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Letter

Stay-at-Home Orders during the COVID-19 Pandemic Reduced Urban Water Use

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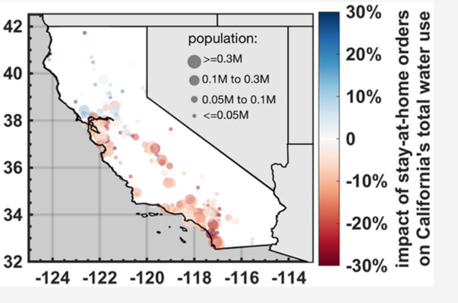
ABSTRACT: In response to the outbreak of the COVID-19 pandemic, many governments instituted "stay-at-home" orders to prevent the spread of the coronavirus. The resulting changes in work and life routines had the potential to substantially perturb typical patterns of urban water use. We present here an analysis of how these pandemic responses affected California's urban water consumption. Using water demand modeling that fuses an integrated water use database, we first simulated the water use in a business-as-usual (non-pandemic) scenario for essentially all urban areas in California. We then subtracted the business-as-usual water use from the actual use to isolate the changes caused solely by the pandemic response. We found that the pandemic response decreased California's urban water use by 7.9%, which can be largely attributed to an 11.2% decrease in the commercial, industrial, and institutional sector that more than offset a 1.4% increase in the residential sector. The influence of the stay-at-home practices on urban water use is slightly stronger than the combined influences of all non-pandemic factors. This study covers both metropolitans and suburbs; therefore, the results could also be useful for analysis of the impacts of COVID-19 on water use in other urban areas.



■ INTRODUCTION

The pandemic associated with novel coronavirus disease 2019 (COVID-19) has resulted in substantial changes in work and life patterns globally, as countries took extraordinary efforts to limit social contact.[1,2] In many cases, governments instituted "stay-at-home" orders, requiring businesses not classified as "essential" to limit operations or close. Many office-based enterprises transitioned to employees working predominantly from home rather than within office buildings. Extensive socioeconomic changes followed, including increased unemployment, altered transportation patterns, and diminished economic activities.[3] These disruptions in life and work patterns had the potential to significantly affect how and where water was consumed during the pandemic.[4] Water use data from water supply agencies reveal net water use changes caused by all natural and anthropogenic factors during the pandemic,[5] but such data do not separate the influence of pandemic response from the effects of other concurrent factors that are known to impact water consumption, e.g., meteorological, climatic, economic, geographic, seasonal, and regulatory factors.[6] The extent and effects of changes resulting from stay-at-home orders on water use patterns have yet to be evaluated.[7]

Urban areas in California provide an outsized example for such an evaluation. The state's urban water retailers supply water to >10% of the entire U.S. population.[8] On March 19, 2020, the State of California issued a stay-at-home order that closed most businesses, institutions, and public spaces across the state.[9] Starting May 4, 2020, the state moved to a more limited quarantine, with some commercial businesses allowed to open in a limited capacity.[10] Therefore, there were approximately 6 weeks (March 20 to May 4) during which the full, statewide stay-at-home restrictions were in effect. Starting with the 2013−2016 drought, approximately 400 water retailers across California have been required to report monthly data on water use as a way to track progress on statewide conservation goals.[11] The resulting statewide database of self-reported water use, coupled with the statewide action in response to the pandemic, creates a unique opportunity to analyze the effects of a major policy intervention and the associated large-scale behavioral changes on water use in California's urban areas. In this study, we quantify the influence of the pandemic response during the COVID-19 pandemic on California's urban water use. Herein, "pandemic responses" refer to both the stay-at-home orders and the resulting changes in work and life routines, which directly disrupted water use patterns.

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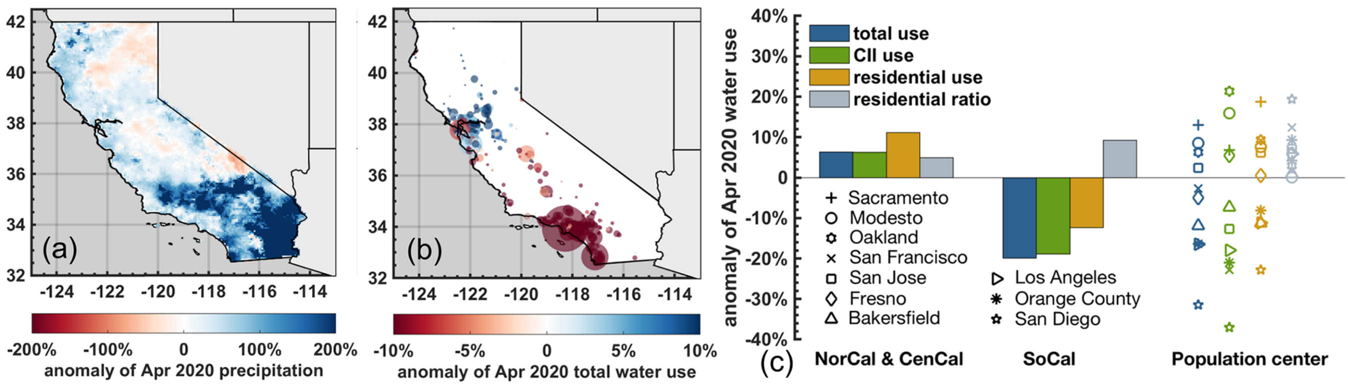

Figure 1. Actual water use in April 2020 was affected by the COVID-19 pandemic and a variety of non-pandemic factors, among which precipitation is the most dominant. (a) April 2020 precipitation anomaly relative to the mean April precipitation for 1990−2019. In April 2020, the Southern California precipitation erased the precipitation deficit that had accumulated from the earlier months of 2020 (Figure S5) while Northern California was still in a severe drought. (b) April 2020 total water use anomaly relative to the average April total water use from 2014 to 2019 across the 395 urban water supply agencies in California. The circle size is proportional to the population within each agency's servicing territory. (c) Average anomalies of the April 2020 water use in Northern and Central California (NorCal and CenCal, respectively), Southern California (SoCal), and the 10 most populous urban centers in California compared with the mean 2014−2019 April water use in major urban sectors.

■ MATERIALS AND METHODS

As noted, the full stay-at-home restrictions were in effect from late March to early May; to ensure that we capture the period of quarantine in our monthly water use data from the State Water Board Conservation Report[11] without interference, all of our analyses herein focus on April 2020, which was completely within the quarantine period. Three urban water use statistics that are available for all of California's water retailers are of interest: total water use; commercial, industrial, and institutional (CII) water use; and residential use. Across all urban areas in California, CII and residential water use comprise roughly 30% and 65% of the total water use, respectively. The 5% residual comprises the water used for power generation and the water lost in distribution.[12] For the residential sector, we evaluate both the residential water use volume and the residential water use ratio, which is defined as the ratio of the residential use volume to the total use volume.

Our analysis starts by comparing reported (actual) water use during April 2020 with the reported use in April of previous years; these comparisons elucidate the joint influence of the convolving pandemic and non-pandemic factors during April 2020.[6] To evaluate the water use change caused solely by pandemic responses, we enhance and extend an existing set of water demand models across 395 water retailers in California to estimate the "business-as-usual" water use that would have occurred during April 2020 had no pandemic occurred (more details in section SI-1 of the Supporting Information). We subtract the business-as-usual water use from the actual water use to isolate the impact of the pandemic response. To derive business-as-usual water use estimates in April 2020, our water demand models first quantify connections between the water use of each sector and the factors that affected water use in the prepandemic period (January 2014 to February 2020). The regression relationships are then projected forward to April 2020 to derive business-as-usual estimates. We also compare the magnitude of the pandemic impact with the combined impacts of all non-pandemic factors on water use. The derived regression relationships for all water use sectors are statistically significant ($p < 0.05$), and the modeled volumetric water use during the prepandemic period is highly consistent with the reported data, with an overall relative root-mean-square error of 0.4% and an R^2 of 0.85 (more details in section SI-2). The Supporting Information contains further details about model design, implementation, and validation.

■ RESULTS AND DISCUSSION

Precipitation is a strong predictor of urban water use in California[13] (Figure 1). This is primarily due to the Mediterranean climate with strongly winter-dominant precipitation,[14] which results in large seasonal variations in urban water use patterns. Coincident with the outbreak of the pandemic, California experienced both statewide and regional anomalies in precipitation. Based on the data from the UCLA (University of California Los Angeles) drought monitor,[15] prepandemic January and February of 2020 were the third driest for those two months combined in the past 100 years; the cumulative precipitation for January and February of 2020 was 62% less than the average for the same months in the drought years of 2013−2016 (Figure S5). The statewide precipitation deficit was eventually alleviated by late spring precipitation events in March and early April 2020. However, the precipitation was highly heterogeneous geographically (Figure 1a). April rainfall was 267% of the normal April precipitation for the past 30 years in Southern California, but April precipitation in Northern California was only moderately higher than normal for the same 30-year period (117% of normal). As a result, by the end of April 2020, the accumulated precipitation deficit from the preceding winter months in Southern California had been erased but Northern California was still in the grips of a severe drought.

Annual comparisons of April water use confirm the general inverse relationship between water use and precipitation (Figure 1). Total water use was lower in Southern California in April 2020 than in Aprils of previous years, mainly because of the anomalously high rainfall. In contrast, total April water use in Northern California was mostly higher than the average of April 2014−2019, except for coastal population centers that had above normal April precipitation.

Compared with the data from previous years, CII water use in April 2020 was lower in Southern California and in dense urban areas of Northern California, including San Francisco and San Jose (Figure S6 and Figure 1c). This likely is a signature of the stay-at-home order. In Southern California,

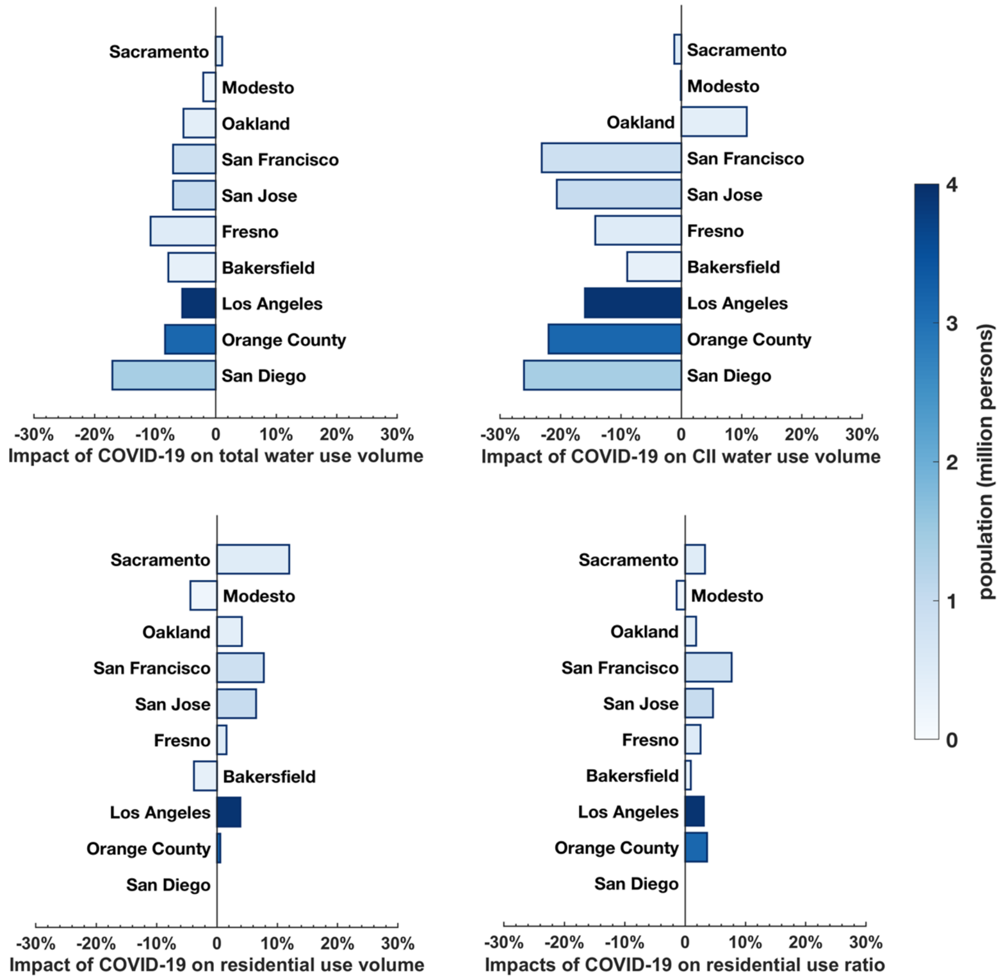

Figure 2. Impact of the pandemic response during the COVID-19 pandemic on urban water use in the 10 most populous urban centers in California during April 2020. The impact is represented as the changes in April 2020 water use attributable solely to pandemic responses relative to the mean April water use for 2014–2019. The impacts on all 395 water retailers across the state are shown in Figure S7.

above normal April precipitation also contributed to a decrease in CII water use. However, much of Northern California showed increased CII water use. CII water use can be divided into two components: indoor consumption (in buildings such as shops, hotels, schools, and restaurants) and outdoor consumption for landscape irrigation and recreation.[16,17] Notwithstanding the absence of formal reporting of indoor and outdoor CII volumes, we hypothesize that the increase in CII water use in Northern California in April 2020 likely is attributable to the dry 2020 conditions that increased the outdoor portion of CII water use.

Residential water use is also highly correlated with precipitation anomalies (Figure S6). In April 2020, Southern California's residential water use was lower than in previous years whereas Northern California's was higher. This is likely attributable to outdoor residential use, which is inversely correlated with precipitation and is a significant contributor to residential water use.[16,17] While a statewide stay-at-home order would be expected to increase the residential water use over the entire state, the north–south variations in residential use related to precipitation anomalies imply the tremendous impact of non-pandemic factors on actual water use. The influence of the pandemic alone is not clear from an analysis of only the actual water use anomalies.

After the influence of non-pandemic factors is filtered out, the isolated impact of the pandemic response on water use is relatively uniform across the state. In comparison with a business-as-usual scenario that accounts for only non-pandemic effects, total urban water use in April 2020 declined by an average of 7.0% in the 10 most populous cities (Figure 2) and by 7.9% across the 395 water retailers in the state (Figure S7).

Our sector-specific analyses show the decrease in total water use is due to the substantial reductions in CII water use that more than fully offset the mild increases in residential water use. The pandemic response reduced CII water use by 11.6% on average statewide (Figure S7), as schools and libraries shut down, businesses closed, and non-essential workers stayed home. The largest decreases in CII water use were in populous areas (10 largest urban centers), where the CII sector reduced by an average of 14.7% relative to business as usual during April 2020. We note that these effects represent the CII sector as a whole, as the available data do not support conclusions of effects across different industries (e.g., offices vs restaurants) or across indoor and outdoor uses. We also note that some areas in Northern California experienced increases in CII water use in April 2020 that we attribute to the pandemic responses (Figure S7). This is likely because some major water-consuming industries in this area, such as agriculture product

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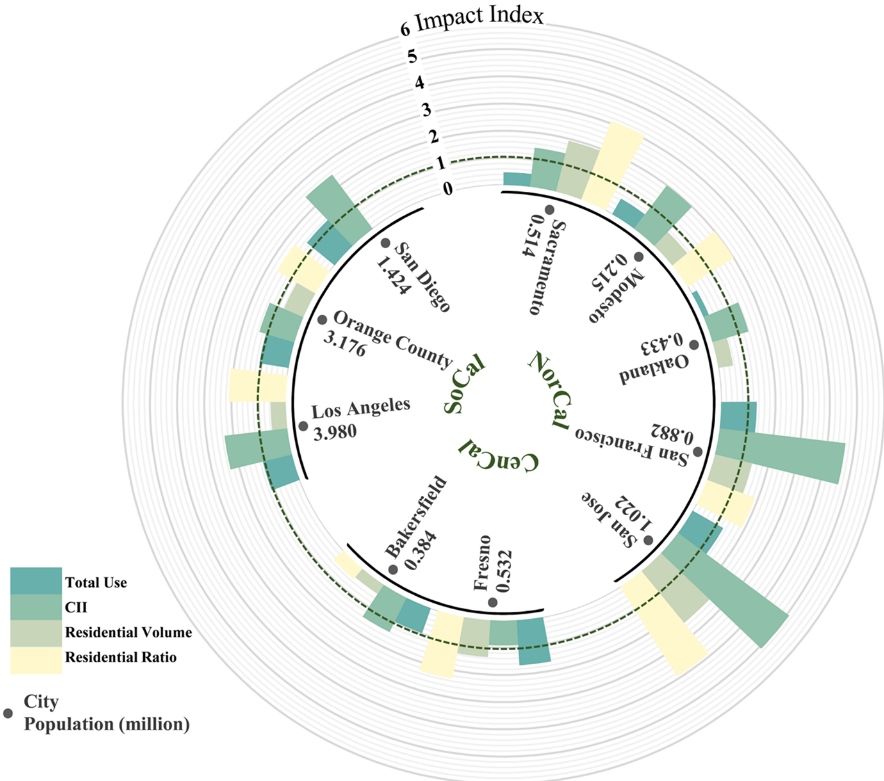

Figure 3. Impact indices of water use in California's 10 most populous urban centers. The impact index for individual water retailers is shown in Figure S8. The impact indices compare the influence of the pandemic responses on water use with the combined influence of all non-pandemic factors. Overall, the pandemic responses were slightly more influential than the combined effects of all non-pandemic factors on urban water use.

processing enterprises, were essential businesses and remained in operation under extremely dry conditions during the pandemic. In addition, increased outdoor CII water use in large cities could also contribute to the increased CII water use in these areas during the pandemic.

Residential water use increased by 1.4% statewide compared with business-as-usual use (Figure S7). The largest volumetric increases were in densely populated areas; the 10 urban centers with the largest populations had an average residential water use increase of 2.4% (Figure 2). As a large portion of California's 40 million people began to work, study, and live primarily at home, residential water use increased. The ratio of residential water use to total water use increased by 3.2% statewide in comparison with business-as-usual data in April 2020 (Figure S7), demonstrating that the stay-at-home order shifted water use from the CII sector to the residential sector. Note that some water retailers report residential water use based on a temporally static ratio to the total water use, rather than actual residential volumes. In the pandemic period, when sizable intersector water use shifts occurred, these static ratios are likely inaccurate. We therefore excluded the 81 water retailers (which account for 19% of the statewide average total water use) that reported residential water use in this way from our residential sector analysis.

Despite the fact that pandemic responses impacted water use more substantially in areas with larger populations, the overall direction of their impact (i.e., increasing or decreasing) on each water use sector is consistent among urban areas regardless of the population served. Table S2 provides more details about water use changes according to the population served by each water retailer.

We created an impact index to measure the influence of pandemic response on water use relative to the effects of all non-pandemic factors (which include climate, water rates, seasonality, inflation, population, and regulatory responses to drought). We defined the impact index as the ratio of the magnitude of the pandemic response's impact to the magnitude of the combined impact of all non-pandemic factors (details in the Supporting Information). An impact index of 1.0 indicates that the pandemic responses are equally influential to the net effects of all non-pandemic factors. An impact index of >1.0 means the pandemic responses are more influential, and vice versa. We find that the pandemic response had substantial (and statistically significant) impacts on water use. In every sector examined, and across all 395 water retailers, the average impact index is >1, meaning that statewide, the pandemic response had a greater impact on water use than the combined impacts of all other non-pandemic factors, both natural and anthropogenic.

Across the 395 water retailers in California (Figure S8), the average impact index for total water use in April 2020 was 1.08, implying that the overall effect of the pandemic response was slightly greater than all non-pandemic effects combined. For CII water use, the average impact index is 1.80 across the state. The effect of the pandemic response on CII water use was strongest in population centers with dense industry and commercial businesses (Figure 3), where the average impact index for the CII sector was 2.31. In San Jose and San Francisco, the impact index for the CII sector was as much as 5.

The average statewide impact index for residential water use was 1.02. The stay-at-home behaviors had less impact on residential use compared with CII use, mainly because the

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residential sector is comparatively less impactable. For example, while frequent hand washing is a common practice during the pandemic, in most cases one washes hands only a few times a day at home, but hand washing in a restaurant can be much more frequent by different customers and staff when it is open. Also, the relatively large number of essential workers who still went to work during April 2020 diluted the impact on the residential sector and enhanced the impact on the CII sector.[18] The effects of the pandemic response on residential use were slightly more pronounced in large cities (Figure 3), where the average impact index was 1.09. Because the impact indices of the residential and CII sectors were larger in cities, and because the residential sector moved toward increased water use while the CII sector moved toward decreased water use, the impact index of the total water use for large cities (1.01) does not significantly differ from that of the whole state (1.08).

While our study is limited to California due to data availability, it reflects the behavioral patterns of a large population, spans both major metropolitan areas and suburbs, and covers a diverse set of industries and commercial businesses. The method accounts for local physical contexts, which are filtered out to probe the water use perturbations caused solely by the stay-at-home order and the associated behavioral changes. We therefore believe the results could be useful (and even provide a benchmark) for analysis of impacts of COVID-19 on other urban areas. The results from this study provide insights for planning across urban areas with seasonal patterns of water consumption. The approach demonstrates an innovation in using cultivated and standardized data to deploy an infrastructure planning model across urban utilities of many sizes and types in a region. The models presented here for urban water agencies in California are directly relevant to many parts of the western United States, as well as Mediterranean climate areas throughout the globe with similar long periods of aridity. Using the regression method in this study (section SI-1) and the associated open-source software package,[20,21] urban resource agencies in other regions can conduct rapid assessments of resource consumption that help resilience planning.

This study substantially benefits from the timely reporting of water use data[19] to build a relationship between water use and local natural and anthropogenic factors during a very recent time period of interest. Even six years ago, there would not have been enough data to support a statistical analysis for water use estimation at the scale in this study. In the long run, resilience planning requires preparing for disruptions and shocks that could significantly alter the typical water use patterns;[22,23] the ability of urban utilities, regulatory agencies, and research to respond to such changes with empirical analysis that informs adaptive actions requires data that are made available in a timely fashion. Longer data records will increase the robustness of model estimates, facilitating more confident forecasts and predictions. We therefore advocate for integrated and systematic water use reporting and the publishing of these data in a timely fashion.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00979.

Details of the water use forecasting model design and implementation, validation of all modeling results, and spatially distributed version of the water use changes (PDF)

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Author Contributions

D.L., R.A.E., X.M., and E.P. carried out the experiment. All authors contributed to the project preparation, analyses, and manuscript writing.

Notes

The authors declare no competing financial interest.

The data, code, and materials that can fully reproduce and extend the analyses in this paper are archived in a public repository (10.6084/m9.figshare.13325393).

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