Water Affordability in the United States

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Abstract

In the US, the cost of water and wastewater services is rising three-times faster than inflation. Over the next 20–25 years, required investments in water infrastructure are estimated to exceed $1 trillion, further increasing service costs. Combined with stagnating income levels, especially for poor households, increased costs will likely aggravate water affordability issues. Here, we document the extent of water affordability concerns in the US across income, geography, and race. We find that 10% of households face water affordability concerns, defined as expenditures on essential water and sewer services greater than 4.5% of annual household income. Households in the lowest income decile pay on average 6.8% of their annual income on water and sewer service. Our estimates are based on one of the most comprehensive data sets of water and sewer prices to date, matched with Census block-group-level socioeconomic characteristics and covering approximately 45% of the US population. We demonstrate that using median household income at the county level drastically understates the extent of the water affordability problem. Additionally, we find that the number of households facing affordability concerns is positively associated with water and sewer price levels, impoverished residents, and the proportion of black residents even after conditioning on poverty levels. Lastly, we show that self-sufficient water affordability policies that provide a lump-sum rebate to low-income households and are paid for by income taxes are more effective at redistributing the burden borne by low-income customers than policies that change marginal incentives for water and sewer consumption.

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1 Introduction

Water is necessary for human survival. The United Nations identified "equitable access to safe and clean drinking water and sanitation as an integral component of the realization of all human rights" (UN General Assembly, 2010). Water is also an economic good, whose price should reflect its value to society and the long-run costs associated with its treatment and distribution to customers (Olmstead, 2010). Utilities typically price water to recover costs of provision and recent evidence suggests that utilities do not price water to reflect scarcity (Luby, Polasky, & Swackhamer, 2018). To maintain current levels of service in the US, however, water and wastewater infrastructure will require substantial investment over the next several decades, with some estimates totaling more than 1-trillion USD (American Water Works Association, 2012). Compliance with the US Environmental Protection Agency's (EPA) Clean Water Act and Safe Drinking Water Act further adds to water supply costs (National Academy of Public Administration, 2017; Jerch, 2019). The vast majority of those costs will end up on household water and wastewater bills, potentially tripling the current cost of water and sewer service for US households (American Water Works Association, 2012). Water providers are thus faced with balancing multiple, competing objectives: efficient pricing, covering costs, and also keeping water bills affordable (Martins, Quintal, Cruz, & Barata, 2016; Whittington, Nauges, Fuente, & Wu, 2015).

In this paper, we demonstrate how widespread water affordability issues are in the US, how policies can be designed to reduce burdens on low-income populations, and how underlying economic incentives drive policy effectiveness. We estimate that approximately 10% of households in the US face water affordability concerns by assembling one of most comprehensive data sets of water and sewer rates to date, using rate structures from 1,545 utilities that provide water and sewer service to approximately 45% of the US population. Our data set is compiled from rates surveys conducted by the Environmental Finance Center at the University of North Carolina at Chapel Hill (UNC EFC) and the American Water Works Association (AWWA) and includes water and sewer prices matched with community-level socioeconomic characteristics and typical water use. With these data, we show that using the full income-distribution at a local level, rather than median household income, is imperative for capturing the water affordability burden of low-income households. We estimate that households in the lowest income decile spend on average 6.8% of their annual income on essential water and sewer services. Additionally, we find that water affordability concerns are positively correlated with price levels, the proportion of impoverished residents, and the proportion of black residents within a Census block-group even after conditioning on poverty rates. Finally, we investigate the effectiveness of different policies designed to alleviate affordability concerns. To do so, we simulate the effects of self-funded assistance programs that combine different benefits—lower water rates vs. rebates—and funding sources—higher water rates vs. local income tax for non-assisted households. We show that policies that provide a lump-sum rebate to low-income households and are paid for by income taxes dominate policies that change marginal incentives for water and sewer consumption.

In the US, recent trends suggest that the cost of water and wastewater is rising three times faster than other goods and services at a time when economic inequality is increasing (Figure 1). States and municipal authorities are beginning to develop policies to reduce the burden of water and sewer bills for low-income households—in 2015, California passed a law to develop a statewide low-income water rate assistance program (California State Assembly, 2015), the City of Philadelphia implemented in July 2017 the nation's first income-based water rates (City of Philadelphia, 2015), and many utilities are adopting low-income water rate assistance programs. In 2021, in response to the increased stringency of water affordability issues during the COVID-19 pandemic, the federal government started the Low Income Household Water Assistance Program (LIHWAP). The LIHWAP provide grants to states in order to fund programs that assist low-income households with water and wastewater bills. In this paper, we provide wide-scale estimates of the extent of the water affordability problem and results that contribute to the design of effective water affordability policies.

Surprisingly, there are very few national estimates of water affordability and the geographic distribution of the most vulnerable communities is poorly understood. In perhaps the first paper to perform such a calculation, Mack and Wrase (2017) provide a large-scale geographic assessment of communities that are at-risk of water poverty, although their analysis relies on several limiting assumptions. The authors evaluate water bills at a constant level much larger than typical household consumption levels and overlook geographic differences in water prices and consumption patterns, resulting in an assumption that every household in the country spends $120 per month in water bills. Moreover, that study evaluates affordability using the median income at the Census-tract level, which limits the validity and usefulness of those estimates because it ignores the lower part of the income distribution where affordability concerns are likely more prevalent. In practice, these assumptions are equivalent to a fixed-income threshold that assigns unaffordable water services to all households in any Census tract with median annual income below $32,000. In the present manuscript, we approach a similar question with much more tenable assumptions. By examining the full household income distribution at a finer resolution, our framework not only addresses the shortcomings of previous analyses but also provides a richer set of policy-relevant results that allow for policy simulations and assessment of distributional impacts.

In another related study, Teodoro (2018) offers a critique of EPA's affordability metric. The author proposes two metrics that assess water and sewer bills relative to alternative income measurements: hourly minimum wage or the 20th percentile of household disposable income. Bases on these two metrics, the study then estimates the extent of affordability concerns for the 25 largest cities in the U.S. In a subsequent paper, the author expands the analysis and estimates affordability metrics to a stratified sample of 360 utilities covering a served population of 38 million (Teodoro, 2019). Though similar in spirit, our paper takes a different approach and emphasizes the need to evaluate water affordability while accounting for full income distribution rather than specific quantiles. In doing so, our method delivers a flexible metric that not only informs policymakers about the consequences of their choices but also—and most importantly—allows for a detailed evaluation of potential policies to alleviate concerns about water affordability. In the Supporting Information, we provide a detailed comparison to previous work and discuss overlaps and complementarities.

1.1 Measuring affordability

EPA's oft-used threshold for determining a "high burden" of water and sewer bills—whether combined water and sewer bills (CWSBs) exceed 4.5% of a community's median household income—has received increasing scrutiny as an adequate measure of a household's ability to pay for water and sewer services (National Academy of Public Administration, 2017; Teodoro, 2018; Mumm & Ciaccia, 2017). The origins of this median household income threshold can be traced back to EPA guidance for determining economic impacts of water quality regulations, but no formal justification for the level of the threshold was provided (U.S. EPA, 1995, 1997). Common concerns are that using median household income at a community level poorly captures the burdens on the most vulnerable low-income residents and the 4.5% threshold (for combined water and sewer bills) is arbitrary; some of these concerns have been included in more recent guidance for the evaluation of financial capabilities of local governments in providing clean water (U.S. EPA, 2020). In this analysis, we follow the panel recommendations from the National Academy of Public Administration

(NAPA) for defining community affordability criteria for clean water services (National Academy of Public Administration, 2017). These recommendations include development of an improved affordability metric that is: (i) readily available from public data sources; (ii) clearly defined and understood; (iii) simple, direct, and consistent, (iv) valid and reliable according to conventional research standards, and (v) applicable for comparative analyses.

In line with current EPA guidance and forward-looking NAPA recommendations, we put forward transparent and readily calculable metrics for ease of communication and decision-making by policymakers. Furthermore, we contrast the burden of water and sewer expenditures under varying definitions of water affordability. Our preferred affordability measure is defined as the proportion of households that pays more than 4.5% of annual household income on water and sewer service at the essential level of consumption (50 gallons per person-day, or gppd). We apply that standard at different income and geographic resolutions, and consider alternative levels of consumption. Moreover, the 4.5% threshold is readily scalable to different income thresholds—a higher threshold leads to a lower population not meeting the affordability criteria and vice-versa. For context, the average US household spends 4.6% of their annual income on health insurance and 4.6% percent of their income on food away from home, according to the 2017 Bureau of Labor Statistics Consumer Expenditure Survey.

2 Materials and Methods

2.1 Data and calculations

Our primary data set contains water and sewer rates from 1,545 utilities that cover 92,445 Census block groups from 521 counties across 42 states. This sample corresponds to approximately 52 million households and 145 million people, which comprises 45% of the total U.S. population as of 2016. This data set combines local water and sewer rates, number of service accounts, average consumption, climate characteristics, and a variety of socioeconomic indicators.

We consider four levels of geographic resolution (or aggregation). The unit of observation in the lowest resolution (the highest aggregation) is a county, which considers a representative household that has its characteristics matching county averages. Similarly, in the second resolution level, each block group is represented by a single household with the block-group median/average characteristics; for reference, Census block groups are small geographic areas with typical population between 600 and 3,000 individuals. In the third resolution level, block groups are represented by 16 households that share the same socio-demographic characteristics but with different incomes corresponding to the center of US Census income brackets. Each of the 16 households has a different weight that matches the block-group income distribution. The fourth and highest resolution considers a continuum of households with income varying within each block group. In this latter approach, we interpolate a 16-node income distribution using monotone preserving cubic splines to obtain a continuous cumulative probability distribution function.

Water and sewer rates are obtained from two sources: rate surveys cataloged by the Environmental Finance Center at the University of North Carolina at Chapel Hill (EFC), current as of July 1, 2017, and the 2016 American Water Works Association (AWWA) Water and Wastewater Rate Survey. Geo-referenced data on the service area of each water district are rare, thus hindering the matching between block groups and utility companies. To overcome this limitation, we aggregate water and sewer rates to the county level, weighted by the number of accounts in each utility. To account for block rates, we approximate rate structures as a piecewise linear function of consumption with up to three rate blocks.

Our main water affordability metrics are based on the CWSB for a fixed level of water consumption deemed essential. We report metrics for an essential consumption at 50 gppd and consider alternative scenarios for levels at 25, 75, and 100 gppd. The focus on expenditures at a minimum level aligns with concerns of affordable water and sewer services for basic household needs and dignity. In doing so, these metrics intend to be robust to non-essential water use that could lead to a large CWSB.

Formally, affordability metrics are calculated as follows. Let b and c denote the block group and county, and i denote a node of the 16-node income distribution given by Census. Monthly household consumption in a block group is given by

$$W_{bc} = 30 \times h_{bc} \times \omega, \tag{1}$$

where h_{bc} is the average household size in a block group and ω is the essential daily per capita consumption level. Let Φ_c be the function mapping monthly water consumption to CWSBs for households in a county. Then, the annual share of income corresponding to the CWSB for a household in income node i is

$$\hat{s}_{ibc} = \frac{12 \times \Phi\left(W_{bc}\right)}{y_i}. \tag{2}$$

2.2 Estimation of socioeconomic and demographic conditional correlations

We investigate whether local water affordability is correlated with a set of local socioeconomic and demographic factors including:

1. Population density, measured in persons per square mile.
2. The percentage of a block group population that identifies their race as Black or African American alone.
3. The percentage of a block group population that identifies being of Hispanic or Latino origin.
4. The percentages of households with income below the Census Bureau poverty threshold, and with income between one and two times that threshold.
5. The median age of housing units.
6. The median gross rent as a percentage of the household income.
7. The average household size.
8. The percentage of rented units relative to all occupied units.

Local affordability is calculated using the distribution of income and CWSBs within each block group. In particular, the affordability metric of interest is the percentage of households with CWSBs above 4.5% of their income calculated with the essential consumption level, which we represent by $\hat{U}_{bc}$.

We estimate conditional correlations by estimating the parameter vector $\mathbf{\Gamma}$ in

$$\hat{U}_{bc} = \mathbf{X}_{bc}'\mathbf{\Gamma} + \sum_{z \in Z} \gamma_z 1\left(CZ_c = z\right) + \sum_{s \in S} \delta_s 1\left(State_c = s\right) + u_{bc}, \tag{3}$$

where $\mathbf{X}_{bc}$ is the vector of local socioeconomic and demographic factors defined above. The remaining terms in the equation represent climate zone fixed effect, state fixed effects, and an idiosyncratic error term, u_{bc}.

2.3 Policy simulations

Local affordability metrics provide useful tools to identify affordability concerns at the community level. However, these metrics do not offer guidance on how to remediate concerns. Affordability policies can reduce the burden of water and sewer bills for low-income customers, although there is virtually no comparative research highlighting the relative effectiveness of different types of programs despite policies being adopted at scale. Assistance programs might change the incentives to consume and conserve water, further affecting household expenditures. In assessing the relative advantages of policies, it is important to look beyond the essential consumption and also account for households' responses to changes in service costs. To do so, we simulate the effects of different assistance programs on the income share households allocate to water services.

Our policy simulations are simplistic by design, although they possess the key elements inherent in many water affordability policies (California State Assembly, 2015; City of Philadelphia, 2015). In our framework, households above the 4.5% affordability threshold for essential use (50 gppd) are eligible for aid and those below the threshold are not. We consider four illustrative policy options that differ in how programs reduce water and sewer expenditures for low-income customers and in how the programs are funded. In our scenarios, low-income assistance takes the form of a uniform lump-sum transfer or a 50% rate discount for eligible households. These programs are funded either by a uniform water rate increase or a local income tax on non-eligible households. All affordability programs are assumed to be administered at the county level. These options are illustrative and abstract from local regulations that prohibit using water prices for redistributive purposes and any prevailing water affordability programs or rate structures (e.g., "lifeline" rates) that are currently in use. Additionally, we abstract from costs associated with policy implementation.

For each policy option, we adjust households' water consumption given changes in prices and income. These adjustments are based on a constant price elasticity $\epsilon_p = -0.3$ (Dalhuisen, Florax, De Groot, & Nijkamp, 2003), a constant income elasticity $\epsilon_y = 0.1$ (Havranek, Irsova, & Vlach, 2018), and initial household consumption at the estimated level (see the Supporting Information for details of the estimation model and sensitivity analyses on these parameter choices). We note that estimated levels can offer only an imprecise approximation of current household consumption. However, this approximation suffices as our focus is on the relative—rather than the absolute—performance of different policy options. These illustrations demonstrate key mechanisms of assistance programs but their results should not be interpreted as predictive of absolute levels of affordability concerns.

To make a fair comparison of outcomes, all four programs have the same size, set equal to the dollar amount needed to cover the 50% rate discount option. To determine the size of the programs in each county, we first adjust water consumption for assisted households based on a 50% rate discount in all rate blocks. Then, we calculate the amount necessary to fund these discounts. We set uniform lump-sum transfers that match the size of the rate discount program. Similarly, we calculate the uniform income tax rate and the price increase needed to fund the assistance programs in each county. We assume general equilibrium changes (e.g., changes in labor supply) in response to small income changes are negligible. The average-income tax rate increase is 0.1 percentage points and the average lump-sum transfer is $34.6 per month.

3 Results

3.1 High-resolution income data and local prices are critical for measuring household-level water affordability

We calculate the number of households whose annual combined water and sewer bills exceed 4.5% of their annual household income for different definitions of income and consumption in Table 1. Comparing average water and sewer consumption at the county level with 4.5% of county-level median household income identifies virtually no households with unaffordable water and sewer service in our sample. But this is clearly misleading as it tells us only about a household with median income. Narrowing the geographic area at which we apply our median-income threshold provides a better approximation of local income distributions. Using median household income at the Census block-group level induces a modest increase in the proportion of households that exceed the water and sewer affordability threshold—0.8% for 50 gallons per person per day (gppd) and 4.8% for 100 gppd. In these results, 50 gppd is intended to capture essential water consumption; 75 gppd approximates the sample mean of reported county-average consumption of 78.1 gppd.

By using income-group midpoints of a 16-node income distribution at the block-group level to calculate affordability (see Supporting Information), we determine that 10.0% of households have CWSB greater than 4.5% of income for essential consumption levels. Results are nearly identical when using an interpolated income distribution. These quantities are 4–12 times greater than quantities calculated with coarser income information based on median household income. This result is driven by the fact that we are able to identify more households with unaffordable water by using more granular data on income. Income aggregation reduces our ability to identify households in the very low portion of the income distribution. When calculating the distributional burden of water and sewer expenditures it is imperative to capture the local income distribution in its entirety.

3.2 One out of every ten households spends more than 4.5% of annual income on essential water and sewer services

As shown in Table 1 and Figure 2, around 10% of households in our sample face water and sewer service rates for essential consumption (50 gppd) that exceed EPA's 4.5% affordability threshold. This estimate corresponds to more than 5-million households in our sample; a nationally representative estimate of the number of households with unaffordable water and sewer services would be much larger. We obtain this estimate by applying the 4.5% affordability threshold to representative households within a 16-node income distribution for each Census block groups. Although applying an affordability threshold at 4.5% of income is arbitrary, this threshold provides a useful benchmark to compare the burden of water and sewer expenditures across geographies. Furthermore, our method is flexible in this sense and can be applied at any income threshold.

We also calculate the proportion of households above the affordability threshold based on alternative levels of consumption per person-day. As shown in Figure 3, evaluating affordability either at 75 gppd (approximately the average estimated consumption level) indicates that about 14%—one out of every seven—households pay more than 4.5% of their annual income on water and sewer bills. Even at 25 gppd, or less than a third of average consumption levels, unaffordability still affects one out of every sixteen households in our sample.

3.3 Households in the lowest income bracket pay 6.8% of annual income on essential water and sewer services

We calculate the burden of water and sewer bills for each income bracket in our data in Table 2. As shown, households with annual income less than $15,000 have, on average, essential water and sewer services that cost 6.8% of household income. This statistic represents 11.4% of households in our sample. For contrast, households in the $45,000–$59,999 income group, near the US median household income, spend on average 1.2% of their annual household income on water and sewer bills. For the top income group—households earning $200,000 or more—this statistic is only 0.3%. This analysis reveals that the vast majority of households facing unaffordable water service are concentrated in the lowest income deciles.

These results highlight the regressivity of water and sewer bills relative to contemporaneous income. Nevertheless, the literature on the expenditure burden of energy taxes has indicated that, due to limitations of contemporaneous income measurements, metrics that incorporate life-cycles might provide a more appropriate assessment (Hassett, Mathur, & Metcalf, 2009; West & Williams III, 2004). In the Supporting Information, we compare water and sewer expenditures to total household expenditure—a proxy for lifetime income. We find that water bills are still regressive even under alternative metrics of income.

3.4 Water affordability concerns are pervasive across the US, driven by the local income distribution

Geographically, we find some differences in water affordability across the US. In panel (a) of Figure 4, we plot the proportion of households with unaffordable water within each county. We calculate affordability based on essential consumption levels (see Materials and Methods). Some counties in the desert Southwest display high levels of unaffordable service, with rates of unaffordable water exceeding 25% of households. Several states in the Southeast also possess counties with high rates of unaffordable water and sewer bills.

County-level comparisons, however, mask important heterogeneity at a finer geographic scale. In panels (b)-(d) of Figure 4, we plot the same metric evaluated at the Census block-group level. This analysis reveals pockets of water affordability concerns at a more local level. In the Southeast (panel (e)), we observe a patchwork of block groups with high rates of households with unaffordable water bills. Even in the relatively wealthy Northeast (panel (d)), we identify many Census block groups with more than 25% of households facing unaffordable water and sewer services.

Local maps also illustrate the importance of analyzing water affordability issues at a high resolution. Figure 5 shows the percentage of households facing unaffordable water services in block groups of counties corresponding to two large urban areas: Atlanta, GA, and Chicago, IL. In these cities, we observe clusters of block groups with households facing unaffordable water, which in many cases geographically correlates with low-income areas. The high resolution of the data also allows us to identify several isolated pockets of water affordability concerns.

Overall, we find evidence that water affordability concerns are pervasive in the Southwest and Southeast. However, we also uncover serious concerns within states and within urban areas across the US. Because of these findings, we conclude that affordability concerns are inherently a local issue dictated by the distribution of income within a community.

3.5 Water affordability concerns are significantly correlated with select community characteristics

We conduct a statistical analysis to test whether the proportion of households with unaffordable water and sewer service is significantly correlated with socio-economic-demographic community characteristics. To develop statistical tests of conditional correlation, we regress the proportion of households above the affordability threshold on community characteristics and state and climate-zone fixed effects (see Methods and Materials and Supporting Information for our detailed statistical methodology).

Table 3 shows the estimated conditional correlation coefficients between the proportion of households facing unaffordable CWSBs and select community characteristics. Confidence intervals are based on standard errors clustered at the county level. The percentage of the population below the federal poverty limit is strongly associated with the prevalence of water affordability concerns. A one percentage point increase in the number of households below the poverty limit is associated with a 0.492 [0.448, 0.536; 95% CI] percentage points increase in the number of households above the affordability threshold. Additionally, we report a significant positive relationship between water affordability concerns and the proportion of black households within a community (0.019 [0.002, 0.036; 95% CI]) even after controlling for poverty levels. However, results indicate the opposite for the relationship between affordability and the proportion of Hispanic residents (-0.023 [-0.043, 0.004; 95% CI]). We also find a small positive correlation between affordability concerns and the proportion of renters within a block group and the median cost of rent relative to income.

Additionally, by using the natural log of population density as a proxy of urbanicity, we find that population density has a negative association with the proportion of households above the affordability threshold. A one log-point increase in population density is associated with a -0.507 [-0.711, -0.302; 95% CI] percentage point decrease in the number of households above the affordability threshold. The magnitude of this effect, however, is quite small. In other words, a one-percent increase in population density is associated with a -0.005 percentage point decrease in affordability concerns. Nevertheless, we believe that we are more likely to falsely assign rural households to utilities when they might in fact not receive public water or sewer service (e.g., rural households are more likely to have septic systems and thus not pay for sewer services directly). As a result, we cannot rule out that that water affordability might be a concern for both urban and rural areas.

We include two variables that capture the role of water rate-setting practices. One variable captures the mean volumetric price for monthly consumption between 5 and 10 ccf. This variable is positively associated with water affordability concerns. A one log-point increase in average water rates is positively correlated (8.419 [5.956, 10.882; 95% CI]) with the proportion of households above the affordability threshold. Put another way, a one-percent increase in volumetric water rates is associated with a 0.084 percentage point increase in affordability concerns. A second variable captures the proportion of a customer's bill (evaluated at 50 gppd) that is composed of the fixed access charge. This variable is also positively correlated with the proportion of households with unaffordable water (0.115 [0.066, 0.164; 95% CI]), which suggests that affordability concerns are not driven entirely by the volumetric price of water and sewer services, but also the fixed service fee.

Overall, the proportion of impoverished households within a block-group and average water prices are strongly associated with unaffordable water. We also find evidence that the proportion of black households is correlated with unaffordable water after conditioning on poverty levels and other socioeconomic characteristics. This correlation, however, is reversed when we consider the proportion of Hispanic residents within a block group. Additionally, we find positive correlations between water affordability concerns and household size as well as median rents as a proportion of household income.

3.6 Affordability policies that provide lump-sum rebates for low-income households and are funded by income taxes are most effective

We compare the effectiveness of four illustrative policies resulting from the combination of two options for the assistance they provide and how they are funded. Assisted households receive either a 50% rate discount or a uniform rebate. Programs are funded by non-assisted households that face either a uniform rate increase or local income tax. Eligible households have an annual income such that a CWSBs at the essential level would represent an income share above 4.5%.

Figure 6 shows the relative outcomes of these policies. These comparisons consider initial expenditures in water and sewer services at the estimated level of consumption (an income-based adjustment of average county consumption; see Supporting Information for details). In the top right panel, we show average expenditure shares for the business-as-usual scenario and for each of our four policy options. Each program reduces the average number of households above the affordability threshold, although aid transfers reduce the number of households above the affordability threshold in the lowest income bracket more than rate reductions. For example, at the 4.5% threshold, all programs considered reduce the 75th percentile of CWSBs to less than 7% of annual income, with transfers reducing it further to approximately 5%. In the top right panel of Figure 6, we show changes in CWSBs for each policy. All policies substantially reduce the total bills for households in the lowest income bracket, although rebates decrease the net cost to low-income customers by the greatest degree. Raising revenue by price increases for wealthier households leads to higher bills relative to raising revenue via an income tax.

Additionally, in the bottom left panel of Figure 6, we plot the change in the number of households above the water affordability threshold for each program. Programs designed with income transfers rather than rate reductions can reduce the number of households with CWSBs above 4.5% of annual income from 11.0% to 6.7%, if funded by rate increases, and from 9.8% to 5.6%, if funded by income taxes. For programs of a similar size, structuring water affordability aid as an income transfer funded by income taxes dominates policy options that alter the unit price of water and sewer consumption. As a practical matter, an income transfer could take the form of individual-specific credits on customer bills (so long as they are not misperceived as a reduction in the price of water (Wichman, 2017)) or a rate structure in which households pay different fixed access fees for water and sewer services. This finding is a result of the relative sensitivity of water and sewer consumption to changes in price and income.

Our baseline program simulations follow previous findings that the price elasticity of water and sewer demand is greater in absolute magnitude than the income elasticity of water and sewer demand (Dalhuisen et al., 2003; Olmstead, Hanemann, & Stavins, 2007; Wichman, 2014; Klaiber, Smith, Kaminsky, & Strong, 2014; Wichman, Taylor, & von Haefen, 2016; Havranek et al., 2018). We report a sensitivity analysis on these parameters in the Supporting Information. Among other results, our sensitivity analysis shows substantial differences in program performances even when both elasticities have equal magnitude; these findings are due to the fact that price reductions are, in relative terms, a bigger shock than their corresponding lump-sum income increase. Because rate reductions distort marginal incentives for households to consume water more than income transfers do, low-income customers tend to consume more water as a result of affordability policies that make additional water use cheaper. This feedback counteracts the goal of the affordability program. As a result, it is important to understand the demand implications of water affordability policies.

4 Discussion

In this section, we discuss the limitations of our analysis and their implications; a detailed explanation of robustness checks that explore these implications is presented in the Supporting Information. First, our sample covers only 45 percent of the US population, which skews towards urban areas and is not representative of the US. Our population of interest, however, is US residents who receive water and sewer service from public or private water utilities, which mitigates this sample-selection concern. As we show in the Supporting Information (Figure S8), the income distribution in our sample is virtually identical to that of the nation as a whole. Moreover, although our sample is not comprehensive, we are aware of no other data set of water and sewer rates matched with socioeconomic characteristics and estimates of consumption as comprehensive as ours.

Second, our results rely on a metric that has received increasing scrutiny as a useful tool for measuring affordability concerns in part because the 4.5% of median-household income threshold is arbitrary and that median income poorly captures the full income distribution. We have shown empirically the substantial difference that using MHI and the full income distribution can have when measuring affordability. Additionally, two alternative metrics of affordability have been proposed recently and are gaining traction as useful policy tools (Teodoro, 2018). The first is an "affordability ratio" that captures the ratio of essential water and sewer expenditures to a subjective measure of disposable income, evaluated at the 20th percentile of income within a service area. The second is essential water and sewer expenditures in units of hours worked at the minimum wage. Our focus in this analysis is not on contrasting alternative metrics, but we perform a simple comparison in the Supporting Information. For the 20 overlapping cities in our sample and in (Teodoro, 2018), our preferred metric correlates strongly with these new metrics, which suggests these alternatives may not dominate an income-based threshold affordability metric at face value (see Table S6). This result is important as income-based thresholds are used in the vast majority of other means-tested assistance programs (e.g., the Supplemental Nutrition Assistance Program, the Low Income Home Energy Assistance Program, and California's proposed statewide Low-

Income Water Rate Assistance Program). Additionally, our affordability metric is readily scalable and can be used holistically in two ways: (i) to identify communities with a high burden of water and sewer expenditures and (ii) to establish household-level eligibility in low-income water rate assistance programs.

Third, we do not know whether the representative customers in our sample are homeowners or renters (who may not pay for water and sewer services directly). If the costs of water and sewer services are passed-through to renters fully in the cost of their rent, affordability is still a concern, but it changes the incentives for efficient water use. We know of no large-scale data set that contains this information at the scale of our analysis. To mitigate this concern in our regressions, we control for the proportion of renters within a Census block group and housing rental rates as a proportion of income.

Lastly, many utilities have existing rate structures for low-income customers across the US. We know of no large-scale database of these types of rate structures or a synthesis of what the eligibility requirements are. Many of these rate structures lower the marginal price for water consumption for customers with low income. In our policy simulations, we show that lowering the marginal price of water counteracts the effectiveness of low-income water rates, which suggests that "lifeline" rates may be inefficient policies. Exploring ways to address affordability issues for renters and understanding the dynamics of local or more aggregate policies (e.g., state or national) are fruitful areas for future research.

5 Conclusions

Provision of affordable water and sewer service is a growing concern in the United States, although the extent of the problem is not known and the effectiveness of corrective policy options are underexplored. In this paper, we have compiled a database of water and sewer prices for approximately 45% of the United States population to estimate annual expenditures on water and sewer service. We find that nearly one in ten households spend more than 4.5% of their annual household income on essential water and sewer services, and that affordability concerns are significantly correlated with race after conditioning on poverty levels. Our analysis shows the importance of incorporating geographically resolute information on the local income distribution of residents. Results from policy simulations demonstrate that redistributive water affordability policies designed to provide lump-sum rebates to low-income customers that are funded by income tax increases on relatively wealthier individuals are more effective at reducing the number of households with unaffordable water and sewer services than policies that distort marginal incentives to consume water.

Our analysis provides a consistent framework to evaluate the extent of the water affordability burden. Importantly, this framework also facilitates the assessment of policies to ameliorate the worst consequences of unaffordable water as municipalities and regulators grapple with alternatives to fund water infrastructure improvements equitably. Ultimately, affordability metrics rely on judgments about what is essential consumption and what defines low-income customers. As illustrated in Figure 3, our framework is easily adaptable to inform and account for the decisions of policymakers over affordability thresholds and essential water consumption.

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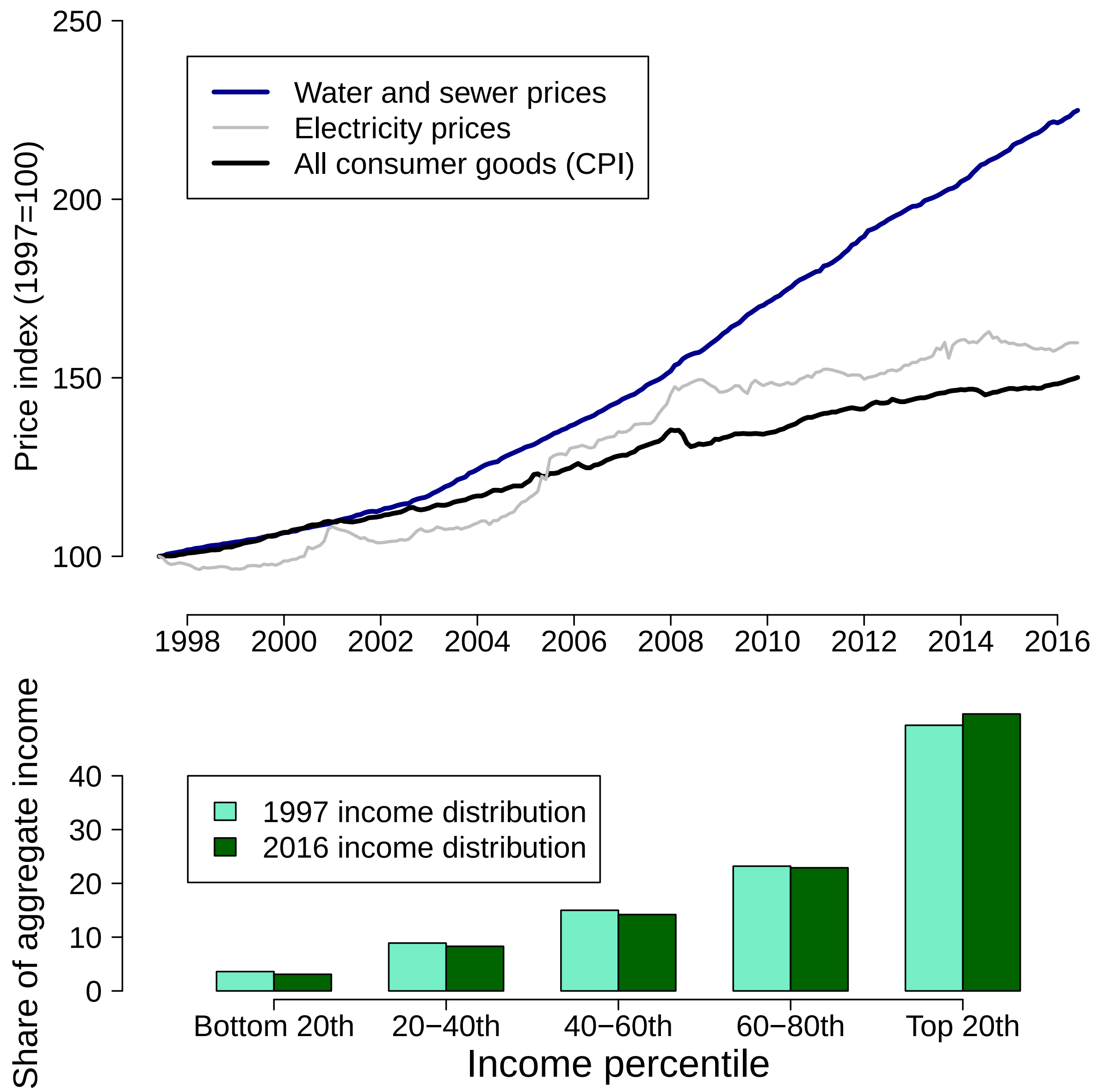


Figure 1: U.S. price indexes and income distribution over time. **Top Panel:** Monthly price (U.S. city average, all urban consumers, seasonally adjusted) for all consumer goods, electricity, and water and sewer. Series begins in December 1997 (=100). Water and sewer price index includes trash collection. *Source:* U.S. Bureau of Labor Statistics. **Bottom Panel:** Share of aggregate income received by each fifth of households in 1997 and 2016. *Source:* U.S. Census Bureau, Current Population Survey, Annual Social and Economic Supplements.

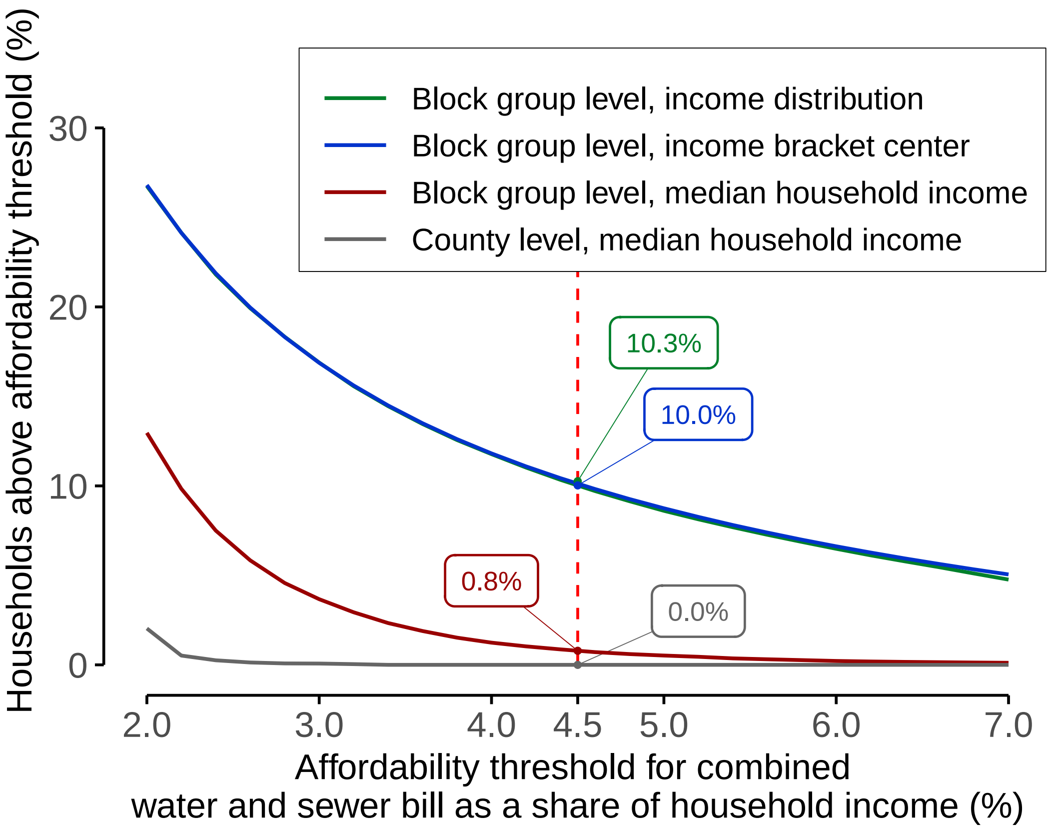


Figure 2: Proportion of households above affordability threshold for essential water and sewer expenditure as a share of income, based on varying degrees of income data resolution.

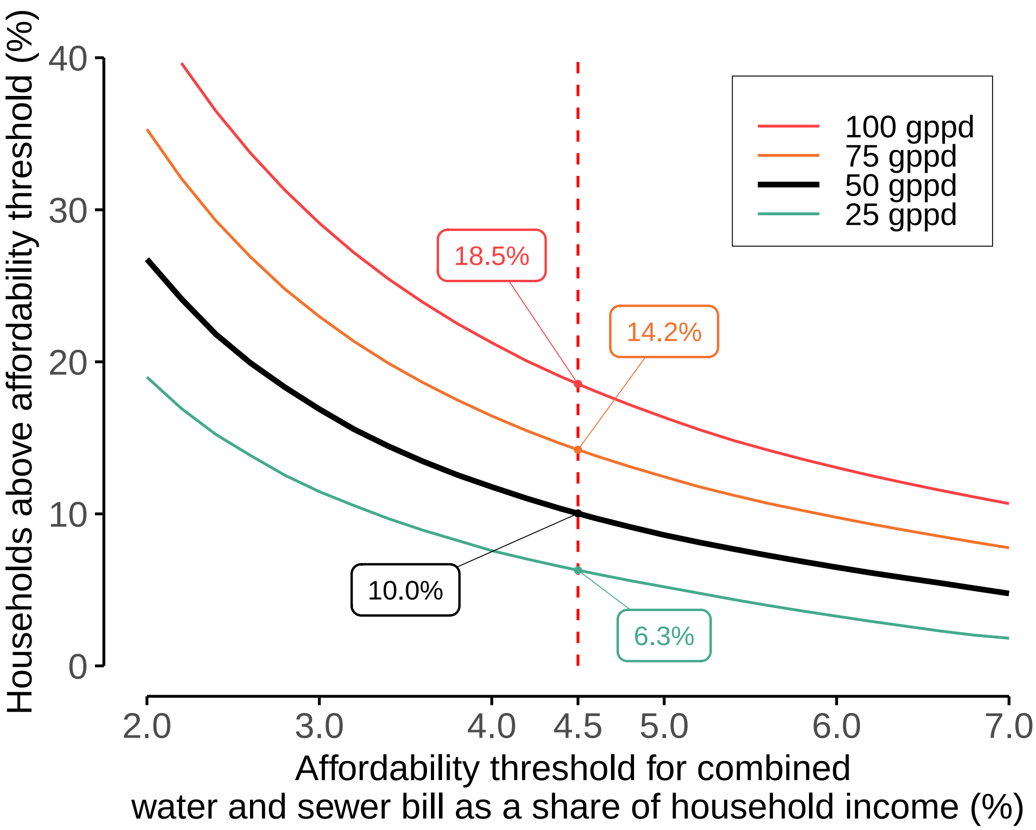


Figure 3: Proportion of households above affordability threshold for water and sewer expenditure as a share of income, based on varying levels of daily per capita consumption (in gallons per capita-day).

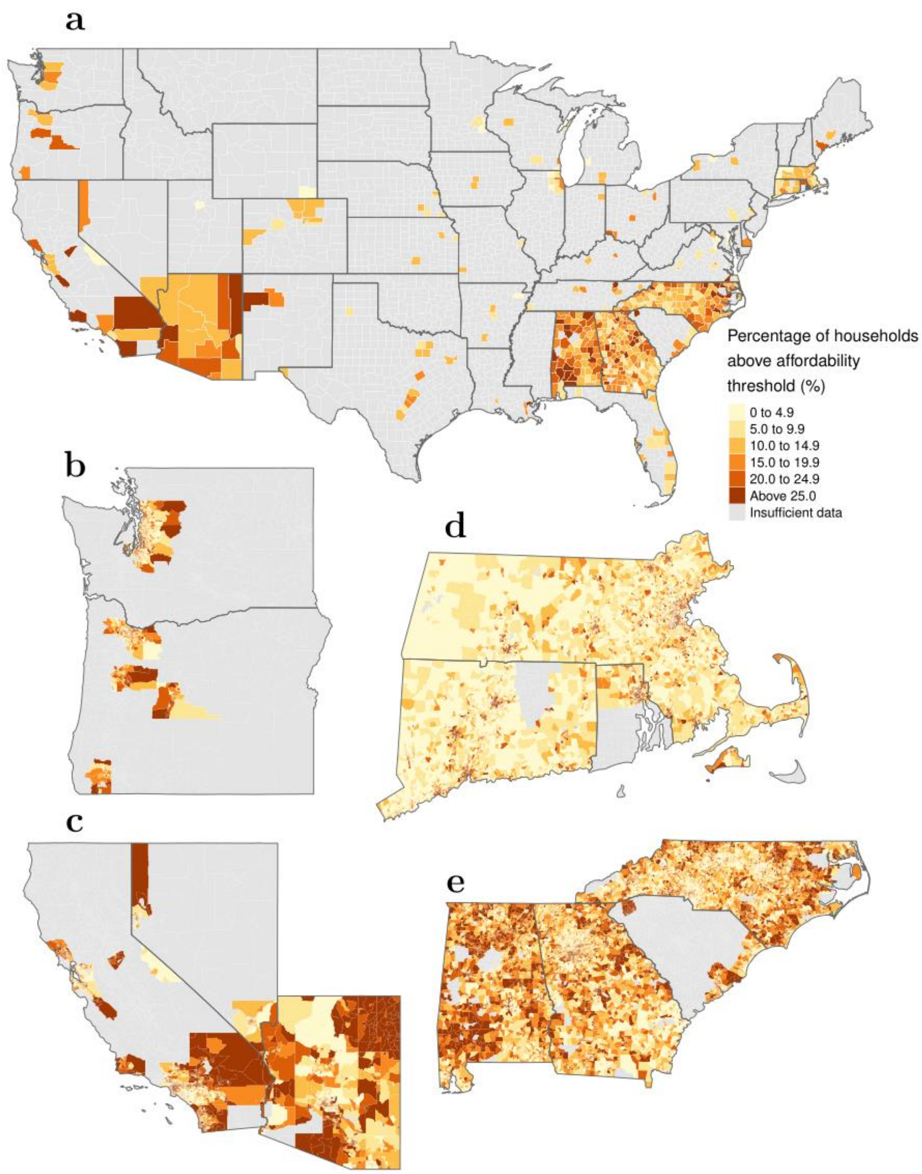


Figure 4: Geographic distribution of water affordability within regions. Shaded colors show the percentage of households within each county (in **a**) and Census block group (in **b**–**e**) that have combined water and sewer bills above 4.5 percent of annual household income. Combined water and sewer bills are calculated at the essential consumption level of 50 gallons per person-day.

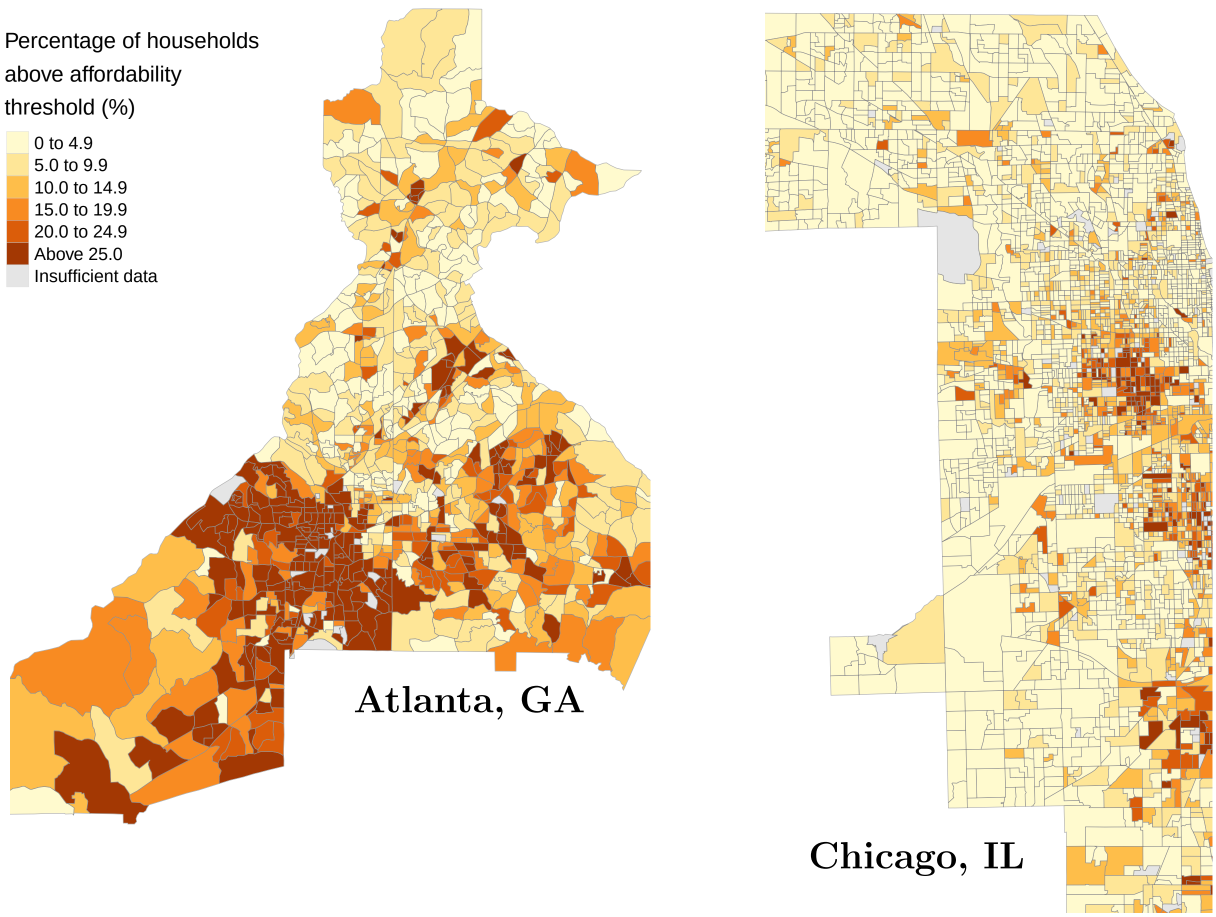


Figure 5: Geographic distribution of water affordability in block groups within urban areas. Results are presented for Atlanta, GA (DeKalb and Fulton counties) and Chicago, IL (Cook county). Shaded colors show the percentage of households within each Census block group that have combined water and sewer bills above 4.5 percent of annual household income. Combined water and sewer bills are calculated at the essential consumption level of 50 gallons per person-day.

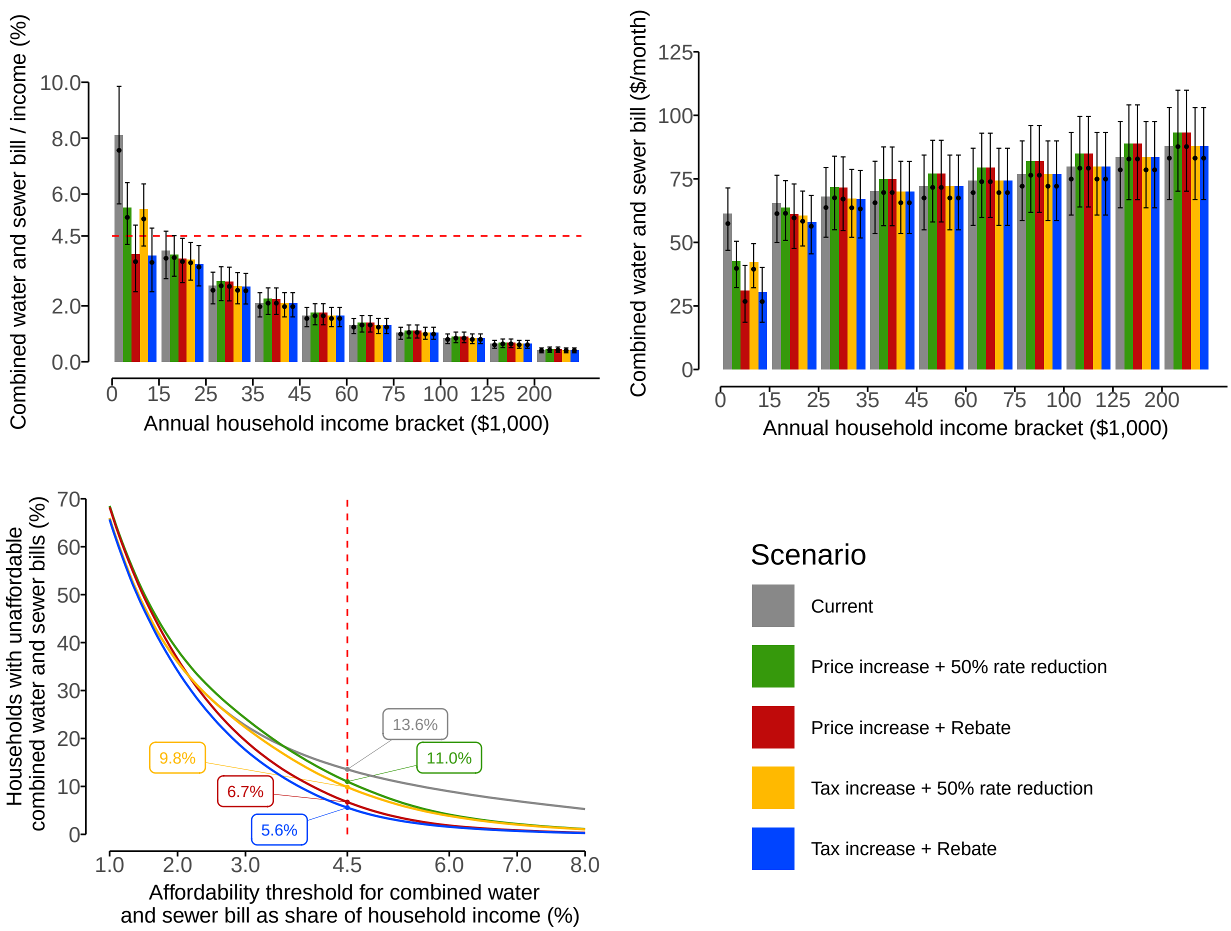


Figure 6: Results of program simulations. **Top left panel:** Average expenditure shares on water and sewer service by income bracket for business-as-usual and each policy option. Expenditures are based on the estimated level of consumption. **Top right panel:** Combined water and sewer bill by income bracket for business-as-usual and each policy option. **Bottom left panel:** Distribution of sample with unaffordable water and sewer expenditures based on affordability threshold for business-as-usual and each policy option. In all bar charts, whiskers show the interquartile ranges and dots represent median values.

Table 1: Percentage of households who pay more than 4.5 percent of annual household income on combined water and sewer bills by income and consumption data resolution

		Consumption level			
Unit of analysis	**Income metric**	**25 gppd**	**50 gppd**	**75 gppd**	**100 gppd**
County	Median household income	0.00%	0.00%	0.00%	0.09%
Block group	Median household income	0.26%	0.79%	2.15%	4.83%
Block group	Income bracket midpoint	6.29%	10.03%	14.21%	18.54%
Block group	Income distribution	6.44%	10.26%	14.48%	18.73%

[a]Results are presented for three income metrics: (i) "Median household income" represents median incomes at the county or block-group level; (ii) "Income bracket midpoint" measures incomes at the midpoint of income brackets evaluated at the block-group level; and (iii) "Income distribution" represents the interpolated income distribution for each block group based on the 16-brackets discrete distribution reported in Census data.

Table 2: Expenditure on water and sewer relative to income by income bracket[a]

Annual income[a]	**Frequency (thousands)**	**Percentage**	**Percentile**	**Average CWSB/Income**[b]
Under $15,000	5,923	11.4%	11.4	6.8%
$15,000 to $24,999	4,988	9.6%	21.0	3.1%
$25,000 to $34,999	4,899	9.4%	30.5	2.1%
$35,000 to $44,999	4,620	8.9%	39.4	1.6%
$45,000 to $59,999	6,036	11.6%	51.0	1.2%
$60,000 to $74,999	5,092	9.8%	60.8	1.0%
$75,000 to $99,999	6,361	12.3%	73.0	0.8%
$100,000 to $124,999	4,517	8.7%	81.7	0.6%
$125,000 to $199,999	6,013	11.6%	93.3	0.4%
$200,000 and over	3,468	6.7%	100.0	0.3%

[a]Income distribution data are obtained from the U.S. Census 2016 5-Year American Community Survey. Frequencies, percentages, and percentiles are relative to the aggregate income distribution in our sample.
[b]Combined water and sewer bills (CWSB) are evaluated at 50 gppd.

Table 3: Conditional correlations between water affordability and select socioeconomic characteristics[a]

	Coef.	SE	99% CI
log(Population density) (Persons/Sq. mi)	-0.507	0.104	[-0.711,-0.302]
Average household size (Persons)	0.925	0.367	[0.206, 1.644]
log(Volumetric rate at 5–10 ccf) (USD/1,000 gallons)	8.419	1.257	[5.956, 10.882]
Base charge relative to CWSB at essential level (%)	0.115	0.025	[0.066, 0.164]
Households below poverty level (%)	0.492	0.023	[0.448, 0.536]
Households between 1 and 2× poverty level (%)	0.100	0.014	[0.073, 0.127]
Median gross rent relative to income (%)	0.058	0.008	[0.042, 0.074]
Occupied units that are rented (%)	0.012	0.006	[0.001, 0.022]
Median age of housing unit (Years)	-0.005	0.007	[-0.019, 0.009]
Population identified as Black/African American (%)	0.019	0.009	[0.002, 0.036]
Population identified as Hispanic/Latino (%)	-0.023	0.010	[-0.043,-0.004]
State fixed effects		Yes	
Climate zone fixed effects		Yes	
Observations		76,240	
R^2		0.571	
F-statistic		1693.31	

[a]Dependent variable is the percentage of households in a block group above the 4.5 percent water affordability threshold calculated at the essential consumption level (50 gallons per person-day). The mean of the dependent variable is 11.49 and its standard deviation is 11.67. Summary statistics for other variables are presented in the Supporting Information. Standard errors are clustered at the county level. All variables are defined at the block-group level.

Supporting Information

Supporting Information is structured as follows. Section A describes the sources of data and outlines the steps in assembling our data set. Section B outlines the methods used in thr regression analysis and policy simulations. Section C examines how sensitive our policy simulations are to key parameters in the model. Section D presents complementary analyses in four subsections. Subsection D.1 discusses water sewer and bills regressivity using alternative income metrics. Subsection D.2 estimates conditional correlations of unaffordability and socio-economic-demographic factors in select US region. Subsection D.3 compares our approach to alternative metrics in the literature. Finally, subsection D.4 reports simulation results only for counties in which we have data on average consumption levels.

A Data

Our data set includes 92,445 census block groups from 521 counties across 42 states. The data set covers approximately 145 million people—around 45% of the total US population as of 2016. This data set combines local water and sewer rates, number of service accounts, average consumption, climate characteristics, and a multitude of socio-economic-demographic indicators. Below we cover each domain of the data set and its respective sources.

A.1 Water rates

To estimate local rates for water and sewer services, we combine data from two sources. The first source is the Water and Wastewater Rates Dashboard, provided by the Environmental Finance Center (EFC) at the University of North Carolina. The EFC offers a free online dashboard tool, with detailed information on water and sewer bills at different consumption levels from several utilities in 13 states. We gathered the data available in those dashboards either through published tables or via a custom software code that extracts relevant information from the dashboards. From the dashboards, we include data on 1,356 utilities, from 7 states, that showed the necessary information for our analysis. The second source is the 2016 Water and Wastewater Rate Survey, conducted by the American Water Works Association (AWWA); it includes 264 water and 183 wastewater utilities from 42 states, out of which we consider 189 utilities that have the necessary information on rates and consumer base.[S1] The AWWA data are proprietary but can be purchased from AWWA by anyone.

Merging data from AWWA and EFC poses three main challenges: (i) water bills are reported at distinct consumption levels in each source; (ii) the exact geographical boundaries of the area served by each utility are not provided and are difficult to establish in practice; (iii) data from EFC do not contain information on average consumption. Below, we explain how we address each of these issues.

The AWWA survey asks participants to report the year-round (non-seasonal) total monthly bill of residential water and wastewater at six different levels of consumption: 0, 5, 10, 15, and 30 ccf (hundred cubic feet), and at average residential consumption levels. However, the EFC dashboards report total monthly bills at levels from 0 to 15,000 gallons, in increments of 500 gallons. In order to combine these data, we linearly interpolate values from EFC to obtain estimated bills at levels that match those reported by AWWA: 0, 5, 10, and 15 ccf (0, 3740, 7480, and 11220 gallons). Having the data at these four levels, we calculate the total monthly bills at other consumption levels using linear interpolation. Hence, we approximate each utility's rate schedule to block pricing with up to three blocks with different rates: below 5 ccf, between 5 and 10 ccf, and above 10 ccf per month.

Determining the precise area covered by each water utility proved to be a difficult task. In most cases, this information is not available or formatted for electronic use. To overcome this limitation, our analysis estimates local water rates using county-level averages weighted by the number of accounts in each utility within a county. The data show that in most cases rates within counties are similar. This procedure, however, does not come without loss: in counties with very different rate structures, the weighted average approximates more closely the estimation of water affordability for utilities with more customers.

Figure S1 illustrates the heterogeneity of water rates across the country. Each horizontal bar represents a county with a population above 500,000; the leftmost, light gray segment is the base rate, and each subsequent segment accounts for the incremental charge of consuming an additional 5 ccf. The white dots show the estimated average bill.

Additionally, in Figure S2 we plot the unconditional correlation between the proportion of

[S1] For the 26 utilities with at least 200,000 accounts and missing data on sewer (but not water) rates, we imputed the missing values with data obtained directly from these utilities.

the CWSB that is the fixed service fee (for CWSBs evaluated at 50 gppd) and the proportion of households who have unaffordable water and sewer at the essential level (50 gppd) service within the county. Interestingly, we see a positive correlation between the proportion of the bill that is fixed and affordability concerns. We can infer from this figure that the unconditional correlation between the proportion of CWSBs that is volumetric at essential levels is negatively correlated with affordability concerns. This analysis suggests that affordability concerns are associated with bills that have high fixed service fees.

A.2 Climate zones

The definition of climate zones follows the 2004 International Energy Conservation Code (IECC). Each zone is characterized along two dimensions: average temperatures, categorized by a number from 1 (hottest) to 8 (coldest), and humidity, categorized by letters A (humid), B (dry), or C (marine). County-level climate zone data is obtained from the County Characteristics 2000-2007 data set, compiled by the Inter-University Consortium for Political and Social Research (ICPSR 20660).

A.3 Socioeconomic-demographic factors

Population, income, and other socioeconomic data come from the 2016 5-Year American Community Survey (ACS), conducted by the US Census Bureau. The publicly available data are reported at the block group level; each census block group typically includes from 600 to 3,000 people. We map block groups to counties using the 12-digit FIPS code identifier.

Of particular interest for our analysis are the income data reported by the ACS. For each block group, there are data on the median annual household income and an estimate of the number of households in each of the 16 income brackets. These values allow us to construct block-group level income distributions and to estimate more precisely the number of households facing affordability issues. Using the information on the population in each block group, we can also aggregate local distributions to obtain a county-level summary of income. Having an income distribution instead of only local medians makes it possible to estimate the local distribution of the ratio between water and sewer bills to income, which is central to our analysis.

In addition to data on income, the ACS provides a rich characterization of the social, economic, and demographic factors within a block group. Among the extensive list of indicators available in ACS, we study the correlations between water affordability and a selected set of factors aggregated to the block level group:

1. Population density, measured in persons per square mile.
2. The percentage of the block group population that identifies their race as Black or African American alone.
3. The percentage of the block group population that identifies being of Hispanic or Latino origin.
4. The percentages of households with income below the Census Bureau poverty threshold[S2] and with income between one and two times that threshold.
5. The median age of housing units.
6. The median gross rent as a percentage of the household income.
7. The average household size.
8. The percentage of rented units relative to all occupied units.

B Methods

B.1 Preliminaries

This section establishes common definitions and assumptions of our analysis. As described in the paper, we examine metrics using four levels of aggregation (or resolution): county, Census block group, household income brackets within a block group, and a continuum of households within a block group.

The socio-demographic regressions and policy simulations are based on the third resolution level, i.e, a representative household of an income bracket within a block group. For each block group, the ACS provides an estimate of the number of households in each of the sixteen annual income brackets. Using this information, we construct a sixteen-node income distribution per block group, using the center of each bracket as a node. There are two exceptions: (i) for the lowest bracket (up to $10,000) we set the node at $7,500, which follows from assuming $5,000 is the lowest possible income; (ii) for the upper bracket, we set the node at $250,000, assuming $300,000 as the highest possible income.

A household is indexed by its income node i, its block group b, and its county c. We denote

[S2] This poverty threshold is adjusted for inflation and takes into account the size of the householder's family. More details can be found at the ACS documentation.

the income level corresponding to an income node as y_i, and the set of all income nodes as I. Each income node has a probability mass (or share) $f_b(y_i)$ within its block group. Each county c is formed by a set B_c of block groups. Each block group has a probability mass $f_c(b)$ within a county.

A variable x observed at the household level is represented as x_{ibc}. Block-group averages are then defined as

$$\bar{x}_{bc} = \sum_{i \in I} x_{ibc} f_{bc}(y_i).$$

County averages are defined as

$$\bar{x}_c = \sum_{b \in B_c} \left[\sum_{i \in I} x_{ibc} f_{bc}(y_i) \right] f_c(b).$$

Letting ω denote the chosen level of essential consumption (in gppd) and $\bar{h}_{bc}$ the average household size in block group b, the household's monthly consumption of water is given by

$$W_{ibc} = 30\bar{h}_{bc}\omega. \tag{S1}$$

Let $\Phi_c(W_{ibc})$ denote the monthly combined water and sewer bill (CWSB) for county c, where W_{ibc} is given in gallons per month. In this paper, we assume Φ_c is piecewise linear to approximate block pricing schedules. This approximation allows for up to three blocks following the AWWA reported data, with breakpoints at 3,740 and 7,480 gallons per month (or 5 and 10 hundred cubic feet). Then, the estimated CWSB is given by $\Phi_c\left(\hat{W}_{ibc}\right)$. Hence, the annual share of income corresponding to the CWSB is

$$\hat{s}_{ibc} = 12\frac{\Phi_c\left(30\bar{h}_{bc}\omega\right)}{y_i}. \tag{S2}$$

B.2 Regression analysis

This section describes the procedure to estimate the conditional correlations between water service affordability and socio-economic-demographic characteristics.

We start by calculating local (un)affordability. Let t be the affordability threshold, usually defined as 4.5% of the annual income. We define the local unaffordability metric, i.e., the percentage of households with CWSBs above the affordability threshold within a block group, as follows:

$$\hat{U}_{bc} = \sum_{i \in I} 1(\hat{s}_{ibc} \geq t) f_{cb}\left(y_i\right),$$

where $1(\hat{s}_{ibc} \geq t)$ is an indicator function receiving 1 if $\hat{s}_{ibc} \geq t$ or 0 otherwise. Thus, $\hat{U}_{bc}$ is effectively a block-group average of the unaffordability indicator. We can also denote $\hat{U}_{bc}$ as a nonlinear function $U\left(\omega, t, \bar{h}_{bc}, \Phi_c, \mathbf{f}_{bc}\right)$, where $\mathbf{f}_{bc}$ is a vector with $f_{bc}\left(y_i\right)$ evaluated at all $i \in I$.

Similarly, at the county level, we have

$$\hat{U}_c = \sum_{b \in B_c} \left[\sum_{i \in I} 1(\hat{s}_{ibc} \geq t) f_{bc}\left(y_i\right) \right] f_c\left(b\right).$$

Next, we estimate the linear association between local unaffordability and various socioeconomic-demographic factors. In doing so, we note that this estimation does not intend to uncover causal relationships. Instead, the goal of this exercise is to make sense of which socioeconomic and demographic factors are correlated with local water affordability after controlling for prices and other variables.

Let $\mathbf{X}_{bc}$ be a $n \times 1$ vector of n socio-economic-demographic factors of a block group. We want to estimate the $n \times 1$ parameter vector Γ in the following equation:

$$U\left(\omega, t, \bar{h}_{bc}, \Phi_c, \mathbf{f}_{bc}\right) = \hat{U}_{bc} = \mathbf{X}_{bc}'\Gamma + \sum_{z \in Z} \gamma_z 1(CZ_c = z) + \sum_{s \in S} \delta_s 1(State_c = s) + u_{bc}, \tag{S3}$$

where $1(CZ_c = z)$ is a dummy variable equal to 1 if county c is in climate region z and 0 otherwise, $1(State_c = s)$ is a dummy variable equal to 1 if county c is in state s and 0 otherwise, and u_{bc} is the idiosyncratic error term. Summary statistics for the variables used in this regression are presented in Table S1.

B.3 Policy illustrations

B.3.1 Affordability programs and relative performance metrics

We investigate the effects of four hypothetical assistance programs with different benefits and funding options. The benefits can be either a uniform lump-sum transfer or a 50% rate discount for assisted households. The programs can be funded either by a uniform water rate increase or local income tax, both considering only non-assisted households.

In our simulations, programs are implemented at the county level. To make comparisons fair, all programs have equal size, as measured by the annual aggregated transfers. To determine the size of the programs in each county, we first adjust water consumption for assisted households based on a rate discount of 50% in all price blocks. Then, we calculate the dollar amount necessary to fund the discounts in a scenario of increased consumption; this amount sets the size of all four programs. Once the size is fixed, we calculate the uniform lump-sum transfers for the programs that offer such benefit. Similarly, we calculate the income tax rate and the price increase necessary to raise funds for their corresponding benefits.

Households are eligible for assistance if their annual expenditure in water services at 50 gppd is greater than or equal to 4.5% of their annual income. Using this threshold, we obtain an estimate of the number of assisted households per county. The assistance programs affect water consumption by either changing water prices or income of a household. For a relative price change Δ_p and a constant price elasticity ϵ_p, the ratio of water consumption after and before the change is $\Delta_p^{\epsilon_p}$. Hence, the adjusted expenditure on water services after a rate change d is given by

$$\hat{\phi}_{ibc} = \Phi_c\left(\hat{W}_{ibc}\Delta_p^{\epsilon_p}\right), \tag{S4}$$

where $\hat{W}_{ibc}$ is the estimated level of consumption (see details in Section B.3.2). Similarly, for a relative income change Δ_y and a constant income elasticity ϵ_y, the ratio of water consumption is $\Phi_c\left(\hat{W}_{ibc}\Delta_y^{\epsilon_y}\right)$.

The baseline simulations assume a constant price elasticity $\epsilon_p = -0.3$ (Dalhuisen et al., 2003) and a constant income elasticity $\epsilon_y = 0.1$ (Havranek et al., 2018). For reference, the illustrated rate discount of 50% ($d = -0.5$) increases water consumption by about 23% and decreases water expenditure by approximately 38%.

We evaluate the results of simulations based on two metrics that emphasize the distribution of expenditure shares rather than point values. The first metric is the interquartile range of expenditure shares per income bracket; this metric allows us to observe not only the effect of a policy in reducing the average burden on poorer households but also how it alleviates those under the most stress by lowering the upper bound. The second metric is the tail (or complementary cumulative) distribution function, which indicates the percentage of households with expenditure share greater than or equal to a specific value; using this curve, we assess how each program promotes redistribution by shifting relative mass from higher to lower expenditure shares.

B.3.2 Estimating initial consumption levels

Our simulations illustrate the responses of household water consumption to the different incentives programs offer by changing prices and income. In doing so, we focus on initial (or before any program) levels of consumption that adjust to different shocks. We estimate initial levels by adjusting household consumption based on the average county-level consumption and the fixed income elasticity of $\epsilon_y = 0.1$. As indicated in the paper, the performance of simulated policies should be interpreted in relation to each other—and not as absolute predictions of their outcomes should they be implemented. The need to interpret them in such a way follows from the fact that they rely on a simple model of consumption estimation that has limited power in reproducing the rich distribution of water consumption in observed data (see an assessment of estimated levels in Section B.3.3). In particular, we assume the following concerning water demand functions:

1. County average consumption per capita, $\bar{w}_c$, corresponds to a household with the county median income
2. Household consumption per capita follows:

$$\hat{w}_{ibc} = \bar{w}_c \left(\frac{y_i}{\bar{y}_c} \right)^{\epsilon_y}, \tag{S5}$$

where $\bar{w}_c$ is the average consumption per capita in county c, $\bar{y}_c$ is the median household income in county c, and y_i is household i's income. Then, a household monthly consumption is given by

$$\hat{W}_{ibc} = 30\bar{h}_{bc}\hat{w}_{ibc}, \tag{S6}$$

where $\bar{h}_{bc}$ is the average household size in block group b in county c.

The AWWA data set provides the average household water consumption by utility, W_u. However, EFC data—which account for approximately 21% of households in our dataset—do not. We use W_u to (i) calculate the county average water consumption per capita ($\bar{w}_c$) for block groups in the AWWA data and (ii) use these values to predict $\hat{\bar{w}}_c$ for EFC counties. If a county has more than one utility, we calculate $\bar{W}_c$ by averaging all values of W_u weighted by the number of accounts. Then, $\bar{w}_c = \frac{\bar{W}_c}{\bar{h}_c}$, where $\bar{h}_c$ is the county average household size.

Next, we estimate the parameter vectors β, δ, γ in the following linear model for county average per capita consumption:

$$\log(\bar{w}_c) = \beta_0 + \beta_1 \log(Pop_c) + \beta_2 \log(\bar{y}_c) + \beta_3 BaseCharge_c + \beta_4 \log(Rate5_c) + \\ +\beta_5 \log(Rate10_c) + \textstyle\sum_{z \in Z} \gamma_z 1(CZ_c = z) + \sum_{s \in S} \delta_s 1(State_c = s) + e_c, \tag{S7}$$

where Pop_c is the county population, $\bar{y}_c$ is the county median household income, $BaseCharge_c$ is the minimum service fee charged to households, $Rate5_c$ and $Rate10_c$ are the marginal combined water and sewer volumetric rates charged between 5 and 10 ccf (3,740 and 7,480 gallons) and above 10 ccf per month, $1(CZ_c = z)$ is a dummy variable equal to 1 if county c is in climate region z and 0 otherwise, $1(State_c = s)$ is a dummy variable equal to 1 if county c is in state s and 0 otherwise, and e_c is the idiosyncratic error term.

Summary statistics for the variables used in this regression are presented in Table S2. The estimation results of this stage are reported in Table S3. Despite our aggregation to the county level, point estimates for the elasticities relative to median income (0.0999) and rate at 5–10 ccf (-0.2952) are representative of central values of the ranges estimated in the literature (Dalhuisen et al., 2003; Havranek et al., 2018) and close to the values assumed in our analyses. Nevertheless, we reiterate that the goal of this regression is the prediction of local average per capita consumption levels rather than the identification of elasticity parameters of aggregate water demand. As such, state and climate zone fixed effects play an important role and explain approximately 30% of the variance in water consumption. Furthermore, prediction error can raise concerns that the policy simulations that use these estimates might be affected; we show in Section D.4 that results using only AWWA data are very similar to those including our entire sample.

B.3.3 Assessing the estimation of initial consumption levels

Our illustrations of the effects of different water affordability policies rely on estimated levels of consumption—a distribution of household water consumption generated by adjusting consumption with a fixed income elasticity. In this section, we compare individual water consumption data from two water districts with the estimated consumption from our predictive model. Even though these districts are not representative of our sample, their data allow us to gauge the extent to which our estimates track the observed distribution of water consumption.

The microdata necessary to perform this analysis were obtained through a data-sharing agreement with the California Data Collaborative after the terms had been approved by each water district. The two water districts analyzed here are located in southern California counties near Los Angeles. Due to data confidentiality agreements, we cannot disclose their identities—we will refer to them as WD1 and WD2. These data contain detailed information about water bills, including: the class of service (single residential unit, multiple residential units, irrigation, agricultural, commercial, or industrial), start and end dates of the billing cycle, full street address, Census block identifier, meter size, usage amount, total bill value, and household size, among other variables. While the data set contains billing information from 2009 to 2018, we only use data from 2016 to align with the main data set used in our paper. Moreover, to adequately observe single household annual consumption, our comparative analysis only considers single-unit residential users that were continuously served by their respective utilities in all months of 2016. The resulting sample for our analysis contains 12 monthly bills for 16,463 billing accounts in WD1 and 24,546 billing accounts in WD2.

As Figure S3 shows, both water districts are within wealthy areas when compared to the national income distribution. In 2016, the median household income for WD1 coverage area was in the \$75,000–100,000 bracket, whereas for WD2 it was in the \$100,000–125,000 bracket; for reference, the US national median income household for that year was approximately \$61,000.

We compare the predicted and observed distributions of household consumption in Figure S4. The graphs on the left-hand side display quantile-quantile, or Q-Q plots. If the predicted distribution matches exactly the observed one, the resulting curve in a Q-Q plot should be a 45-degree line (shown as a dashed line for reference). The graphs on the right-hand side show a comparative histograms, which are normalized such that the density integrates to 1.

The Q-Q plots in Figure S4 show that the model approximates the observed distribution around quantile 0.6. However, the model has limited ability to replicate both the lower and upper tails of the distributions. In particular, for the lowest deciles, the model substantially overpredicts consumption. The lower tail differences are partially due to the fact that a considerable proportion of properties in this area are subject to seasonal occupation, thus leading to an average monthly consumption that does not reflect typical consumption levels. On the upper tail, the differences indicate the models inability to predict the typical higher outdoor water use of wealthy households in this region. The comparative histograms confirm these limitations by showing that the predicted distribution is more concentrated around the median consumption level.

Given the limited predictive power of the elasticity-based adjustment model, we exercise caution in interpreting the results of program simulations, which are based on estimated levels of consumption. In doing so, we focus on the relative performance of these stylized programs rather than interpreting them as predictions of absolute performance.

C Sensitivity analysis

Two key parameters in our program simulations are the income and price elasticities of household water consumption. The income elasticity determines the estimated level of consumption and the behavior of households when their income changes due to programs based on rebates or income taxes. The price elasticity determines how households adjust their water consumption in price-based programs and the size of the programs. Our baseline scenario assumes an income elasticity of 0.1 and a price elasticity of -0.3, both values taken from point estimates in the literature (Dalhuisen et al., 2003; Havranek et al., 2018); these values are also in line with our estimates for per capita consumption aggregated at the county level (Table S3).

To illustrate the impact of these parameters in our framework, we consider four scenarios: two-by-two combinations of "low" and "high" magnitudes of each elasticity. The "low" case for each elasticity is zero. For income elasticity, the "high" case is equal to 0.4, corresponding to the highest point estimates reported in Dalhuisen et al. (2003). For price elasticity, we define the "high" magnitude (in absolute terms) as -0.8. Even though price elasticities below -1 are possible in theory, the programs considered in this paper rely on water demand being inelastic; when the price elasticity is equal to or smaller than -1, water utilities cannot raise revenue to fund programs by increasing prices. Moreover, for elasticities above but close to -1, the implied price increase for non-assisted households becomes unreasonably large.

Figure S5 shows the average fraction of income spent in water and sewer for each alternative scenario. Bar charts represent averages by income bracket and program; whiskers represent interquartile ranges, with dots representing medians. When the price elasticity is zero, all four programs deliver similar outcomes, as illustrated in panels (a) and (c). If households receiving a 50% rate discount do not increase their consumption, the discount is fully passed on to their expenditures. Moreover, price increases to fund programs are relatively smaller, as non-assisted households do not adjust to a lower consumption level. As shown in panel (c), these results hold even when income elasticity is high (0.4): rebates and taxes represent a tiny fraction of income and result in negligible consumption adjustments.

When price elasticity is high (in absolute value), price-based programs do little to alleviate unaffordability concerns (panels (b) and (d)). A program based on price discounts funded by price increases may even make the problem worse, as non-assisted households near the eligibility threshold may experience substantially higher water bills (panel (b)); for instance, the average volumetric cost for non-assisted households jumps from around $12 per thousand gallons to above $20 per thousand gallons.

Even though the relative magnitude of elasticities plays a role in determining the different performances between programs, such differences are still present even if the elasticities have the same magnitude. Panel (e) shows that rebate-based programs result in higher reduction of affordability concerns when the absolute value of both elasticities is equal to 0.1. These results follow from the fact that price discounts provide a stronger incentive to increase consumption than rebates because any corresponding lump-sum change in income is relatively small.

Overall, this analysis shows that price elasticity drives the difference in outcomes between programs, whereas income elasticity has little effect on their relative performances. Hence, except when the price elasticity is zero, we expect programs based on rebates/taxes to be more effective than programs based on price changes in reducing the burden of water bills for assisted households.

D Complementary analyses

D.1 Water and sewer bills regressivity with alternative income metrics

In other contexts, researchers have argued that contemporaneous income provides a poor proxy for the expenditure burdens of energy taxes, for example, because reported income fails to capture government transfers, retirement benefits, unreported income, or "lifetime income" (Hassett et al., 2009; West & Williams III, 2004). We follow these authors and assume that current expenditures provide a proxy for income throughout the life-cycle as postulated by the permanent-income hypothesis. In Figure S6, we plot nationally representative water and sewer expenditures, as reported in the 2016 Consumer Expenditure Survey (CES), as a share of annual income and as a share of total annual household expenditures. The results based on income-shares are consistent with our previous results. However, water expenditures as a share of total expenditures are less regressive than when calculating the water-expenditure share of income. Despite this result, water-expenditure shares of total expenditures decrease monotonically as income rises, which suggests that water bills are still regressive when using alternative formulations of lifetime income. Using the CES data, we find little evidence of regional or racial heterogeneity in regressivity.

D.2 Water affordability and socio-economic-demographic factors in US regions

Our main regression focuses on national averages of correlations between water affordability and socio-economic-demographic factors. Nevertheless, heterogeneity is likely to exist across different regions of the US. In this section, we estimate conditional correlations for three regions with higher data availability in our sample: New England, Southeast, and Southwest. The definition of regions follows the Bureau of Economic Analysis (BEA). The New England region includes Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, and Vermont. The Southeast region includes Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia. The Southwest region includes Arizona, New Mexico, Oklahoma, and Texas.

Table S5 presents the estimates and clustered standard errors for regional regressions, with summary statistics presented in Table S4. With fewer observations than the national case and less variation in the covariates that are correlated regionally, the regional regressions have less statistical power and larger standard errors.

Overall, poverty and water rates remain important determinants of water affordability in regional regressions. The magnitude of conditional correlations for each region varies but stays qualitatively similar to the estimates with all regions. We focus next on the relevant exception cases. First, we observe that the coefficient on population density is similar to the national average for Southeast and Southwest regions, though not for our highly urbanized sample in New England. Second, the general effect of higher rates leading to increased affordability concerns is observed in New England and Southeast. However, that correlation is not present for our sample of the Southwest region, which has a limited number of counties (31) and, consequently, limited variation in prices. Finally, we observe that correlations with racial factors vary substantially from region to region. The Southeast mimics the average correlation pattern of the full sample regression, with higher Hispanic/Latinos representation being correlated with lower affordability concerns and the opposite effect for Black/African Americans, though the estimates are not statistically significant at 5%. Similarly, the regression for New England finds a stronger positive correlation between Black/African Americans representation and the share of households facing unaffordable water rates. In contrast, estimates for the Southwest region show that a higher representation of these two groups is correlated with lower affordability concerns. These result illustrate how the mechanisms of demographic factors may play different roles across regions with different racial compositions.

D.3 Comparison to other metrics in the literature

In this section, we present a detailed comparison of our methodology and findings with two recent studies on the topic of water affordability in the US. The first part replicates the method proposed by Mack and Wrase (2017) to our sample and discusses the results. The second part contrasts our metrics with those proposed by Teodoro (2018) and their results for large US cities.

D.3.1 National affordability assessment in Mack and Wrase

The study by Mack and Wrase (2017), henceforth MW, is one of the first affordability assessments of water and sewer costs at the national level for the US. Adopting the EPA criterion of 4.5% of income spent on water and sewer bills, MW identify at-risk households based on the median household income at the Census tract level. They find that 11.9% of all households in the continental US face unaffordable water and sewer bills; the estimation is based on 2015 data from the AWWA Survey and the US Census American Community Survey. Furthermore, the study indicates that the number of households facing unaffordable water and sewer bills could triple in five years if the trend of increasing water rates persists.

The results in MW have brought greater attention to the debate of water affordability in the US. However, the validity of their estimates is affected by the overly restrictive assumptions made in their approach, especially those related to water demand.

First, MW assume that all households in the US consume the same amount of water: 12,000 gallons per month. Such an assumption is the result of assuming a fixed individual consumption of 100 gppd and a fixed household size of 4. In contrast, the 2016 AWWA survey shows the average consumption is 78 gppd, and the 2016 ACS shows the average household size is approximately 2.6. The resulting monthly consumption using 2016 averages is around 6,100 gallons per month—roughly half of the amount assumed in MW.

Second, the approach in MW assumes that all households in the US pay the same for water services. As shown in Figure S1, however, combined water and sewer bills (CWSBs) can vary by a factor of five across counties with a population above 500,000. Using the AWWA survey, MW estimate the average unit cost of water and sewer services to be \$0.01/gallon. Combined with the volumetric assumption, this implies that all households pay \$120/month in water and sewer bills. Then, based on the EPA's 4.5% criterion, any household with an annual income at or below \$32,000 is deemed to face unaffordable water and sewer. Thus, in practice, the affordability metric proposed in MW is a fixed income threshold.

Third, MW's affordability threshold is evaluated at the median household income of Census tracts. As our results in the main manuscript point out (see Figure 2), estimates based on median income may largely underestimate affordability concerns, as they are not able to capture the lower end of the income distribution.

To illustrate the consequences of the limiting assumptions in MW, we replicate their approach using our sample. We consider both the unit cost in MW (\$0.01/gallon based on the 2015 AWWA survey) and a unit cost of \$0.0125/gallon, based on the 2016 AWWA survey used in our sample. We highlight that the set of utility companies participating in each survey is different; thus, we cannot attribute this 25% increase to an average rate increase across utilities. These two unit costs result in fixed monthly CWSBs of \$120 and \$150, respectively.

Figure S7 presents the comparison between MW's approach and our assessment based on essential consumption and income at the bracket center. At the 4.5% threshold, these approaches produce dramatically different outcomes: MW's method using the updated unit cost (black line) indicates that 19.4% of households in our sample face unaffordable water and sewer, whereas our preferred assessment (blue line) indicates 10%. Furthermore, the distribution of expenditure shares implied by MW's method is substantially steeper for values below 5%. Such a difference in slope is the result of assuming a fixed CWSB, which exaggerates the expenditure of low-income households. As a consequence, the assessment in MW is highly sensitive to changes in the threshold: at 3%, MW's method using the updated unit cost indicates that 49.4% of households in our sample face unaffordable water and sewer, whereas our assessment indicates 16.9%.

Considering MW's original unit cost (gray line in Figure S7), the proportion of households facing unaffordable water and sewer is 8.6%—below the 11.9% found in MW. This difference is driven by our sample, which skews towards urban areas and, thus, with higher incomes. Figure

S8 demonstrates the difference in the income distributions in our sample and for the entire United States. Compared to the national distribution, households with annual incomes below $75,000 are underrepresented in our sample. Nevertheless, using the full national income distribution may also provide a biased assessment of affordability because rural areas are less likely to receive water and sewer services from utility companies.

Based on the comparisons above, we contend that our approach delivers a more reliable assessment of water and sewer affordability than MW. Moreover, our method allows policymakers to go one step further and identify which households to target in policies to ameliorate unaffordability concerns.

D.3.2 Local affordability assessments using alternative metrics

Another study offers a critique of EPA's affordability criterion (i.e., 4.5% of median household income) and proposes two metrics that bring additional considerations to the discussion of water affordability (Teodoro, 2018). In this paper, Teodoro argues that EPA's criterion possesses at least four flaws in its ability to provide an accurate picture of water affordability: (i) it focuses on average use rather than basic needs; (ii) it focuses on median income, thus overlooking poor households; (iii) it disregards other essential living costs; and (iv) it poses a binary standard set at an arbitrary threshold.

To overcome the limitations of EPA's criterion, Teodoro proposes two complementary metrics. The first metric is the affordability ratio, or AR_{20}. This metric is the ratio between the basic monthly water and sewer bill and disposable income evaluated at the 20th income percentile. The disposable income is defined as the household income minus essential nonwater/sewer expenses, such as taxes, health care, food, housing, and home energy.[S3] The second metric is hours of labor at minimum wage, or HM. This metric calculates the number of labor hours at the local minimum wage rate necessary to pay for basic water and sewer services.

Teodoro calculates both metrics for the 25 largest cities in the US to illustrate how water and sewer affordability varies across urban areas. To compare our approach to Teodoro's metrics, we compute our metrics for 20 of those cities which are present in our sample (which does not include New York, NY, Houston, TX, Indianapolis, IN, Washington, DC, and Detroit, MI). In line with Teodoro's focus on basic consumption, our comparisons assume the essential level of consumption

[S3] Typically, disposable income is defined as after-tax income.

(50 gppd) and use interpolated local income distributions.

Table S6 presents a comparison between the results following our approach and Teodoro's analysis. Based on the metrics calculated in Teodoro's study, we rank the 20 cities overlapping our sample. Columns 3 and 4 are directly obtained from Teodoro's study (Teodoro, 2018). In column 5, we present our calculated metric, denoted as U_{50}. Columns 6 and 7 display the rank-order of each city according to metrics AR_{20} and HM. Column 8 shows the average rank-order for both of Teodoro's metrics combined. Finally, column 9 shows the rank order based on our U_{50} metric.

To compare the outcomes of each metric, the bottom rows of Table S6 show Spearman rank-order correlations. As the results indicate, our approach generates similar outcomes and is strongly correlated with the average rank of AR_{20} and HM metrics, with a correlation coefficient of 0.7. It is also markedly correlated with metrics AR_{20} (0.65) and HM (0.62) separately. For a reference of magnitudes, the rank-correlation between both of Teodoro's metrics is 0.64.

The comparisons above illustrate the complementarities between approaches and are not designed to determine a single best metric. Nevertheless, we reiterate some relative advantages our method possesses. First, we follow the recommendations of the National Academy of Public Administration (National Academy of Public Administration, 2017), with our metrics relying on data available from public sources. Second, we provide metrics that can be directly applied to simulate and implement policies, as our analysis is performed at the representative household level and accounts for the full distribution of income rather than specific percentiles; this feature identifies which household groups face a higher burden of unaffordable water and sewer services. Third, our method is scalable, and our metrics can be calculated at various levels of aggregation. Finally, our metrics are flexible, in the sense that they are not tied to a specific threshold, and present a complete picture of the potential distributional impacts of affordability programs. As illustrated in Figure 6, for example, our methods can inform policymakers about the consequences and potential size of affordability programs at any given income threshold, which is the norm in existing low-income rate assistance for water utilities, as well as for defining household eligibility in other means-tested programs.

D.4 Program simulations with AWWA data only

Approximately 21% of the households in our sample are in counties covered only in the EFC data set. Since this dataset does not provide information on average consumption, we estimate this quantity following the procedure outlined in Section B.3.2. Due to the limited number of factors included in this estimation, we might be concerned that any prediction errors may affect the program simulations that rely on county averages to estimate individual consumption. To address this concern, we report simulation results including only counties in the AWWA dataset, in which utilities report county average consumption levels.

Figure S9 shows the results of program simulations that consider only counties for which average consumption information was available. We note that results reported in this Figure are very close to those reported for the full sample (Figure 6 in the paper). The similarity is due to the fact that we only need to estimate county average consumption for an area that cover approximately one-fifth of the sample. Hence, any lessons drawn from the simulations over the entire sample are not affected by that initial estimation.

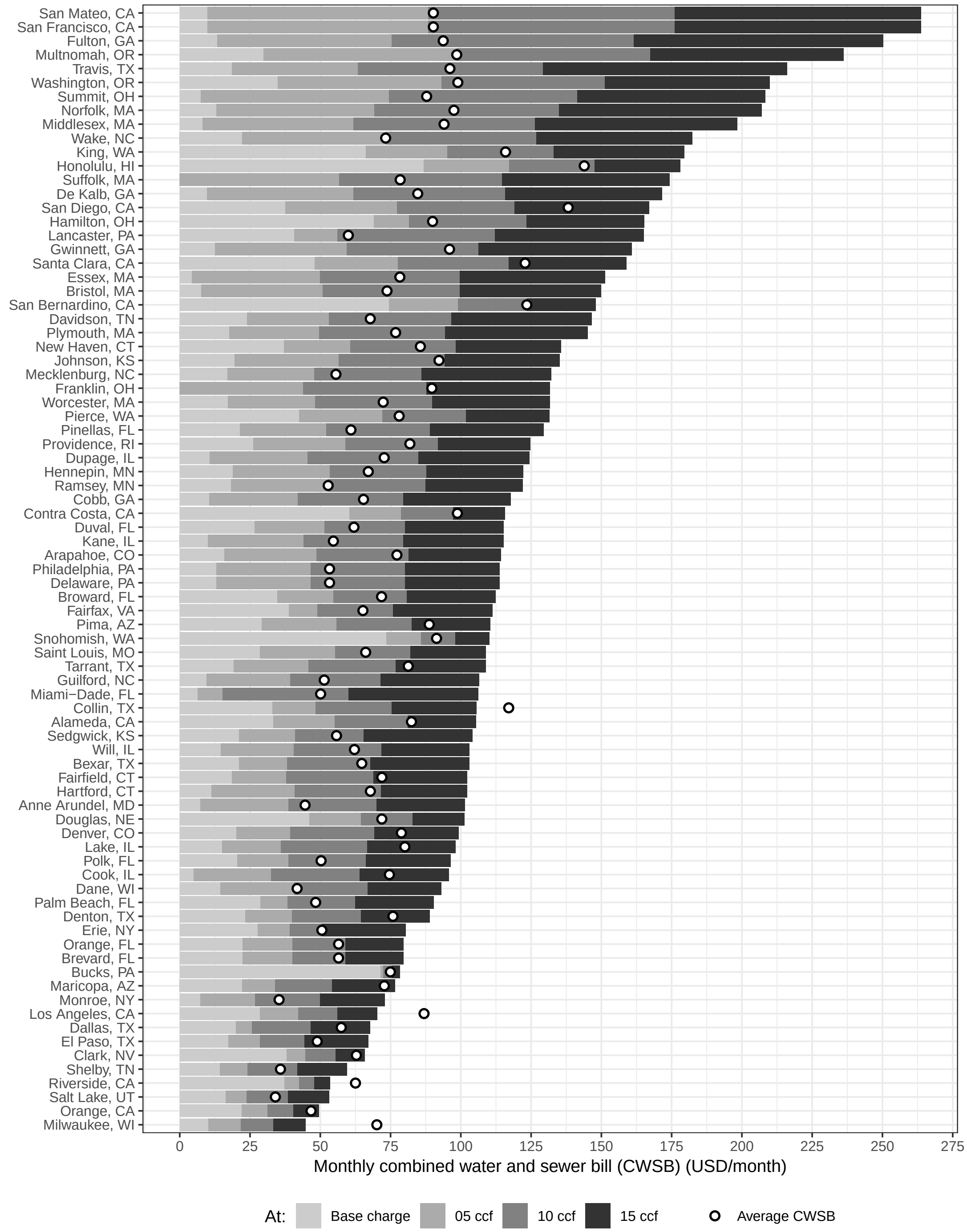


Figure S1: Combined water and sewer bills in counties with populations greater than 500,000. *Source:* Authors' calculations from AWWA and EFC data.

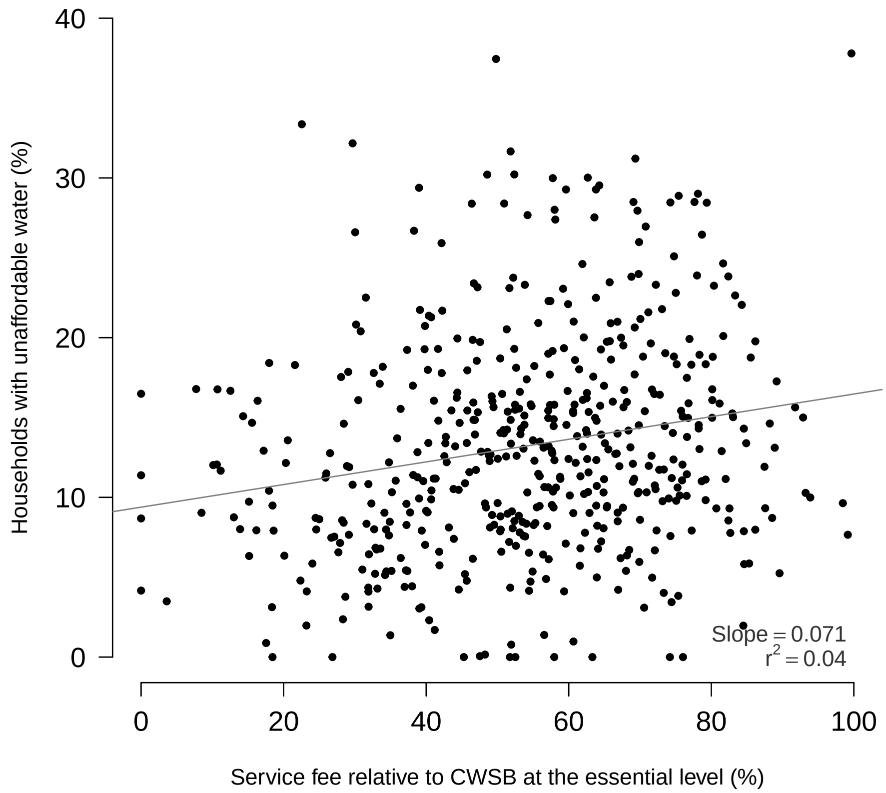


Figure S2: Correlation between the proportion of the combined water and sewer bill (CWSB) that is the fixed access fee (evaluated at 50 gppd) relative to the proportion of households with unaffordable water and sewer service at the essential level within a county.

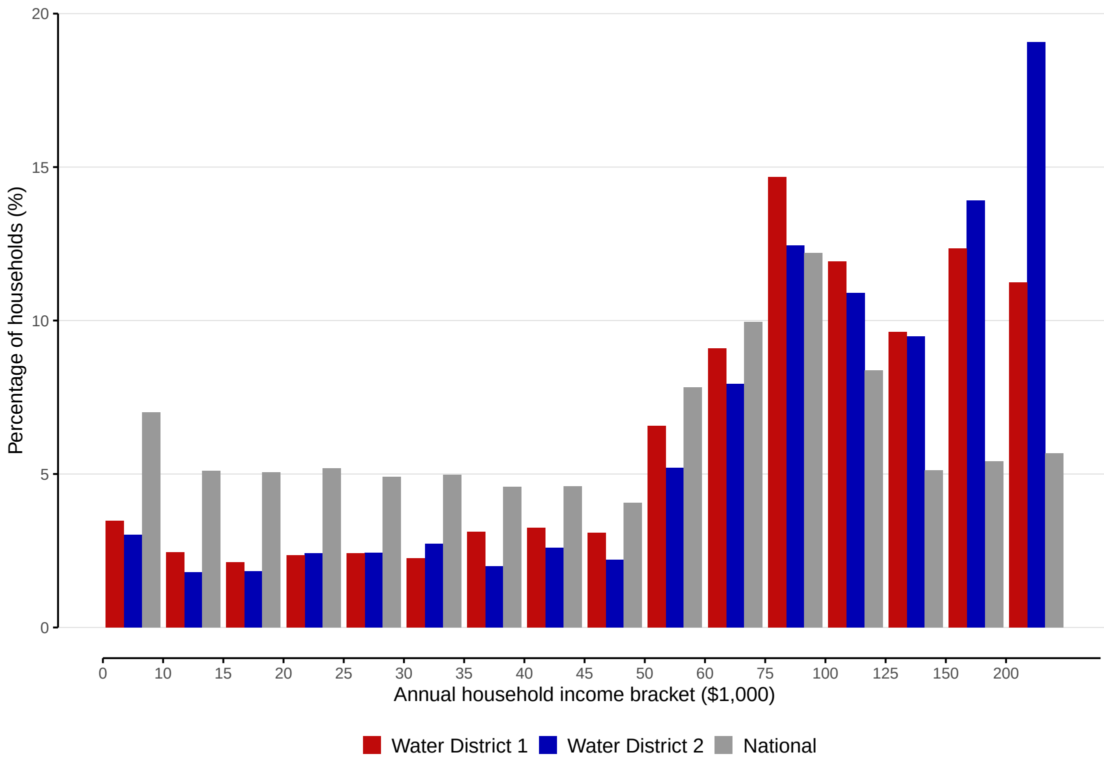
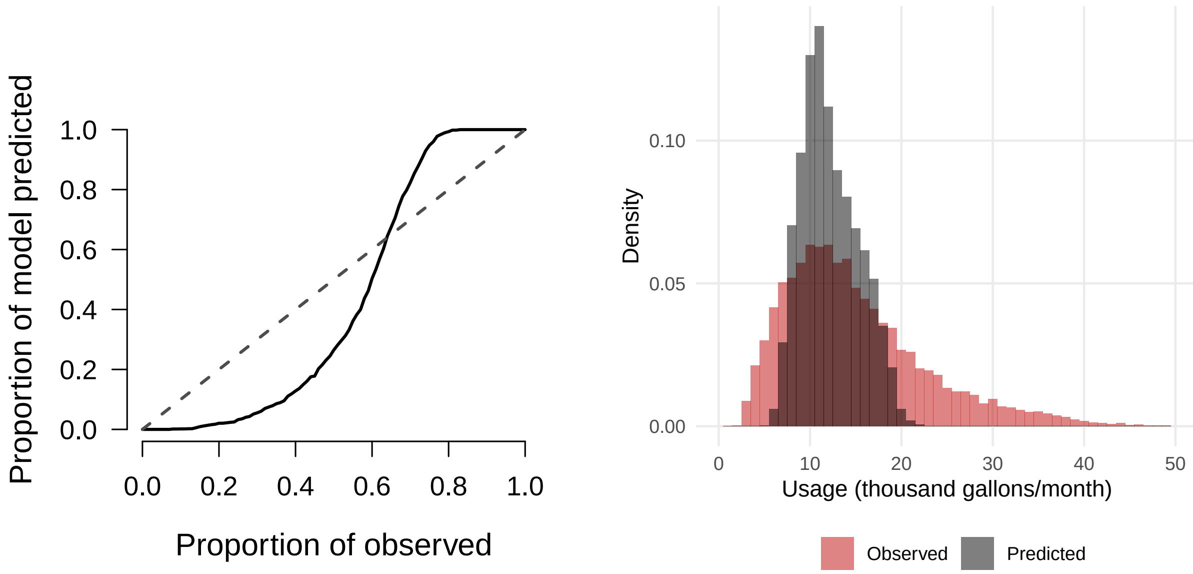


Figure S3: Household annual income distributions for analyzed water districts. *Source:* US Census, American Community Survey.

(a) Q-Q plot and histograms for WD1



(b) Q-Q plot and histograms for WD2

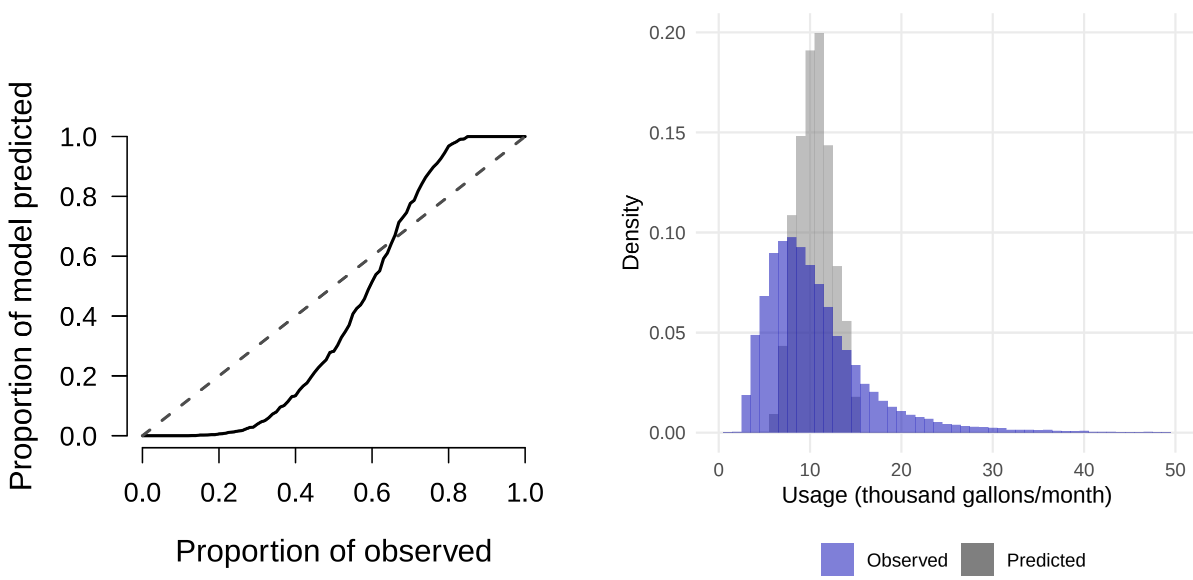


Figure S4: Plots comparing the distributions of observed and predicted household consumption. *Source:* Household consumption data from analyzed water districts and authors' calculations based on other sources listed in Section A.

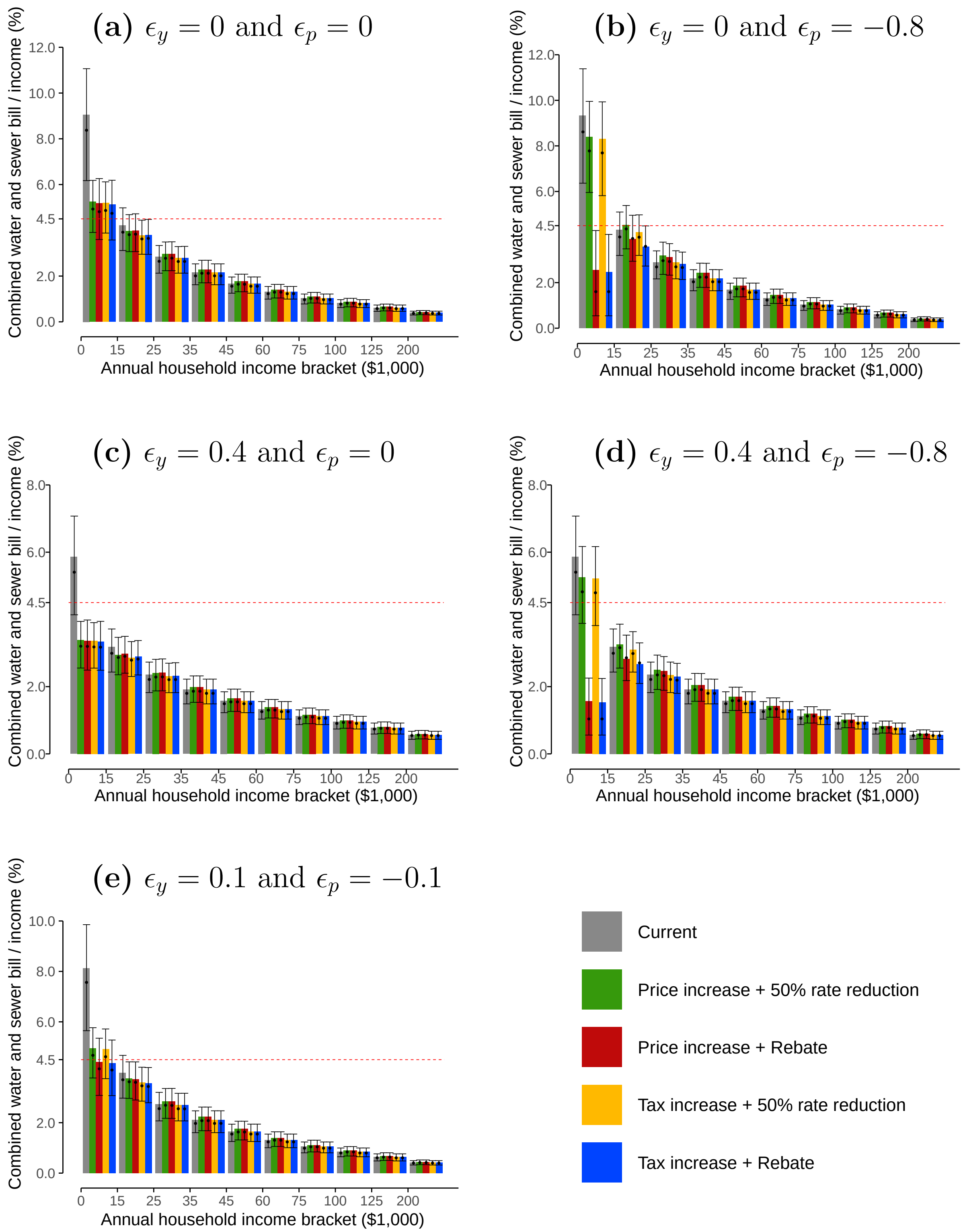


Figure S5: Average expenditure shares on water and sewer service by income bracket for business-as-usual and each policy option assuming different values of income elasticity (ϵ_y) and price elasticity (ϵ_p). In all bar charts, whiskers show the interquartile ranges and dots represent median values.

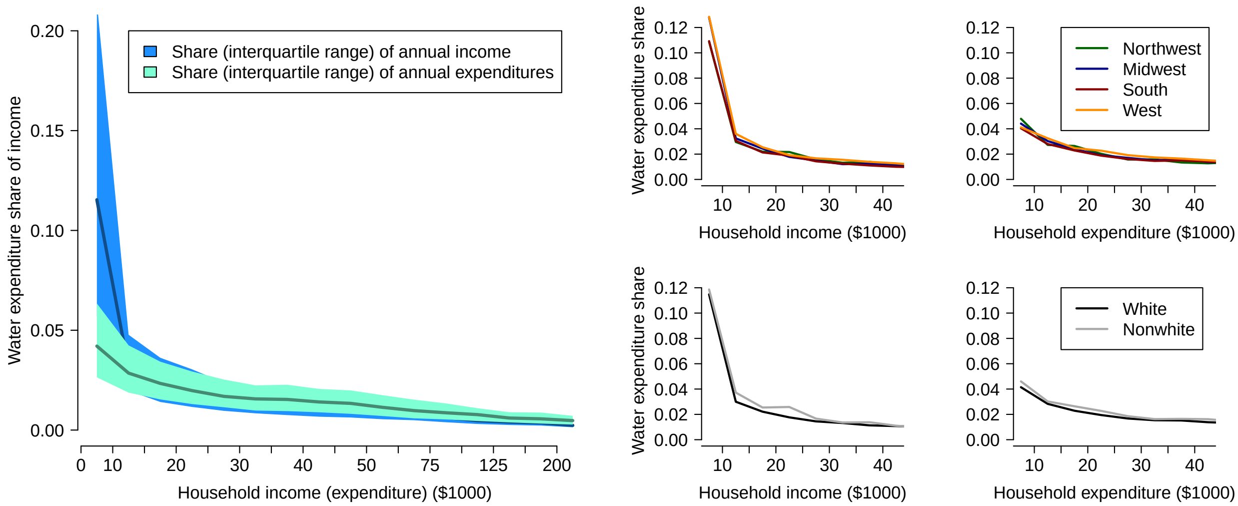


Figure S6: Incidence of US water bills using Consumer Expenditure Survey data. **Left panel:** Median annual water expenditure share (solid lines) and 25th–75th percentile range (shaded regions) as a proportion of annual household income or total annual household expenditures. Annualized water expenditures presented are calculated from survey responses of quarterly 'water and other public services' expenditures at primary place of residence. Statistics include information only for survey respondents that reported positive water expenditures. Medians and percentile ranges are weighted to account for the nationally representative survey sampling design. **Top right panels:** Statistics presented are medians weighted to account for the survey sampling design. Geographic definitions are adopted from BLS. **Bottom right panels:** Statistics presented are medians weighted to account for the survey sampling design. White households are defined as survey households in which the survey respondent identified as Caucasian. Minority households are defined as survey households in which the survey respondent as anything other than Caucasian. *Source:* Authors' calculations using Public Use Micro Data from 2016 Consumer Expenditure Survey.

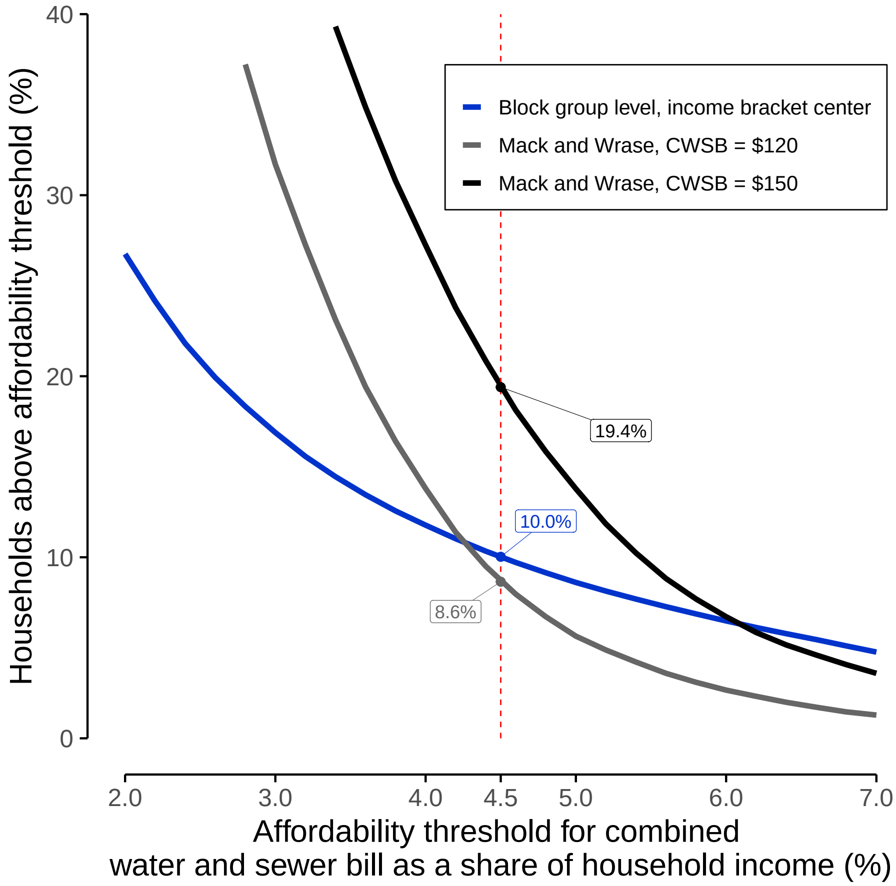


Figure S7: A comparison of the proportion of households above affordability threshold for Mack and Wrase's approach (MW) and our proposed method. The gray line follows MW method, considering an updated unit cost of $0.0125/gallon and a monthly combined water and sewer bill (CWSB) is $150 for all households in the sample. The blue line uses our method based on income bracket centers at the block-group level and the essential level of consumption.

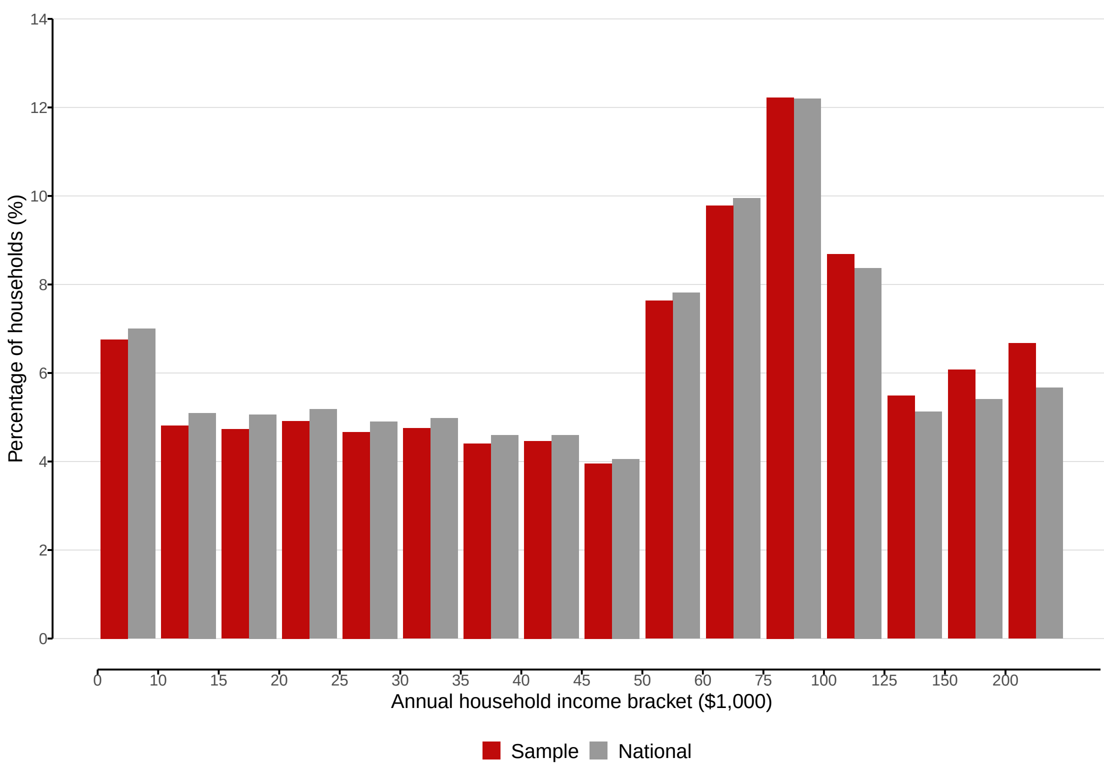


Figure S8: Household annual income distributions in our sample and for the entire United States. *Source:* US Census, American Community Survey.

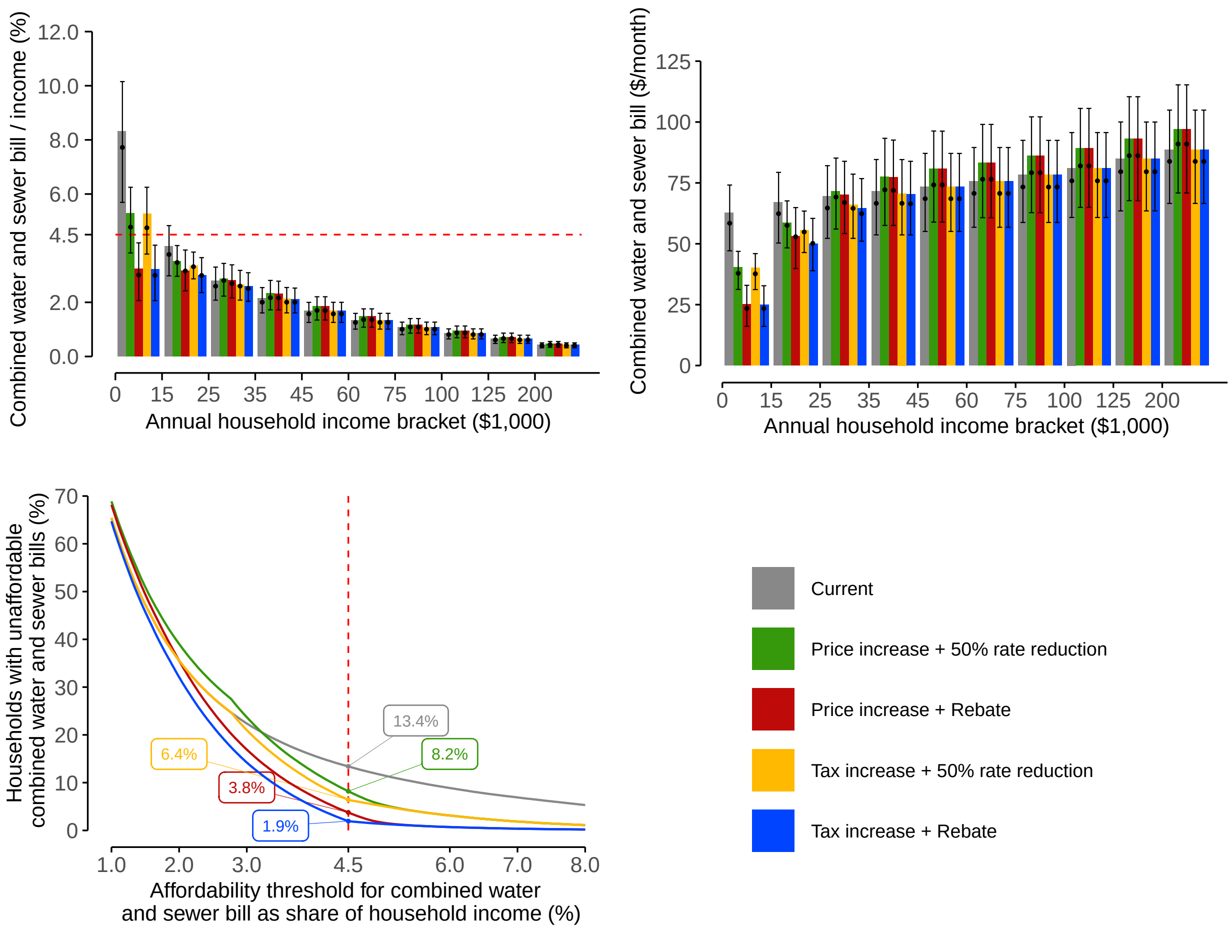


Figure S9: Results of program simulations only for counties with available data on county average consumption (AWWA data). **Top left panel:** Average expenditure shares on water and sewer service by income bracket for business-as-usual and each policy option. Expenditures are based on the estimated level of consumption. **Top right panel:** Combined water and sewer bill by income bracket for business-as-usual and each policy option. **Bottom left panel:** Distribution of sample with unaffordable water and sewer expenditures based on affordability threshold for business-as-usual and each policy option. In all bar charts, whiskers show the interquartile ranges and dots represent median values.

Table S1: Summary statistics for the socio-economic-demographic factors regression

	Mean	Median	Min	Max	SD
Households above affordability threshold at essential level (%)	11.49	8.06	0.00	100.00	11.67
Population density (Persons/Sq. mi)	7,141.02	4,461.77	0.13	656,711.81	9,952.46
Average household size (Persons)	2.71	2.64	1.02	9.34	0.67
Volumetric rate at 5–10 ccf (USD/1,000 gallons)	8.39	8.16	0.80	23.42	4.22
Base charge relative to CWSB at essential level (%)	48.49	50.84	0.00	100.00	22.06
Households below poverty level (%)	17.09	12.84	0.00	100.00	14.63
Households between 1 and 2× poverty level (%)	19.75	18.01	0.00	90.19	12.49
Median gross rent relative to income (%)	32.34	31.00	10.00	50.00	9.71
Occupied units that are rented (%)	43.63	39.27	1.19	100.00	25.24
Median age of housing unit (Years)	45.24	43.00	2.00	77.00	18.66
Population identified as Black/African American (%)	16.24	5.37	0.00	100.00	24.24
Population identified as Hispanic/Latino (%)	21.40	10.73	0.00	100.00	25.21
Observations	76,240				

Marginal prices are aggregated to the county level. All other variables are aggregated to the block group level.

Table S2: Summary statistics for the county-average consumption regression

	Mean	Median	Min	Max	SD
Average consumption (gallons per person per day)	78.06	69.39	43.65	266.14	32.67
Median household income (1,000 USD)	64.01	60.57	31.98	129.74	17.65
Population (1,000 persons)	631.74	329.97	8.15	10,030.21	1,037.18
Base charge (USD)	27.62	22.43	0.00	142.94	19.90
Volumetric rate at 5–10 ccf (USD/1,000 gallons)	8.53	8.01	0.80	23.42	4.23
Volumetric rate above 10 ccf (USD/1,000 gallons)	9.19	8.39	0.80	23.89	4.91
Observations	175				

All variables are aggregated to the county level.

Table S3: Results for the county-average consumption regression

	Coef.	SE	95% CI
log(Median household income) (1,000 USD)	0.0999	0.1769	[-0.2468, 0.4467]
log(Population) (Persons)	0.0453	0.0252	[-0.0041, 0.0948]
Base charge (USD)	-0.0027	0.0018	[-0.0063, 0.0008]
Volumetric rate at 5–10 ccf (USD/1,000 gallons)	-0.2952	0.1335	[-0.5568,-0.0336]
Volumetric rate above 10 ccf (USD/1,000 gallons)	0.0094	0.1342	[-0.2535, 0.2724]
Constant	3.3609	1.7617	[-0.0920, 6.8139]
State fixed effects		Yes	
Climate zone fixed effects		Yes	
Observations		175	
R^2		0.5756	
F-statistic		3.10	

Dependent variable is the log of county average per capita water consumption. All variables are defined at the county level.

Table S4: Summary statistics for select US regions

(a) New England

	Mean	Median	Min	Max	SD
Households above affordability threshold at essential level (%)	10.74	7.41	0.00	77.94	10.70
Population density (Persons/Sq. mi)	8099.53	4177.46	16.77	179414.23	11419.34
Average household size (Persons)	2.51	2.49	1.16	4.87	0.48
Volumetric rate at 5–10 ccf (USD/1,000 gallons)	12.12	11.49	2.00	17.58	3.46
Base charge relative to CWSB at essential level (%)	29.02	27.93	0.00	91.88	19.77
Households below poverty level (%)	13.71	9.03	0.00	88.61	13.45
Households between 1 and 2× poverty level (%)	15.47	12.97	0.00	78.50	11.27
Median gross rent relative to income (%)	31.45	30.00	10.00	50.00	9.47
Occupied units that are rented (%)	44.13	40.85	2.86	100.00	25.86
Median age of housing unit (Years)	59.33	61.00	4.00	77.00	16.61
Population identified as Black/African American (%)	9.64	2.96	0.00	100.00	16.01
Population identified as Hispanic/Latino (%)	14.50	6.13	0.00	100.00	19.11
Observations	6304				

(b) Southeast

	Mean	Median	Min	Max	SD
Households above affordability threshold at essential level (%)	13.39	10.28	0.00	96.00	12.14
Population density (Persons/Sq. mi)	3230.89	1856.58	0.91	136167.10	5116.18
Average household size (Persons)	2.60	2.57	1.09	5.99	0.54
Volumetric rate at 5–10 ccf (USD/1,000 gallons)	9.37	9.47	1.50	23.03	3.46
Base charge relative to CWSB at essential level (%)	48.48	49.73	6.53	99.85	18.31
Households below poverty level (%)	19.83	16.28	0.00	100.00	14.91
Households between 1 and 2× poverty level (%)	22.27	21.18	0.00	90.19	11.88
Median gross rent relative to income (%)	32.66	31.40	10.00	50.00	10.03
Occupied units that are rented (%)	40.36	35.31	2.00	100.00	23.42
Median age of housing unit (Years)	37.46	36.00	5.00	77.00	15.10
Population identified as Black/African American (%)	26.99	15.62	0.00	100.00	29.03
Population identified as Hispanic/Latino (%)	12.97	5.36	0.00	100.00	19.57
Observations	20411				

(c) Southwest

	Mean	Median	Min	Max	SD
Households above affordability threshold at essential level (%)	9.68	6.36	0.00	100.00	10.67
Population density (Persons/Sq. mi)	5128.33	4291.43	0.14	75048.68	4896.00
Average household size (Persons)	2.80	2.77	1.14	9.34	0.70
Volumetric rate at 5–10 ccf (USD/1,000 gallons)	7.17	5.61	1.86	17.59	3.49
Base charge relative to CWSB at essential level (%)	56.49	56.51	14.05	92.79	16.36
Households below poverty level (%)	18.79	14.46	0.00	100.00	15.63
Households between 1 and 2× poverty level (%)	22.09	20.51	0.00	87.84	13.47
Median gross rent relative to income (%)	30.95	29.30	10.00	50.00	9.43
Occupied units that are rented (%)	43.96	38.26	1.99	100.00	26.34
Median age of housing unit (Years)	35.43	34.00	3.00	77.00	16.33
Population identified as Black/African American (%)	9.56	3.77	0.00	100.00	14.98
Population identified as Hispanic/Latino (%)	37.26	28.81	0.00	100.00	28.44
Observations	9066				

Marginal prices are aggregated to the county level. All other variables are aggregated to the block group level.

Table S5: Conditional correlations between water affordability and select socioeconomic characteristics for subsamples containing states in US regions

	All regions	New England	Southeast	Southwest
log(Population density) (Persons/Sq. mi)	−0.507**	0.014	−0.555**	−0.655**
	(0.104)	(0.199)	(0.181)	(0.154)
Average household size (Persons)	0.925*	0.804	2.585**	−1.246
	(0.367)	(0.439)	(0.759)	(1.064)
log(Volumetric rate at 5–10 ccf) (USD/1,000 gallons)	8.419**	10.363**	11.263**	−0.607
	(1.257)	(2.187)	(1.340)	(3.439)
Base charge relative to CWSB at essential level (%)	0.115**	0.057**	0.137**	−0.113
	(0.025)	(0.022)	(0.036)	(0.095)
Households below poverty level (%)	0.492**	0.537**	0.488**	0.462**
	(0.023)	(0.029)	(0.034)	(0.058)
Households between 1 and 2× poverty level (%)	0.100**	0.061**	0.083**	0.087**
	(0.014)	(0.019)	(0.015)	(0.018)
Median gross rent relative to income (%)	0.058**	0.042**	0.060**	0.042**
	(0.008)	(0.016)	(0.013)	(0.012)
Occupied units that are rented (%)	0.012*	0.016	0.029**	0.002
	(0.006)	(0.009)	(0.010)	(0.005)
Median age of housing unit (Years)	−0.005	−0.034**	0.026**	0.003
	(0.007)	(0.012)	(0.010)	(0.017)
Population identified as Black/African American (%)	0.019*	0.057**	0.012	−0.056**
	(0.009)	(0.019)	(0.012)	(0.022)
Population identified as Hispanic/Latino (%)	−0.023*	0.022	−0.110**	−0.036**
	(0.010)	(0.020)	(0.026)	(0.013)
State fixed effects	Yes	Yes	Yes	Yes
Climate zone fixed effects	Yes	Yes	Yes	Yes
Observations	76,240	6,304	20,411	9,066
R^2	0.571	0.661	0.567	0.548
F-statistic	1693	874	1212	608

* and ** denote statistical significance at 5% and 1%.
The dependent variable is the proportion of households above the 4.5% water affordability threshold within a block group evaluated at the essential level of consumption (50 gppd). Standard errors clustered at the county level in parentheses. Marginal prices are aggregated to the county level. All other variables are aggregated to the block group level.

Table S6: A comparison between Teodoro's AR_{20} and HM metrics for water and sewer affordability and our method for most populous US cities[a]

Population Rank	City, State	$AR_{20}{}^{b}$ (%)	HM (hours)[c]	U_{50} (%)[d]	AR_{20} Rank[e]	HM Rank	AR_{20} & HM Avg. Rank	U_{50} Rank
1	New York, NY	14.1	6.8					
2	Los Angeles, CA	8.2	7	8.6	10.5	16.5	13.5	12.5
3	Chicago, IL	8.2	4.5	6.6	10.5	19	14.75	17
4	Houston, TX	11.7	10.3					
5	Phoenix, AZ	4.8	4	6.3	20	20	20	18
6	Philadelphia, PA	11.2	8.1	17.8	6	13	9.5	1
7	San Antonio, TX	5.9	7.6	9	19	14	16.5	10
8	San Diego, CA	17.1	9.5	15.4	3	6.5	4.75	4
9	Dallas, TX	8.7	8.3	4	8	12	10	19
10	San Jose, CA	8.8	9.9	10.7	7	5	6	9
11	Austin, TX	8.3	12.6	12.1	9	3	6	7
12	Jacksonville, FL	7.8	8.5	12.2	13	11	12	6
13	San Francisco, CA	26.9	13.6	16.8	1	1	1	2
14	Columbus, OH	12.7	13.1	8.9	5	2	3.5	11
15	Indianapolis, IN	13.5	13.5					
16	Fort Worth, TX	8	9.2	8	12	8	10	14
17	Charlotte, NC	6.6	9.5	8.6	17	6.5	11.75	12.5
18	Seattle, WA	18.8	12	14.4	2	4	3	5
19	Denver, CO	7.3	7	7.9	14	16.5	15.25	15
20	El Paso, TX	6.9	7.5	6.9	16	15	15.5	16
21	Washington, DC	14.3	9.8					
22	Boston, MA	16.5	9	16.5	4	10	7	3
23	Detroit, MI	24.4	10.4					
24	Nashville, TN	7.1	9.1	11.3	15	9	12	8
25	Memphis, TN	6.4	5.5	3.7	18	18	18	20
Spearman rank-order correlations								
AR_{20} and HM		0.64						
AR_{20} and U_{50}		0.65						
HM and U_{50}		0.62						
AR_{20} & HM Avg. and U_{50}		0.70						

[a] Our sample does not contain data for 5 of 25 most populous cities: New York, NY, Houston, TX, Indianapolis, IN, Washington, DC, and Detroit, MI. Ranks are calculated for the remaining twenty cities.
[b] As defined in (Teodoro, 2018), AR_{20} is the affordability ratio at the 20th income percentile: the share of disposable income spent on basic water and sewer for the income level at the 20th percentile.
[c] HM is the hours of labor at minimum wage required to pay for basic water and sewer.
[d] U_{50} is the percentage of households above with combined water and sewer bills greater than 4.5% of annual household income evaluated at an essential consumption level of 50 gppd.
[e] AR_{20} & HM Avg. rank denotes the average ranks of these two metrics combined. *Source:* AR_{20} and HM metrics are from (Teodoro, 2018). U_{50}, ranks, and correlations are authors' calculations.