few empirical papers investigating the issue of rate structure change by water agencies. Using household-level monthly water use data for Organisation for Economic Co-operation and Development (OECD) countries and developing countries in 2008, Nauges and Whittington argue that different IBR designs perform poorly in targeting subsidies to low-income households by analyzing the effect of the shift from a uniform volumetric structure to an IBR structure on water use and water bills of households in the light of measures of equity and economic efficiency. Zhang, et al. investigated the effectiveness of this national policy reform comparing household-level monthly water use data in 28 cities that adopted IBR pricing structures during 2002–2009, with that of 110 cities that had not yet done so. The authors found that the policy reform to IBR adoption reduces annual water consumption by 3.3%, on average.

Given the potential of water structure change that affects water conservation effectiveness and the lack of enough information on water rate structure change, the efficacy of any part of a holistic water conservation program will diminish. Our study can empower both the water agency and the household with new and essential information they need to improve efficiency.

3. Conceptual framework

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

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 weight on the expected utility that households will get through future consumption. Correspondingly, household utility maximization is[4]:

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

$$\text{s.t.} \quad C_t + \frac{C_{t+1}}{1+r} = y_t + \frac{y_{t+1}}{1+r}$$

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

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[4] See Appendix (B): Mathematical Derivation for details

over time. In other words, within a water agency, the demographics and socioeconomic factors of the households, such as household size and income, would be identical either at the period *t* or at period *t+1*. Otherwise, the question could be raised whether this change in water consumption was due to a change in the characteristics of the households. For example, one may doubt whether the household income within an agency during the period *t+1* changes relative to that 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.

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

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

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

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

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

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

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

Consequently, derived the equilibrium water consumption path is:

(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 (Raftelis, 2005).

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

(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 consumption decreases less?). Based on Figure A1, ($\frac{C_{t+1}}{C_t}$) increases over γ; thus, $\left(\frac{C_{t+1}}{C_t}\right)_A < \left(\frac{C_{t+1}}{C_t}\right)_B$ at $\gamma_A < \gamma_B$. This implies that a household that experienced a given rate structure for a longer time has a lower γ than a household that stayed for a shorter time period (i.e., $\gamma_{lonr} < \gamma_{short}$), the degree of reduction in water consumption in a long period is greater than that in a short period (i.e., $\left(\frac{C_{t+1}}{C_t}\right)_{long} < \left(\frac{C_{t+1}}{C_t}\right)_{short}$).

What happens to water consumption when one agency switches one price structure to another structure? We try to answer this main question through the change of γ, which is represented by the household's response. Thus, the testable hypothesis under this relationship is that the agency's price structure change due to intervention affects the household's water consumption. Our conceptual framework shows that the impact of such structure change on household consumption depends on the length of time spent in the existing rate structure before changing to another structure. We infer this hypothesis by applying an empirical investigation on our dataset's different lengths of time and structures.

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 Water Resources Control Board, 2018, Lee, et al., 2021, Nemati, et al., 2018). 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.

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

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

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

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.

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

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

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

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

where the outcome of interest is the log of aggregate water consumption for agency *i* in year *y*, and month *m*, $ln(q_{iym})$. In this specification, we include indicators for months before and after a change in the pricing structure. The variable of interest is $Rate\ Structure_{iym}$ which denotes the type of rate structure an agency is using. We consider flat, uniform, tiered, and budget. α_i captures the average change in the different water consumption measured in GPCD under certain rate structures relative to the reference rate structures. By considering the length of time staying in the same rate structures, β_i captures the specific change in the different water consumption 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 calendar month fixed effects, and μ_y refers to agency calendar year fixed effects. Lastly, ε_{iym} captures all remaining unobservable effects that affect the dependent variable.

As mentioned earlier, $Length_{iym}$, 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.

For this, we divided the length of time the agency kept an existing rate structure into three cut-offs for the case of switching from non-conservation-based to conservation-based rate structures, respectively (i.e., less than or equal to two years; between two and five years; and more than five years). We then examined two cut-offs for the case of switching from conservation-based to non-conservation-based rate structures (i.e., less than or equal to two 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 agencies, and the latter contained 18 unique agencies. We describe the estimation of the effects reflecting these cut-offs separately from the estimation of the average treatment effects that do not consider the length of time at all in the results section.

6. Empirical Results

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

Table 5 shows the estimated coefficients from the fixed-effect model after controlling agency, month, and year fixed effects estimation for the change from one rate structure to another structure. For this, we performed a separate regression on each structure change. As we expected, column 1 shows a negative coefficient sign. When the agency switched its rate structure from uniform to tiered, average water use is decreased by 2.9%. However, we did not find a statistically significant effect for all other switches, which could be due to the low number of observations in these cases. We combined conservation-based rate structure and non-conservation-based rate structures and re-estimated the models (Table 6).

Column 1 in Table 6 reports the estimated average treatment effects of policy intervention—switching to the conservation-based rate structures from non-conservation-based rate structures. We found evidence that when an agency switches its rate structure from non-conservation-based to conservation-based, the average GPCD decreases by 3.2%. This clearly indicates that water-saving policy interventions result in water consumption reductions.

Unlike column 1, which did not consider the duration of the policy intervention, columns 2 and 3 show the results of adding the duration of policy intervention into the formula. In other words, it shows how the degree of water consumption reduction varies according to the length of time remaining in the existing rate structure before changing to the new structure. Specifically, column 2 shows a water-saving effect of about 1.7% when the length of time spent in the previous non-conservation-based rate structure was less than two years. On the other hand, when staying in the previous non-conservation-based rate structure was between two and five years, the water consumption decreased by 4.7%. Finally, when the time remaining in the same rate structure was longer than five years, water consumption decreased by 6.0%.

Regression results of switching from a conservation-based rate structure to a non-conservation-based rate structure are shown in Table 7. Column 1 indicates no statistically significant effect on water use when an agency switches from conservation-based rate structures to a non-conservation-based rate structure. However, the results changes when we break down the sample by the length of time stayed in conservation-based rate structures. As shown in column 2, when an agency had a conservation-based rate structure for less than two years before switching to a non-conservation-based structure, we observed a positive and statistically significant effect on GPCD—average GPCD increased by 9.8%. In contrast, column 3 presents a 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 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 knowledge, awareness or perceptions, and consequential habits.

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

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

The households that remained in the non-conservation-based rate structure for a long period of time (i.e., more than two years or five years in columns 3 and 4 of Table 6), did not have the incentives to conserve water like households with conservation-based rate structures. First, under the non-conservation-based structure, households could use water at a relatively low price for a long period of time; they did not need to adjust their behaviors. Second, households had no incentives to purchase and install water-saving features or change water-use behaviors. Third, households had little need to entail sunk costs with monetary or time aspects. Accordingly, when households with lower water prices from long-term non-conservation-based rate structures experience policy changes to a conservation-based rate structure because of droughts, their reduction in water consumption appeared much greater.

Table 7 shows three insights according to different durations of policy intervention. First, when the time spent in the conservation-based rate structure is two years or less (column 2), households made no short-term behavioral adjustments for conservation policies. Second, households made fewer water-saving capital investments for relatively long-term physical capital adjustments. For instance, households might make investments in water-efficient devices (e.g., appliances, fixtures, garden irrigation), or perhaps a long-term behavior change (e.g., fully loading the dishwasher, taking shorter showers), and third, less sunk costs. Hence, when the policy was changed to a non-conservation-based rate structure, and the policy intervention for conservation disappears, households increased water consumption again.

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 consumption after the agency returns to non-conservation pricing. This result suggests that the 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 asymmetric effects depending on which structure is changed to which structure.

The possible reasons for this are that some households experienced higher rates from conservation pricing for a much longer period of time, which resulted in behavioral adjustments. They also had time to make water-saving capital investments for relatively long-term physical capital adjustments. These households tend to continue to reduce water use because of invested behavioral and capital adjustments, and either monetary or time sunk costs. These consistencies can be seen as positive spillover effects from the policy intervention on water conservation. This 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.

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-conservation-based (i.e., flat and uniform) to conservation-based rate structures (i.e., budget-based and tiered).

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

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

Our work adds to the literature in several ways: first, we provide new information on rate structure changes to water agencies, regulators, and policymakers, who are stakeholders first and fundamentally involved in the price structure. Regulators may exploit this information to reduce demand during periods of scarcity, and agencies often facing zero-profit constraints may use this information to estimate the impact of rate changes on total revenues. Second, California appears to have a particularly proactive set of urban water management policies, compared to other states with water scarcity. Given the current and anticipated water scarcity situation and broader interest in using management tools for water conservation in other states, California's studies on water management issues hold potentially important lessons for other jurisdictions that face similar conditions. More broadly, it can play a role as a harbinger in water issues that can similarly arise anywhere in the world, wherever population and industries are growing.

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

Author & Year	Rate (Price) Structures Analyzed*	Findings	Data Description
Olmstead, et al. (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
Reynaud (2006)	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
Gaudin (2006)	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
Olmstead, et al. (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.
Nataraj and Hanemann (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

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.

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

Year	Mean of GPCD	Number of Agencies	Number of agencies by rate 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 3. Matrix for total change count in rate structures.

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

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.

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

Model Structure	(1) OLS	(2) Fixed effects	(3) 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	N	Y	Y
Month FEs	N	Y	Y
Year FEs	N	N	Y
No. Obs.	20643	20643	20643
R^2	0.023	0.369	0.483

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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

Structure changes Reference structure	(1)	(2)	(3)	(4)
	Uniform To Uniform to Tiered	Tiered to Uniform	Uniform to Budget	Tiered to Budget
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 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 non-conservation Structure	(1) No length	(2) Less than or equal to two years (i.e., ≤2)	(3) Between two and five years (i.e., >2 & 5)	(4) More than five years (i.e., >5)
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 conservation / Structure	(1) No length	(2) Less than or equal to two years (i.e., ≤2)	(3) More than two years (i.e., >2)
Conservation to non-conservation (Reference rate structure: Conservation)	-0.014 (0.021)	0.098*** (0.034)	-0.027 (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

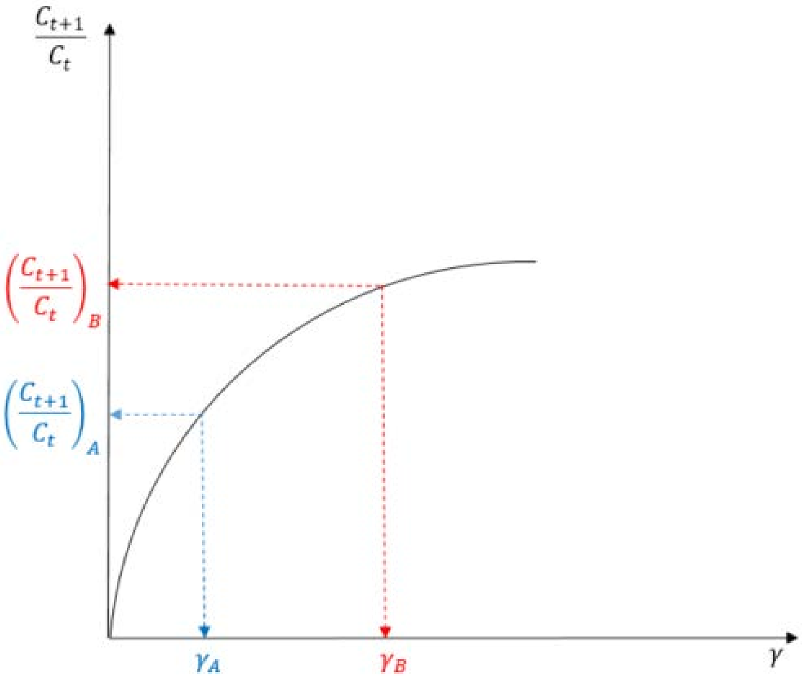

Figure A1. Relationship between intertemporal consumption and subjective preference rate.

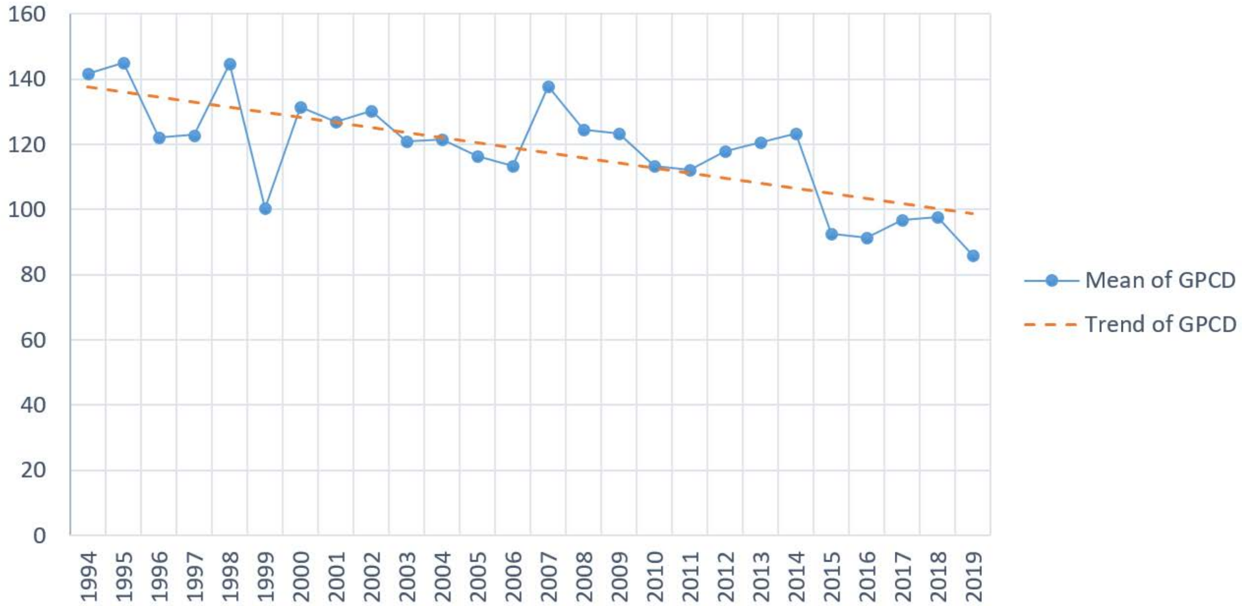

Figure A2. The average water use in the surveyed water agencies measured in gallons per capita per day (GPCD) over time.

Appendix (B): Mathematical Derivation

The utility function is given by $U(C_t) = \frac{{C_t}^{1-\gamma}}{1-\gamma}$ at time *t* ($\Rightarrow\ U^{'}(C_t) = {C_t}^{-\gamma}$). Considering the two-period model, $U = U(C_t) + \beta U(C_{t+1})$, the objective function is:

(A1)
$$\underbrace{Max}_{C_t, C_{t+1}} \quad U(C_t) + \beta U(C_{t+1})$$

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

$$\Rightarrow \frac{C_{t+1}}{1+r} = y_t - C_t + \frac{y_{t+1}}{1+r}$$

$$\Rightarrow C_{t+1} = (1+r)(y_t - C_t) + y_{t-1}$$

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

(A2)
$$\underbrace{Max}_{C_t} \quad U(C_t) + \beta U\{(1+r)(y_t - C_t) + y_{t-1}\}$$

$$FOC\text{:} \;\; U'(C_t) - \beta\, U'\{(1+r)(y_t - C_t) + y_{t-1}\}(1+r) = 0$$

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

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

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

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 non-conservation-based structures. Using the relative price, the objective function is written as:

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

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

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

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

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

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

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

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

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