Title

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ASSESSING THE IMPACTS OF URBAN WATER USE RESTRICTIONS AT THE DISTRICT LEVEL: A CASE STUDY OF CALIFORNIA'S DROUGHT MANDATE

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ABSTRACT

This paper estimates feasible water savings for a sample of nine urban water districts in California during the height of the 2012-16 drought, just prior to the implementation of mandatory water use reductions, using household production theory and stochastic frontier analysis. Estimates of feasible savings are compared to mandated reductions and actual reductions in each district. Although the mandated reductions were generally feasible, our results show that they had asymmetric impacts across districts and tended to impose larger burdens on some disadvantaged groups.

Keywords: Water Conservation, Mandatory restrictions, Efficiency Analysis, Stochastic Frontier Analysis

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INTRODUCTION

Although droughts are part of regular climate cycles, their frequency and intensity has increased in recent decades across many parts of the world, such as Southern Europe, Africa, Eastern Asia, Southern Australia and Western United States (Spinoni et al., 2014; Cook et al., 2018). With such related increasing concerns about water scarcity, a variety of water conservation policies have been adopted and/or expanded by urban water districts in drought-prone regions. Some approaches are more voluntary in nature, such as messaging campaigns, social norming (i.e. publishing average neighborhood use on each household billing statement), and rebate programs to encourage adoption of water efficient technologies. Others are harder for households to avoid or ignore, such as scarcity pricing and mandatory water use restrictions with penalties for non-compliance. Scarcity pricing has advantages from the perspective of economic efficiency, but often is viewed as inequitable because water is an essential good at low levels of use. Thus, districts often resort to use restrictions under extreme water scarcity. Such restrictions may target type of use (such as washing sidewalks and driveways), time of use (such as irrigating during the day), or total amount used (often referred to as rationing).

A common mandatory water restriction is rationing by percent reduction, in which the amount of allocated water is defined as a percentage of water use in a baseline period before the drought. During California's recent drought (2012-16), which was particularly severe (Mount et al., 2016), the State Water Resources Control Board (State Board) imposed mandatory percent reductions on more than 400 large urban water districts in April 2015. These mandatory restrictions were imposed because of the low level of statewide water savings achieved in 2014, when California Governor Jerry Brown had requested a 20% voluntary reduction in urban areas. After achieving only half of this requested cutback, followed by a record-low snow-pack in the winter of 2015, the State Board imposed mandatory water restrictions to reduce statewide urban water use by 25% relative to 2013 levels. District-level targets ranged from 4 to 36% relative to water use in 2013. To meet these targets, some districts changed the emphasis of their water conservation actions from voluntary approaches, like information campaigns, to more severe actions such as penalties, aggressive pricing, and customer-level water use prohibitions (McCann et al., 2017).

As noted by Mitchell et al. (2017), the State Board achieved its overall goal but the mandate had asymmetric impacts on residents throughout the state. For example, Mitchell et al. (2017) notes that compliance with the mandate was more difficult for some districts, especially those with higher targets. Moreover, after the drought, most but not all districts reported that the mandate had strained relationships with their customers (McCann et al., 2017). In one high-profile case, the board of directors for a southern California water district was recalled and replaced due to extreme customer dissatisfaction (Stevens and Lin, 2016). These observations are consistent with those by Lund and Reed (1995), who argue it can be challenging for districts and their customers who have already adopted long-term water conservation strategies to comply with restrictions by percent reduction.

In addition, many water districts felt that the State Board had over-reached, usurped local control, and undermined their pre-existing drought contingency plans. In some cases, state intervention effectively stranded available water supplies that districts had previously paid to secure. The inability to sell this water produced unanticipated financial stresses in such districts. In other cases, customers who had previously undertaken conservation efforts at the behest of their water district were "rewarded" with a rate increase needed to compensate for lost revenue and pay for fixed operating expenses (Mitchell et al., 2017).

Although the State Board has since adopted a new approach based on stress-testing that allows for greater local control, analysis of the impacts of the mandate can help inform debates on the use of mandatory percent reductions and centralized versus decentralized water conservation authority. The logic for centralized control in California is that most urban residents are served by a large interconnected statewide water system and thus a major drought is best addressed through coordinated, collective action to promote cooperation and reduce shirking - i.e., an equitable sharing of the burden. The logic for decentralized control is that the state already requires districts to develop and implement individual drought contingency plans, and each district is in the best position to monitor and respond to its own local conditions. If some districts make preventative drought-related investments, then they should be able to reap the benefits when droughts occur. Committing to local control incentivizes such investments, thus reducing the need for (what is perceived as) more blunt state intervention. The State Board attempted to equitably share the burden through a mostly formulaic approach to setting individual mandate levels that it felt was fair and responsive to local conditions. However, the anecdotal evidence mentioned above suggests that this approach was not entirely successful.

The present study contributes to this discussion in two ways. First, we quantify the district-level impacts of California's statewide conservation mandate across a sample of urban water suppliers. Second, we investigate how the impacts correlate with socio-economic characteristics. We accomplish this with stochastic frontier analysis and show how this method also could be used by water districts to gauge the conservation potential of a customer base, and thus to evaluate the feasibility of various conservation targets.

In order to address the first objective, we estimate a local measure of potential water use efficiency during the year prior to the state mandate. In doing so, we identify the potential water savings in a given district conditional on household characteristics and available conservation technologies during that period. Water use efficiency is measured using a household production theory approach in which households produce water services using water and other marketed goods as inputs. In this context, we can estimate a water demand frontier that allows us to compute the level of efficiency in water use and potential water savings at the time of the mandate. The second objective is achieved by regressing the difference between the estimated efficient water use and the mandated conservation target on a set of socioeconomic and demographic characteristics. This allows us to see how the relative feasibility of the mandated reductions correlate with district-level traits.

Using a sample of nine districts located throughout California, we find evidence that the mandated conservation targets were generally feasible, but also hit some districts, and some typically disadvantaged groups, harder than others. These findings support claims of some water districts that the state's approach, while well-intentioned, did not adequately account for local conditions and fell short of achieving an equitable sharing of the conservation burden. We also show that the household production approach may be effective for districts needing a method to estimate contemporaneous water use efficiency potential, and to assess the feasibility of water reductions in a short-run context such as drought emergencies.

MEASURING EFFICIENCY IN WATER USE

The water demand frontier approach

The household production theory approach proposed by Becker (1965) offers a useful framework for measuring efficiency in water use. To implement this framework, we assume that consumers obtain utility from water services produced in the household using inputs of market goods such as water and capital. As in Filippini and Hunt (2011, 2015), an input (water) demand frontier function can be derived from a cost minimization problem as:

$$\begin{gathered} \min_{W} P_W W + P_K K \\ \text{such that } T(WS, W, K) = 0 \end{gathered} \tag{1}$$

where WS is a vector of water services, which are produced using inputs W and K, i.e., water use and a vector containing other inputs, respectively. P_W and P_K are the input prices for each of the previously defined inputs, and T represents the technologies available to the household. This cost minimization problem is assuming that the other inputs K are fixed, and therefore, it identifies the level of water use that minimizes the cost of producing water services WS given the level of other inputs K and the available technology.

In order to solve this cost minimization problem, Filippini and Hunt (2011) propose a non-radial measure of efficiency that allows one to identify the potential reduction of only one input, as opposed to the standard input oriented radial measure, in which the contribution of each input to technical efficiency is equiproportionate. The differences between these two measures are explained in Figure 1 by plotting an isoquant and an isocost line. The isoquant represents all technically efficient combinations of W and K used to produce a given level of WS^*. The isocost line illustrates all the input combinations that share the same cost. Having this in mind, the point x^* where the isocost is tangent to the isoquant represents the cost-minimizing combination of inputs, that is, W^* and K^*. A household using W_1 and K_1 to produce WS^* is both technically and cost inefficient. Since the standard input oriented radial measure implies an equiproportionate reduction of each of the inputs, the level of technical inefficiency using this measure is defined as the ratio of the distance from the origin to the technically efficient point θx_1 and the distance from the origin to input combination x_1. Similarly, cost efficiency is measured as the ratio of the distance from the origin to βx_1 and the distance from the origin to x_1, implying a different input allocation. However, as discussed by Filippini and Hunt (2015), with the non-radial measure, the inefficiency is the difference between the cost-minimizing water use W^* and the observed water use W_1.

We obtain the non-radial measure by estimating a single conditional water demand frontier function for each water district, anticipating that households within the same district are more similar to each other in terms of water conservation technologies and habits, and thus neighbors provide a more meaningful efficiency benchmark than residents from other parts of the state. Blasch et al. (2017) note that this frontier function represents the minimum amount of water needed to produce a desired level of water services, given input prices, for a household in the sample that uses the most efficient production technology. Households not consuming on the frontier are considered inefficient, and the level of inefficiency can be measured as the distance to the efficient frontier.

Following Filippini and Hunt (2011), we use the stochastic frontier approach introduced by Aigner et al. (1977).The reader may wonder why we do not use data envelope analysis (DEA). DEA is a deterministic method to estimate efficiency, and therefore it does not consider an error term in the estimation. In the case of household level data, we can expect a high level of unobserved heterogeneity that could lead to misleading efficiency estimates. Therefore, we follow seminal papers in the energy literature to estimate efficiency such as Filippini and Hunt (2011, 2015) and use a stochastic frontier model. The water demand frontier function can be specified as:

$$lnW_{it} = \alpha + \beta_1 lnP_{Wit} + \beta_2 WS_{it} + v_{it} + u_{it} \tag{2}$$

where W_{it} is the water use for household i and period t, P_{Wit} is the average price of water, and WS_{it} is a vector of water services (defined later in the Data Section) produced in the household, v_{it} is a noise term, assumed to be normally distributed, and u_{it} is a one-sided non-negative random disturbance representing the inefficiency term.

All households in our sample face Increasing Block Rates (IBR), which present a simultaneity concern as the marginal price increases (decreases) with the quantity consumed. To estimate the stochastic frontier model in Equation (2) while correcting for this problem of price endogeneity, we use Corrected Two-Stage Least Squares (2SLS) (Amsler et al., 2016), which is a generalization of corrected ordinary least squares (COLS). In this case, we first estimate Equation 2 by 2SLS using a set of instruments Z to obtain the 2SLS estimates $\hat{\alpha}$, $\hat{\beta}_1$ and $\hat{\beta}_2$. Then, we construct the correct 2SLS residuals as:

$$e_{it} = lnW_{it} - \hat{\alpha} - \hat{\beta}_1 lnP_{it} + \hat{\beta}_2 WS_{it} \tag{3}$$

Importantly, we do not construct the residuals using $\hat{lnP}_{it}$ from the 2SLS. As indicated by Amsler et al. (2016), once we construct e_{it} we calculate the second $(\hat{\sigma_e^2})$ and the third $(\hat{\mu_3'})$ moments of the residuals, and we calculate $\hat{\sigma_u^2}$ and $\hat{\sigma_v^2}$ as:

$$\hat{\sigma_u^2} = \left(\frac{\pi}{4-\pi} \sqrt{\frac{\pi}{2}} \mu_3' \right)^{2/3} \tag{4}$$

$$\hat{\sigma_v^2} = \hat{\sigma_e^2} - \frac{\pi - 2}{\pi} \hat{\sigma_u^2} \tag{5}$$

To solve for σ_u^2 and σ_v^2 in terms of sample quantities, $\mu_3' < 0$. If $\mu_3' > 0$, we face the "wrong skewness" phenomenon (Waldman, 1982).Simar and Wilson (2009) indicate that this issue is not an estimation failure, but a finite sample problem that occurs when the variance ratio of the inefficiency component to the composite error is small. Following Amsler et al. (2016), in such cases we set $\sigma_u^2 = 0$. Once we calculate σ_u^2 and σ_v^2, we correct the intercept as $\tilde{\alpha} = \hat{\alpha} + \sqrt{\frac{2}{\pi}}\hat{\sigma}_u$, and the COLS estimates are $\tilde{\alpha}$, $\hat{\beta}$, $\hat{\sigma}_u^2$ and $\hat{\sigma}_v^2$.

After obtaining these parameters, we predict the inefficiency term using the point estimator in (Kumbhakar and Lovell, 2000, p.142):

$$WE_i = E(exp\{-u_i\}|e_i) = \left[\frac{1 - \Phi(\sigma_* - \mu_{*i}/\sigma_*)}{1 - \Phi(\mu_{*i}/\sigma_*)}\right] exp\left[-\mu_{*i} + \frac{1}{2}\sigma_*^2\right] \tag{6}$$

where $\mu_{*i} = \epsilon_i \sigma_u^2/\sigma^2$ and $\sigma_*^2 = \sigma_u^2\sigma_v^2/\sigma^2$ and $\Phi(.)$ is the standard normal cumulative distribution function. A water use efficiency score (*WE*) of 1 indicates the household is efficient, and a water use score below 1 indicates that the household could reduce water use by (1 - *WE*) by adopting water use habits and/or technologies currently used by the most efficient households. Because we estimate a water demand frontier function for each water district, this measure is relative to the most efficient households in a given household's water district.

Efficient and mandate-level water use

Once we estimate the efficiency scores, the efficient level of water use for each household in each month can be computed as:

$$\text{Efficient Water use}_{it} = \text{Actual water use}_{it} \times WE_{it} \tag{7}$$

Moreover, we can then compute the mean efficient water use for each district by month, and then calculate the distance between the log of this measure and the log of the state mandated conservation target assigned to each district:

$$\text{Feasibility}_{dt} = \log(\text{Mandate Water use}_{dt}) - log(\text{Efficient Water use}_{dt}) \tag{8}$$

This distance measure can be viewed as a feasibility indicator for each district in each month. If the mandated conservation target is higher than efficient use, then the target is "feasible" given current water use habits and technologies employed by the most efficient households in a given district. If the target is less than efficient use, then the target is not feasible in this sense. Rather, novel habits and technologies not currently used by even the most efficient households would be needed to meet such a target. Thus, the measure provides a sense of the reasonableness or fairness of each conservation target. This enables assessment of whether the targets were generally feasible and achievable. Moreover, we can regress this measure on socioeconomic, demographic, and seasonal variables to assess how these might be correlated with feasibility.

DATA DESCRIPTION

Our data set is consists of household level data from nine water districts in California from May 2014 to June 2015, that is, the drought's so-called voluntary conservation period. We remove households reporting consumption levels equal to 0, as likely being unoccupied. Moreover, we balance the panel to consider households observed for the entire period of analysis. This period immediately precedes the mandate period to provide an accurate picture of technologies in use going into the mandate.

Figure 2 shows counties including water districts in the analysis (in gray). These counties span the most populous regions of central and southern California. At the request of the water districts that have generously shared their data with us, we do not specifically identify any individual district. The household-level data set includes water use, water prices and housing characteristics such as the number of bathrooms in the house and household irrigated areas. These data were merged with socioeconomic and demographic characteristics at the district level from the American Community Survey (ACS) of the US Census, and with data on evapotranspiration from the California Irrigation Management Information System (CIMIS).

Table 1 shows some descriptive statistics by water district of variables used to estimate the water demand frontiers. For the dependent variable we use monthly water use (*water use*) measured in cubic meters (m^3). For water services, i.e., the outputs to be produced by the household, we use the number of bathrooms (*Bathrooms*) as a proxy for indoor water services, and as proxies for outdoor water services, the amount of irrigated area (*Irrigated area*) measured in square meters and the average monthly evapotranspiration rate (ET). The evapotranspiration rate is an indicator of weather variability, and therefore, the need for outdoor water services. We consider this indicator rather than precipitation or temperature because Baerenklau et al. (2014) found that it captures more than 90% of weather variability for another application involving CIMIS data. The year each house was built (*Year Built*) is included to control for housing characteristics that may affect their ability to produce water services. Last, we include the average water price (*Avg P*). The district with the highest water use also has the largest average irrigated area, but this district also shows a high standard deviation in this variable, i.e, there is more variability within the district. This district also has the highest average price. While this can be due to higher marginal prices for each block, it may also reflect that households in this district tend to consume in a higher block and so are charged a higher rate. Districts with less water use and water services (both indoor and outdoor) tend to be more urban.

Table 2 shows descriptive statistics for variables considered in the second stage regression for our feasibility measure. For this regression, we consider a set of socioeconomic and demographic characteristics at the district level obtained from the US Census. Specifically, we include median household income (*Income*), median age (*Age*), the percent of population under 10 (*Pop<10*) and over 75 years of age (*Pop>75*), the percent of population identifying as Hispanic, (*Pop Hispanic*), the percent of population with bachelors degrees (*Pop bachelor*), and the mandatory water restriction assigned to the district (*Mandate level*). We also include three seasonal dummy variables: *winter* for December-February, *spring* for March-May, and *summer* for June-August. Last, we include a monthly time trend t that controls for temporal changes in water consumption observed during the period of analysis. Several variables had high dispersion, such as *Income*, *Pop Hispanic*, and *Pop bachelor*. This indicates that districts considered in the analysis are quite heterogeneous, and we might expect differences in their ability to respond to mandatory restrictions.

It is worth noting that most of the variables considered in the second stage regression are related to the ability to reduce water use, as opposed to the variables included in the first stage that are directly related to the production of water services and the installed technologies. As discussed by Kay et al. (1994) for the case of agricultural efficiency, differences in performance are often due to variation in management. However, management is not directly measured. For this reason, Rougoor et al. (1998) propose to use personal aspects (such as socioeconomic and demographic characteristics and abilities) and aspects of the decision-making process as proxies for the ability of a farmer to influence performance. Therefore, in this paper we follow a similar approach including "managerial variables" as determinants of the districts' ability to meet the mandate.

RESULTS

Efficiency in water use

The estimation results for the water demand frontier models for each district are shown in Table 3. The estimated coefficients have the expected signs for all models and are statistically significant for most variables. Price elasticities are negative and significant for all districts. Although they differ in magnitude, elasticity estimates are all within the common range reported in Sebri (2014).

As expected, the proxies for water services *Bathroom*, *ET* and *Irrigated area* have a positive and significant effect on water use in all models. Moreover, the coefficient for *Year built* is negative and significant in most cases. This negative effect can be explained by newer houses tending to be more efficiently equipped when initially built.

The mean efficiency scores and standard deviations are shown at the bottom of Table 3. We observe that there is some heterogeneity in both the mean score and the dispersion. Five of the districts show mean efficiency scores ranging from 0.680 to 0.860, indicating that on average these districts could reduce water use by 14%-32%. However, the remaining four districts suffer from the wrong skewness issue (explained in Section 2) and thus it is not possible to identify inefficiency during the period of analysis. In order to have a better understanding of the distribution of efficiency scores, in Figure 3 we show the histograms of the efficiency scores for the first 5 districts. The vertical lines indicate the 1^{st} quartile, median and 3^{rd} quartile in brown, blue and red, respectively. We observe that, while there are differences in the distributions across districts, at least 25% of the households in each district have relatively high efficiency scores around 0.9.

Figures 4 and 5 compare the evolution of water use by each district during three periods: the year prior to the voluntary conservation period (the pre-voluntary period, June 2013 - May 2014), the voluntary conservation period (June 2014 - May 2015), and the mandatory conservation period (June 2015 - December 2015) (the mandatory period continued into 2016, however our data set ends in December 2015). Each figure also shows the state-mandated water use level (with the conservation target shown in parentheses in the figure legend, as a percent of the pre-voluntary use level) and our estimated efficient water use level. The panels in the figures are arranged in descending order by mandate level.

Generally, the efficient water use levels are below the state-mandated levels in most months. These positive differences imply the mandated reductions were generally feasible. However, often in late winter and early spring, mandate levels are below efficient use, so achieving the mandates without affecting the level of water services would require implementing water use habits and technologies beyond even the most efficient households in those districts. Two districts show this pattern in summer months, as well.

The figures also allow comparison of actual and efficient use. The most meaningful comparison involves actual use in the voluntary period because our estimate of efficient use is derived from this data. This comparison shows that actual use during this time exceeded efficient use for five of nine districts, implying these districts had “room to improve” when entering the mandate period. However, as noted above, for the remaining four districts, we face the wrong skewness issue (explained in Section 2) and thus cannot identify inefficiency during the period of analysis. Here, our efficient use estimate coincides with actual use, implying use was already efficient before the mandate period. This result is not surprising as the water use during the voluntary period was already near the level required by the mandate. For these districts the mandate levels were often near or below efficient use.

A related comparison is between actual use during the mandate period and efficient use. In most cases, actual use during the mandate period exceeded efficient use, which makes intuitive sense. But this is not always the case. Sometimes actual use during the mandate period fell below our estimate of efficient use. This suggests households were adopting new habits and technologies as the state transitioned to mandatory cutbacks in water use-habits and technologies that were uncommon even among efficient households prior to the mandate period.

Further insights can be gleaned by examining the three districts that were assigned a mandated reduction in the range of 20% to 24%. Two of these districts have relatively low water use and less seasonal fluctuation. The third has higher overall use and greater seasonal differences. More interesting is how water use evolved from the pre-voluntary to the voluntary periods in these districts. The first two districts achieved little conservation during the voluntary period while the third achieved more. Yet all three were assigned 20-24% reductions based on the pre-voluntary baseline. Not surprisingly, the mandatory reductions were more easily achieved (as defined by our feasibility measure) in the first two districts than in the third, where our efficiency estimate coincides with actual use. This suggests there were asymmetric impacts of the mandate, and supports arguments that a state-level approach-even one that was thoughtfully designed to equitably share the burden-did not adequately capture local conditions.

Feasibility and the role of districts' characteristics

To further explore asymmetric impacts, we consider the possibility that observed differences in feasibility across districts might correlate with observable customer traits. To do so, we regress monthly measures of our difference variable (*Feasibility*) on districts' socio-economic and demographic characteristics (explained in the Data Section). Negative values of *Feasibility* indicate that the mandate is below our estimate of efficient water use, implying the mandate would not be feasible with water conservation habits and technologies already in use at the time. Conversely, positive values imply more feasible and easily achievable mandated conservation levels. We also include seasonal dummies as explanatory variables and a monthly time trend in these regressions. We do this because the preceding analysis shows that households tend to be less efficient during the earlier months of the analysis, which includes the summer. Including both seasonal dummies and a trend helps disentangle these effects.

Estimation results for this analysis appear in Table 4. Not surprisingly, *Mandate level* is strongly negatively correlated with our dependent variable: higher percent reductions occur with lower feasibility (a higher compliance burden). The time trend t is positively correlated with the feasibility measure, indicating that compliance generally becomes easier through time. This makes intuitive sense to the extent that households change their water use habits and technologies over time. The seasonal dummies for spring and winter are negatively correlated, indicating greater difficulty in achieving compliance with the mandate during the cooler, wetter time of year. This also makes intuitive sense and is consistent with Lund et al. (2018) who note that landscape irrigation represents a high proportion of urban water use in California, and reductions during the 2012-16 drought were mostly achieved by reducing this water use.

Regarding the socio-demographic regressors, *Income* has a positive and significant effect on *Feasibility.* The mandated reductions were more feasible (easier to comply with) wealthier districts, and more difficult in poorer districts. Districts with an older population, a higher percentage of children under 10 and adults over 75 also found it more difficult to comply with their mandated reductions. A similar effect occurred for districts with larger percentages of Hispanic residents, with feasibility measures being lower in such districts. In each of these cases, a greater compliance burden occurs with traits that often indicates an already disadvantaged community: lower income, more children and elderly residents to care for, and a larger under-represented minority population. However, this is not true for our education variable. The proportion of bachelor's degree holders has a negative and significant effect on the *Feasibility* variable, indicating greater feasibility in districts with lower educational attainment.

To assess the economic significance of these regression estimates, we report the elasticities for the socioeconomic and demographic regressors in Table 5. A change in any of these variables produces an elastic response in our feasibility measure. For example, a 1% increase in *Age* and *Pop<10* would lead to a 23.6% and 20% decrease in the feasibility measure, respectively. A 1% decrease in median household income would lead to an 11% decrease in the feasibility measure. The impact on the feasibility measure of a 1% change in any of these socio-demographic variables is larger than that of a 1% increase in the mandate level which produces an inelastic response. These are not trivial differences in policy impacts across districts.

CONCLUSIONS

This paper analyzes the mandatory water restrictions implemented during the 2012-16 California drought by using household production theory and stochastic frontier analysis, both widely used in the economics literature, including applications to energy consumption. In general, the restrictions were not excessive, consistent with work by Mitchell et al. (2017) who observe that most districts achieved their mandated reductions in 2015-16 and that California historically has been able to achieve short-term urban water use reductions of around 20%. However, the present work adds important context to these findings by motivating a measure of water conservation feasibility and using this measure to show that the state mandate imposed larger burdens on some districts.

To further investigate the asymmetric impacts of the state mandate, we regress our feasibility measure against several socioeconomic and demographic characteristics. Although the

State Board's approach to setting the mandate levels did not directly target such characteristics, they nonetheless seem to correlate such that poorer and older communities, those with more children and/or more elderly residents, and those with more Hispanic residents were harder hit by the regulations. While speculative, this may be because poorer and older communities are less able to purchase and install water efficient technologies as a response to drought. Those with children may find it more challenging to control indoor use and may be less willing to forego a green lawn. And Hispanic communities may be less likely to receive water district messages in their native language and thus less likely to be responsive.

From a policy perspective and looking ahead to future droughts, our results provide a rationale for greater local control, to the extent such control could be more responsive to local conditions and mitigate undesirable differential impacts. Moreover, while our approach could be implemented by state regulators, water districts have a potential advantage for tailoring short-term water restrictions as they have immediate access to household level customer information and a better understanding of heterogeneity within the district. The observed feasibility of the mandate levels generally increasing during the drought also suggests that a more flexible approach is warranted - one that adapts conservation targets to changes in technology and behavior that appear to occur during a drought. In this context, our methodological approach could be useful for water districts. Rather than setting fixed percent reduction targets from an arbitrary baseline, our approach would allow districts to assess conservation potential in near-real-time. This would enable water managers to estimate their available demand-side "cushion" as water scarcity concerns increase during the onset of a drought. Analyzing this conservation potential in the context of available reserves could then help inform policy decisions about actions that might be needed to help customers install new technologies not currently in use. By regularly updating the calculations, water managers could judge whether and to what extent percent reductions might be increased in an ongoing drought without creating excessive burdens for customers.

DATA AVAILABILITY STATEMENT

The data supporting our paper is a large household-level data set that includes monthly water consumption records and household characteristics considered by the water districts to be confidential information. The code generated during the study is available from the corresponding author by request.

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List of Tables

		District A	District B	District C	District D	District E	District F	District G	District H	District I
County	Statistic	San Mateo	Santa Clara	Solano	Alameda	Los Angeles	San Joaquin	Monterey	Los Angeles	San Mateo
Water use (m^3)	Mean	58.89	36.31	34.85	29.78	39.57	52.36	35.58	20.51	37.28
	Std Dev	82.25	29.84	21.12	21.76	27.23	53.35	30.58	12.74	36.20
	Min	2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.83
	Max	2217.20	419.09	464.40	563.50	586.16	1826.43	968.43	283.17	1551.76
Bathrooms	Mean	2.75	2.05	1.47	2.40	2.01	2.79	2.45	1.80	1.72
	Std Dev	1.31	0.62	0.65	1.08	0.68	1.01	0.86	0.83	0.78
	Min	1	1	1	1	1	1	1	1	1
	Max	10	5.	8	10	5	10	8	8	8
Irrigated area (m^2)	Mean	1283.30	360.80	172.90	154.76	237.34	756.19	668.43	201.09	393.06
	Std Dev	1664.61	368.64	102.26	135.35	200.47	966.73	849.93	215.06	320.86
	Min	0.00	3.00	13.68	0.00	8.11	0.00	57.18	0.00	0.00
	Max	8427.49	10176.85	1613.26	2077.94	3406.24	17738.18	20391.28	3999.73	9688.44
ET (cm/month)	Mean	54.83	63.01	68.15	66.19	63.79	54.83	61.22	54.83	59.46
	Std Dev	7.66	16.37	10.96	10.25	11.56	7.66	12.76	7.66	14.42
	Min	33.12	37.41	48.93	47.92	41.13	43.17	42.30	43.17	37.00
	Max	73.91	85.70	84.10	81.32	77.48	64.83	80.42	64.83	78.21
Year Built	Mean	1959	1968	1940	1964	1978	1964	1973	1955	1951
	Std Dev	22	20	16	23	24	19	18	15	16
	Min	1860	1880	1890	1808	1900	1880	1880	1900	1895
	Max	2015	2008	2010	2015	2007	2014	2011	2011	2010
Avg P ($\$/m^3$)	Mean	2.61	0.73	0.60	1.90	1.54	1.90	1.92	2.43	1.48
	Std Dev	0.85	0.36	0.19	0.46	0.69	0.69	0.74	0.69	0.70
	Min	1.81	0.31	0.45	1.34	0.85	1.29	1.19	1.68	0.83
	Max	8.56	3.39	2.68	5.34	8.31	7.25	7.32	6.49	6.36
N households		8193	8785	1501	9521	9520	5641	973	9679	6822

TABLE 1: Descriptive statistics by district

Statistic	Mean	St. Dev.	Min	Max
Income ($1000)	91.014	34.607	41.152	132.652
Age	37.996	4.042	27.748	41.731
Pop <10 (%)	13.660	1.529	11.877	18.010
Pop >75 (%)	5.977	1.119	3.500	7.845
Pop Hispanic (%)	27.762	25.927	7.405	82.047
Pop bachelor (%)	22.683	10.748	5.199	35.359
Mandate level	20.60	6.40	8.00	36.00

TABLE 2: Descriptive statistics for variables in the second stage

TABLE 3: Results

	Dependent variable:								
	log(water use)								
Variables	District A	District B	District C	District D	District E	District F	District G	District H	District I
ET	0.040***	0.037***	0.015***	0.017***	0.008***	0.022***	0.017***	0.009***	0.011***
	(0.0004)	(0.001)	(0.0005)	(0.0002)	(0.0002)	(0.0002)	(0.001)	(0.0002)	(0.0003)
Bathrooms	0.226***	0.221***	0.182***	0.186***	0.132***	0.224***	0.140***	0.105***	0.112***
	(0.002)	(0.003)	(0.007)	(0.002)	(0.002)	(0.003)	(0.008)	(0.003)	(0.003)
Irrigated area	0.0001***	0.0001***	0.0002***	0.0001***	0.001***	0.0002***	0.0004***	0.0004***	0.0001***
	(0.00000)	(0.00000)	(0.00001)	(0.00000)	(0.00001)	(0.00001)	(0.00003)	(0.00002)	(0.00001)
Year Built	-0.001***	-0.003***	-0.00000	0.005***	-0.001***	0.0002	-0.0001	-0.002***	-0.002***
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0001)	(0.0001)
log(Avg P)	-0.659***	-0.684***	-0.537***	-0.815***	-0.482***	-0.305***	-0.314***	-0.136***	-0.315***
	(0.051)	(0.063)	(0.029)	(0.019)	(0.032)	(0.019)	(0.031)	(0.015)	(0.026)
Constant	3.129***	7.484***	1.733***	-6.879***	4.622***	1.303***	2.240***	7.157***	7.026***
	(0.235)	(0.255)	(0.409)	(0.221)	(0.175)	(0.312)	(0.494)	(0.225)	(0.273)
Efficiency scores									
Mean	0.708	0.726	0.860	0.680	0.857	-	-	-	-
Std Dev	0.185	0.180	0.108	0.204	0.107	-	-	-	-
N	98316	105420	18012	114252	114240	67692	11676	116148	81864

Note: ***p<0.01

TABLE 4: Estimation results - Second stage

	Coefficients	Std. Errors
Intercept	7.51 ***	2.89
t	0.05***	0.01
Summer	0.04	0.04
Spring	-0.52***	0.07
Winter	-0.18***	0.03
Income	0.02***	0.00
Age	-0.11**	0.05
%Pop<10	-0.22***	0.08
%Pop>75	-0.21***	0.06
%Pop Hispanic	-0.01***	0.00
%Pop Bachelor	-0.03***	0.01
Mandate level	-0.006***	0.003

TABLE 5: Elasticities for socioeconomic and demographic characteristics

	Elasticities
Income	11.01
Age	-23.60
%Pop<10	-20.07
%Pop>75	-7.34
%Pop Hispanic	-1.60
%Pop Bachelor	-4.09
Mandate level	-0.85

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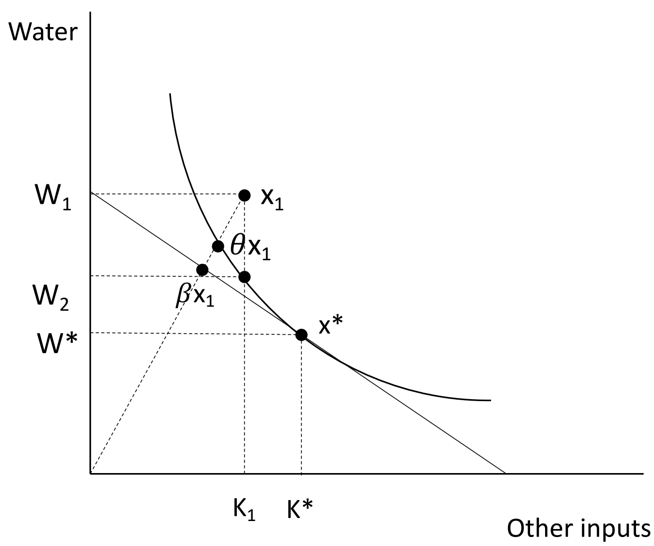
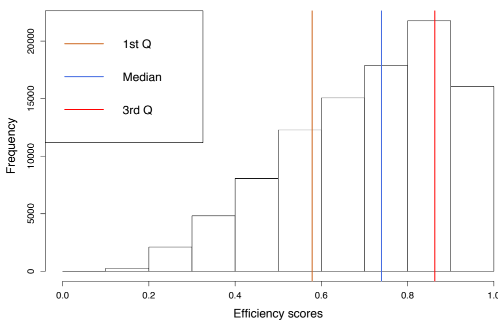
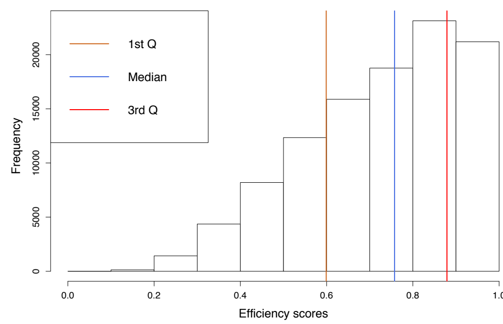


FIG. 1: Cost efficiency

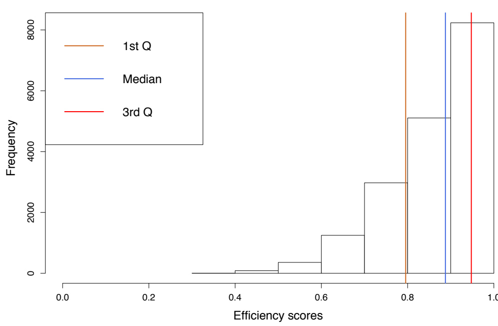
FIG. 2: Distribution of water districts in the analysis



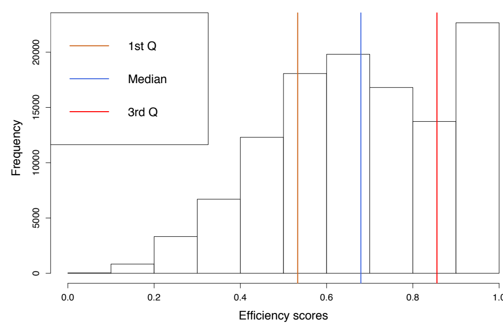
(a) Histogram Efficiency Scores - District A



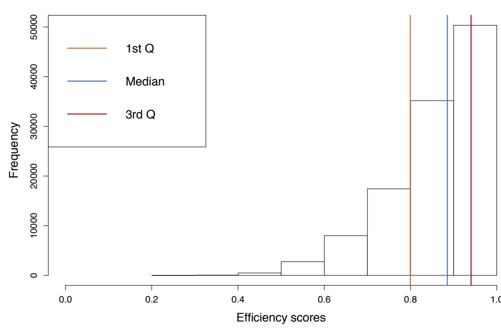
(b) Histogram Efficiency Scores - District B



(c) Histogram Efficiency Scores - District C



(d) Histogram Efficiency Scores - District D



(e) Histogram Efficiency Scores - District E

FIG. 3: Histogram Efficiency Scores

FIG. 3: Histogram Efficiency Scores

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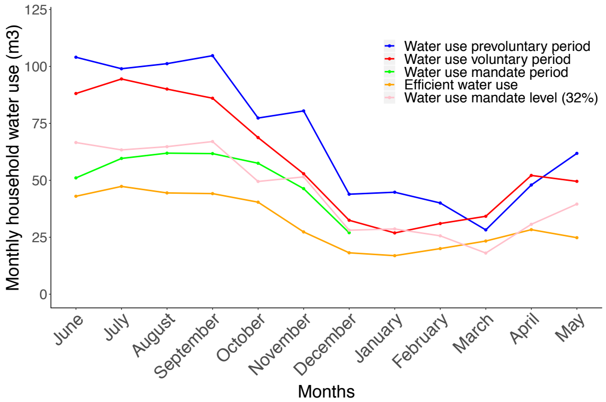
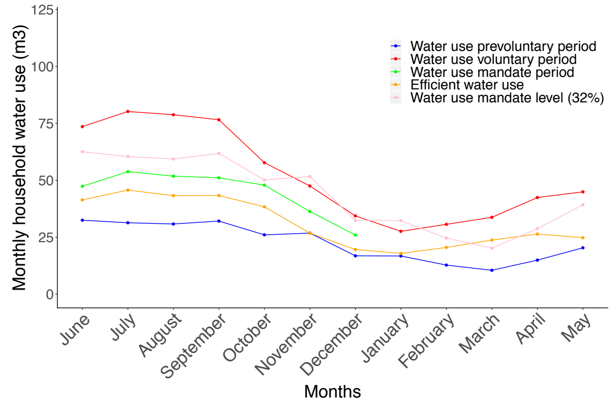
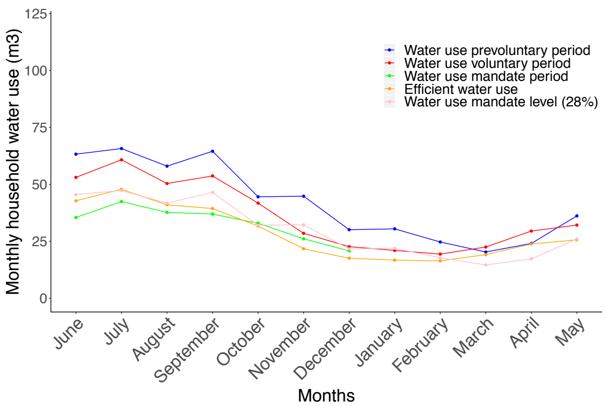


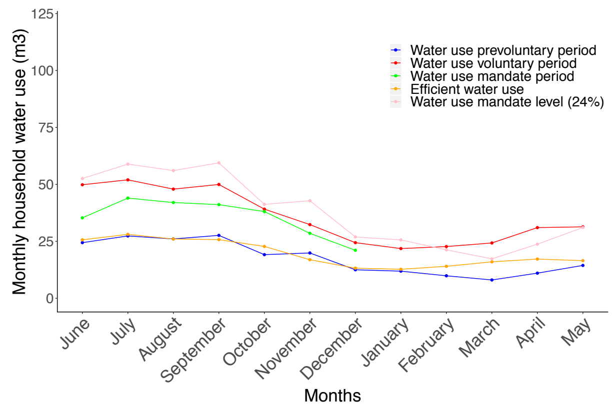
(a) Evolution of water use - District A



(b) Evolution of water use - District B

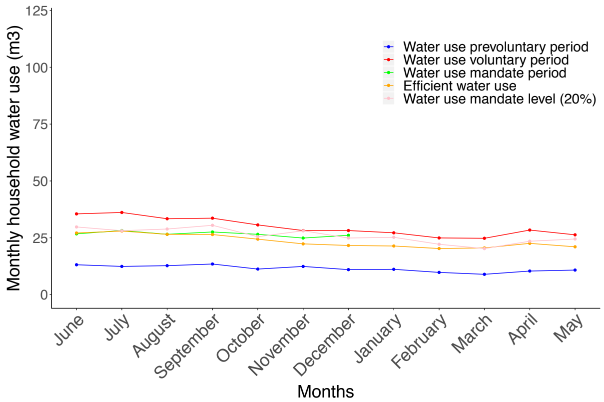


(c) Evolution of water use - District C

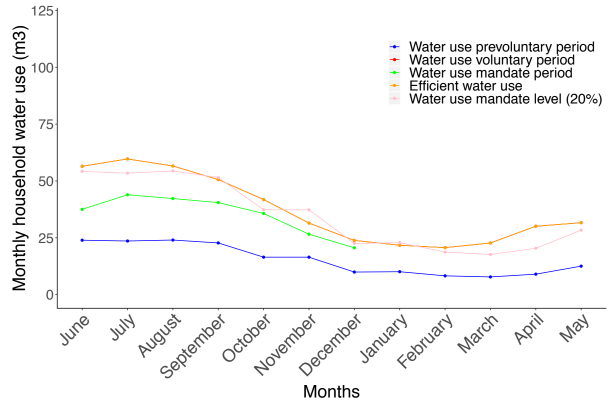


(d) Evolution of water use - District D

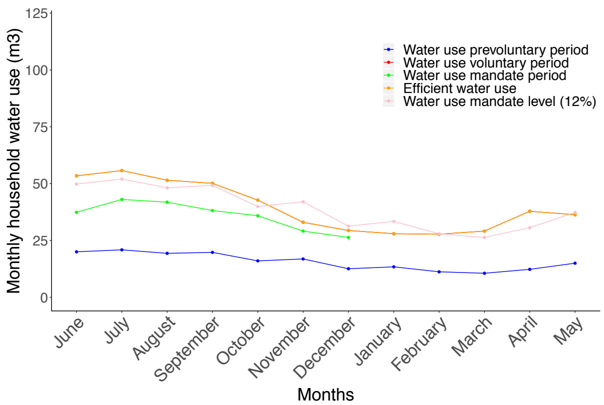
FIG. 4: Evolution of water use for different districts



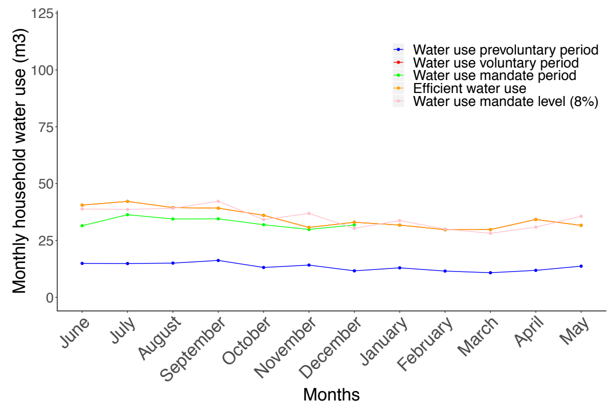
(a) Evolution of water use - District E



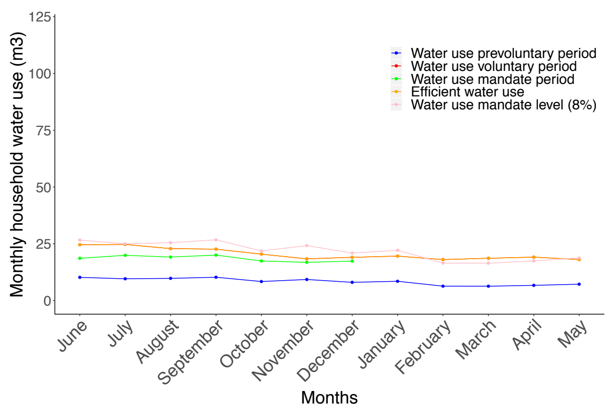
(b) Evolution of water use - District F



(c) Evolution of water use - District G



(d) Evolution of water use District H



(e) Evolution of water use - District I

FIG. 5: Evolution of water use for different districts