ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research®

RESEARCH ARTICLE
10.1029/2022WR032169

Key Points:

- Our results suggest that the 2015 California water mandate resulted in temporary and permanent reductions in water use
- Rebound effects are more prevalent in the warm season than in other months and for lower-end water users than high-end water users
- Our results also show that, due to the mandate, the peak hour water consumption shifted to the earlier hours of the day

Correspondence to:
M. Nemati,
mehdin@ucr.edu

Citation:
Nemati, M., Tran, D., & Schwabe, K. (2023). Residential water conservation and the rebound effect: A temporal decomposition and investigation. *Water Resources Research*, *59*, e2022WR032169. https://doi.org/10.1029/2022WR032169

Received 10 FEB 2022
Accepted 22 MAR 2023

Author Contributions:
Conceptualization: Mehdi Nemati, Kurt Schwabe
Data curation: Mehdi Nemati, Dat Tran
Formal analysis: Mehdi Nemati, Dat Tran
Funding acquisition: Mehdi Nemati
Investigation: Mehdi Nemati
Methodology: Mehdi Nemati, Kurt Schwabe
Project Administration: Mehdi Nemati, Kurt Schwabe
Resources: Mehdi Nemati
Software: Mehdi Nemati, Dat Tran
Supervision: Mehdi Nemati, Kurt Schwabe
Validation: Mehdi Nemati
Visualization: Mehdi Nemati, Dat Tran
Writing – original draft: Mehdi Nemati, Dat Tran
Writing – review & editing: Mehdi Nemati, Kurt Schwabe

Residential Water Conservation and the Rebound Effect: A Temporal Decomposition and Investigation

Mehdi Nemati[1], Dat Tran[2], and Kurt Schwabe[1]

[1]School of Public Policy, University of California, Riverside, CA, USA, [2]School of Public Policy, Office of Economic and Demographic Research, Tallahassee, FL, USA

Abstract Water conservation in California has been a major subject of concern for agencies in their efforts to satisfy their residential demand while coping with frequent shortfalls, especially in periods of drought. During the 2012–2016 severe drought in California, the state enacted a conservation mandate that imposed specific conservation targets of 4% up to 36% for water utilities. While the utilities met those targets in 2015, water use, on average, has slowly crept up or rebounded subsequently, although not to pre-drought levels. Understanding the manner and degree to which water use rebounds can be critically important for water utilities in their planning and investment decisions. Using a unique panel dataset on single-family residential water use by nearly 20,000 customers of a Northern California water agency from 2013 to 2019, this paper explores the magnitude and character of the rebound effect that occurred after the cessation of a statewide conservation mandate that was imposed on water use in response a severe drought enveloping California from 2014 through 2016. Our results suggest the presence of a significant rebound in water use—of approximately 9% on average—after the conservation mandate ended. Yet, and novel to our research, we find significant heterogeneity in the rebound effects across seasons and water users, with a greater rebound in the warm season months relative to other months and among lower water use households relative to higher water use households. Our results also suggest a significant shift in water use to earlier periods of the day once the mandate was lifted. Understanding the magnitude and variation in rebound effects both temporally and across different types of water users can be useful to water agencies in their efforts to make informed decisions surrounding investments, management, and messaging in response to drought, conservation, and water scarcity.

Plain Language Summary Given the prominence of demand-side management in the water utilities toolbox for addressing increasing water shortages driven by drought and climate change, understanding how water use changes during a drought along with how and to what extent it increases, or "rebounds," afterward can be useful if not necessary in making informed policy decisions and cost-effective investments. This research develops a unique data set consisting of household-level daily and hourly water use by nearly 19,500 residential accounts from a California water utility from 2013 through 2019. It explores how water use changed during and post-drought relative to pre-drought levels. During this period, California entered a significant drought. Its governor requested a voluntary cutback, imposed a conservation mandate, and implemented a self-certification requirement lasting until the drought eased. We find that residential water use decreased by 26% during the conservation mandate relative to pre-drought levels but rebounded by approximately 9% post-mandate. The "rebound" effect varied across the season (greatest in summer months) and water user type (lower-end water users showed a larger percentage rebound than higher-end water users). Our results suggest that due to the mandate, the peak hour water consumption shifted to the earlier hours of the day.

1. Introduction

The frequency, longevity, and severity of droughts and rapidly growing populations are depleting water resources in many arid and semi-arid regions globally, increasing the challenges urban water managers confront in their efforts to balance water supplies and demands. In addition to the effects of climate change, water supply availability in California is not evenly distributed temporally and spatially relative to demand, putting municipal water supplies in a precarious situation (Brown et al., 2019; Diffenbaugh et al., 2015; Hanak & Lund, 2012; Mann & Gleick, 2015; Sandoval-Solis, 2020; Woodhouse et al., 2020). In response to these evolving realities and associated challenges, policymakers and urban water managers are adopting demand-side management strategies to encourage water use reductions to buffer against short-term water supply shortfalls (Buck et al., 2021; Lee et al., 2022; Nemati et al., 2018).

Within the U.S., California is a prime example of how water conservation has become a priority in urban water management (Schwabe et al., 2014). The state and local water utilities continue to invest and encourage conservation by introducing new technologies to increase water use efficiency. In addition, they may implement policy measures for improved water-saving, such as water pricing, direct financial incentives, or regulations, including water quotas and use bans (Baerenklau et al., 2014; Gilligan et al., 2018; Grafton et al., 2020; Nataraj & Hanemann, 2011; Olmstead et al., 2007; Olmstead & Stavins, 2009; Zhang et al., 2017). During severe drought, water managers often rely on the latter approach in the form of a mandate to require customers to change their water use behavior in a particular way. In general, these bans or quotas on water use—which typically focus on outdoor water use and vary dramatically from limiting days of outdoor irrigation (e.g., 2 days per week), hours of irrigation, and method of irrigation (hand-watering)—have been shown to be inefficient relative to pricing in achieving water use reductions (Brennan et al., 2007; Dupont, 2015; Grafton & Ward, 2008; Timmins, 2003).

During the 2012–2016 drought in California, one such ban labeled a “conservation mandate” was enacted. It required water utilities to reduce their water use below some defined threshold so that the state would achieve an overall 25% reduction in water use relative to a baseline (non-drought period), which was determined to be 2013. The mandatory urban water use restrictions imposed from June 2015 to May 2016 resulted in statewide urban water use reductions of 25% relative to 2013 levels, with some utilities managing cumulative savings as high as 31% (Buck et al., 2021; Nemati et al., 2018; Spang et al., 2018). However, water consumption bounced back after the 2015 drought mandate was lifted (Gonzales & Ajami, 2017). This phenomenon, known as the “rebound” effect, often occurs following a period of sustained low demand, such as during drought, and is triggered after the cessation of water restrictions and media campaigns to conserve water (Beal et al., 2014; Gonzales & Ajami, 2017).

A lack of understanding surrounding the rebound effect can have significant implications on water utility pricing and investment decisions. For instance, most water utilities still tie a significant fraction of their revenues to volumetric pricing while their costs are mostly fixed, often upwards of 80%–85% (Schmidt & Lewis, 2017; Spang et al., 2015). As such, imposing a ban during a drought can result in a significant loss in revenue, which in turn threatens financial stability. A common response by utilities to these revenue shortfalls is to raise prices, especially if they don't recognize the possible rebound effect once the drought subsides. While raising prices can be an efficient water conservation strategy, uninformed price increases—especially following water reductions by customers in response to utility requests—can lead to customer relations challenges. Second, and from a longer-term perspective, such misunderstanding as to how demand might evolve following drought can lead to poor investment decisions by the utility through over- or under-investment strategies. Utilities are often under enormous pressure to “do something” during a drought—even enact long-term investments that will not necessarily affect water scarcity in the present drought. If based on a poor understanding of how demand may evolve after the drought, such decisions may lead to inefficient investment choices.

With these concerns in mind, the motivation for the analysis is multifold. First, despite the growing importance and adoption of voluntary and mandatory water conservation regulations in urban water management and the significance of the behavioral response of community members, few empirical studies have explored the rebound effects of these programs (Beal et al., 2014; Gonzales & Ajami, 2017). Using a unique dataset consisting of daily and hourly water use from approximately 19,500 households within a utility in Northern California from 2013 through 2019, we estimate the magnitude and characteristics of the rebound effect following the cessation of statewide conservation mandate that was imposed from June 2015 through May 2016.

Because we have data on water use at the individual residential household level, both daily and hourly, we extend our understanding of the rebound effect in three dimensions. First, we extend the literature on rebound effects in water usage by identifying how rebound effects differ across lower-end versus higher-end water users. Such information can be important to effective and targeted messaging and marketing campaigns related to conservation and efficiency programs, but also in understanding where future reductions in water use might come from (and how much). Second, with daily data across each year from 2013 through 2019, we can identify the degree to which there is a seasonality that might characterize the rebound effect. Given the significant differences in water use across seasons, with summer and warmer season months typically being characterized by significantly greater water use than winter or cooler season months (Lee et al., 2022), information on the possibility seasonality associated with the rebound effect can help water agencies better identify effective strategies for future conservation and efficiency efforts that recognize such seasonality.

Third, with hourly data on water use from 2015 through 2019, we investigate whether water use practices following the cessation of the mandate changed throughout the day (e.g., peak vs. off-peak hours) and in a manner more consistent with recommended water efficient practices. Previous studies of hourly water consumption showed consumption concentrated during two periods: peak hour demand and peak day demand (Cole & Stewart, 2013). Our analysis extends the literature by investigating how hourly water use changed over time, and specifically how it changed after the drought mandate relative to during the drought mandate. Irrigation specialists and water agencies are increasingly emphasizing in their messaging to water users that watering lawns earlier in the morning, and certainly not during mid-day, is a water-efficient practice due to more of the water percolating rather than evaporating during a cooler part of the day (Park & Smith, 2008). Indeed, many agencies and the state have enacted bans restricting the timing of outdoor irrigation (Riverside Public Utilities (RPU), 2022). Thus, understanding specific characteristics of outdoor water use and how it evolved following the drought can give agencies a better understanding of the degree to which additional efforts are needed to encourage more efficient irrigation practices.

In the analysis and discussion of possible water use reductions and rebound effects that follow, it is important to recognize a general distinction between "conservation" and "efficiency." Water conservation is defined as a reduction in water use that may occur through short-term behavioral changes. Reducing water use through increasing water use efficiency often is considered to be permanent, such as what might happen through hardwiring some technological improvement like reduced water use dishwashers, or low-flush toilets and low-flow showerheads (Vickers, 1999). Rebounds occur only if water reductions were made from water conservation (short-term reductions in water use) since efficiency improvements are more permanent.

2. Data and Methods

2.1. Study Area Background

Our analysis focuses on single-family residential households that receive water from a mid-sized water utility located in Northern California. The area served by this utility has cool and humid winters with hot and dry summers. The rainy season typically begins in November and ends in March, with low humidity during the summer months. For the period 1998–2019, average annual rainfall was measured as 20.6 inches. The wettest months are December, January, and February, and the driest months are normally July and August. Typically, July and August are the hottest months of the year, with an average daily temperature of approximately 76°F, though daytime high temperatures average close to 93°. December and January are generally the coolest months of the year, with an average annual temperature of about 48°, with the average minimum dipping down to 39°. In terms of income, according to the 2010 Census, the median household income in the utility service area is $94,642.

Nearly 70% of the utility's water supply comes from surface water sources, while 21% and 8% come from purchased surface water and local groundwater sources, respectively. On the demand side, in 2019, there were about 19,500 single-family residential, 6,000 multi-family, 1,500 commercial/industrial, and about 1,000 municipal/park connections serving approximately 70,000 people. In terms of annual water consumption share, in 2019, approximately 54% of total potable water was delivered to single-family residential customers, about 27% to commercial and industrial customers, and approximately 10% to multi-family residential customers. Based on the water utility's 2019 estimates, water consumption was about 256 gallons per capita day (gpcd).

Under the 2015 California conservation mandate, the water utility for our study was required to reduce water consumption by 32% compared to 2013 levels. To achieve this goal, the utility offered rebates to replace lawns, upgrade irrigation systems, and install high-efficiency toilets and clothes washers. During the mandate, water use restrictions were enforced, including no runoff or gutter flooding and no emptying and refilling of pools and water features except for health, structural or maintenance purposes. Additional restrictions included banning spraying of impervious surfaces (sidewalks, streets, etc.), requiring shut-off nozzles for hoses, banning outdoor watering during rain events or between the hours of 10 a.m. to 10 p.m., and limiting landscape irrigation to a maximum of 2 days per week based on the odd-even schedule. In terms of pricing and pricing structure, there were no changes in either over the study period—January 2013 to December 2019—by the utility, which employed a three-tier pricing structure.

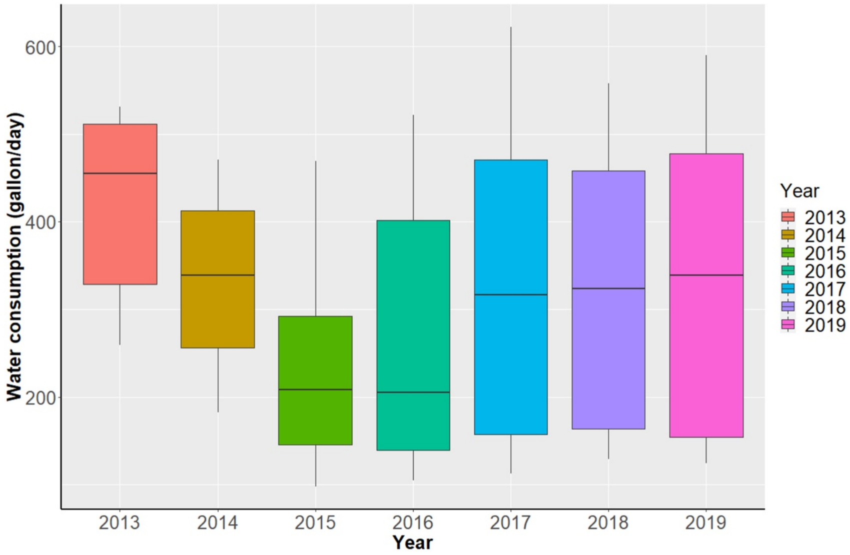

Figure 1. Summary of single-family residential annual water consumption (gallons/day) from 2013 to 2019 in the study area. *Note*: For each year, median daily water use is represented by the dark horizontal line; the upper and lower parts of the colored box represent the third and first quartiles of the daily water use for that year; the line extending above and below the colored boxes represent daily water use outside of the middle 50th percentile (fourth and first quartile).

2.2. Data Description

This analysis consists of 7 years of data—2013 through 2019—from approximately 19,500 single-family residential households that receive water from a mid-sized water utility located in Northern California. We were able to collect daily data from 2013 through 2019 and hourly data from 2015 through 2019, resulting in over 430 million data points. The ability to use hourly data arose as a result of the utility adopting, in 2014, advanced metering infrastructure (AMI)—also known as smart meters—that transmit water use data continuously to the utility. Given the importance of weather in driving residential water use, our dataset included data on daily temperature and precipitation in the study area from the PRISM climate group (PRISM Climate Group, 2020).

Figure 1 shows the average annual single-family residential water consumption from 2013 through 2019. On average, water use in the study area is higher from 2017 through 2019 relative to 2015–2016, albeit lower than 2013 levels. The reduction in water consumption during the 2015–2016 period to approximately 220 gallons/day was likely a direct consequence of the mandatory water restrictions the state of California implemented (from June 2015 through May 2016) to cope with the extreme drought conditions it was experiencing. The mandate was eased in May 2016 and replaced with a self-certification process until April 2017 due to the drought subsiding. Following the lifting of the statewide mandate in 2016, utilities still had to meet the state conservation mandate requirements if they could not "self-certify" that they had reasonable supply reserves to cover demand. As shown in Figure 1, residential water use rose after 2016 relative to earlier years, increasing by approximately 45% during the 2017–2019 period compared to 2015–2016.

Rather than comparing water use by year, Figure 2 (and Table A1 in the appendix) summarizes hourly water use throughout the day for the mandate and post-mandate periods. During the mandate period, both average hourly water consumption and standard deviations were lower than those after the mandate period for every hour of the day. During the mandate period, average hourly water consumption stood at 9.07 gallons/hr, which was lower relative to post-mandate (13.36 gallons/hr), implying a rebound of approximately 4.29 gallons/hr in water use, on average. The peak hourly water consumption during the mandate was at 7 a.m., while it was 2 hr earlier (5 a.m.) after the mandate period. By far, the most significant period of hourly water consumption during the mandate period was between 6 and 9 a.m. versus from 4 to 6 a.m. after the mandate. As mentioned above, because the utility installed the AMI in 2014, we are not able to compare hourly water use to the pre-mandate levels. Yet we do know that while overall water use increased after the conservation mandate was lifted, on average, it did return to pre-mandate levels.

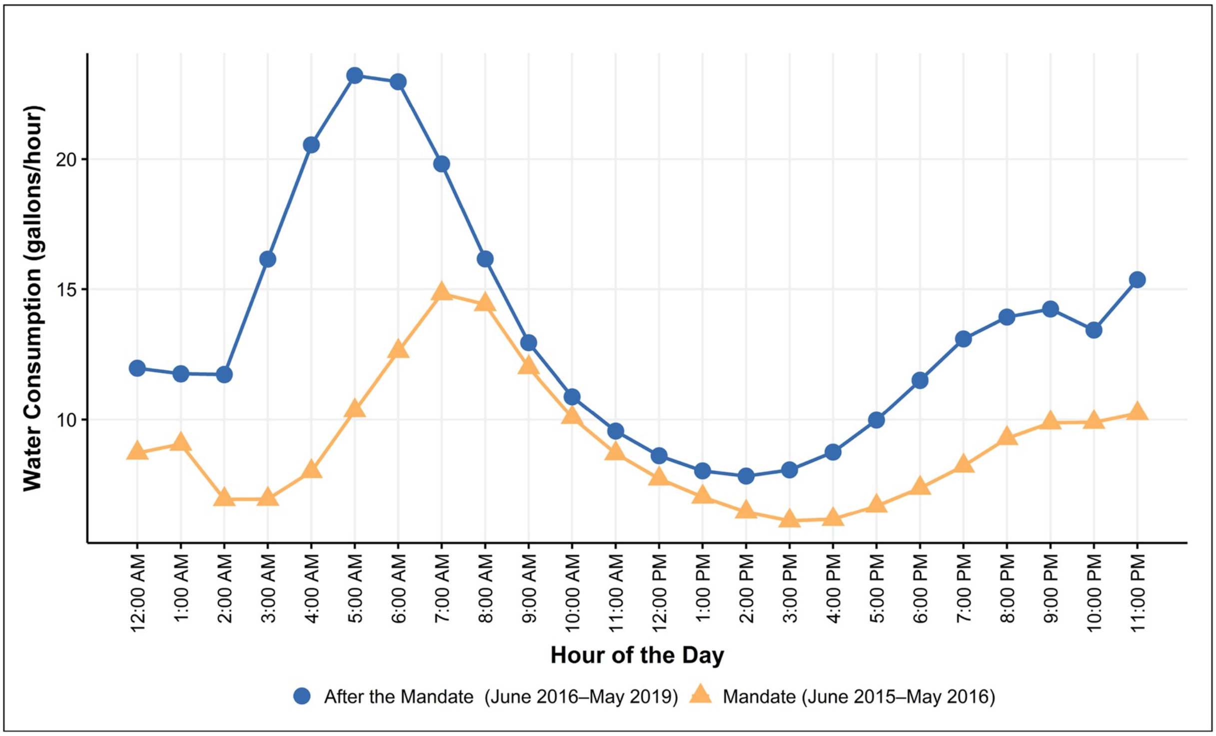

Figure 2. Average water consumption (gallons/hr) during (June 2015 to May 2016) and after (June 2016 to May 2019) the mandate.

2.3. Econometric Model

To explore how water use changed over time and the presence and characteristics of a rebound effect, a fixed-effects regression model of water use at the household level is developed using both daily and hourly data. The rich panel dataset allows us to control for omitted unobservable variable bias in the analysis via numerous fixed-effects controls. Our fixed-effects estimating equation of household-level water use is given in Equation 1, where *i* represents the household and *t* time.

$$\log(q_{it}) = \alpha_1.\mathrm{Mandate}_{it} + \alpha_2.\mathrm{PostMandate}_{it} + \vartheta W_t + \gamma_i + \mu_m + \theta_w + \delta_d + \varepsilon_{it} \quad (1)$$

As shown, the outcome of interest, $\log(q_{it})$, is the natural log of water consumption for household *i* in day *t*. The variables of interest are "*Mandate*" and "*PostMandate*." $\mathrm{Mandate}_{it}$ is an indicator variable that is set equal to one for all observations in the mandate period (June 2015 to May 2016), else zero; similarly, $\mathrm{PostMandate}_{it}$ is an indicator variable that is set equal to one for the post-mandate observations (June 2016 to May 2019), else zero. Weather controls are represented by W_t (i.e., cooling- and heating-degree days as well as precipitation). γ_i indicates household fixed effects; μ_m indicates calendar month fixed effects; θ_w indicates the week of the year fixed effects, and δ_d indicates the day of the week fixed effects. Lastly, ε_{it} captures all remaining unobservables that affect the dependent variable. The Halvorsen–Palmquist transformation is applied to calculate the correct percentage changes for the "*Mandate*" and "*PostMandate*" indicator variables (Giles, 1982; Halvorsen & Palmquist, 1980; Kennedy, 1981). For example, for calculating the percentage change in water consumption associated with switching "*Mandate*" from 0 to 1, a transformation of $100 \times (e^{\alpha_1} - 1)$, where e^{α_1} is the exponential transformation of the estimated coefficient, is required.

In addition to testing for overall rebound effects, we investigate the degree to which heterogeneous rebound effects may arise across different water user types. Specifically, we catalog residential water users into quintiles based on average warm season months' pre-mandate water use as the baseline. Warm season months of water consumption in California typically are defined from May through September (Jenkins et al., 2003; Lee et al., 2022), which is when households use the most water due to the demands associated with outdoor water use. Indicator variables are created for whether the mean warm season months pre-mandate water consumption is in the first, second, third, fourth, or fifth quintile of the whole sample warm season months pre-mandate consumption (i.e., Q.1, Q.2, etc.). These quintile binary variables are interacted with time indicators to highlight how they change over time. Quintile thresholds are 446.12 gallons per day (gpd) and lower in average warm season months water use for the first quintile, 446–659 gpd for the second, 659–808 gpd for the third, 808–1,047 gpd for the fourth, and 1,047 gpd and higher for the fifth quintile. The estimating equation is as follows, where Q_j is the quintile indicator, and other variables are similar to the definitions in Equation 1.

$$\log(q_{it}) = \sum_{j=1}^{j=5} \alpha_j Q_j .\mathrm{Mandate}_{it} + \sum_{j=1}^{j=5} \beta_j Q_j .\mathrm{PostMandate}_{it} + \vartheta W_t + \gamma_i + \mu_m + \theta_w + \delta_d + \varepsilon_{it} \tag{2}$$

In addition to the daily data spanning 2013 through 2019, household-level hourly water use data is collected from January 2015 to December 2019. This data set, which is available due to the utility's adoption of an AMI throughout 2014, allows us to investigate at a much more granular level how water use (throughout the day) changed after the state-imposed water restrictions relative to the mandate period. To do this, we estimate a second fixed-effects model in which the dependent variable is the hourly water use at household i and time t, as shown in Equation 3.

$$q^*_{it} = \alpha_1.\mathrm{PostMandate}_{it} + \vartheta W_t + \gamma_i + \mu_m + \theta_w + \delta_d + \tau_h + \varepsilon_{it} \tag{3}$$

In Equation 3, the outcome of interest, q^*_{it}, is the transformed hourly water consumption for household i and hour t using the inverse hyperbolic sine transformation—a logarithmic-like transformation that allows us to keep zero-valued observations and which allows us to interpret coefficients as semi elasticities as suggested by Burbidge et al. (1988) and MacKinnon and Magee (1990) and used in the previous studies (e.g., Bellemare et al., 2013; Moss & Shonkwiler, 1993; Pence, 2006). We use adjusted Halvorsen–Palmquist transformation as suggested by Bellemare and Wichman (2020) to calculate the correct percentage changes (Halvorsen & Palmquist, 1980).

The variable of interest is "$\mathrm{PostMandate}_{it}$," which is an indicator variable that is set equal to one for all observations in the post-mandate period (June 2016 to May 2019) and zero otherwise (June 2015 to May 2016). In addition to the fixed effects described in Equation 1, τ_h is included to capture the hour of the day fixed effects, and ε_{it} captures remaining unobservables that affect the dependent variable. Finally, using the following equation, we capture the heterogeneity in the estimated changes in water consumption by the hour of the day post-mandate relative to the mandate period. Note that H_j is the hour of the day indicator, and other variables are similar to the definitions in Equation 3.

$$q^*_{it} = \sum_{h=0}^{h=23} \alpha_j H_j .\alpha_1.\mathrm{PostMandate}_{it} + \vartheta W_t + \gamma_i + \mu_m + \theta_w + \delta_d + \tau_h + \varepsilon_{it} \tag{4}$$

To address possible autocorrelation bias in the standard errors in all of our estimating equations, we clustered standard errors at the household level, thereby allowing observations within a household to be spatially correlated but independent across the water utility (Bertrand et al., 2004; Cameron & Miller, 2015). Note that while using a fixed effects estimator, we can control for unobservable or unmeasurable characteristics that do not vary over time. Still, there is a limitation in controlling for unmeasured characteristics that vary over time. Also, this estimator assumes the structural relationship between water demand variables remains unchanged over time. If the 2015 drought event caused these structural relationships to change, then caution is warranted in the interpretation of the estimated coefficients. Finally, we reiterate that in this part of our analysis, we make comparisons with the hourly data between the mandate and post-mandate periods and not relative to the pre-mandate period since the hourly data is not available prior to 2015.

3. Results

In the analysis that follows, we first investigate—with daily water use data—the extent to which single-family residential water use changed during (mandate period) and after (post-mandate) the drought relative to the pre-drought period. Following an analysis of inter- and intra-annual daily water use, we explore the characteristics of the rebound on a much more granular level by evaluating how hourly water use changed post-mandate relative to use during the mandate.

3.1. Exploring the Rebound Effect: Analysis of Daily Data

Figure 3 provides a comparison of average daily water consumption for single-family residential accounts across each month of the calendar year from 2013 through 2019. In comparing the distributions, we see a reduction in water consumption every month from 2013 through 2015. After 2015, water use during the warm season months

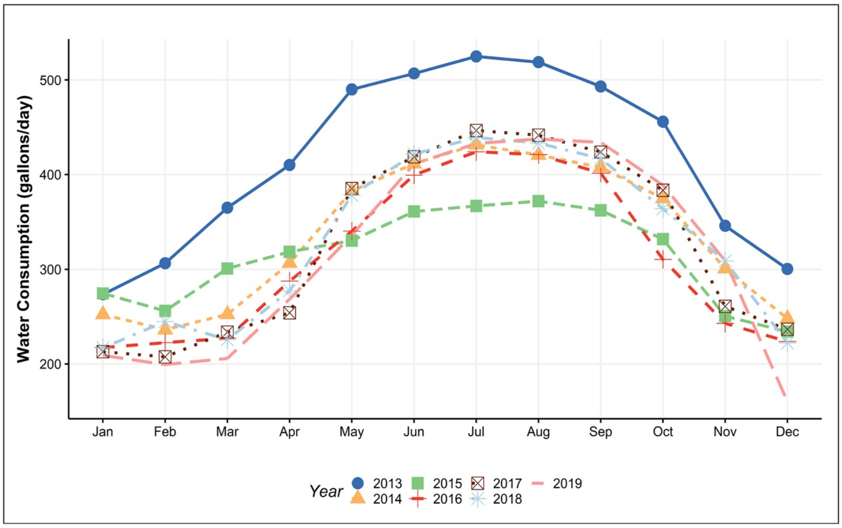

Figure 3. Average monthly water consumption (gallons/day) from 2013 to 2019 in the study area.

relative to 2015 rose (e.g., including both after the mandate and self-certification period ended). While the higher water consumption in the warm season months is not surprising, an interesting artifact that falls out of these comparisons is the manner in which water use rebounded. Prior to the mandate, the distribution of water use had much larger tails (higher non-warm season month usage) and a higher mode (high warm season month usage). The effect of the mandate was to essentially shift the distribution of water use across months downward relative to the pre-drought years, indicating that, on average, water use every month decreased.

After 2015, though, as illustrated by the narrower distributions and increasing modes, warm season month water use crept up through 2019, yet water use in non-warm season months, particularly in the early part of the year, stayed relatively constant. So, the "rebound" was driven by increases in water use during the warm-season months—likely as households increased their outdoor water use—but during non-warm season water consumption, often represented by more indoor water use, did not rebound in any appreciable manner and, in some cases, actually decreased. Overall, the distributions suggest a large rebound in water use after the mandate was lifted, mostly occurring in the warm season months when outdoor water use predominates.

Figure 3 also highlights how, following the mandate, water use continued to stay low and even declined during some of the non-warm season months while rebounding during the warm season months. From a water management perspective, households, on average, continue to reduce water use in the non-warm season months, and utilities may want to focus efforts on understanding how to incentivize, encourage, and equip households to reduce water use in the warm season months.

Table 1 presents the results of the estimated change in daily water consumption from (June 2015 to May 2016) and after the mandate (June 2016 to May 2019) relative to the pre-mandate period (June 2013 to May 2015). The columns of Table 1, moving left to right, increasingly add controls for unobservable time-invariant factors. Column (1), which represents our baseline fixed-effects model, suggests that during the drought mandate, average daily water use decreased by nearly 22.1% relative to the pre-drought period and decreased by approximately 9.60% post-mandate relative to the pre-mandate period. In columns (2) and (3), weather variables (cooling- and heating-degree days as well as monthly precipitation) and month-of-year fixed effects are added to control for seasonality. More granular temporal controls, such as the week-of-the-year fixed effects and day-of-week fixed effects, are added in column (4).

Column (4) of Table 1 presents our final and preferred specification and shows that water consumption declined by 26.10% during the conservation mandate period compared to the pre-mandate period. This finding is slightly lower than the conservation mandate requirement for the water utility under the study. That is, under the 2015 California conservation mandate program, the water utility we focus on was required to reduce water consumption by 32% compared to 2013 levels. Comparing the reductions during and after the mandate period to the pre-mandate period indicates that overall water use post-mandate crept up approximately 9.01% relative to the

Table 1
The Estimated Change in Water Consumption (gallons/day) During and After the Mandate Relative to the Pre-Mandate Period (June 2013 to May 2015)

	(1)	(2)	(3)	(4)
During the mandate (June 2015 to May 2016)	−0.221*** (0.003)	−0.220*** (0.003)	−0.258*** (0.003)	−0.261*** (0.003)
After the mandate (June 2016 to May 2019)	−0.096*** (0.003)	−0.095*** (0.003)	−0.170*** (0.003)	−0.171*** (0.003)
Difference (%)	12.513	12.526	8.797	9.011
Number of observations	32,098,745	32,098,745	32,098,745	32,098,745
Number of accounts	19,476	19,476	19,476	19,476
Household fixed effects	Yes	Yes	Yes	Yes
Weather controls	No	Yes	Yes	Yes
Month fixed effects	No	No	Yes	Yes
Week of the year fixed effects	No	No	No	Yes
Day of the week fixed effects	No	No	No	Yes

Note: Robust Hubert-White standard errors are clustered at the household level in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. The dependent variable is the log of daily water consumption. Average water consumption during and after the mandate was 431.17 and 506.79 gallons/day, respectively.

mandate period (although it was still lower than the pre-drought averages). The change in average gallons per day is an estimated 112 fewer gallons for the average household during the mandate period compared to the pre-drought period and 86 fewer gallons post-mandate period compared to the pre-drought period. The results agree with previous research finding a rebound in water use following a period of sustained low demand, such as during drought, but not to pre-drought levels (Beal et al., 2014; Gonzales & Ajami, 2017). To consider the cases where water users might have started to cut back on water use before/after the mandate took effect, we also estimated the change in water consumption a month prior to and a month subsequent to the mandate period. These changes did not result in any appreciable differences in our estimates and, thus, did not alter the general conclusion that water consumption after the mandate did not bounce back to the pre-mandate levels.

Figure 4 (and Table A2 in the appendix) explores whether and the extent to which water use and the rebound effect varied across different user groups as defined by the water use quintile. Using the preferred specification from Table 1 (Column 4) results in Figure 4 show that water use by higher quintile water users decreased by more in percentage terms during both the mandate and post-mandate period relative to the pre-drought period. Yet, as shown, the rebound effect for these high-water users was lower in percentage terms relative to water use by the lower quintile users. The lower percentage rebound by the highest quintile group suggests adopting strategies to reduce water use more permanently during the mandate relative to lower water users. For example, users in quintile 5 reduced their water consumption by nearly 25.20% post-mandate compared to pre-drought. This is only a few percentage points less than what they achieved during the mandate than pre-drought (i.e., 29.90% during the mandate compared to the pre-mandate).

The most significant “rebound” effects—in percentage terms—occur for those users in quintiles 1 and 2, with an approximate 13.47% and 14.45% increase in water use after the mandate. The initial water use reductions were somewhat similar to the higher water users, but the higher water users only had an increase of approximately 6.76% (quintile 3), 5.59% (quintile 4), and 4.71% (quintile 5) in water use following the mandate. While our data does not allow us to identify whether higher water user types engaged in more permanent water-efficient practices while lower water user types engaged in shorter-term behavioral adjustments that were relaxed after the mandate, we do know that a significant number of ratepayers replaced their lawns with more drought-friendly landscaping and that numerous households also let their lawns turn brown and/or die (*Yachnin*, 2022). For instance, the Metropolitan Water Agency of Southern California provided rebates to over 46,000 homeowners resulting in the replacement of over 165 million square feet of turfgrass.

3.2. Exploring the Rebound Effect: Analysis of Hourly Data

Having established with the daily data the presence of a rebound in water use following the drought mandate and identifying characteristics of the rebound effect both seasonally and across different user types, we now turn our attention to better understanding the characteristics of the rebound with more temporally granular hourly data. Figure 5

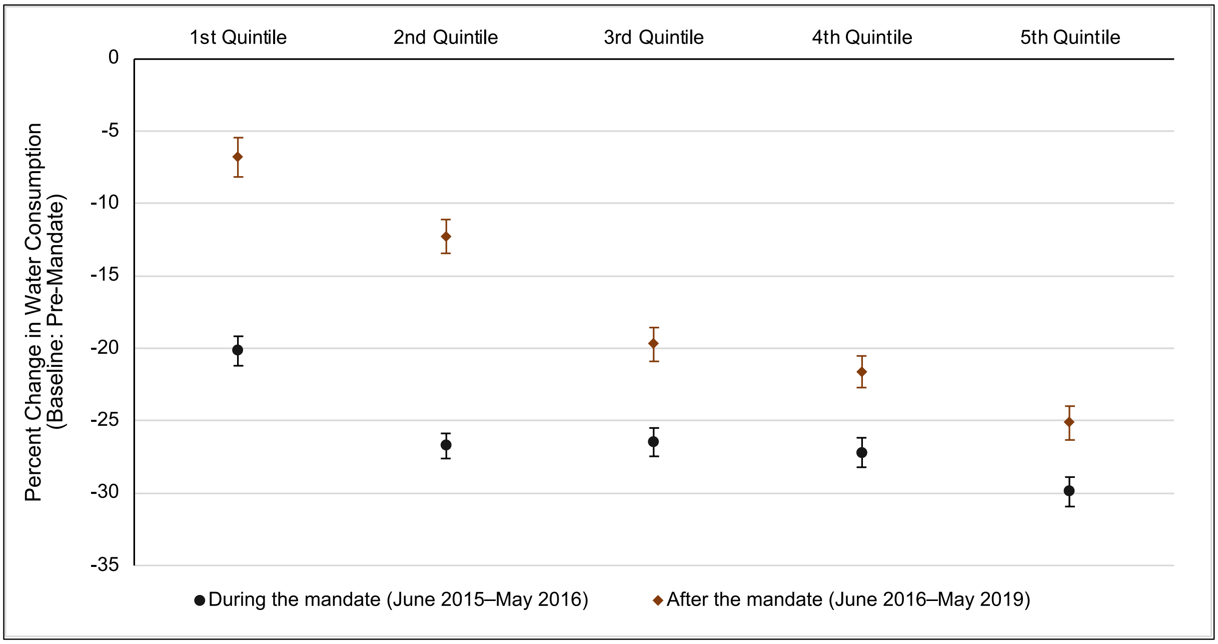

Figure 4. Heterogeneity in the estimated rebound effect of California mandate on daily water consumption by quintile of water consumption. *Note*: Robust Hubert-White standard errors are clustered at the household level in parentheses $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. The dependent variable is the log of daily water consumption. Average water consumption during and after the mandate was 431.17 and 506.79 gallons/day, respectively. The average and standard deviation of water consumption in first quintile are 214.31 and 214.77, in second quintile are 404.05 and 335.29, in third are 560.95 and 396.78, in fourth quintile are 689.59 and 475.95, and in the fifth quintile are 995.65, and 704.80 gallons/day, respectively.

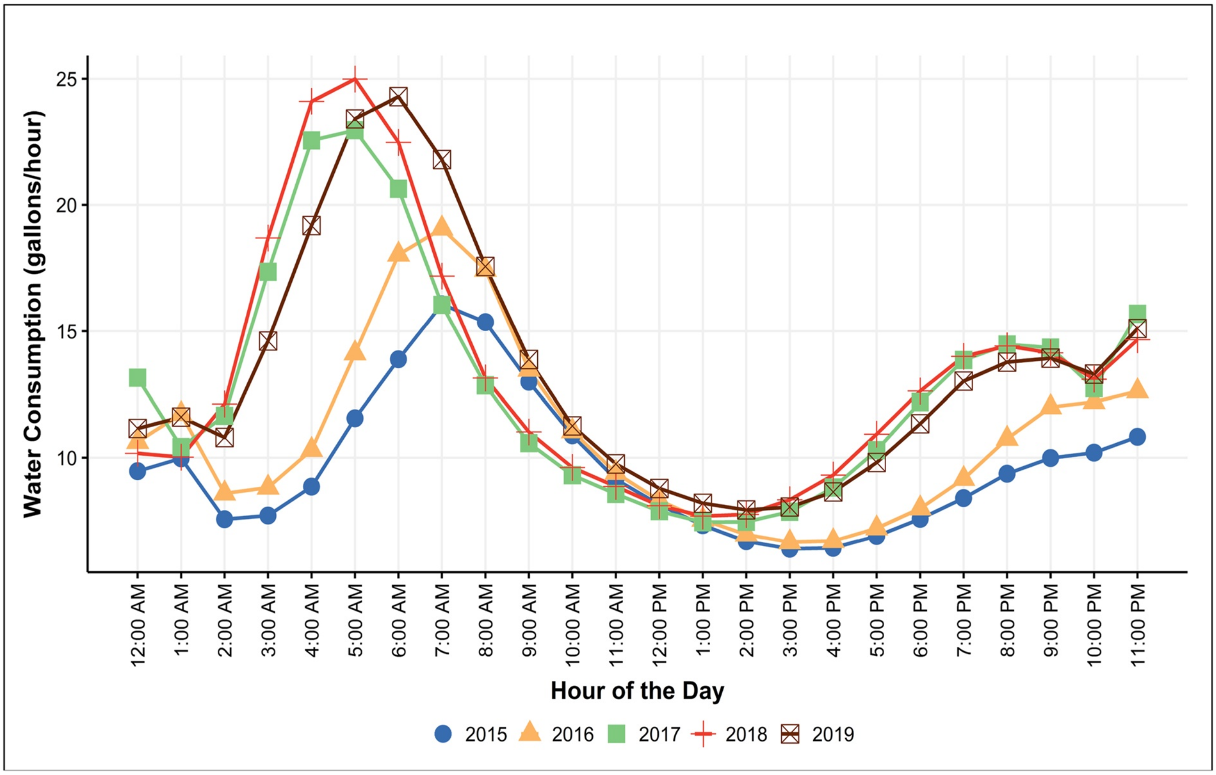

Figure 5. Average hourly water consumption (gallons/hr) from 2015 to 2019 in the study area.

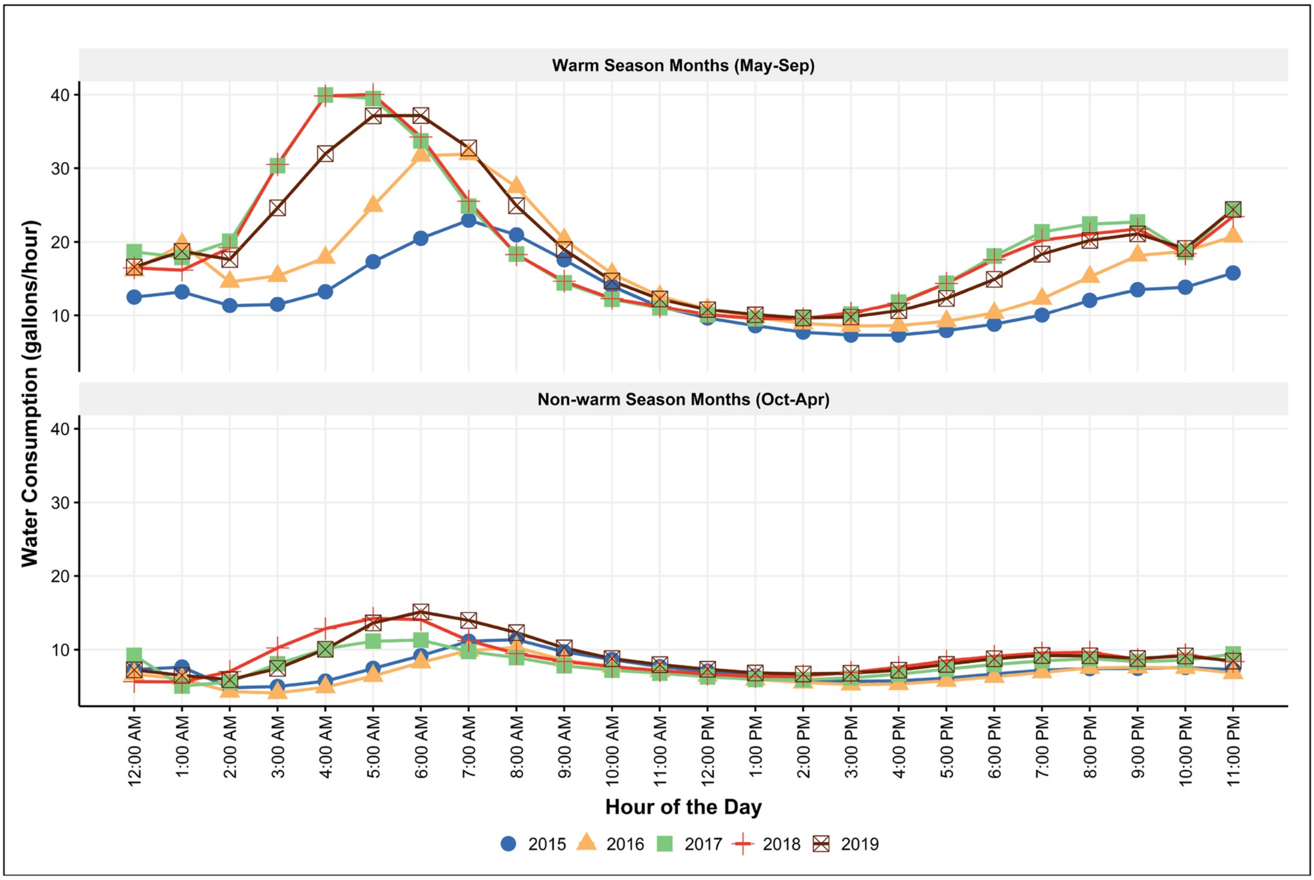

Figure 6. Average hourly water consumption (gallons/hr) in the warm season months (May–September) and other non-warm season months (October–April) from 2015 to 2019.

provides the distribution of average hourly water use over the hours of a day each year from 2015 to 2019. While all the distributions are bimodal, albeit with a clear mode (peak-hour demand) in the morning hours, there is a distinct difference between 2015 and 2016 relative to 2018 and thereafter. The modes for 2015 and 2016 are significantly lower and later in the morning than those after 2016. Additionally, the lowest water use occurred around 3 p.m. in 2015 and 2016. A takeaway from these comparisons is that peak demand grew significantly from 2015 through 2019, together with much tighter distributions.

To better understand the characteristics associated with what appears to be a structural change in water use between 2015 and 2016 relative to 2017 through 2019, Figure 6 presents the average hourly distributions from 2015 to 2019 by high water use months (May–September) and low water use months (October–April). As shown, the distributions of hourly water use during the warmer season months are significantly more dispersed than those for the cooler season months. More specifically, water use during cooler months in the years 2015 and 2016 was similar to the levels from 2017 through 2019. The highest rebound happened during the warm season months. It is apparent that the peak hourly demands were between 4 and 6 a.m., although, consistent with Figure 5, a general leftward shift of the mode of the distribution occurred from 2015 through 2019. The change in water use pattern over time, with warmer season water use at an earlier (i.e., 4 a.m.) hour, would be consistent with households increasing outdoor irrigation following the drought yet moving more watering to a few hours earlier in the day. Moving irrigation to earlier in the morning is a practice recommended by water agencies and professionals to allow more infiltration of water for plant uptake and less evaporation of the water as the day warms.

Table 2 reports the estimated rebound effect using different model configurations, from no control and no fixed effects to various weather controls and fixed effects. As shown, the estimated increase in post-mandate water use compared with use during the mandate is positive and significant regardless of the model configurations considered. Second, except for the month-fixed effects that control for seasonality, other time-fixed effects

Table 2

The Estimated Hourly Change in Water Use Post-Mandate Compared to During the Mandate Period (gallons/hr)

	(1)	(2)	(3)	(4)	(5)	(6)
After the mandate (June 2016 to May 2019)	0.188*** (0.004)	0.189*** (0.005)	0.143*** (0.005)	0.145*** (0.005)	0.146*** (0.005)	0.100*** (0.005)
After the mandate × warm season	-	-	-	-	-	0.113*** (0.004)
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	No	Yes	Yes	Yes	Yes	Yes
Month fixed effects	No	No	Yes	Yes	Yes	Yes
Week of the year fixed effects	No	No	No	Yes	Yes	Yes
Day of the week fixed effects	No	No	No	Yes	Yes	Yes
Hour of the day fixed effects	No	No	No	No	Yes	Yes

Note: Robust Hubert-White standard errors are clustered at the household level in parentheses $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Observations are equal to 429,589,840 in all the columns.

(week-of-the-year, day-of-the-week, and hour-of-the-day fixed effects) seem to have little impact on the point estimates. As indicated in column 5, hourly water use increased by nearly 14.60% post-mandate compared to the mandate period.

The last column of Table 2 shows how the change in water consumption differs by warm season (May–September) versus non-warm season months. As shown, warm season month water use post-mandate relative to the mandate period increased by 21.30% compared to the 10.00% increase during the non-warm season months. As a robustness check, we alternatively define the warm season as July–September months as well as June–August. As presented in Table A3 in the appendix, our overall findings are robust across these definitions—the rebound effect during the warm season months is about 11.30%–12.60% higher than in non-warm season months.

Figure 7 (also Table A4) presents the estimated changes in water use by the hour of the day post-mandate relative to the mandate period. As shown, the increase in water use was high during the early morning hours and then reduced rapidly after reaching its peak at 5 a.m. Also, we see that the change in water use was negative at some hours, indicating that water users shifted their water usage patterns to using less water during the daytime hours after the mandate was lifted. These findings again highlight the shift in the hourly distribution of water use after the mandate, most likely by increasing water use for irrigation while reducing water usage around midday, when average daily temperatures and thus evaporation would be high relative to morning. Water experts and popular press (Crotta, 2014; Hughes, 2020) have been highlighting the benefits of watering during the early morning hours for years. As such, to see a shift in average watering toward these early morning hours is consistent with best practices. While we cannot test specifically if such outreach was responsible for this change, there is strong evidence that such outreach can impact water use (Gonzales & Ajami, 2017).

Figure 8 summarizes hourly water use throughout the day for the mandate and post-mandate periods by quintile of water use. Regardless of the baseline quintile, during the mandate period, average hourly water consumption was lower than those after the mandate period. The peak hourly water consumption during the mandate was at 7 a.m., while it was 2 hr earlier (5 a.m.) after the mandate period. In all quintiles, the most significant period of hourly water consumption during the mandate period was between 6 and 9 a.m. versus from 4 to 6 a.m. after the mandate.

4. Conclusions

Water managers often use demand-based policies to cope with supply shortfalls during drought periods, but water use tends to rebound after these policies are no longer in effect (Beal et al., 2014; Gonzales & Ajami, 2017). We investigated California's 2015 "conservation mandate" rebound effects to identify the magnitude and characteristics of these effects temporally and across different types of water users using daily and hourly data on single-family water consumption provided by a water utility in Northern California from 2013 through 2019.

Consistent with previous studies (e.g., Gonzales & Ajami, 2017), our baseline estimates indicate a rebound in water consumption after the 2015 mandate was lifted. That is, the results showed that water consumption after

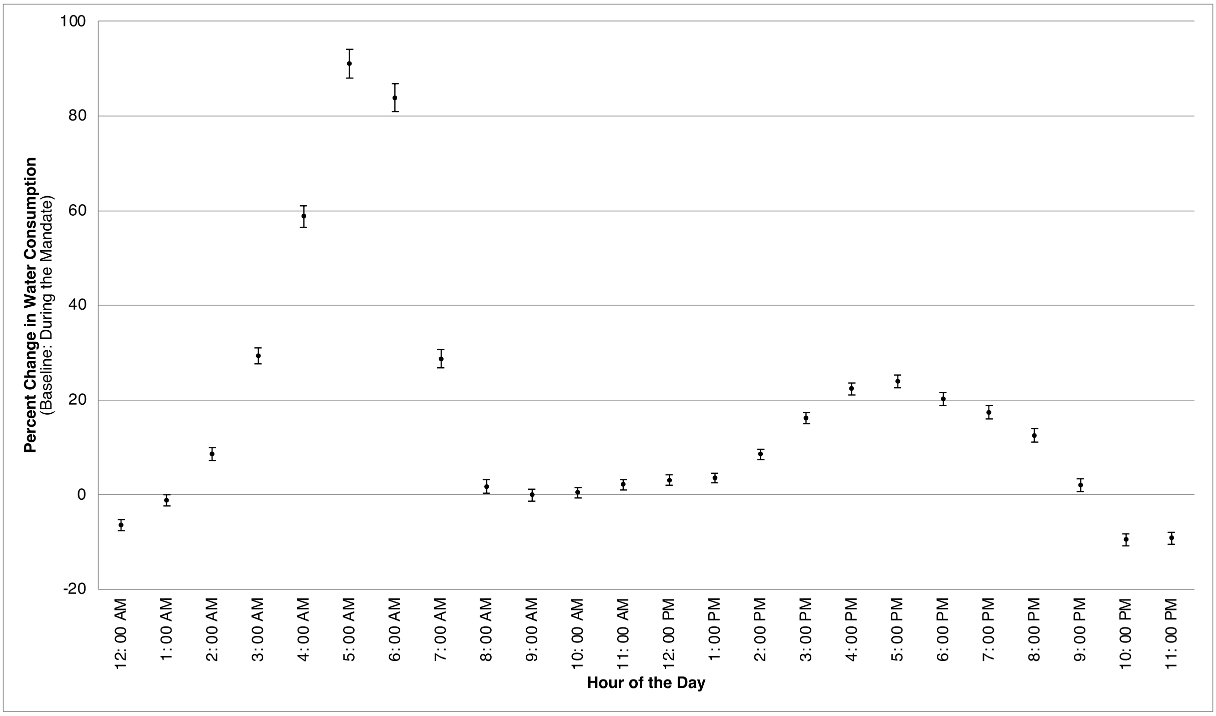

Figure 7. Heterogeneity in the estimated hourly change in water use post-mandate relative to mandate period (gallons/hr). *Note*: The figure plots point estimates showing percent changes in water consumption post-mandate (June 2016 to May 2019) compared to during the mandate (June 2015 to May 2016) period by the hour of the day. The point estimates are denoted as circles. The 95% confidence intervals are plotted. Robust Hubert-White standard errors are clustered at the household level. The estimated regression includes weather controls, calendar month, week of the year, day of the week, and hour of day fixed effects. Observations are equal to 429,589,840.

the mandate crept up by around 9.01% after the mandate was lifted. Yet the rebound did not fully erase all water reductions since 2013 since overall water use was still around 17.1% lower than the pre-mandate period.

One novel contribution to better understanding the rebound effect is our exploration into user characteristics that may be associated with more or less of a rebound. We found that the highest water users had the lowest percentage rebound. In contrast, those water users in the lower quintiles of water use had the largest percentage rebound. Unfortunately, our current data set does not allow us to explore this issue in more detail to identify whether there were distinct differences in the strategies that different user groups enacted during and after the drought. A promising area of future research would be to explore this issue with household-level data on water conservation program participation which is available from some agencies and investigate the means by which the higher water use households responded to the mandate relative to the lower water use households. Such knowledge can be useful in the development, financing, and messaging of conservation programs. Given the significant investments that water agencies are making to encourage water use reductions—e.g., Metropolitan Water District of Southern California alone has spent nearly $900 million on conservation programs (MWD, 2023)—understanding these responses—whether there are particular types of households that engage in particular types of strategies—can be useful to water utilities in their efforts to better understand to what extent different types of customers respond to conservation requests, how they respond, and how agencies can develop and message programs more effectively to help customers meet such requests (Vercammen, 2015).

A second novel contribution of this research is to identify temporal characteristics of how water use changed during and after the conservation restrictions—both seasonally and hourly. From a seasonal perspective, our results illustrate that the rebound effect occurred primarily in the summer months rather than the non-summer months. Indeed, water use in the non-warm season months has continued to decrease following the end of the mandate. As such, future efforts for increased water use efficiency and conservation will likely have the highest returns through focusing on water use during the warmer parts of the year, that is, the summer months. This is not surprising since approximately 50% or more of residential water use is used for outdoor irrigation of yards and lawns, and water demand by lawns and yards is greatest in the warm season months. Consequently, efforts to both reduce water use as well as encourage conservation would likely be best served by focusing attention—both

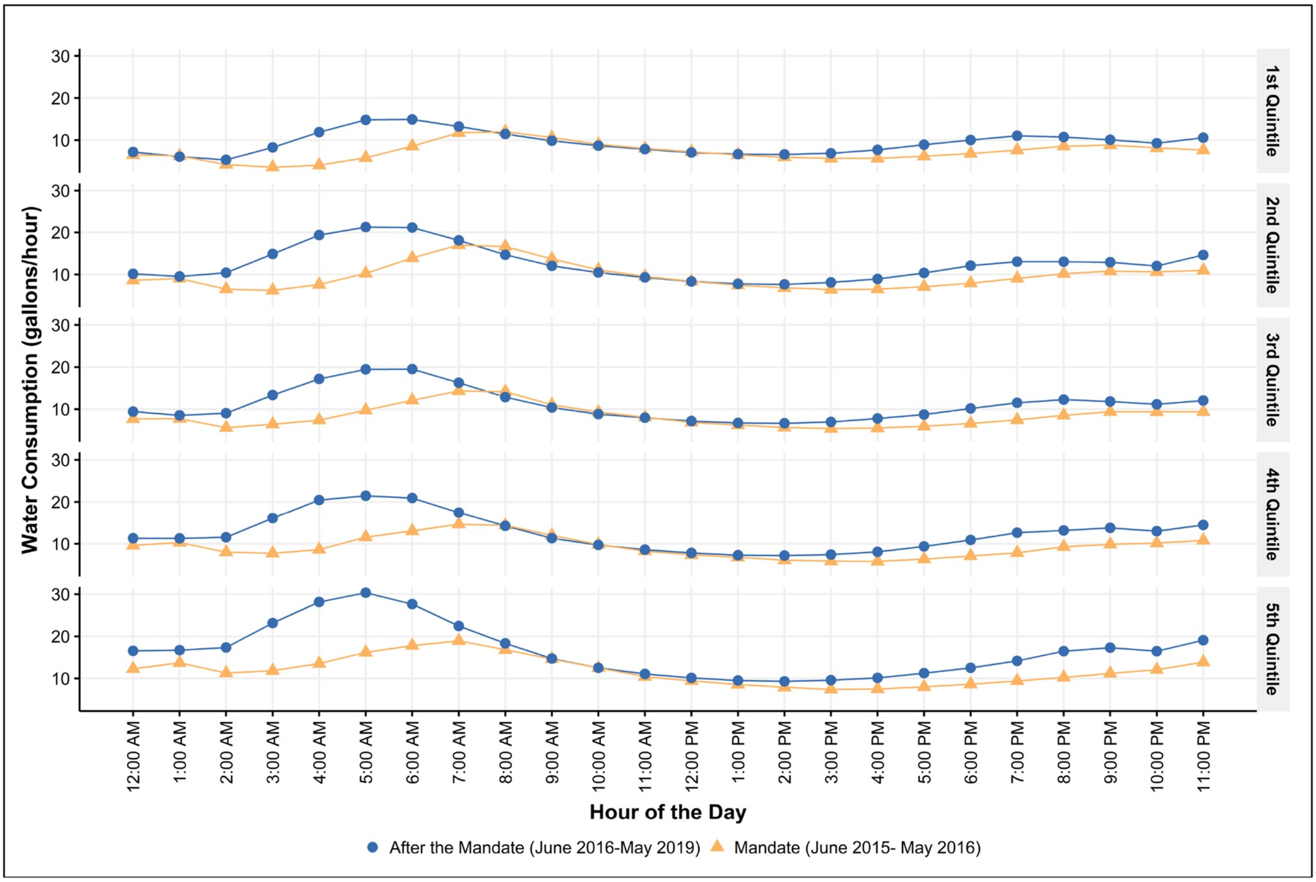

Figure 8. Average water consumption (gallons/hr) during (June 2015 to May 2016) and after (June 2016 to May 2019) the mandate by the quintile of baseline water consumption.

financial resources such as rebates and information resources such as messaging—on opportunities to reduce outdoor watering.

From an hourly perspective, we find distinct differences in the timing of water use, with water use after the mandate migrating toward the early morning hours of, say, 3–4 a.m. post-mandate relative to 5–6 a.m. during the mandate. Changes in water use post-mandate varied considerably by the hour of the day, season, and user baseline consumption levels. Relative to the mandate period, the highest increase post-mandate was observed at 5 a.m., while changes during the 4 p.m. to 2 a.m. period were noticeably flat. Interestingly, we found that average water use declined during the post-mandate 8 a.m. to 2 p.m. period relative to the mandate period. From a water use efficiency perspective, such a shift in water use—which is most likely associated with outdoor water use—is consistent with best practices for outdoor irrigation due to the lower evaporative loss that occurs earlier in the morning relative to later in the morning thereby allowing more of the applied water to reach the plant's roots. Unfortunately, we do not have access to hourly data prior to the enactment of the drought mandate and thus cannot identify to the extent to which hourly water use behavior subsequent to the drought mandate was similar to hourly water use behavior pre-drought.

Combined, these three novel contributions, which provide further insight into the rebound effect and changes in water use following the cessation of water use restrictions, can help inform water utilities in their efforts to develop more effective conservation policies as well as better understand how water use might change following a drought. Such information is important for the efficient adoption of management actions during and after periods of drought.

While our results support previous findings that short-term restrictions and/or mandates on water use implemented during drought typically result in increased use post-mandate, we characterize this rebound effect on a more granular level temporally and across different user groups than previously presented. In addition to highlighting how the rebound effect is more prevalent in the warm season months than in other months, we show that the distribution of water use after the mandate shifted to the earlier hours of the day, which is a strategy that is consistent with best outdoor irrigation practices to avoid excessive evaporation due to aridity and wind (UC IPM, 2022).

Appendix A: Additional Summary Statistics and Robustness Check Results

Table A1 summarizes hourly water use throughout the day for the mandate and post-mandate periods. During the mandate period, both average hourly water consumption and standard deviations were lower than those after the mandate period for every hour of the day.

Table A2 explores whether and the extent to which water use and the rebound effect varied across different user groups as defined by the water use quintile.

Table A3 explores the robustness of the findings to various definitions of the warm season. As indicated, our overall findings are robust across these definitions—the rebound effect during the warm season months is about 11.30%-12.60% higher than in non-warm season months.

Table A1
Summary of Water Consumption (gallons/hr) During and After the Mandate

	Mandate (June 2015 to May 2016)		After the mandate (June 2016 to May 2019)		
Hour	Mean	Standard deviation	Mean	Standard deviation	Difference
12 a.m.	8.72	[43.55]	11.97	[55.06]	3.25
01 a.m.	9.06	[49.00]	11.76	[56.68]	2.70
02 a.m.	6.94	[41.67]	11.73	[56.47	4.80
03 a.m.	6.95	[42.88]	16.15	[67.52]	9.20
04 a.m.	8.01	[47.42]	20.55	[75.36]	12.54
05 a.m.	10.35	[53.12]	23.22	[76.43]	12.87
06 a.m.	12.62	[55.39]	22.98	[72.41]	10.36
07 a.m.	14.83	[54.72]	19.82	[63.93]	4.99
08 a.m.	14.42	[49.20]	16.16	[53.50]	1.74
09 a.m.	12.00	[42.63]	12.95	[44.21]	0.94
10 a.m.	10.09	[36.29]	10.88	[38.15]	0.79
11 a.m.	8.70	[30.69]	9.56	[33.82]	0.86
12 p.m.	7.73	[28.17]	8.61	[31.45]	0.88
01 p.m.	7.03	[26.31]	8.03	[30.17]	1.00
02 p.m.	6.45	[24.95]	7.83	[29.64]	1.38
03 p.m.	6.11	[24.11]	8.07	[30.22]	1.96
04 p.m.	6.17	[24.03]	8.75	[31.84]	2.58
05 p.m.	6.68	[25.44]	9.98	[35.42]	3.29
06 p.m.	7.37	[27.27]	11.51	[40.36]	4.14
07 p.m.	8.22	[29.84]	13.09	[46.15]	4.86
08 p.m.	9.28	[34.20]	13.93	[50.74]	4.65
09 p.m.	9.88	[37.72]	14.24	[54.87]	4.36
10 p.m.	9.90	[40.46]	13.43	[54.88]	3.52
11 p.m.	10.24	[46.55]	15.36	[64.28]	5.12
All	**9.07**	**[39.55]**	**13.36**	**[52.08]**	**4.29**

Table A2
Heterogeneity in the Estimated Rebound Effect of California Mandate on Daily Water Consumption by Quintile of Water Consumption

	(1)	(2) Difference (%)[a]
During the mandate × Quintile 1 (June 2016 to May 2019)	−0.202*** (0.006)	13.468
After the mandate × Quintile 1 (June 2016 to May 2019)	−0.068*** (0.007)	
During the mandate × Quintile 2 (June 2015 to May 2016)	−0.267*** (0.006)	14.450
After the mandate × Quintile 2 (June 2016 to May 2019)	−0.123*** (0.007)	
During the mandate × Quintile 3 (June 2015 to May 2016)	−0.265*** (0.007)	6.760
After the mandate × Quintile 3 (June 2016 to May 2019)	−0.197*** (0.008)	
During the mandate × Quintile 4 (June 2015 to May 2016)	−0.272*** (0.007)	5.588
After the mandate × Quintile 4 (June 2016 to May 2019)	−0.217*** (0.007)	
During the mandate × Quintile 5 (June 2015 to May 2016)	−0.299*** (0.008)	4.709
After the mandate × Quintile 5 (June 2016 to May 2019)	−0.252*** (0.008)	
Number of obs.	32,098,745	-
Household fixed effects	Yes	-
Weather controls	Yes	-
Month fixed effects	Yes	-
Week of the year fixed effects	Yes	-
Day of the week fixed effects	Yes	-

Note: Robust Hubert-White standard errors are clustered at the household level in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. The dependent variable is the log of daily water consumption.

Quintiles are defined using average warm season months (May through September) pre-mandate water use as the baseline (2013 and 2014). Indicator variables are created for whether mean warm season months pre-mandate water consumption is in the first, second, third, fourth, or fifth quintile of the whole sample warm season months pre-mandate consumption (i.e., Q.1, Q.2, etc.). Quintile thresholds are 446.12 gallons per day (gpd) and lower in average warm season months water use for the first quintile, 446.12–658.87 gpd for the second, 658.87–808.24 gpd for the third, 808.24–1,046.97 gpd for the fourth, and 1,046.97 gpd and higher for the fifth quintile.

[a]Difference is calculated using the after-the-mandate and during-the-mandate estimated semi-elasticities (columns 1 and 2).

Table A3
The Estimated Hourly Change in Water Use Post-Mandate Compared to During the Mandate Period (gallons/hr) by Various Warm Season Months Definitions

	(1)	(2)	(3)
After the mandate (June 2016 to May 2019)	0.100*** (0.005)	0.117*** (0.004)	0.117*** (0.005)
After the mandate × Warm season months (May–Sep)	0.113*** (0.004)	-	-
After the mandate × Warm season months (July–Sep)	-	0.126*** (0.005)	-
After the mandate × Warm season months (June–Aug)	-	-	0.126*** (0.004)
Household fixed effects	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes
Month fixed effects	Yes	Yes	Yes
Week of the year fixed effects	Yes	Yes	Yes
Day of the week fixed effects	Yes	Yes	Yes
Hour of the day fixed effects	Yes	Yes	Yes

Note: Robust Hubert-White standard errors are clustered at the household level in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Observations are equal to 429,589,840 in all the columns.

Table A4
Heterogeneity in the Estimated Hourly Change in Water Use Post-Mandate Relative to Mandate Period (gallons/hr)

Hour of the day	Estimated effect	95% Confidence interval	
12:00 a.m.	−0.065	−0.076	−0.053
1:00 a.m.	−0.012	−0.024	0.000
2:00 a.m.	0.086	0.073	0.099
3:00 a.m.	0.293	0.276	0.310
4:00 a.m.	0.588	0.565	0.611
5:00 a.m.	0.910	0.880	0.941
6:00 a.m.	0.838	0.809	0.868
7:00 a.m.	0.287	0.268	0.307
8:00 a.m.	0.017	0.003	0.031
9:00 a.m.	0.000	−0.013	0.012
10:00 a.m.	0.004	−0.008	0.016
11:00 a.m.	0.021	0.010	0.033
12:00 p.m.	0.031	0.020	0.042
1:00 p.m.	0.035	0.025	0.046
2:00 p.m.	0.085	0.074	0.096
3:00 p.m.	0.162	0.151	0.174
4:00 p.m.	0.224	0.211	0.237
5:00 p.m.	0.239	0.225	0.252
6:00 p.m.	0.202	0.189	0.216
7:00 p.m.	0.174	0.160	0.188
8:00 p.m.	0.125	0.111	0.139
9:00 p.m.	0.020	0.007	0.034
10:00 p.m.	−0.095	−0.107	−0.083
11:00 p.m.	−0.092	−0.104	−0.080

Note: The figure plots point estimates showing percent changes in water consumption post-mandate (June 2016 to May 2019) compared to during the mandate (June 2015 to May 2016) period by the hour of the day. Robust Hubert-White standard errors are clustered at the household level. The estimated regression includes weather controls, calendar month, week of the year, day of the week, and hour of day fixed effects. Observations are equal to 429,589,840.

Data Availability Statement

The daily and hourly, household-level anonymized water use data used in this study were provided by Dropcountr and are protected under a nondisclosure agreement. Interested parties can contact the corresponding author (mehdin@ucr.edu) for further information regarding data access.

Acknowledgments
Partial support from the W4190 Multistate NIFA-USDA-funded project, Management and Policy Challenges in a Water-Scarce World, and The Giannini Foundation of Agricultural Economics are greatly appreciated. We would like to thank Robb Barnitt and Dropcountr for sharing the anonymized dataset for this analysis.

References

Baerenklau, K. A., Schwabe, K. A., & Dinar, A. (2014). The residential water demand effect of increasing block rate water budgets. *Land Economics*, *90*(4), 683–699. https://doi.org/10.3368/le.90.4.683

Beal, C. D., Makki, A., & Stewart, R. A. (2014). What does rebounding water use look like? An examination of post-drought and post-flood water end-use demand in Queensland, Australia. *Water Science and Technology: Water Supply*, *14*(4), 561–568. https://doi.org/10.2166/ws.2014.008

Bellemare, M. F., Barrett, C. B., & Just, D. R. (2013). The welfare impacts of commodity price volatility: Evidence from rural Ethiopia. *American Journal of Agricultural Economics*, *95*(4), 877–899. https://doi.org/10.1093/ajae/aat018

Bellemare, M. F., & Wichman, C. J. (2020). Elasticities and the inverse hyperbolic sine transformation. *Oxford Bulletin of Economics & Statistics*, *82*(1), 50–61. https://doi.org/10.1111/obes.12325

Bertrand, M., Duflo, E., & Mullainathan, S. (2004). How much should we trust differences-in-differences estimates? *Quarterly Journal of Economics*, *119*(1), 249–275. https://doi.org/10.1162/003355304772839588

Brennan, D., Tapsuwan, S., & Ingram, G. (2007). The welfare costs of urban outdoor water restrictions. *Australian Journal of Agricultural and Resource Economics*, *51*(3), 243–261. https://doi.org/10.1111/j.1467-8489.2007.00395.x

Brown, T. C., Mahat, V., & Ramirez, J. A. (2019). Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future*, *7*(3), 219–234. https://doi.org/10.1029/2018ef001091

Buck, S., Nemati, M., & Sunding, D. (2021). Consumer welfare consequences of the California drought conservation mandate. *Applied Economic Perspectives and Policy*, *45*(1), 510–533. https://doi.org/10.1002/aepp.13213

Burbidge, J. B., Magee, L., & Robb, A. L. (1988). Alternative transformations to handle extreme values of the dependent variable. *Journal of the American Statistical Association*, *83*(401), 123–127. https://doi.org/10.1080/01621459.1988.10478575

Cameron, A. C., & Miller, D. L. (2015). A practitioner's guide to cluster-robust inference. *Journal of Human Resources*, *50*(2), 317–372. https://doi.org/10.3368/jhr.50.2.317

Cole, G., & Stewart, R. A. (2013). Smart meter enabled disaggregation of urban peak water demand: Precursor to effective urban water planning. *Urban Water Journal*, *10*(3), 174–194. https://doi.org/10.1080/1573062x.2012.716446

Crotta, C. (2014). Seven tips for a water-wise lawn. *Los Angeles Times*. https://www.latimes.com/home/la-lh-drought-gardening-tips-for-a-waterwise-lawn-20140418-story.html

Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences*, *112*(13), 3931–3936. 201422385. https://doi.org/10.1073/pnas.1422385112

Dupont, D. (2015). Water conservation: Thinking beyond the tap. In *Handbook of water economics*. Edward Elgar Publishing.

Giles, D. E. (1982). The interpretation of dummy variables in semilogarithmic equations: Unbiased estimation. *Economics Letters*, *10*(1–2), 77–79. https://doi.org/10.1016/0165-1765(82)90119-7

Gilligan, J. M., Wold, C. A., Worland, S. C., Nay, J. J., Hess, D. J., & Hornberger, G. M. (2018). Urban water conservation policies in the United States. *Earth's Future*, *6*(7), 955–967. https://doi.org/10.1029/2017ef000797

Gonzales, P., & Ajami, N. (2017). Social and structural patterns of drought-related water conservation and rebound. *Water Resources Research*, *53*(12), 10619–10634. https://doi.org/10.1002/2017wr021852

Grafton, R. Q., Chu, L., & Wyrwoll, P. (2020). The paradox of water pricing: Dichotomies, dilemmas, and decisions. *Oxford Review of Economic Policy*, *36*(1), 86–107. https://doi.org/10.1093/oxrep/grz030

Grafton, R. Q., & Ward, M. B. (2008). Prices versus rationing: Marshallian surplus and mandatory water restrictions. *Economic Record*, *84*, S57–S65. https://doi.org/10.1111/j.1475-4932.2008.00483.x

Halvorsen, R., & Palmquist, R. (1980). The interpretation of dummy variables in semilogarithmic equations. *American Economic Review*, *70*(3), 474–475.

Hanak, E., & Lund, J. R. (2012). Adapting California's water management to climate change. *Climatic Change*, *111*(1), 17–44. https://doi.org/10.1007/s10584-011-0241-3

Hughes, M. (2020). This is the best time of day to water your lawn. *Better Homes & Gardens*. https://www.bhg.com/gardening/yard/lawn-care/is-it-okay-to-water-my-yard-in-the-middle-of-the-day-when-its-hot/

Jenkins, M. W., Lund, J. R., & Howitt, R. E. (2003). Using economic loss functions to value urban water scarcity in California. *Journal-American Water Works Association*, *95*(2), 58–70. https://doi.org/10.1002/j.1551-8833.2003.tb10292.x

Kennedy, P. E. (1981). Estimation with correctly interpreted dummy variables in semilogarithmic equations [the interpretation of dummy variables in semilogarithmic equations]. *American Economic Review*, *71*(4), 801.

Lee, J., Nemati, M., & Dinar, A. (2022). Historical trends of residential water use in California: Effects of droughts and conservation policies. *Applied Economic Perspectives and Policy*, *44*(1), 511–530. https://doi.org/10.1002/aepp.13149

MacKinnon, J. G., & Magee, L. (1990). Transforming the dependent variable in regression models. *International Economic Review*, *31*(2), 315–339. https://doi.org/10.2307/2526842

Mann, M. E., & Gleick, P. H. (2015). Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences*, *112*(13), 3858–3859. https://doi.org/10.1073/pnas.1503667112

Metropolitan Water District of Southern California (MWD). (2023). Retrieved from https://www.mwdh2o.com/budget-finance/

Moss, C. B., & Shonkwiler, J. S. (1993). Estimating yield distributions with a stochastic trend and nonnormal errors. *American Journal of Agricultural Economics*, *75*(4), 1056–1062. https://doi.org/10.2307/1243993

Nataraj, S., & Hanemann, W. M. (2011). Does marginal price matter? A regression discontinuity approach to estimating water demand. *Journal of Environmental Economics and Management*, *61*(2), 198–212. https://doi.org/10.1016/j.jeem.2010.06.003

Nemati, M., Buck, S., & Sunding, D. (2018). Cost of California's 2015 drought water conservation mandate. *ARE Update*, *21*(4), 9–11.

Olmstead, S. M., Hanemann, W. M., & Stavins, R. N. (2007). Water demand under alternative price structures. *Journal of Environmental Economics and Management*, *54*(2), 181–198. https://doi.org/10.1016/j.jeem.2007.03.002

Olmstead, S. M., & Stavins, R. N. (2009). Comparing price and nonprice approaches to urban water conservation. *Water Resources Research*, *45*, 4W04301. https://doi.org/10.1029/2008wr007227

Park, D., & Smith, W. (2008). *Landscape irrigation management Part 5: Irrigation time of day*. HGIC.

Pence, K. M. (2006). The role of wealth transformations: An application to estimating the effect of tax incentives on saving. *Contributions in Economic Analysis & Policy*, *5*(1), 1–24. https://doi.org/10.2202/1538-0645.1430

PRISM Climate Group. (2020). *PRISM climate group*. O. S. University.

Riverside Public Utilities (RPU). (2022). *Don't doubt the drought*. RPU Water Use Regulations.

Sandoval-Solis, S. (2020). Water resources management in California. In *Integrated water resource management* (pp. 35–44). Springer.

Schmidt, A., & Lewis, L. (2017). The cost of stability: Consumption-based fixed rate billing for water utilities. *Journal of Contemporary Water Research & Education*, *160*(1), 5–24. https://doi.org/10.1111/j.1936-704x.2017.03237.x

Schwabe, K. A., Baerenklau, K. A., & Dinar, A. (2014). Coping with water scarcity: The effectiveness of allocation-based pricing and conservation rebate programs in California's urban sector. *Policy Matters*, *6*(1), 1–7.

Spang, E. S., Holguin, A. J., & Loge, F. J. (2018). The estimated impact of California's urban water conservation mandate on electricity consumption and greenhouse gas emissions. *Environmental Research Letters*, *13*(1), 014016. https://doi.org/10.1088/1748-9326/aa9b89

Spang, E. S., Miller, S., Williams, M., & Loge, F. J. (2015). Consumption-based fixed rates: Harmonizing water conservation and revenue stability. *Journal-American Water Works Association*, *107*(3), E164–E173. https://doi.org/10.5942/jawwa.2015.107.0001

Timmins, C. (2003). Demand-side technology standards under inefficient pricing regimes. *Environmental and Resource Economics*, *26*(1), 107–124. https://doi.org/10.1023/a:1025689706396

UC IPM. (2022). The UC guide to healthy lawns. Retrieved from http://ipm.ucanr.edu/TOOLS/TURF/MAINTAIN/irrwhen.html

Vercammen, P. (2015). California drought: Rebates offered for ripping out lawns under nation's largest program. *CNN*. https://www.cnn.com/2015/06/26/us/california-drought-lawn-sod-replacement-rebates

Vickers, A. L. (1999). *Handbook of water use and conservation*. Waterplow Press.

Woodhouse, C., Meko, D., & Bigio, E. (2020). A long view of Southern California water supply: Perfect droughts revisited. *JAWRA Journal of the American Water Resources Association*, *56*(2), 212–229. https://doi.org/10.1111/1752-1688.12822

Yachnin, J. (2022). Western states turn to homeowners to deflect drought. *Greenwire*. https://www.eenews.net/articles/western-states-turn-to-homeowners-to-deflect-drought/

Zhang, B., Fang, K. H., & Baerenklau, K. A. (2017). Have Chinese water pricing reforms reduced urban residential water demand? *Water Resources Research*, *53*(6), 5057–5069. https://doi.org/10.1002/2017wr020463