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Urban water affordability crisis exacerbated by climate change

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Climate change intensifies water stress globally, necessitating expensive infrastructure interventions to maintain reliable supply. To fund infrastructure, utilities often raise rates, increasing water bills for low-income households. The resulting affordability impacts depend on utility costs and interactions between rate design, financing, climate and household demands. Here we develop a city-scale modelling framework to estimate climate change impacts on water affordability, integrating climate, utility adaptation decisions and demand. In Santa Cruz, California, we find that climate change alone could double water bills by mid-century, leaving an additional 7–16% of Santa Cruz households with unaffordable water. Our results suggest that climate change may lead to greater water affordability challenges than previously estimated in hotspots where supply is vulnerable to climate change. This highlights the need for policy intervention and financing to ensure climate adaptation does not compromise affordability. The magnitude of climate-related affordability challenges depends on local context, requiring city-scale assessments.

Water affordability is a growing challenge in high-income countries across the globe[1–5]. Over the past two decades, water rates have risen three times faster than inflation[6,7], driven primarily by deferred maintenance and ageing infrastructure. If historical trends continue, more than one-third of US households could face unaffordable water bills within a decade[1]. However, emerging contaminants requiring advanced treatment and climate change necessitating new supplies are compounding longstanding cost pressures for utilities[1,8,9]. Unaffordable water can limit access for drinking and hygiene[2], force difficult trade-offs with other necessities such as healthcare[3,10] and pose negative health impacts[11], disproportionately impacting low-income and minority communities[2].

In many cities, climate change challenges utilities' ability to provide reliable, affordable water access[12–14] by straining supplies[12,13] and driving demands higher as temperatures rise[15,16]. On the supply side, climate change can alter the frequency, severity and duration of droughts[17,18] and cause drier baseline conditions[14,19]. Utilities respond by either reducing demands or expanding supplies[20], often through costly infrastructure projects that increase rates for customers[8,21]. Utilities manage demands using curtailment measures during droughts or water-use efficiency programmes, increasing water rates through surcharges needed to pay for lost volumetric revenue or investments in efficiency upgrades and monitoring equipment[20,22].

Recent studies document growing affordability challenges[1,2,4] but offer limited insight into future trends. Water affordability projections typically extrapolate historical trends but without analysing specific cost drivers such as climate that may change in the future[1]. In addition, social and institutional factors such as demand patterns and rate structures affect affordability[23], but estimates typically neglect these factors[5,24]. One study highlights cost–demand interactions, demonstrating how low-income rate assistance programmes, which decrease household water costs, can increase use[7]. In addition, most empirical studies assess affordability at one point in time[3,5], neglecting seasonal and temporal variability that may exacerbate short-term challenges[4,23,25,26]. High-quality projections of future water affordability challenges are essential to developing effective and sustainable policy solutions at the city, state and federal levels.

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Drought and climate change may prompt costly water infrastructure investments, but their affordability impacts are poorly understood. Extensive research assesses water supply infrastructure needs due to climate change, but focuses on utility-scale costs and performance[27–30] rather than household-scale affordability[31]. In addition, infrastructure financing and rate design are typically analysed from a utility rather than household cost perspective[31,32]. Recent work advances understanding of climate-related infrastructure impacts on low-income households but does not consider demand feedbacks or financing mechanisms[33]. Other work models affordability impacts of rate increases due to droughts but focuses on short-term impacts, not climate change[22,34]. To our knowledge, no study has comprehensively assessed the integrated climate, infrastructure and demand drivers to quantify climate change impacts on water affordability.

Our research objective is to quantify the impact of climate change on urban water affordability. We develop a rigorous city-scale modelling framework that captures the integrated climate, utility adaptation decisions and demand drivers shaping household affordability burdens in US cities. We combine a hydrological and water supply system model with infrastructure financing and rate design models, and an econometric model of household water demands. We assess the affordability impacts of utility adaptation decisions needed to maintain reliable water supply in future climates. This can include new infrastructure investments, financing mechanisms, rate structures, assistance, curtailment policies and efficiency programmes. We hypothesize that climate change could create water affordability hotspots, where existing affordability challenges are exacerbated in cities with water supply vulnerability and limited demand management opportunities.

Here we complete a city-scale assessment of climate change impacts on water affordability using Santa Cruz, California as a case study and focusing on mid-century impacts. Santa Cruz has low residential water use owing to the city's previous drought experiences[35], limiting the scope for low-cost adaptation options such as demand reduction via curtailment or efficiency policies. It is also reliant on local surface water, making it vulnerable to drought[36]. By examining a city that has largely exhausted lower-cost options for climate adaptation such as demand-side management, we focus on costly, long-term infrastructure decisions and highlight challenges probably faced by other cities with similar climate, behavioural and regulatory conditions.

Results

Affordability implications of climate adaptation

We present a modelling framework to quantify the water affordability impacts of climate change and related adaptation measures on water supply and demand. Our model captures the interacting climate, utility adaptation decisions, financing and demand drivers that determine household affordability (Fig. 1a). First, we input future climate scenarios, developed by combining a climate model ensemble with a stochastic weather generator, into water supply systems models, which simulate river flows at the reservoir and diversions, and water allocations from the diversions to the water treatment plants. Second, we model utility adaptation decisions using a risk-of-failure (ROF) approach in which utilities take action in response to declining storage levels. Third, we assess the water rate impacts of those interventions using an infrastructure financing and rate design model. Using Santa Cruz as a case study, we focus on utility decision-making around infrastructure investments, evaluating multiple planning scenarios that determine when and what new infrastructure is developed. Fourth, we simulate household water use patterns as a function of demographics, climate, water costs and housing characteristics, capturing dynamic feedback between household behaviours, water supplies and utility decisions. For example, when the city builds new infrastructure, they pay for that infrastructure by increasing water rates; when water bills rise, households use less water, altering how much water the system needs. Finally, our framework results in estimated water bill and affordability burdens (the percentage of household income spent on water bills) across income groups.

Using this framework, we assess how different climate scenarios drive affordability impacts. Figure 1b,c shows two illustrative, contrasting climate simulations selected to visualize the mechanisms through which infrastructure development affects affordability for two sample households. In one plausible moderate, cool climate simulation, no new infrastructure is needed, although the low-income household is already spending more than the 2.5% affordability threshold recommended by the US Environmental Protection Agency (EPA)[1,3,37] (Fig. 1c). In one plausible dry, hot climate simulation, declining reservoir storage levels trigger construction of a four million gallon per day (MGD) desalination plant, leading to rate increases and higher water bills. In this example, the affordability burden for a sample low-income household increases from 4% to 6%, while a sample high-income household has negligible impacts. These examples demonstrate how climate stress can exacerbate underlying affordability burdens for low-income households.

Unaffordable water under a drier climate

Next, we present aggregate results across many stochastic simulations. In Santa Cruz, our scenarios show that climate change could nearly double water bills, which could leave an additional 7–16% of households with unaffordable water (Fig. 2). We test four plausible scenarios that combine contrasting climates and infrastructure planning adaptation strategies: first, our 'baseline' scenario with no new infrastructure and a moderate, cool climate, similar to the present-day; second, a 'moderate climate with adaptation' in which new infrastructure is built as needed under the same moderate, cool climate; third, a 'dry climate with adaptation', in which new infrastructure is built as needed under a dry, hot climate; and fourth, an 'all climate simulations' scenario, with the entire range of climate simulations. We choose the climate scenarios to be contrasting but within the range of CMIP6 (Supplementary Fig. 1). For each climate, we develop 50-year stochastic climate simulations, developed using precipitation and temperature changes in the CMIP6 ensemble to inform a stochastic weather generator. In the scenarios with adaptation, new infrastructure is deployed as needed using a ROF approach, in which the utility develops new infrastructure when the projected risk of storage falling below a critical threshold within 2 years exceeds a defined level (Methods; Supplementary Fig. 2). The planning strategy presented here first builds a desalination plant, although alternative strategies are compared later. We analyse the periods where infrastructure investments lead to the largest rate increases, using these periods to estimate monthly reservoir storage, added water supply costs for new infrastructure, monthly water bills and affordability burdens across households, resulting in a distribution of outcomes for each scenario.

We assess the impact of climate change-driven infrastructure investments on household bills and affordability burdens in the absence of policy interventions. In the moderate climate with adaptation, building more infrastructure leads to greater water availability via higher reservoir storage compared with the baseline scenario (Fig. 2a). By contrast, the dry climate with adaptation results in decreased and more variable reservoir storage. Low reservoir levels risk supply shortfalls, triggering new infrastructure investments. Differences in reservoir storage across scenarios with adaptation drive varying supply costs, impacting household water bills (Fig. 2b). In the moderate climate with adaptation, 60% of months require no new supply costs, whereas in the dry climate with adaptation, over 50% of months require over US$1 M in additional costs to maintain reliable supply. As we assume these costs are fully passed on to households without policy intervention, infrastructure investments translate directly into substantial increases in household water bills (Fig. 2c). The 50th percentile bills increase from US$64 to US$80 (moderate climate with adaptation) or US$120 (dry climate with adaptation). The 80th percentile bills rise from US$100 to US$148 (moderate climate with adaptation) or US$204 (dry climate

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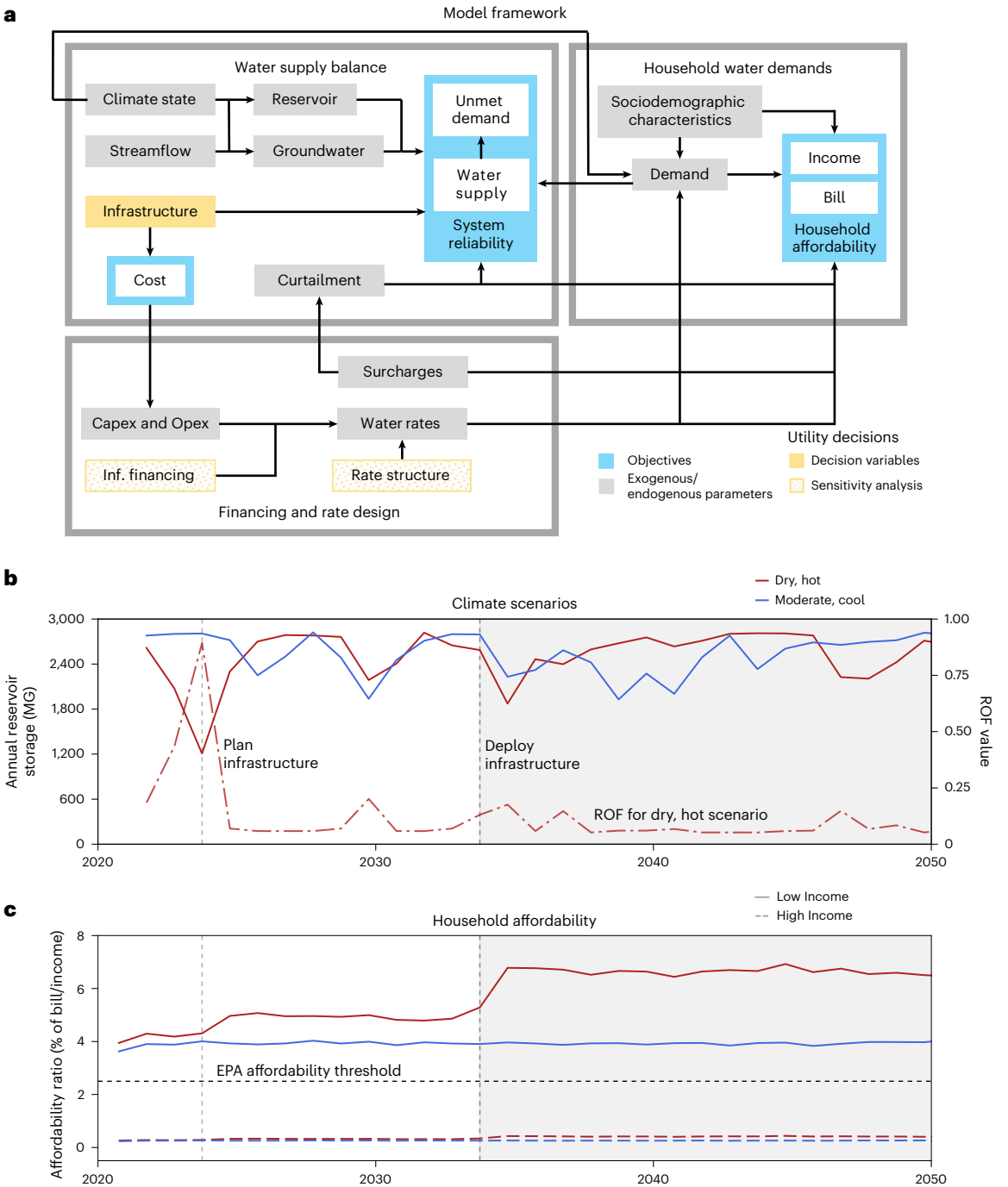


Fig. 1 | Model framework and example simulations. a, Affordability modelling framework, which integrates the water supply system with infrastructure financing, rate design and household water demand patterns. The boxes shaded in yellow indicate utility decisions, with patterns indicating decision variables assessed in this work (solid) and parameters chosen to match the case study and then tested in the sensitivity analysis (stippling). Blue boxes indicate model objectives and grey boxes indicate exogenous and endogenous parameters. Capex, capital cost; Opex, operational cost. **b**, An illustrative example to visualize the mechanisms through which infrastructure development impacts affordability, including reservoir storage levels under sample simulated dry, hot and moderate, cool climates and ROF values for the dry, hot scenario. **c**, Sample low- and high-income annual household affordability by climate scenario. We highlight the period from 2020 to 2050 for illustrative purposes, since all climate simulations are stationary. Households were randomly sampled from those below the poverty line and those in the upper quartile for income. The dashed vertical lines indicate infrastructure planning and deployment for the dry, hot climate simulation conditional on reservoir storage, total water demands and previously deployed infrastructure. The time between infrastructure planning and deployment shows the construction time, which is incorporated into our modelling framework.

with adaptation). Under the dry climate with adaptation, median water bills could nearly double from current levels.

Rising bills increase the proportion of households paying more than the EPA's affordability threshold (Fig. 2d). Currently, 19% of households exceed this threshold, highlighting the existing affordability challenges in Santa Cruz. This share could rise to 26% under a moderate climate and to 35% under a dry climate, when additional infrastructure is built for reliability. In the dry climate more than one-third of households in Santa Cruz could struggle to afford water, highlighting the scale of potential impacts without any additional policy interventions.

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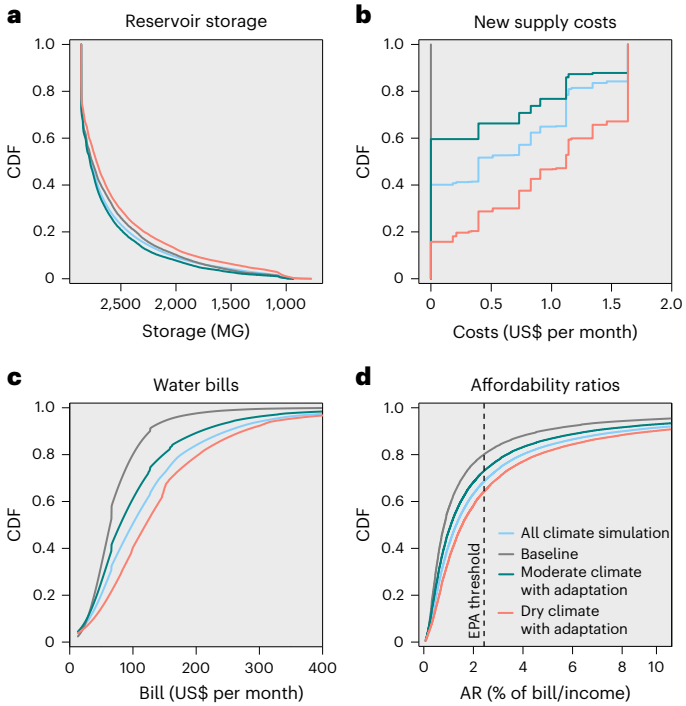


Fig. 2 | Projected climate change and adaptation impacts on household affordability. a–d, Cumulative distribution functions (CDFs) across four projected climate scenarios, each with multiple stochastic climate simulations: a baseline similar to the present-day, a moderate climate with adaptation, a dry climate with adaptation and all climate simulations for total city reservoir storage (**a**), new utility supply costs (**b**), household water bills (**c**) and household affordability ratios (**d**). Horizontal axes in **c** and **d** are truncated for visual clarity.

Low-income unaffordability under climate change

Next, we analyse how simulated demands, bills and affordability trends for low-income households compare with the remaining population in Santa Cruz, finding that while low-income demands and bills are lower, their affordability burdens are substantially higher (Fig. 3). First, we find that water demand differences across income groups and scenarios are small. Across the scenarios, average low-income water use is about 0.4 hundred cubic feet (ccf) less than other households, with 80th percentile demands increasing to around 0.6 ccf lower than all other households (Fig. 3a). Small demand differences across income groups align with previous work that finds widespread demand hardening in Santa Cruz due to household efficiency and conservation behaviours[36]. Under the moderate climate with adaptation, building infrastructure decreases demands by about 0.5 ccf, primarily due to increased water prices and household price elasticity responses. Between the moderate and dry climates with adaptation, differences in demands are negligible (<0.1 ccf), as greater temperatures and decreased precipitation counteract cost-driven demand decreases. These results suggest that the affordability impacts of climate change in Santa Cruz are driven by supply-side factors over demand-side ones. Sensitivity analysis on modelled demand parameters shows that while changing price elasticity and single-family home demands can affect affordability outcomes, climate factors play a larger role in our case study (Supplementary Text 3).

In comparison to demands, water bill differences across climate scenarios and affordability differences across income groups, are larger (Fig. 3b,c). Differences in water bills between low-income and all other income group bills are small, with median differences ranging from US$5 per month to US$11 per month across scenarios. By contrast, when we compare the baseline scenario with the dry climate with adaptation, low-income median bills increase from US$60 per month to US$111 per month (US$51 increase) and 80th percentile bills increase from US$92 per month to US$186 per month (US$94 increase). While low-income bills are smaller than other income groups, low-income affordability impacts are greater. Under the baseline scenario, median low-income affordability burdens are 3.9%, already above the EPA's threshold, underscoring existing affordability challenges in Santa Cruz (Fig. 3c). Under the moderate climate with adaptation, building infrastructure increases low-income median affordability burdens to 5.1% (for other incomes, affordability burdens increase from 0.6% to 0.8%). The dry climate with adaptation increases low-income median affordability burdens further to 7.3% (1.1% for other incomes).

In addition, low-income 90th percentile affordability burdens increase from 16% to 30% of income, a magnitude that probably forces trade-offs between essential expenditures[3,10]. This highlights the vulnerability of low-income households to water price increases driven by climate change.

Precipitation uncertainty and low-income affordability

We then assess the relative impact of different climate factors on water affordability, finding that average precipitation decreases lead to the greatest increases in affordability burden (Fig. 4). We simulate hundreds of stochastic climate simulations, filtering for different characteristics individually to assess which aspects of climate change most impact affordability. Since precipitation quantity is a primary driver of water availability, declining averages drive new infrastructure needs. Precipitation variability also has a moderate impact on affordability burden. Even if precipitation averages stay constant, greater variability can necessitate additional infrastructure to ensure supply due to more extreme droughts. This is particularly relevant for Santa Cruz, where the city's single reservoir has limited capacity for interannual storage, limiting its ability to buffer against extreme variability. Rising temperatures moderately affect affordability by increasing both evapotranspiration, which decreases water availability[14], and household demands, although supply-side impacts are more pronounced due to demand hardening[38] (Supplementary Fig. 7).

Across all climate factors, where we analyse the minimum and maximum values used throughout the analysis, the largest affordability differences are in the upper percentiles, suggesting that climate change disproportionately impacts households already struggling to pay bills. While median affordability ratios range from 1.0 to 1.5 (difference of 0.5), box plot upper bounds rise from 5.5 to 8.1 (difference of 2.6). Similar trends appear in water bill costs (Supplementary Fig. 8), probably due to steeper increases for high water users. Low-income households with high water usage—possibly due to larger household sizes[38]—may be especially vulnerable to climate-driven cost changes.

Infrastructure strategies for reliability and affordability

An important driver of our results is what and when infrastructure is built, and we find that different infrastructure investment strategies shape system reliability and affordability outcomes. Our baseline strategy ('Strategy A') prioritizes a 4-MGD desalination plant, which we choose because this option has a risk of failure threshold such that reliability declines during major drought events in the model are similar in magnitude to those of the 2013 California drought (Supplementary Text 5). Alternative utility strategies could deploy contrasting amounts of new infrastructure, resulting in different reliability impacts. To explore this, we develop optimal planning strategies that minimize new utility supply costs and unmet demands (Fig. 5a). Each planning strategy dictates when and which infrastructure is built using ROF thresholds calculated based on water demands, reservoir storage and prior investments (Methods). We choose two additional planning strategies for comparison: one risk-averse strategy where a low ROF threshold builds large infrastructure earlier ('Strategy B') and one risk-tolerant strategy with a high ROF threshold where smaller-capacity infrastructure is built first ('Strategy C') (Supplementary Table 4). Applying sensitivity

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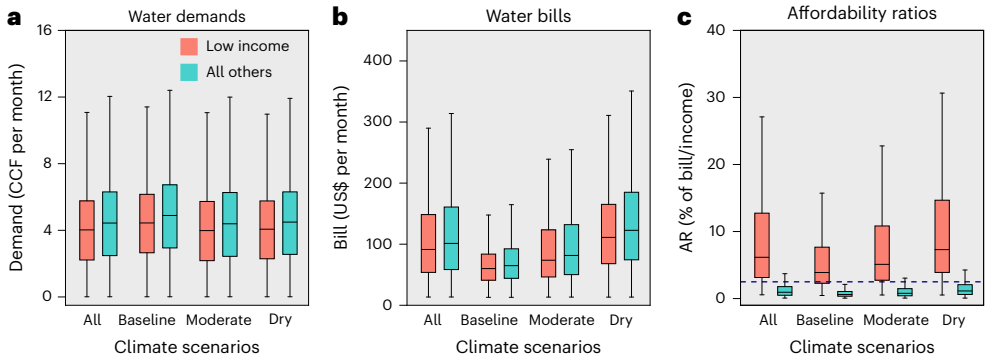


Fig. 3 | Low-income household affordability impacts. Box plots (showing the median, first and third quartiles, and whiskers of ±1.5 the interquartile range) comparing low (<US$39,900 per year) and all other income classes for water demands (**a**), water bills (**b**) and affordability ratios (**c**) across projected climate scenarios: all ($n = 1.04 \times 10^9/3.42 \times 10^9$ household water demands/bills/affordability ratios for low/all others), baseline ($n = 5.99 \times 10^7/1.97 \times 10^8$), moderate ($n = 2.49 \times 10^7/8.16 \times 10^7$) and dry ($n = 2.86 \times 10^7/9.37 \times 10^7$). Distributions show monthly values for all households across multiple stochastic climate simulations. The dotted line in **c** denotes the EPA affordability threshold of 2.5%.

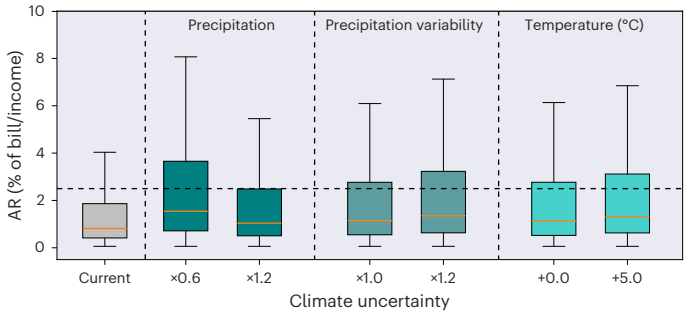


Fig. 4 | Climate uncertainty impacts on affordability. Box plots (showing the median, first and third quartiles, and whiskers of ±1.5 the interquartile range) comparing the distribution of monthly affordability ratios under the baseline scenario ($n = 1.28 \times 10^8$ household water affordability ratios) versus varying climate impacts across the entire analysis range with adaptation, including changes to average precipitation (multiplier of historical average) ($n = 3.12 \times 10^8/5.34 \times 10^8$ for ×0.6/×1.2), annual precipitation variability (multiplier relative to historical coefficient of variation) ($n = 9.93 \times 10^8/6.47 \times 10^8$ for ×1.0/×1.2) and temperature (change from historical average in degrees Celsius) ($n = 3.53 \times 10^8/3.85 \times 10^8$ for +0.0/+5.0). Distributions show monthly values for all households across each subset of sampled stochastic climate simulations. The dashed line indicates the EPA affordability threshold of 2.5%.

analysis, we find the choice of planning strategy to be insensitive to small changes in demand, deployment time and infrastructure costs.

Comparing planning strategies A, B and C highlights their substantial influence on utility costs, reliability, and affordability (Fig. 5). Strategy B, with the lowest risk tolerance and earliest infrastructure deployment, ensures 98.8% average annual reliability (averaged across each simulation and then across all simulations) but adds at least US$9.4 M per year in costs, increasing the 80th percentile affordability burden to 5.2%. Strategy C, with delayed, lower-cost investments, limits new spending to US$1.4 M per year and lowers the 80th percentile affordability burden to 2.7%. While average annual reliability remains relatively high at 96.8%, the average minimum annual reliability (that is, the minimum annual reliability in each simulation, averaged across simulations) is only 61%—probably unacceptable for most water utilities owing to the severe impact of large-scale water shortages. Santa Cruz, for instance, estimates that a 30% water use reduction during a water shortage could shrink economic output by over US$100 M (1.1–2.4% loss)[39]. Strategy A, our baseline, has a wider cost spread due to its moderate investment approach. However, since it deploys desalination first like Strategy B, both maintain average minimum annual reliability levels above 70% (Supplementary Fig. 11). Ultimately, under the current US water infrastructure financing model, climate change pits affordability against reliability, despite both being essential for water access.

Discussion

This study develops a city-scale modelling framework to quantify the impacts of climate change on urban water affordability. Previous work documenting affordability challenges does not reflect how climate change may fundamentally alter the cost structures, infrastructure needs and household responses that shape affordability[1,4,5]. By explicitly modelling climate-driven water stress alongside utility adaptation decisions, infrastructure financing, rate design and household demand and income, this study provides a comprehensive assessment of how climate change alone may exacerbate urban water affordability challenges.

Our work extends the water affordability literature by connecting it to climate adaptation and infrastructure planning processes that have historically been analysed separately. Previous work evaluates adaptation strategies under climate change through reliability–cost trade-offs, focusing on system performance and aggregate utility expenditures[27–30]. However, cost increases do not translate directly into affordability impacts. Instead, household affordability outcomes depend on how costs are recovered through rates, how households adjust water use in response to rate changes and how income is distributed across the population[22,34]. Quantifying reliability–affordability trade-offs therefore reveals dynamics that are largely invisible in cost-based analyses and highlights distributional consequences that are central to water access but often absent from adaptation planning[40].

Understanding the magnitude of climate-driven affordability impacts is essential for designing effective policy responses. If only a small fraction of households experiences unaffordable water bills, local customer assistance programmes may be sufficient to mitigate hardship. By contrast, if a large share of the population faces affordability challenges, utility-funded assistance programmes may be financially infeasible, and addressing the problem probably requires state or federal intervention through infrastructure financing, regulatory reform or direct household support[37,41]. In Santa Cruz, our results suggest that climate change alone could leave an additional 7–16% of households with unaffordable water. This finding underscores the importance of evaluating climate adaptation strategies through an affordability lens.

Affordability outcomes are not determined by climate alone, but by interactions between climate stress and a set of hydrological, institutional and social characteristics that shape how utilities respond and how costs are distributed across households. Table 1 summarizes these dimensions and clarifies the class of urban water systems for which our results are most informative. In this sense, Santa Cruz is not presented as representative of cities in general, but as illustrative of systems where

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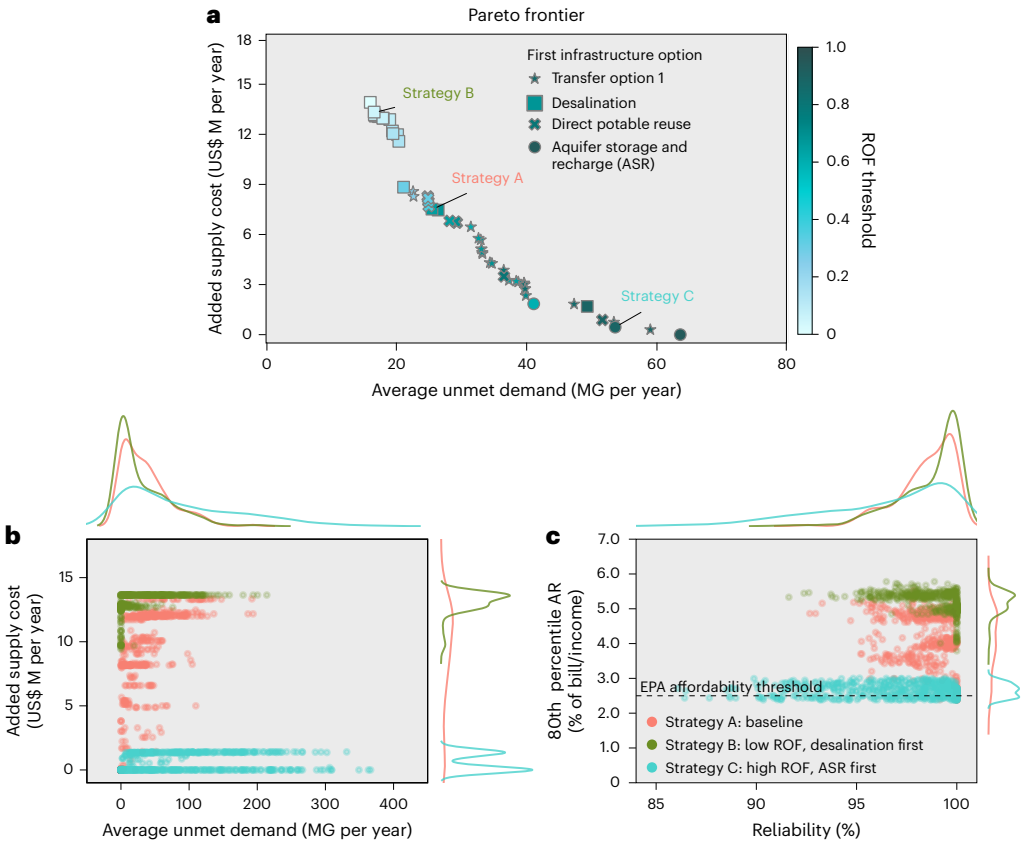


Fig. 5 | Infrastructure planning strategy comparison on utilities and households. a, Scatter plots comparing average added water supply costs and unmet demands for each optimal planning strategy. Shading indicates optimal ROF threshold value and shape indicates the first infrastructure option deployed under that planning strategy. All strategies are optimized over 20 climate simulations representing the range in our analysis. **b**,**c**, Scatter plots comparing three planning strategies, highlighted in **a**, across 500 simulations of plausible climate change impacts for added supply cost and average unmet demand (**b**) and 80th percentile affordability ratios and overall water system reliability (**c**). Kernel density estimation plots in **b** and **c** show the distributions of metrics for each strategy. All scatter points show metric values for a single climate simulation.

climate stress interacts with constrained adaptation options and existing inequality to amplify affordability impacts.

First, climate change-driven water stress increases the need for adaptation to maintain reliable supply. Across California and many semi-arid regions globally, climate projections indicate higher temperatures, altered precipitation patterns and greater hydrologic variability, increasing the likelihood of supply deficits[14]. Water system characteristics shape how and what utility adaptation decisions are realized. For example, in many supply-constrained and storage-limited cities such as Santa Cruz, feasible adaptation pathways involve expensive supply expansion alternatives, including desalination, potable reuse or large-scale transfers[36]. These options are costly relative to conservation or operational measures, leading to larger rate increases. Limited conservation opportunities, often the result of prior investments in efficiency and sustained demand hardening, further shift adaptation pressure towards the supply side[42].

Income inequality amplifies these affordability impacts. Where many households already face affordability challenges, even modest bill increases can push a large share of the population beyond common affordability thresholds[43]. In Santa Cruz, high baseline burdens among low-income households mean climate-driven rate increases compound existing inequities. Finally, constraints on rate design and affordability mitigation play a central role in determining distributional outcomes. Regulatory frameworks restricting cross-subsidization or income-based pricing can force utilities to recover infrastructure costs in ways that disproportionately affect low-income households. In California, Proposition 218 exemplifies this constraint[9,44].

Together, these conditions define a class of urban water systems in which climate change is most likely to exacerbate affordability challenges. Cities that share fewer of these characteristics may experience smaller or qualitatively different impacts. However, other cities may move towards dynamics similar to those observed in Santa Cruz over time as conservation gains are exhausted, baseline rates rise and climate stress intensifies[45]. In this sense, Santa Cruz may represent not an outlier, but a plausible future state for water systems that have already utilized lower-cost adaptation options.

Beyond the Santa Cruz case study, the modelling framework developed here is designed to be broadly applicable across urban water systems. The framework integrates three components that are common across cities: a water resources systems model, a utility financing and rate design model, and a household demand model. While each component must be parameterized with local data, the structure of the framework and the interactions it captures are general. As a result, the framework can be used to assess climate-driven affordability risks in other cities, while allowing results to reflect local hydrology, governance and socioeconomic conditions.

Our findings highlight a fundamental tension in urban water management. Under prevailing financing and regulatory models, climate adaptation aimed at ensuring reliability can directly undermine affordability. Addressing climate-driven water stress without worsening inequity will probably require interventions beyond the utility scale, including regulatory reform, expanded public financing of adaptation infrastructure or targeted assistance programmes funded outside of water rates. More broadly, our results suggest that

Table 1 | Urban household affordability drivers

Unaffordability Driver	Household affordability impacts	Santa Cruz/California context	Cities exhibiting similar characteristics to Santa Cruz
Climate change-driven water stress	Necessitates investments in supply- or demand-side measures for water supply reliability, which can be expensive and are often paid for through rate increases.	Global climate models show much of the region getting hotter and drier, with more extreme dry and wet events.	California: Los Angeles, San Diego, San Francisco; Global: Cape Town, South Africa; Melbourne, Australia[81]
Expensive supply expansion alternatives	Larger infrastructure options tend to be more costly, requiring greater rate increases, increasing household water costs and worsening affordability impacts.	Santa Cruz is considering one or multiple infrastructure options, including: a desalination plant, direct potable reuse, aquifer storage and recovery, and transfers with two neighbouring utilities.	California: Los Angeles, San Francisco; Global: Singapore; Tel Aviv, Israel; Melbourne, Australia[82,83]
Limited over-year water storage	Limits the utility's ability to store water from wet years for use during dry years, limiting what alternative water supply infrastructure can be utilized, potentially necessitating higher investment costs for new infrastructure.	Loch Lomond, Santa Cruz's main reservoir, only holds about 1 year of water supplies.	California: East Palo Alto, San Jose; Global: Cape Town, South Africa.
Limited conservation opportunities	When households are already using water efficiently due to water-saving appliances and limited outdoor/discretional use, there are limited opportunities for households to cut back on water use during droughts or rate increases, making households sensitive to rate changes.	Santa Cruz has already implemented many conservation measures, leading to low gains from new efficiency investments.	California: San Francisco, San Jose, San Diego, Oxnard; Global: Portland, OR; Singapore[84]
Income inequality	More low-income or disadvantaged households can lead to larger affordability impacts across a water system.	Santa Cruz has large income inequality with about 20% of households below the federal poverty line and another 20% earning more than US$200K annually.	California: Oakland, San Francisco, Los Angeles; Global: Barcelona, Spain; Rio de Janeiro, Brazil[85]
Institutional constraints on rate design	When utilities are constrained in how they structure rates or provide subsidies, infrastructure costs are passed directly to households, often through higher baseline charges or volumetric rates that do not protect essential use. This limits utilities' ability to shield low-income households from rate increases associated with climate adaptation.	In California, Proposition 218 requires rates to reflect proportional cost of service, limiting cross-subsidization and many forms of income-based assistance. Santa Cruz already exhibits high baseline rates and limited flexibility to design affordability-protective pricing, amplifying the household impacts of new infrastructure investments.	California: all public utilities impacted Global: Rio de Janeiro, Brazil[85]

A list of unaffordability drivers, their household-level impacts, context in Santa Cruz and other cities exhibiting similar characteristics in California and globally.

evaluations of climate adaptation strategies should routinely assess affordability impacts alongside reliability outcomes. Failing to do so risks shifting the costs of climate adaptation onto households least able to bear them, even when adaptation successfully reduces physical water scarcity.

Limitations

Several limitations condition the interpretation of our results and clarify the scope of their applicability. First, our results are shaped by hydrologic and infrastructural constraints specific to Santa Cruz, including limited over-year storage and the availability of particular supply expansion options[36]. Cities with larger reservoirs, more interconnected systems or access to lower-cost water sources may experience delayed or reduced affordability impacts. Although we evaluate climate scenarios that reflect substantially hotter and drier conditions than observed historically, we treat these conditions as stationary, probably understating affordability impacts that would arise under progressively intensifying climate change, which could produce tipping points in which multiple costly investments are required simultaneously or in rapid succession, sharply worsening affordability outcomes and straining utility finances over a short period[46].

Second, we represent utility decision-making using a rule-based ROF framework that captures planning behaviour in response to supply deficits but omits the political, institutional and social processes driving infrastructure implementation[47]. In practice, permitting delays, public opposition or financing challenges could alter the timing and distribution of costs, potentially increasing short-term affordability shocks or reliability risks relative to modelled outcomes[48].

Third, affordability outcomes are sensitive to rate design and financing rules, which vary widely across jurisdictions[49]. Our analysis reflects regulatory constraints typical of California public utilities, limiting cross-subsidization and income-based pricing[50]. In settings with greater rate flexibility or substantial external funding, affordability impacts could be mitigated under similar infrastructure investments.

Fourth, while we test sensitivity to population size, composition and price elasticity, we do not model long-term demographic change, migration or endogenous behavioural adaptation. These dynamics could either diffuse or concentrate affordability burdens over time, depending on local housing markets and economic conditions.

Finally, our household-level analysis focuses on single-family residential customers due to data limitations. Like in most US cities, multifamily homes in Santa Cruz are not individually metered and are therefore not represented in our billing data. This omission biases our income distribution upward because multifamily homes tend to house lower-income families[51]. In addition, multifamily homes may have more inelastic demand[22]. These limitations probably underestimate the fraction of the population experiencing unaffordability. Addressing this gap will require household surveys or other data collection to estimate water use and affordability among multifamily populations[51].

Despite these limitations, the qualitative insights from this study are robust. Where climate stress intersects with expensive adaptation options, constrained rate design, and existing inequality, climate change can substantially worsen water affordability. The framework presented here is intended not to predict exact outcomes for all cities, but to help utilities and policymakers identify when and why climate adaptation may pose risks to equitable water access.

Methods

Ethics committee approval

The SCWD water billing data use was approved by the Institutional Review Board at Stanford University under eProtocol no. 63914.

Case study

We apply our model to Santa Cruz, a water-stressed city with high income inequality on California's central coast. Relying on locally sourced surface water for around 95% of total supply, Santa Cruz is highly vulnerable to climate-driven water stress[36]. The Santa Cruz Water Department (SCWD), the municipal utility, serves 96,000 residents, managing a system anchored by the Loch Lomond Reservoir, designed to store about a year's supply of water (see Supplementary Fig. 12 for a watershed map)[36]. Santa Cruz, with a median household income of about US$91,900 in 2020 dollars, has high income inequality with 20% of households below the federal poverty level (compared with 11% nationwide) and 20% earning more than US$200,000 annually (14% nationwide)[36,52,53]. The presence of the University of California, Santa Cruz skews the population younger with 27% of residents aged 20–29 years (15% statewide)[36,54]. As a public utility in California, SCWD is limited in how they can structure water rates, fund assistance programmes and increase rates owing to Proposition 218 (refs. 34,44).

Data

We use multiple city- and household-level data sources to parameterize the model. We tailor model parameterization to best estimate current conditions and processes in Santa Cruz. At the city scale, we obtain historical data on utility operational costs, financing and rates from SCWD's long-range financial reports[55,56]; and historical water use data based on the 2020 Urban Water Management Plan[36]. At the household level, we use SCWD monthly water billing data for every account active between January 2009 and December 2021 (n = 2,836,297 bills). Accounts are filtered for adequate length and quality, as detailed in Supplementary Text 8. We merge the billing data with physical housing characteristics from tax records, block-group-level census data and hydrological data, listed in Supplementary Table 5.

Water supply balance model

We use the Santa Cruz Water System Model to estimate water allocations[57]. This model uses Pywr, a Python-based water resources simulation modelling library[58], to simulate daily operations using linear programming and determine how much water should be provided and from which sources[59]. The model includes current and potential future infrastructure, hydrology and system demands. More details can be found in Supplementary Text 9.

Climate and hydrological modelling

Climate scenario generation involves two steps: first, developing stochastic weather simulations that reflect historical climate variability; and second, altering these simulations to capture different climate change impacts using the anomalies from climate models. The resulting simulations capture both short-term stochastic variability and long-term climate impacts and are used to force a hydrological model to develop streamflow scenarios.

The contrasting climate scenarios differ in the range of anomalies utilized from CMIP6 projections[60]. The moderate, cool climate reflects similar climate conditions to historical data and is used in the baseline and moderate climate with adaptation scenarios, while the dry, hot climate reflects worst-case, plausible climate impacts, used in the dry climate with adaptation (Supplementary Fig. 1). To test the full range of climate variability, we utilize a scenario called 'All climate simulations', where we test all combinations of climate anomalies. See Supplementary Text 1 for more details on climate scenario generation[61]. The simulations are run through a lumped hydrological model for the San Lorenzo River, which comprises the majority of water within the basin. Then, regression relationships from historical records are used to develop daily flow records at all locations, as further discussed in Supplementary Text 10.

Infrastructure deployment

We simulate infrastructure deployment under water stress using rule-based ROF thresholds. These probability-based triggers incorporate both supply and demand by estimating the likelihood that reservoir storage will fall below a critical threshold (for example, deadpool levels) within a specified time horizon, as applied in similar urban water supply planning studies[32,47]. One benefit of the ROF approach is that we can easily include deployment time so that infrastructure does not come online instantaneously. The planning strategy utilized first builds a desalination plant when the ROF value surpasses a given threshold, although alternative strategies are compared later in the Results (Fig. 5). For the baseline planning strategy, Supplementary Fig. 2 shows the infrastructure deployment patterns for all scenarios with adaptation as well as the frequency of the number of deployed infrastructure options. We evaluate ROF triggers annually based on three dimensions: current reservoir storage, annual water demand, and planned or implemented infrastructure options. We construct ROF look-up tables by partitioning stochastic climate simulations into 2-year segments, running hundreds of 2-year simulations and estimating the probability of storage falling below the critical threshold for each combination of system conditions. Supplementary Text 11 includes more details on ROF development, including an illustration of system characteristics and thresholds.

Infrastructure options and planning strategies

We model five infrastructure options, ranging from 0.5 to 4 MGD in capacity, that can be implemented individually or combined: two water transfers, aquifer storage and recovery, direct potable reuse and desalination. SCWD is currently considering all included infrastructure options, in various portfolios, in long-term planning efforts. Techno-economic details, including capital and operating costs, based on design studies by SCWD, are included in Supplementary Table 6 (ref. 62).

We develop multiple infrastructure planning strategies that include the ROF threshold and infrastructure deployment order (Supplementary Table 4). We optimize planning strategies with respect to utility costs and system reliability using a multi-objective approach[31,63]. We calculate utility cost as the summation of total utility infrastructure capital and operating costs and reliability using average annual total unmet demand. We average both objectives across 20 climate simulations used in optimization. We use the Borg multi-objective evolutionary algorithm to determine Pareto-approximate infrastructure strategies[64] (detailed in Supplementary Text 13). We choose one planning strategy as a 'baseline' approach determined through conversations with SCWD staff and quantitative analysis comparing reliability declines during historical and simulated drought events, further discussed in Supplementary Text 5.

Modelling water demands

We use a discrete/continuous choice model, an econometric model designed to estimate water demands under increasing block tariffs, to simulate single-family household water demands at the household level[65,66]. We estimate households' monthly water use (w) as

$$w = e^{Z\delta+\alpha\ln p+\gamma\ln y},$$

$$W = w + d_{\mathrm{HH}},$$

where p is the marginal price of water; y is home tax value (a proxy for income[67]); Z is a matrix of housing characteristics and monthly weather data; α, γ and δ are the estimated model coefficients; and W is household water use after including d_{HH}, a direct bias correction

term for each household[65,66]. More details on model parameterization and performance are in Supplementary Text 14 and all model coefficients are listed in Supplementary Table 7. We achieve a model performance of $r^2 = 0.36$ at the household scale, which is comparable with state-of-the-art applications in other regions, and $r^2 = 0.78$ at the income group scale[26,66]. We use the discrete/continuous choice model estimation results to simulate demands for 21,370 single-family residential accounts. We resample the 21,370 accounts from the household-level data so that our outputs for total single-family residential water use match 2020 water use trends and so that the distribution of household properties matches current distributions across the SCWD service area. For our affordability assessment, we estimate household-level income using an approach that maintains the distributions of household income at the census block group scale, which is our unit of analysis. We use a multivariate regression approach to estimate each household's income and then apply quantile mapping to assign household income estimates to 1 of 16 income bins utilized by the American Community Survey at the block group level, detailed in Supplementary Text 15. As our household sample size is large, the effect of error in the regression approach is negligible when aggregating from the household scale to income class scale, which we confirm in Supplementary Table 8 and Supplementary Figs. 18–21. We define low-income households as those below the California Poverty Measure income threshold of US$39,900 per year in 2023[68]. We assess affordability burdens using the affordability ratio, which compares simulated monthly household water bill costs to income during periods with the highest water rates[3,6,37].

We also include total water demands for other customer classes, including multifamily residential and non-residential (commercial, institutional, industrial and irrigation[36]) classes and water losses, to simulate realistic total service area demands. For multifamily and non-residential classes, we create three stationary scenarios to capture a range of plausible conditions. We use the 2020 Urban Water Management Plan data to obtain baseline (average), high (10% above maximum) and low (10% below minimum) average total demands, which we overlay with monthly anomalies to model demand seasonality, based on the water billing data[36] (Supplementary Fig. 22). For water losses, we use a constant scenario of 201 MG per year based on the 2020 Urban Water Management Plan[36].

Infrastructure financing and rate design model

The infrastructure financing model translates new infrastructure investment costs to single-family household water rates following three main steps. First, we determine utility revenue requirements related to the portfolio of infrastructure options. We use a cashflow model to calculate the additional required revenue for the utility to recuperate, categorized into three components: pay-as-you-go costs, where the current year's revenue funds capital expenditures; debt-financed costs, where revenue covers loan repayment; and annual operating costs, which are incurred once infrastructure comes online[56]. General operations and maintenance expenses are modelled exogenously, as further discussed in Supplementary Text 17. Second, we conduct a cost-of-service analysis based on rate design guidance in the AWWA manual where we determine that single-family households should pay for 38% (78%) of any constructed and operated infrastructure accrued through volumetric rates (fixed fees) based on historical volumetric charges (total number of accounts)[69]. Third, we design updated water rates. Santa Cruz uses an increasing block rate (also called an increasing block tariff), where the unit price of water increases above certain thresholds of water use (0–5, 6–9 and 10+ ccf)[34]. Volumetric rates include two components: an infrastructure reinvestment fee charge, which funds pay-as-you-go and debt-financed costs; and a volumetric consumption charge, which funds operating costs. We compute rate increases from new infrastructure using tier cost ratios, simulated water demands and updated revenue requirements. Historically, the ratios between tier 1 and tier 2 or 3 costs, listed in Supplementary Table 10, have been fairly consistent[55,56]. Since volumetric rates depend on water demands, but water demands are inelastic based on marginal water prices, we model this feedback cycle once through to ensure updated rates reflect updated demands. We update rates when infrastructure is planned to fund the investments, when infrastructure is deployed to fund operational costs and when investments are paid off. We illustrate the process from updated revenue requirements to rates and demands in Supplementary Fig. 23. Other financing assumptions are detailed in Supplementary Table 11.

Sensitivity analysis

We performed a sensitivity analysis on a sample of parameters in our framework. For the optimization, we tested one uncertain parameter for each of the three main components of our modelling framework. For the simulation, we performed a fractional factorial analysis, where we analysed high and low values for each parameter, evaluating all parameter combinations[70,71]. We did this separately for (1) infrastructure financing and rate design and (2) demand and demographic parameters, as described in Supplementary Text 3.

Data availability

Publicly available data used in this paper include 2021 property and tax data from the County of Santa Cruz[72], American Community Survey data[54], PUMs data[73], Santa Cruz UWMP data[36], Santa Cruz long-range financial reports[55,56] and climate data[74–78]. Non-proprietary, non-public climate data are available via Zenodo at https://doi.org/10.5281/zenodo.18752509(ref. 79). The water billing dataset from the Santa Cruz Water Department is proprietary under a data-use agreement and is not able to be shared publicly.

Code availability

All non-proprietary software is available via Zenodo at https://doi.org/10.5281/zenodo.18752481 (ref. 80).

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Author contributions

S.F. conceptualized the study. S.F., J.S., C.K., B.F. and A.V. designed the methodology. J.S., C.K., B.F. and C.B. provided software. J.S. performed the analysis. J.S., S.F. and C.K. analysed the data. S.F. provided supervision. J.S. and S.F. drafted the paper. J.S., S.F., B.F. and C.K. revised the paper.

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Competing interests

The authors declare no competing interests.

Additional information

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