

Socio-hydrological drought impacts on urban water affordability

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In water-stressed regions, droughts pose a critical challenge to urban water security for low-income households. Droughts reduce water availability, forcing water providers to invest in additional supplies or enact expensive, short-term emergency measures. These costs are frequently passed on to households through increased rates and surcharges, driving up water bills for low-income households and altering patterns of water consumption. Here we have developed a socio-hydrological modelling approach that integrates hydrology, water infrastructure, utility decision-making and household behaviour to understand the impacts of droughts on household water affordability. We present here an application based on Santa Cruz, California and show that many drought resilience strategies raise water bills for low-income households and lower them for high-income households. We also found that low-income households are most vulnerable to both changing drought characteristics and infrastructure lock-in.

Unaffordable water prices threaten human health and well-being in the United States and beyond^{1–5}. In California alone, one million people lack access to affordable clean drinking water⁶. Low-income households are disproportionately impacted by unaffordable water bills⁴, with one-third of water systems in low-income areas of the United States charging unaffordable rates⁷. Unaffordable water threatens health by limiting both domestic water use⁸ and other essential household expenditures. Indeed, 14% of the US population reports that a US\$12 monthly increase in water bills would reduce access to groceries and basic medical care⁹. Water bills are currently increasing faster than inflation³ and the strain of climate change on water supplies threatens to accelerate cost increases.

Droughts exacerbate affordable water access in many water-stressed regions by reducing water availability and increasing the cost of supplying water. Water providers must use expensive short-term mitigation measures such as curtailment or invest in additional water supplies^{10,11} to provide reliability, but these measures may increase water rates¹². Counterintuitively, these measures can reduce household water security by making water unaffordable for more people^{13,14}. This impact is supported by empirical evidence from recent droughts that showed that households in urban areas of California paid higher water bills during drought periods¹⁵.

Household water-use behaviour compounds the affordability challenges created by droughts and disconnects household and utility water security. During droughts, households change their water use as a result of drought-related water restrictions^{13,16}, responses to price increases^{17,18}, and changing water use based on socio-economic and demographic factors^{19–21}. Household changes in water use in response to exogenous factors alter utility revenue and potentially necessitate additional rate increases. Accordingly, quantifying water affordability requires explicitly incorporating household-level water use and response to rate changes into broader drought planning and management decisions.

Previous studies have investigated drought impacts and solutions for water supplies, but have not captured the interaction between utility-level planning and household-level affordability impacts. In the field of decision support modelling, recent studies have developed low-cost approaches to drought resilience, including diverse supply portfolios^{22,23}, regional water transfers^{12,24}, demand management^{20,25} and flexible capacity expansion²⁶. Many studies have used exploratory modelling to analyse trade-offs between conflicting water resource goals, such as reliability, cost and ecosystem services, during droughts^{27–31}. The infrastructure solutions required to address

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droughts often increase water rates³², but household affordability is typically not included in these planning models. In the area of socio-hydrology, recent work has focused on developing a process-based understanding of coupled human water systems with the aim of identifying critical components, nonlinear interactions and feedback^{33–36}. Recent studies have investigated the connections between human behaviour and flood^{34,37}, agricultural irrigation^{36,38} and drought³⁹. In both decision support modelling and socio-hydrology, existing approaches have focused on aggregate indicators at the city, watershed or regional scale, aligned with the scale of decision-making rather than impact, where household-level affordability is typically addressed separately from water-supply decisions via rate setting and low-income assistance programmes⁴⁰. However, these solutions do not account for the effects of hydrological variability on water bills, potentially overlooking impacts on vulnerable households. Current models are therefore unable to capture water use and costs at the spatiotemporal resolution required to assess the differential affordability impacts of droughts across demographic groups, nor are they able to incorporate the changing household behaviour that occurs as a result of drought resilience measures. This is a key barrier to understanding the distributional equity implications of alternative approaches to drought resilience⁴¹. In short, the potential interactions between droughts and affordability are well known in many stressed water systems, but their interaction remains an emerging area for water resource researchers. A broad Web of Science literature search for the terms ‘droughts’ and ‘water affordability’ returned only 17 publications in the past 10 years.

In this work we assessed the household-level socio-hydrological impacts of drought on water affordability. To do this, we developed a socio-hydrological process model of an urban water system that integrates hydrological drought scenarios: (1) utility water supply and rate decision-making, (2) storage, conveyance and treatment infrastructure, and (3) household water-use behaviour across income classes. We used this model to evaluate the impact of droughts on low- and high-income household water bills under different utility and household drought responses in an application based on Santa Cruz, California during the 2011–2016 drought. Santa Cruz is a coastal California public utility served primarily by surface water. The aim of this application was to develop process-based insights using realistic and generalizable model assumptions, not to design context-specific solutions for Santa Cruz. The results indicate that curtailment-based drought mitigation coupled with drought surcharges decreases water bills for high-income households and increases water bills for low-income households, highlighting the equity implications of drought mitigation decisions. We also found variability in drought characteristics (that is, persistence and intensity), and that changes in household water use in response to price signals disproportionately impact low-income households. We investigated the effects of infrastructure lock-in on affordability and found that higher pre-drought water rates lead to greater bill increases during drought. Finally, we discuss the generalizability and limitations of our findings.

Results

Water affordability modelling framework

We have developed a socio-hydrological modelling framework to assess process-based drivers of household affordability during droughts, including (1) utility cost increases from water-supply infrastructure expansion, temporary water sourcing and demand curtailment, (2) decreased water availability from droughts of varying persistence and intensity, (3) changes in household water use in response to price signals and (4) the impact of pre-drought utility decision-making (Fig. 1a). We simulated different drought scenarios, utility decision-making and household behaviour to determine the drought-related bill increases and surcharges for low- and high-income households as well as the water utility. We categorized low-income households as those below the California Poverty Measure for the region (US\$36,000 yr⁻¹)

and high-income households as those making over twice the median household income (US\$135,000 yr⁻¹). Each household's water use was estimated on the basis of household size, income, price elasticity and response to curtailment mandates. Coupled with increased rates, this information was used to estimate the changes in household water bills resulting from droughts, supply expansion and short-term mitigation (Methods). We modelled drought impacts on affordability as the change in annual household water bills resulting from droughts for high- and low-income households. This approach connects watershed-scale hydrology with both city- and household-level drought decision-making and impacts, enabling assessment of the distributional impacts of drought on affordability.

Household affordability differs from utility costs

Using this framework, our first key finding was the decoupling of household water affordability and total utility cost during droughts. This occurs because of the combination of cost increases for utilities, which are passed to households as increased rates, and household water use reductions (Fig. 1a). We simulated the affordability impacts of two water-supply infrastructure expansions, temporary water sourcing and demand curtailment during multiple drought scenarios. In line with the legal and governance frameworks of our case study as well as the modelling approach used in this work, we assumed that all water-supply infrastructure expansions and temporary water-sourcing purchases increase the unit cost of supplying water, and that demand curtailment decreases retail revenue due to the reduced water sold. We modelled utilities as raising water rates or applying surcharges to fund the additional costs or revenue deficits (Fig. 1b, lower panels), resulting in moderate cost increases (US\$0 to US\$72 month⁻¹) across all scenarios and droughts. Households were modelled as responding to increased water rates or surcharges by reducing water use, and curtailment has the additional effect of mandated reduced household water demand. In the absence of rate increases, water use reductions create moderate (US\$19 to US\$77) decreases in water bills, based on a price elasticity of 0.35 (Methods).

We found that increases in the cost of water to households via surcharges and rate increases combined with household water-use reductions from curtailment and price responsiveness lead to an asymmetric impact of droughts across income classes, and a decoupling of total utility cost and household affordability. This occurs because these two components—the bill increase from rate increases and surcharges, and the decrease from water use reductions—are not equal. They result in a net increase or decrease in the cost of water during droughts that varies according to the magnitude of utility cost increases, household use reductions and the characteristics of the household. For low-income households in our case study, this results in low-to-moderate monthly cost increases (US\$2 to US\$72), whereas for high-income households the impact ranges from low decreases (US\$42) to moderate increases (US\$72). This asymmetry across income classes is driven in part by differences in pre-curtailment water use: high-income households use more water pre-drought and as curtailment was implemented by reducing household water by a percentage, high-income households curtail more during drought. Additionally, surcharges comprise a larger portion of total water bills for low-income households, leading to greater use reductions. Accordingly, a given amount of increased cost to utilities (through revenue reduction or increased spending) does not lead to a one-to-one impact on households. The resulting change in household affordability differs according to how the cost was incurred, and the characteristics of water use and price responsiveness for each household.

Note that throughout this work we report changing water bills as absolute bill increases either per month or per year for low- and high-income households, but we emphasize that this is just one of many ways to quantify affordability. Affordability ratios are a commonly used metric for quantifying water affordability in which water

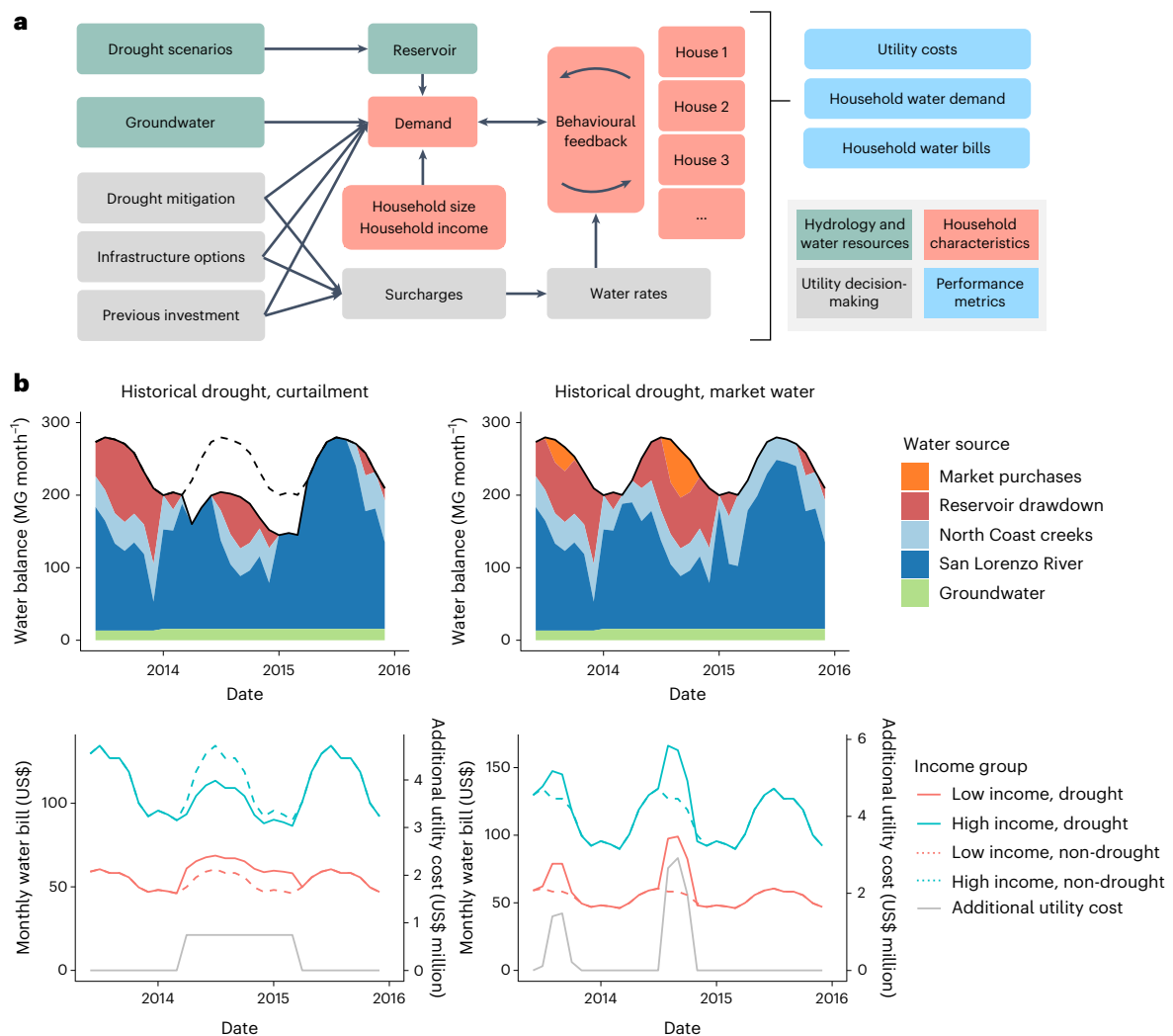


Fig. 1 | Schematic model overview and example model results. a, Framework for the water affordability and utility planning model. **b**, Example water balance (top) and cost increases (bottom) during a historical drought in which

curtailment (left) and market water (right) are used as drought mitigation measures. The dashed lines show the water use (top) and water bills (bottom) in non-drought conditions.

expenditure is divided by total household income leading to a percentage of household income spent on water^{2,3}. This is often compared with a reference value to label water affordable or unaffordable⁴. Broadly, water is considered affordable if households are spending 2–4% of their income on their water bills^{2,4}. For low-income households in our case study, an average pre-drought water bill is approximately US\$54, leading to an affordability ratio of 5.2%. For a high-income household, an equivalent water bill would be approximately US\$120, for an affordability ratio of 0.8%. This parallels a long-understood trend in urban water affordability in which unaffordability is largely an issue for low-income households^{2,4,13}. Our results highlight that there are likely to be households for which drought surcharges are the difference between affordable and unaffordable water when quantified using affordability ratios. Furthermore, in our analysis, we modelled differences in bill changes across income groups as a measure of inequality. However, the same absolute bill change will disproportionately impact low-income households when using affordability ratios. Therefore, the equity impacts of droughts for low-income households are greater.

Utility decision-making and drought characteristics

We analysed the total affordability impacts of utility decision-making during droughts. We found that decisions made by utilities to expand

water supplies, temporarily source water and curtail demand create different cost outcomes for low- and high-income households as well as the utility. We tested three water-supply expansion options: build no infrastructure, build a low-capacity water recycling plant or build a large-scale regional desalination plant. The water recycling plant has a total cost of US\$20.4 million, an additional annual cost of US\$330,000 and it provides 0.5 MG d⁻¹ of capacity for a levelized cost of US\$2,600 AF⁻¹. The high-capacity desalination option has a total cost of US\$115 million, an additional annual operational cost of US\$3.3 million and it provides 2.5 MG d⁻¹ of capacity, with a levelized cost of water of US\$4,300 AF⁻¹. We assumed that all infrastructure options are operational for 30 years and are financed with a 30 year loan at an interest rate of 3% (Methods). Should the given supply infrastructure be unable to meet water demand, one of two mitigation options would be implemented: purchasing water on a water market or curtailing residential water demand, where households are asked to reduce their water consumption (Methods). All utility decision-making was simulated during four drought scenarios: a historical drought, one more intense, one longer, and one longer and more intense (Methods).

We found that—across all drought scenarios—expanding supplies always increases costs for utilities, always reduces affordability for low-income households, but does not always reduce affordability for

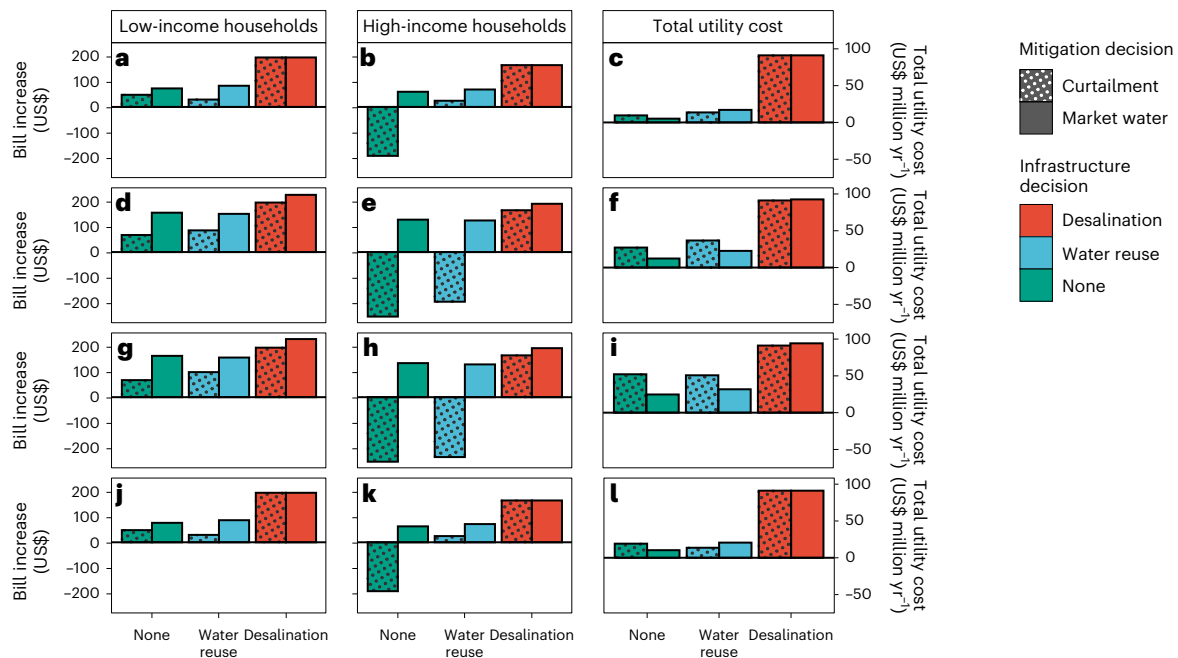


Fig. 2 | Stakeholder cost changes during droughts for given infrastructure, mitigation and drought scenarios. a–l. One-year total cost increases for low-income households (a,d,g,j), high-income households (b,e,h,k) and the utility (c,f,i,l) compared with a non-drought period for four different scenarios:

historical (a–c), intense (d–f), long and intense (g–i), and long (j–l) droughts for different drought mitigation and decisions. Negative numbers represent bill decreases and positive numbers represent bill increases.

high-income households (Fig. 2b,e,h,k). The affordability outcomes for high-income households are driven by demand curtailment and temporary water sourcing. When utilities purchase market water to mitigate any water shortfall not provided by existing water supplies, costs increase for high-income households similarly to low-income households and the utility (Fig. 2, solid bars). However, when utilities implement demand curtailment, it leads to a large reduction in water use for low- and high-income households. For high-income households, this reduction fully offsets the cost increases from curtailment and results in water bill decreases (Fig. 2e,h,k, patterned bars). For low-income households, the reduction in water use from curtailment and price changes does not offset the mitigation and supply-expansion cost increases, reducing affordability (Fig. 2d,g,j, patterned bars).

If supplies are expanded, the impact on low- and high-income affordability is dependent on the characteristics of the expansion option. Building infrastructure results in low cost increases for all populations, as long as there is enough capacity to prevent mitigation from being required. This occurs because the levelized cost of water (LCOW) for supply expansion is cheaper than the LCOW of mitigation measures (US\$2,600 AF⁻¹ versus US\$7,200 AF⁻¹, respectively). Thus, when the size of the expansion is sufficient to supply water during the drought, cost increases are very moderate for all three stakeholders (Fig. 2a–c, blue bars). However, if the expansion is insufficient and requires temporary water sourcing or demand curtailment, the costs increase for low-income households and the utility and decrease for high-income households (Fig. 2d–f). Temporary water sourcing creates more variability in surcharges and leads to more even bill increases across populations (Supplementary Fig. 2).

We also quantified the impact of drought persistence and intensity on affordability across utility decision-making options. We found that drought intensity has the greatest impact on affordability as intense droughts require additional mitigation through temporary water sourcing or demand curtailment. Longer droughts extend the length of time bill increases are incurred, but still remain less expensive than intense droughts, and increase costs at a lower rate (Fig. 2). The greater

cost of drought intensity is a direct result of the greater LCOW from mitigation compared with infrastructure decisions.

Temporal dynamics of bill changes

In addition to total cost increases during a drought, we examined the cumulative household affordability impacts resulting from utility decision-making and drought scenarios over time to compare the temporal dynamics of bill changes. For high-income households, the results indicate that the decision-making options that lead to the lowest total bill increases have the lowest cumulative cost at any point through the drought. However, for low-income households, the decision-making options that lead to the lowest cumulative affordability outcomes change throughout the course of a drought. This effect is mediated by temporary water sourcing and demand curtailment. We show aggregate water availability, the amount of mitigation required by each decision-making option and cumulative additional cost increases per month for low- and high-income households compared with non-drought periods in Fig. 3 (top row to bottom row, respectively). In Fig. 3i–p, the line showing the lowest value for a given point on the x axis represents the utility decision that results in the lowest cumulative cost increase up to that time period.

For high-income households and the utility, building nothing results in the lowest total cost increases as well as the lowest cumulative cost increases at any point throughout any drought scenario (Fig. 3m–p). However, for low-income households, the decision-making options that lead to the lowest total cost increases do not have the lowest cumulative costs throughout the drought. This implies that there is no unilaterally best utility decision-making option across all drought scenarios, nor throughout the duration of each drought for low-income households, and indicates that low-income affordability is driven by the interaction of drought duration and utility decision-making. This is visualized by the lines crossing in Fig. 3i–l.

This demonstrates that low-income households are potentially vulnerable to uncertainty in future drought conditions. In our case study, for a utility aiming to minimize the affordability impacts of

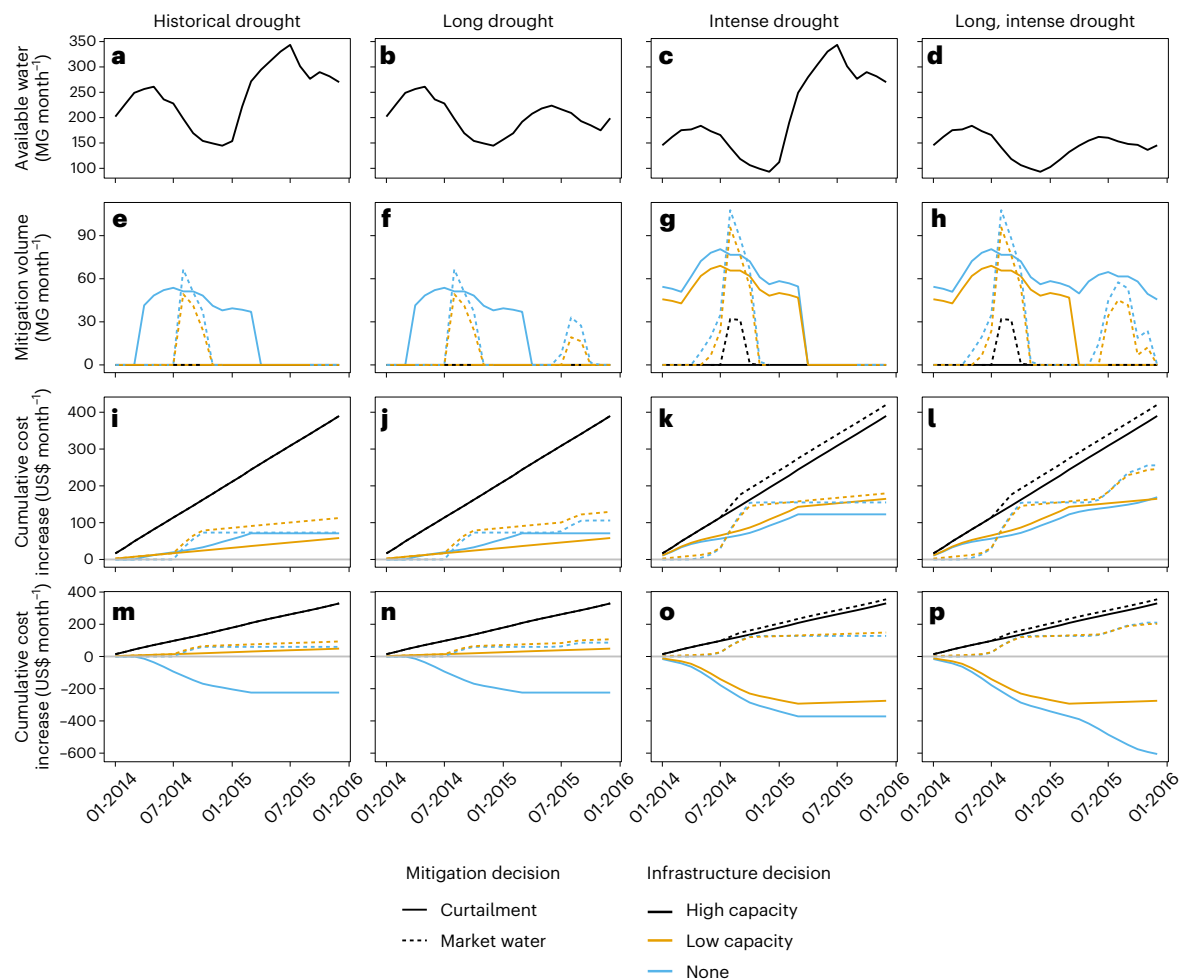


Fig. 3 | Cumulative changes in affordability during drought. a–p. Aggregate water availability from all sources (a–d), volume of mitigation required (e–h) and cumulative cost increases for low-income households (i–l) and high-income households (m–p), compared with a non-drought year, for different drought

scenarios: historical (a,e,i,m), long (b,f,j,n), intense (c,g,k,o) and long and intense (d,h,l,p). A 6-month smoothing was applied for clarity in panels a–d. Each aspect was analysed for different mitigation and infrastructure choices.

droughts for high-income households, one decision would lead to the best total affordability and cumulative affordability outcomes throughout a drought regardless of drought scenario. However, a utility would need to know the specific duration and intensity of a drought to minimize the affordability impacts of droughts for low-income households, as incorrect decision-making with respect to drought length or intensity only creates negative outcomes for low-income households.

We also note that under our present modelling assumptions, the high-capacity desalination plant never provides favourable affordability outcomes. This is due to the capacity and levelized cost: in the worst drought scenario, for affordability, it is better to implement the low-capacity water recycling programme and mitigate the remaining deficit. However, this would likely change over a longer time horizon. By comparing the LCOW for mitigation and the high-capacity desalination plant, we estimated that a long, intense drought approximately 1.8 times the length of the scenarios tested in this work would lead to the desalination plant providing the most favourable affordability outcomes.

Demand response

One contributing factor to the difference between total utility cost and household affordability is changing household water use in response to price increases. We modelled each household as having a response to changing water rates using a price elasticity of demand (PED)

parameter (Methods). Estimates of PED for household water use vary across regions¹⁸, thus we varied PED between 0 and 0.8 in increments of 0.1, reflecting inelastic but non-zero price elasticity of water demand. A PED of 0.1 means a household will respond to a 10% increase in price with a 1% reduction in household water use.

We found that greater ratepayer price elasticity largely improves affordability outcomes for all stakeholders (Fig. 4). Low-income households experience smaller bill increases with greater price elasticity (Fig. 4a). High-income households experience a reduction in their bill decreases due to drought (that is, their bills still go down during droughts, but by less). These results stem from the household reaction to price changes that follow from increased utility costs. At higher PED values, utility decisions with higher cost increases lead to greater reductions in demand. This highlights the connection between PED and adaptive capacity: when households respond to price signals, they add virtual water-supply capacity to the system. This happens across all supply expansion and mitigation measures, and is more pronounced for more expensive options. This can be seen in Fig. 4a by the slopes of the lines connecting the costs at different PED values.

We also found that heterogeneous price sensitivity across income classes impacts all households. We tested a scenario in which we decreased the price responsiveness of low-income households and a scenario in which we decreased the price responsiveness of high-income households (Methods). We found that when either income

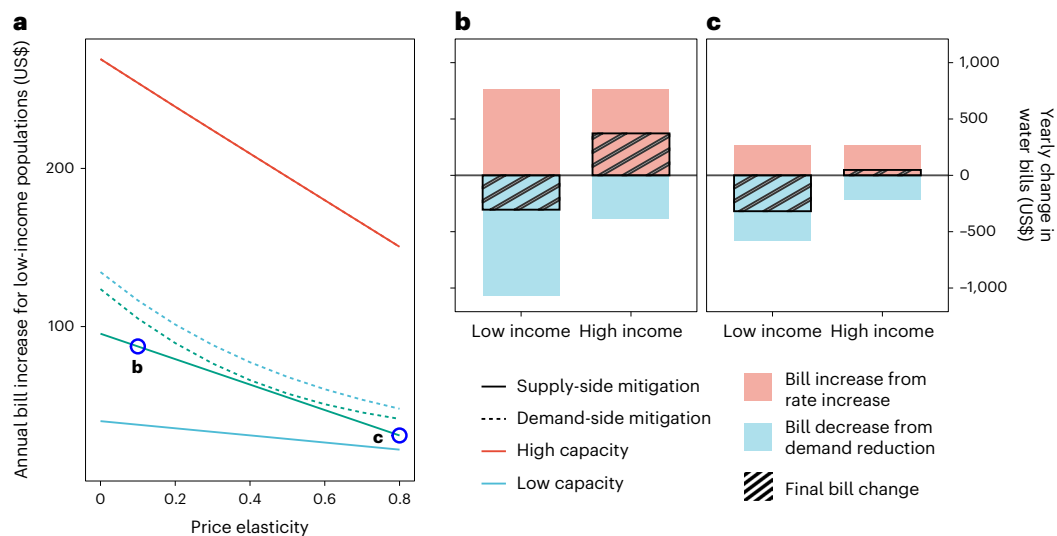


Fig. 4 | Impact of price elasticity of demand on costs. **a**, Annual cost increases for low-income populations under increasing levels of price elasticity. Solid lines show supply-side (market water) mitigation and dashed lines show curtailment. **b,c**, Annual total bill changes for low- and high-income households when the

price elasticity is 0.1 (**b**) and 0.8 (**c**). Low-income households are those with an income below US\$36,000 yr⁻¹, and high-income households are those with an income over US\$135,000 yr⁻¹.

class shows less price responsiveness, bills increase for all households, but less so for the more price-responsive group (Supplementary Figs. 6 and 7). Thus, if any income class shows less price sensitivity, demand reductions in response to price changes are limited. This ultimately leads to greater total water demand, and subsequently greater deficits and surcharges.

Infrastructure lock-in

We found that water bill changes during droughts are a function of the pre-drought base water rates. Water-supply infrastructure decisions made pre-drought therefore affect affordability during droughts (Fig. 5). We show this by raising pre-drought water rates to reflect a scenario in which the utility has previously invested in a high-capacity desalination plant. This phenomenon is called infrastructure lock-in and occurs when utilities invest in expanding water-supply capacity in anticipation of future need, but due to hydrological uncertainty do not ultimately require the additional capacity⁴². Lock-in represents a potential negative consequence of large-scale supply investment due to increased and unneeded financial liability.

We found increased costs to utilities incurred through lock-in also impact affordability, with impacts mediated by temporary water purchases and demand curtailment. Elevated base water rates exacerbate drought-related bill increases for low-income households and bill decreases for high-income households when demand curtailment is used (Fig. 5). This effect holds across all drought scenarios and results from the greater revenue loss that occurs for a given amount of curtailment when base rates are higher. This necessitates a greater surcharge to make up the deficit. Elevated base water rates reduce drought-related cost increases for high- and low-income households when purchasing market water to add temporary supply (Fig. 5). This reduction occurs because of price responsiveness, as the increased costs from higher base rates lead to a greater reduction in household demand.

Discussion

We have developed a socio-hydrological modelling framework to assess the drivers of household affordability during droughts, including utility cost increases, drought characteristics, household water use and pre-drought utility decision-making. This addresses a critical limitation of current water-supply planning: the lack of spatiotemporal resolution

and socio-hydrological feedbacks required to quantify the drivers of household water affordability during droughts. The results from the application demonstrate the nuance and trade-offs between utility-scale decision-making and affordability for high- and low-income households. Importantly, low-income households are disproportionately impacted by demand curtailment coupled with increased water rates and, more broadly, we found that low-income households are the most sensitive stakeholder to utility decision-making and variable drought characteristics.

Incorporating multiple stakeholders into socio-hydrological models is critical to understanding affordability during drought and non-drought periods. This work adds to a substantial body of existing literature emphasizing that affordability calculations based on regional median levels of household income and water use fail to capture the full scope of affordability impacts on households. Given that we see many scenarios in which low-income households experience bill increases, and high-income households experience bill decreases, reporting only aggregated or median bill changes would likely hide the disproportionate impact of droughts on low-income households. Additionally, we see interactions between stakeholders when high- and low-income households have differing price responsiveness. When either low- or high-income households show less demand response to changes in water price, overall residential water demand is higher, leading to greater mitigation needs and increased surcharges for all populations. This connection between the actions of one stakeholder group and the outcomes of another further emphasizes the importance of incorporating multiple stakeholders into socio-hydrological models to assess distributional equity.

We also see a consistent trade-off between utility-scale decision-making and affordability, especially in the impact of expanding water supplies on low-income water affordability. We found that under-expanding supplies relative to a given drought worsens affordability outcomes for low-income households. However, under certain circumstances, infrastructure lock-in also worsens affordability outcomes. This parallels a long-established trade-off in infrastructure planning under uncertainty between maximizing reliability through building larger infrastructure and minimizing cost but exacerbating impacts for vulnerable households. Furthermore, there is no unilaterally best decision-making option for low-income households across drought

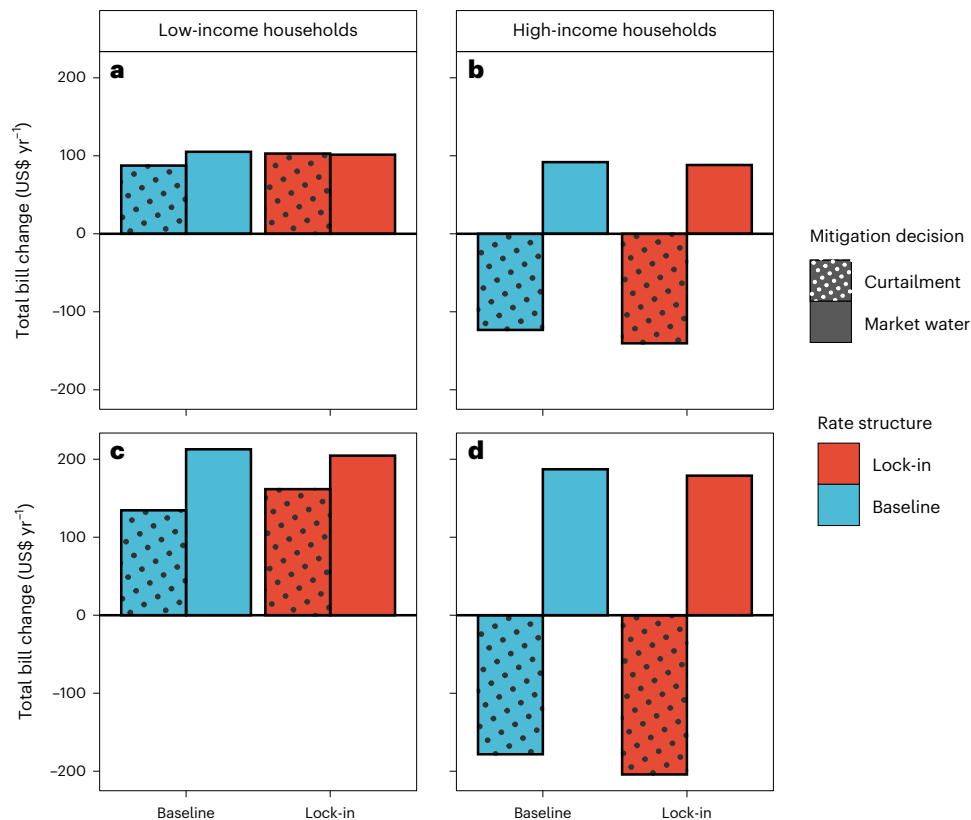


Fig. 5 | Effects of infrastructure lock-in on cost increases. a–d, Total annual cost increases for low-income households (a,c) and high-income households (b,d) during a historical drought scenario (a,b) and a long, intense drought scenario (c,d).

scenarios, emphasizing that performing an affordability analysis at only a household or utility scale may be incomplete. Ongoing work is aiming to extend the computational planning tools used to address this trade-off in systems-level water resources planning to incorporate household-level water affordability.

A major challenge in this work was choosing the measures to quantify affordability during droughts. The persistence of droughts necessitates developing additional affordability metrics that capture the long-term financial burden of accumulated, drought-related rate increases. Here, we used annual bill increases through a drought as our measure of affordability for ease of comparison across household classes, but recognize that this is just one of many ways to quantify affordability over time. For comparison, we performed the same set of analyses and instead quantified the maximum one-month increase in rates experienced by high- and low-income households (Supplementary Fig. 2). Our findings remain largely consistent when looking at maximum bill increases compared with total bill increases, but the two do not perfectly correlate with the mitigation measure driving the difference: demand curtailment leads to rate increases spread out over a longer period of time, while market water purchases focus rate increases in short periods. Future work will explore additional metrics to capture the impact of temporal variability in droughts on affordability and how utility decision-making can be optimized with respect to low-income affordability over a larger number of drought scenarios.

Modelling household water use was another key component of this study. We modelled households as having an inelastic but non-zero response to changes in price. A considerable amount of work has been carried out aiming to estimate the price elasticity of household water demand, with current best estimates ranging from 0.1 to 0.8 (ref. ¹⁸). We performed our analysis assuming a price elasticity of 0.35, based on a suggested value from Dalhuisen et al. ¹⁸. We aim to extend future

work to include empirically derived price elasticity values that differ according to household income and other demographic characteristics, as well as other mechanisms for increasing water rates in response to utility cost increases. This approach could allow water demand estimates to be developed that capture (1) city-specific behaviour, (2) changes in time resulting from demand hardening and (3) correlations between drought conditions and water demand. Demand hardening is especially important to consider when evaluating drought impacts, as persistent or repeated droughts lead households to make permanent changes to water use, for example, installing water-efficient appliances and drought-tolerant landscaping. This limits the ability of repeated curtailment to successfully mitigate water shortages.

We note that there are a myriad of solutions to mitigate drought impacts and address affordability that we have not included in our model but that would likely have favourable outcomes. One possibility is to raise water prices during non-drought periods to promote conservation instead of raising them in response to increased drought-related costs. This may worsen affordability through increased costs or, depending on the price elasticity, could improve affordability as long-term conservation and efficiency lead to lower water use. However, if costs increase dramatically, conservation pricing could drive low-income households to conserve more than is healthy. Additionally, hardening demand could prove extremely costly in future droughts as it limits the utility of curtailment as a mitigation strategy. Similarly, there are many existing and under-development local, state and federal low-income rate-assistance programmes that typically take the form of rebates or discounted marginal water rates⁴³. Similarly, state or federal grant programmes could be designed to provide assistance to utilities to minimize rate increases. In ongoing work we are evaluating the efficacy of different low-income assistance programme structures under drought conditions.

Finally, while Santa Cruz is in many ways representative of large public water utilities in California, there are specifics of the case study we have chosen that prevent these results from being universally applied. First, Santa Cruz was a heavily water-stressed region during California's most recent drought¹⁰. Additionally Santa Cruz is coastal, which opens the possibility for developing high-capacity desalination plants. However, we note that we only modelled increased capacity, not the specifics of the technology in our approach, meaning that this approach would generalize to any additional high-capacity water sources. The utility is also public, which constrains how curtailment is implemented, and this may differ should it be an investor-owned utility. Finally, alternative regional demographics may change revenue losses during curtailment, which may affect how surcharges are applied to high- and low-income households. We detail the specifics of how changes in these attributes impact our results in the Methods.

Methods

We have developed a socio-hydrological model based on Santa Cruz, California, a large retail water system on the central coast of California that was heavily impacted by a drought from 2011 to 2016¹⁰. Socio-hydrology models focus on developing an understanding of how coupled human hydrological systems function with the aim of identifying the critical components, nonlinear interactions and feedbacks³⁶. We used our framework to examine the coupled dynamics of water utilities, human behaviour and hydrology that govern water affordability during droughts. Broadly, we did this in three parts. First, we modelled utility decision-making in response to hydrological drought scenarios, where utilities choose drought resilience measures to respond to drought and adjust water rates accordingly. Second, we linked drought resilience measures and rate increases to household water use through a price elasticity parameter. Third, we estimated household water use and calculated household water bills throughout the duration of a drought.

Water resources

We modelled source water supplies and infrastructure for water storage, conveyance and treatment. Santa Cruz, California has three surface water sources and one ground water source (see study area in Supplementary Fig. 1). One of the three surface water sources inflows to Loch Lomond, a reservoir with a capacity of 2,800 MG. The reservoir is the only source of water during prolonged droughts and is heavily managed with a required environmental flow release of 20 MG d⁻¹. The water balance for our systems model is shown in equation (1).

$$S_{t+1} = S_t + I_t^N + I_t^R + I_t^G + I_t^B + I_t^{WM} - D_t - W_t - E_t - C_t \quad (1)$$

Here, S_t is the storage in the reservoir at time t and S_{t+1} is the storage in the reservoir at time $t + 1$. I_t^N , I_t^R , I_t^G , I_t^B and I_t^{WM} are inflows from the North Coast creeks, San Lorenzo River, Newell Creek, groundwater, additional built infrastructure and water-market purchases, respectively. D_t is the total municipal demand in time period t adjusted for changes in curtailment and price elasticity, W_t is managed reservoir withdrawal, E_t is net reservoir evaporation calculated from Santa Cruz's projected water supplies⁴⁴ and C_t is an environmental flow release of 20 MG d⁻¹.

In April of each year, the management policy for the year is determined on the basis of the available forecasts of water demand and availability of the city's sources. Given the available supply and projected demand, the withdrawal from the reservoir is limited such that the reservoir storage in October will be sufficient to provide enough water given that the following 2 years have the water supply of the driest year on record. If in April there is still projected to be a water deficit, mitigation actions (described below) are taken to meet any additional deficit.

Drought scenarios

We created four hydrological drought scenarios for the years 2009–2016. The first was based on the historical hydrology experienced

by the system during California's 2011–2016 drought. We used water rights data to quantify the amount of water used by the utility from each source. We generated alternative drought scenarios for each water source by varying the persistence and intensity of the 2011–2016 drought. To create a more intense drought, we increased de-seasonalized anomalies by a factor of 1.5, and to create a longer drought, by duplicating the anomalies of the worst drought years—2014 and 2015—into 2016 and 2017. The longer, more intense drought scenario was created by duplicating the amplified anomalies in 2014 into 2016 and 2017. These changes were applied to all three surface water sources. In all scenarios, we used historical groundwater withdrawals as they represent <5% of the water supply for the city.

Infrastructure

We analysed scenarios in which the utility expands water supplies by building additional water-supply infrastructure. We analysed two infrastructure options in this work: a 2.5 MG d⁻¹ high-capacity desalination plant and a 0.5 MG d⁻¹ low-capacity water reuse project. The water reuse option would build an additional water treatment plant for treating tertiary effluent that is subsequently used for irrigation at 34 customer sites in the city. These irrigation sites currently use fresh water supplies; thus, replacing them with recycled water increases available municipal fresh water supplies by an estimated 0.5 MG d⁻¹ (ref. ⁴⁵). These options were selected after consulting reports outlining all potential supply expansion options for the example city and have the lowest LCOW among all low- and high-capacity options.

We assumed that all infrastructure options are financed with a 30 year loan at an interest rate of 3%, terms based on California's general obligation bonds, which are frequently used to finance these types of infrastructure project⁷⁴⁴. The high-capacity option has a total cost of US\$115 million, additional annual operational cost of US\$3.3 million, with a LCOW of US\$4,300 AF⁻¹. The low-capacity option has a total cost of US\$20.4 million, an additional annual cost of US\$330,000 and it provides 178 MG yr⁻¹ of capacity for a levelized cost of US\$2,600 AF⁻¹. Our model assumes that all infrastructure is built and fully operational at the beginning of each simulated scenario and that the additional cost of building infrastructure is passed on in water rates, as described in the following sections.

Mitigation

During droughts, the available freshwater supplies may not meet demand. In this case, the deficit between supply and demand must be made up either by reducing demand through curtailment or by temporarily augmenting supply via purchases on the water market. We modelled curtailment as a fixed percentage reduction of residential demand. The percentage was estimated every April to meet the expected deficit without overdrawing on the reservoir, reflecting current drought management plans in Santa Cruz⁴⁶. We assumed that the curtailment request is fully met by all households, stays in effect until the end of the calendar year and has no lasting impact on demand after the drought.

To model temporary supply-side water augmentation, we assumed that our example system has access to a large water market and the ability to purchase water as necessary on a month-by-month basis. Market water costs vary significantly, even under similar drought conditions⁴⁷. We assumed that the unit cost of market water is equal to the price that residential consumers pay. This results in an equal LCOW for conservation and market water purchases of US\$7,200 AF⁻¹. Our motivation for this modelling choice was twofold. First, we aimed to reduce the influence of financial market variability on our results so that they do not obscure process-based insights. Second, by giving curtailment and market purchase the same unit price, we could directly compare differences due to behaviour change and implementation timing. To validate our approach we modelled historical water availability data during the 2011–2016 drought in Santa Cruz. In 2014, the city asked

residents to curtail water use by 25% in response to the drought⁴⁶. We estimated that a 27% curtailment was necessary to balance water supplies and demand during the same period.

We also modelled drought mitigation occurring through supply-side measures. Water transfers are an increasingly common way for utilities to meet water deficits through supply-side means⁴⁸. We incorporated this by assuming that our example system has access to a large water market and the ability to purchase water as necessary on a month-by-month basis. Market water costs vary significantly, so to avoid results biased by a potentially high or low water cost, we fixed the unit cost of market water to be equal to the unit cost to buy water under the current retail rates. This results in a LCOW for conservation and market water purchases of US\$7,200 AF⁻¹. Our aim by this was to directly compare supply- and demand-side mitigation as purchasing one unit of water on the market will have the same financial impact on the utility as reducing demand by one unit.

Utility finances

The current rate structure has a fixed charge with four tiers of increasing block rates for progressively higher water uses, typical of many urban water rates⁴⁹. We modelled household water bills as a sum of a baseline bill and three types of additional cost that a utility can incur: (1) servicing a debt payment and increased operational cost from building infrastructure, (2) additional one-time costs to purchase market water as a form of supply-side mitigation and (3) an increase in rates to account for revenue loss due to curtailment. These additional costs are passed on directly to ratepayers through surcharges. In California, Proposition 218 limits the ability of utilities to increase water rates and the most common way drought-related surcharges are added to bills is by evenly distributing any cost increases across the base of ratepayers⁴⁵. A study of selected California utilities with drought-specific water rates found that 75% use fixed surcharges to recover drought-related costs⁴⁵. In the specific case study of Santa Cruz, we predefined drought surcharges in line with Proposition 218 guidelines⁵⁰. More broadly, revenue neutrality is a goal of conservation-oriented rate setting⁵¹ and is generally aligned with the American Water Works Association principles of water rate setting⁵².

This pass-through mechanism means that all bills would go up by the same amount. We validated our billing model against the current surcharges used by the City of Santa Cruz. The City assigns a per bill charge of US\$2.45, US\$6.12 and US\$9.79 to recoup annual deficits of US\$1, US\$2.5 and US\$4 million, respectively. Our model calculated a charge of US\$1.75, US\$5.54 and US\$9.26 for the same cost recovery amounts.

Demographics and ratepayer behaviour

We calculated residential water use in the service area as the sum of household water use across income classes. We estimated household water use separately for 16 income classes using an econometric model that includes price and income elasticity. For a given household class c , we calculated their demand in month t , d_c^t , as:

$$d_c^t = \bar{d}^t m_c I_p I_Y (1 - r^t) \quad (2)$$

Each class is an income bin from US\$10,000 up to US\$250,000+ yr⁻¹, taken from the standard 16-node census income distribution^{53,54}. For each class, we began with a cyclostationary, per-capita water use for the region in month t , $\bar{d}^t$, taken from reported monthly water use in Santa Cruz⁴⁴. This was multiplied by m_c , the average household size for houses of class c , calculated using Integrated Public Use Microdata Series (IPUMS) microdata⁵⁵. This water use was then adjusted for changes in price by a factor I_p using a price elasticity parameter ϵ_p such that

$$I_p = 1 + \epsilon_p \left(\frac{p^{t-1} - p^{t-2}}{p^{t-2}} \right) \quad (3)$$

where P^t is a household's water bill in time period t and P^{t-1} and P^{t-2} are the bills for time $t-1$ and $t-2$, respectively. Similarly, water use was adjusted for changes in income relative to the median by a factor I_Y such that

$$I_Y = 1 + \epsilon_Y \left(\frac{Y_c - Y_{MHI}}{Y_{MHI}} \right) \quad (4)$$

where Y_c is the household income of class c , Y_{MHI} is the median income of the population and ϵ_Y is the income elasticity of demand. Curtailment in time period t , r^t , is represented as a number from 0 to 1, where $r^t = 0$ indicates no curtailment and $r^t = 1$ indicates 100% curtailment. Curtailment was applied across households uniformly (for example, r does not vary across classes). Finally, the class demand, d_c^t , was multiplied by the count of households of each income bin in the service region, H_c , which is tabulated in the 2015 American Community Survey⁵⁶, and summed over all classes to give the total residential utility demand in time t , D_{utility}^t :

$$D_{\text{utility}}^t = \sum_c d_c^t H_c \quad (5)$$

Our approach to calculating household water use was based on current literature suggesting that household size is a significant driver of indoor water use and household income a driver of outdoor water use²¹. We adjusted for household size by calculating the average household size of each income class, m_c . Similarly, we adjusted for water use based on income using an income elasticity, ϵ_Y , of 0.15, using a convention for positive income elasticity in which a marginal increase in income leads to a marginal increase in water use. This value was taken from a recent meta-analysis of retail water income elasticity values⁵⁴ and used for all analyses and figures presented in this paper. For completeness, we also tested two alternative income elasticity values, namely 0 and 0.4, and have included the results in Supplementary Figs. 3 and 4. Except for experiments in which we tested the sensitivity of ϵ_p , we used a constant value of 0.35 across income classes, taken from a meta-analysis of price elasticities of retail water⁴⁸. Here, we used a convention in which a positive price elasticity indicates that a marginal increase in price leads to a marginal decrease in water use.

Sensitivity analyses

We performed a number of additional sensitivity analyses in addition to those presented in the Demand response section. First, we analysed alternative price elasticity estimation approaches. Residential water use differs from many other consumer goods in that water users alter their consumption in response to changes in average rather than marginal prices⁵⁷⁻⁵⁹. We included this in our baseline model by calculating price elasticity on the basis of changing average price, which leads to households responding to the addition of flat surcharges. We also modelled an additional scenario in which consumers respond to changes in marginal price, but flat surcharges are applied, altering the average price but eliciting no change in the marginal price of water (Supplementary Fig. 5). In this alternative model, consumers do not respond to price changes. The results show similar dynamics to the price elasticity sensitivity results: a small or non-existent price sensitivity increases bills for all households as they do not lower their water consumption in response to increased rates.

We also tested scenarios in which we varied income elasticity (YED). The results in the main text are reported using an income elasticity value of 0.15, representing a suggested income elasticity value from Havranek et al.⁵⁴. We also ran sensitivity analyses using income elasticities of 0 and 0.4 (Supplementary Figs. 3 and 4). For a YED value

of 0 compared with 0.15, water use is higher for low-income households and lower for high-income households. As Santa Cruz has a higher proportion of high-income households than low-income households, this reduces demand by approximately 10%. When YED was increased to 0.4, water demand was higher by about 20%. At lower YED values, the cost increases due to drought are largely the same for high- and low-income households (Supplementary Fig. 3). This occurs because their baseline water use is only differentiated by differences in household size. More importantly, the lower total residential demand eliminates the need for drought mitigation, which leads to bill increases for low-income households and decreases for high-income households when curtailment is used. At higher elasticity values (Fig. 4), demand is significantly increased, leading to greater curtailment. The disproportionate impact of curtailment on high- and low-income bill increases is exacerbated, and total costs increase for the utility.

Finally, we performed a sensitivity analysis in which we let price elasticity vary with income (Supplementary Figs. 6 and 7). There is a growing body of literature that indicates heterogeneous price responsiveness with respect to income or water use. Some work indicates that low-income customers are more sensitive to price than high-income households⁵⁹, while other work provides contrary evidence that “price elasticity is largely invariant to household wealth” and high water users are more price responsive⁶⁰. Given the discrepancy between these findings, we performed two additional analyses in which we let price elasticity vary with income. In the first, we assumed that high-income households have 0 elasticity, and price responsiveness increased linearly as income decreased until the lowest income classes had a PED of 0.35. This demonstrates a finding similar to that of El-Khattabi et al.⁶⁰ in which low-water-use households respond to price signals and high-water-use households do not. In the second sensitivity analysis, we assumed that low-income households have 0 elasticity, and price responsiveness gradually increased across income classes until the highest income classes had a PED of 0.35. This experiment demonstrates the case in which high-income households respond to price signals but low-income households do not.

Case study attributes

The aim of this work was to develop process-based insights using realistic and generalizable model assumptions, not to design context-specific solutions for Santa Cruz. While the approach is fully general and can be readily applied to other cities, aspects of the specific case study that we chose limit the generalizability of the results. We describe these attributes here.

The City of Santa Cruz operates as a public utility and is accordingly governed by California Proposition 218 (ref.⁵⁰), which strictly governs water rate setting, including drought surcharges. The disproportionate impact of droughts on low-income households will apply when flat drought surcharges, or other regressive surcharge structures, are applied. Flat surcharges comprise the majority of surcharges imposed in California⁴⁵. As an alternative to public utilities, investor-owned utilities (IOUs) are private utilities and in California are subject to regulation by the California Public Utilities Commission. Rate increases from IOUs must be proposed in advance and justified on the basis of utility expenses, details of any infrastructure improvements and expense projections⁶¹. This process happens approximately every 3 years. Given the alternative regulatory structure and utility business model, drought impacts on low-income households in IOU service areas may take the form of gradual rate increases over time rather than short-term impacts.

Current and available water resources also shape the drivers of water affordability. Santa Cruz does not have access to significant groundwater sources (they comprise approximately 5% of available supplies). We hypothesize that utilities with greater access to groundwater resources would be able to use groundwater to mitigate drought impacts by using groundwater when surface water is scarce. Santa

Cruz is also a coastal community. Our high-capacity infrastructure option comprises building a costly desalination plant, and while it does not provide the best affordability outcomes in any scenario that we tested, this type of high-capacity, always-available water source may not be available for all utilities. We also assumed that additional supply infrastructure expansion and temporary water sourcing increase the unit cost of supplying water, which is likely the case in water-stressed regions in which existing supplies have been explored, but this may not be the case in areas with significant freshwater supplies.

Finally, many of our results are shaped by the region's demographics. We used the distribution of household income as inputs to our demand model, and in Santa Cruz there is a high proportion of households in the highest income bracket. We hypothesize that alternative household income distributions would impact affordability as this would change the proportion of utility revenue from high and low water users, thus affecting the revenue losses during curtailment.

Data availability

All raw data used in this manuscript are freely available: hydrological scenarios derived from California Water Rights Databases⁶² (https://www.waterboards.ca.gov/waterrights/water_issues/programs/ewrims/), population and demographic data from IPUMS Microdata samples⁵⁵, infrastructure scenarios from consulting reports⁴⁵ and Urban Water Management Plans⁴⁶ (<https://wuedata.water.ca.gov/>).

Code availability

The relevant code used for water system simulation and bill calculation is available from the corresponding author upon request.

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Author contributions

B.R. and S.F. designed the research and developed the paper. B.R. and S.F. designed the modelling approach and B.R. developed the

codebase and ran experiments. B.R. and S.F. analysed the data and designed the visual elements of the paper. Both authors wrote and critically revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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