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 and water infrastructure will require more than 1-trillion USD in investment over the next 20–25 years. We document the extent of water affordability concerns in the US across income, geography, and race, and we examine how policies can be designed to assist low-income households. We find that 13.6% of households have water and sewer expenditures greater than 4.5% of annual household income in our sample, and those in the lowest income decile pay on average 8.1% 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, capturing approximately 45% of the US population, matched with Census block-group-level socioeconomic characteristics and typical levels of consumption. We demonstrate that using median household income at the county level drastically understates the extent of the water affordability problem relative to using the full income distribution within Census block groups. 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).

Access to affordable, clean water is a significant concern in developing countries (Whittington, Nauges, Fuente, & Wu, 2015), although it is also an issue in developed countries (Martins, Quintal, Cruz, & Barata, 2016). 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 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 14% 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. Using 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 8.1% of their annual income on water and sewer services on average. 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 show that affordability 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.

Surprisingly, there are very few national estimates of water affordability and the geographic distribution of the most vulnerable communities is poorly understood. One exception is a recent paper that provides a large-scale geographic assessment of communities that are at-risk of water poverty, although this analysis relies on several limiting assumptions (Mack & Wrase, 2017). The authors evaluate water bills at a constant level much larger than typical household consumption levels, ignore geographic differences in water prices and consumption patterns, and evaluate all results at the Census tract level, which severely limits the validity and usefulness of those estimates. In the present manuscript, we approach a similar question with much more tenable assumptions. By focusing on behavior at the representative household level, 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.

Further, 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). 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. 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). Here, we demonstrate why using the full income distribution at a local level is imperative for measuring affordability. We do not focus on the normative question of whether EPA's 4.5% threshold is valid, but our methods align with alternative metrics and are general enough to accommodate alternative income-based affordability measures. Finally, there is no comparative evidence on the efficacy or distributional consequences of water affordability policies, which are beginning to be adopted at scale (California State Assembly, 2015; City of Philadelphia, 2015). Within different affordability policies, we show how underlying economic incentives can influence ultimate program effectiveness.

Overall, we provide evidence of the widescale water-affordability burden on low-income households. By assembling a novel data set covering 45% of the US population, we estimate that approximately 1 in 7 (13.6%) households in our sample have water and sewer expenditures that exceed 4.5% of their annual household income. We also show that redistributive programs that do not distort marginal incentives to consume water can be effective policy options.

1.1 Measuring affordability

EPA initially defined a water affordability metric as a tool to measure a community's financial capability for regulatory compliance (U.S. EPA, 1995, 1997). This threshold assigned a high burden of water and sewer expenditures if the typical CWSB exceeded 4.5% of a community's median household income. Critics of this measure often cite the arbitrary nature of the 4.5% threshold, the inability of median income to capture the full distributional burden borne by poorest community members, and whether bills should be evaluated at average or necessary consumption levels (Teodoro, 2018). In this analysis, we follow the recently released 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 contrast the burden of water and sewer expenditures under varying definitions of water affordability. We adopt the threshold that affordable CWSBs should not exceed 4.5% of income, although we apply that standard at different income and geographic resolutions. Our analysis and methods can readily be applied to different thresholds. Second, we consider necessary levels of consumption (50 gallons per person per day, or gppd) as a more appropriate indicator for eligibility in affordability programs. Third, we put forward transparent and readily calculable metrics for ease of communication and decision-making by policymakers, thereby responding directly to NAPA's recommendations. Our preferred affordability measure is defined as the proportion of a community's population that pays more than 4.5% of annual household income on water and sewer service. The 4.5% threshold is readily scalable to different income thresholds. 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 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.

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. We aggregate water and sewer rates to the county level, weighted by the number of accounts in each utility within the county. To account for increasing-block rates, we approximate rate structures as a piecewise linear function of consumption with up to three rate blocks.

Average residential water and sewer usage is reported by the utilities in the AWWA survey but not by those in the EFC survey. We estimate the average consumption per person-day for EFC utilities with following linear model for AWWA utilities,

$$\begin{aligned}\log(w_c) = \quad & \beta_0 + \beta_1 \log(Pop_c) + \beta_2 \log(y_c) + \beta_3 BaseCharge_c \\ & + \beta_4 \log(Rate5_c) + \beta_5 \log(Rate10_c) + \\ & + \textstyle\sum_{z\in Z} \gamma_z 1(CZ_c = z) + \sum_{s\in S} \delta_s 1(State_c = s) + e_i\end{aligned} \tag{1}$$

where $\log(w_c)$ is the log of average consumption per person-day in gallons in county c, Pop_c is county population, y is median household income, $BaseCharge_c$ is the fixed minimum service fee, $Rate5_c$ and $Rate10_c$ are the volumetric rates charged between 5 and 10 ccf 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, and $1(State_c = s)$ is a dummy variable equal to 1 if county c is in state s and 0 otherwise, and e_i is the idiosyncratic error term. The estimated parameters of Equation 1 are used to predict $\log(\hat{w_c})$ for EFC utilities.

We consider four levels of geographic resolution (or aggregation). The unit of observation in the lowest resolution (highest aggregation) is a county, which considers a representative household that has its characteristics set at the county median (or average, depending on the variable). Similarly, in the second resolution level, each block group is represented by a single household with the block-group median/average characteristics. In the third resolution level, block groups are represented by 16 households that share the same socio-demographic characteristics (the block group median/average) but with different incomes corresponding to the center of US Census income brackets. Each of the 16 households has a different weight corresponding to 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.

County-level average per capita consumption is assigned to households within Census block groups 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. For each county, we assume the average per capita water consumption (w_c) corresponds to a household with the median income ($\bar{y}_c$). Using an income elasticity (ϵ_y) of 0.1 (Havranek, Irsova, & Vlach, 2018), we adjust the per capita water consumption for each node in the income distribution (y_i) and multiply by the average household size (h_{bc}) to obtain representative household consumption at the monthly level, given by:

$$W_{ibc} = 30 \times h_{bc} \times w_c \times \left(\frac{y_i}{\bar{y}_c}\right)^{\epsilon_y}. \tag{2}$$

Then, for each block group and using the county average rates, we form a 16-node distribution of combined water and sewer bills (CWSBs).

2.2 Estimation of socioeconomic and demographic conditional correlations

We investigate whether local affordability of water 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 the block group population that identify their race as Black or African American alone.
3. The percentage of the block group population that identify 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 estimated consumption levels, which we represent by $\hat{U}_{bc}$.

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

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

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

A challenge in estimating the standard errors of the previous equation is the fact that $\hat{U}_{bc}$ is measured with error, but the nonlinearity in $\hat{U}_{bc}$ restricts our ability to derive asymptotic properties of the estimators analytically. For this reason, we implement a residual bootstrap strategy to obtain the appropriate standard errors (MacKinnon, 2006). The details of the procedure can be found in the Supporting Information.

2.3 Policy simulations

In our policy simulations, households are eligible for assistance if annual household expenditures on water and sewer services at 50 gppd is greater than or equal to 4.5% of their annual income. The assistance programs affect water consumption by either changing water prices or income of a household. In both cases, we recalculate households' water consumption and expenditures, based on estimated consumption levels, as a result of the policy.

Assuming constant price elasticity ϵ_p, a price change d leads to a change in consumption of d^{ϵ_p}; hence, the new consumption is given by $W_{cb} \times d^{\epsilon_p}$. For a change in income, with a constant income elasticity, we use equation (S3) to recalculate water consumption after an income tax or transfer. Our simulations assume a constant price elasticity $\epsilon_p = -0.3$ (Dalhuisen, Florax, De Groot, & Nijkamp, 2003) and constant income elasticity $\epsilon_y = 0.1$ (Havranek et al., 2018). See the Supporting Information for sensitivity analyses on these parameter choices. The adjusted consumption values are then used to calculate the new expenditure on water and sewer services.

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 the discounts; this amount determines the size of all four programs. 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.

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 (block groups typically contain 600–3000 people) 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), 1.9% for estimated average consumption, and 4.8% for 100 gppd. 50 gppd is intended to capture "essential" water consumption, whereas estimated average consumption captures prevailing water use. The sample average of estimated consumption is 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 13.6% (10.0%) of households have CWSB greater than 4.5% of income for estimated (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 seven households spends more than 4.5% of annual income on water and sewer bills

As shown in Table 1 and Figure 2, around 14% of households in our sample, approximately 1 out of every 7 households, have current annual water expenditures that exceed EPA's 4.5% affordability threshold. This estimate reflects the fact that more than 20-million households in our sample have unaffordable water and sewer service; 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 within 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 and our methods can be applied at any income threshold.

We also calculate the proportion of households above this affordability threshold based on fixed levels of consumption per person-day. When calculating water and sewer bills based on 50 gppd—an amount less than typical consumption, but that would cover "essential" daily usage—we find that approximately 10% of households in our sample would exceed the water affordability threshold. This result suggests that affordability is affected by household consumption levels and for essential levels of consumption, one out of every ten households faces affordability issues.

3.3 Households in the lowest income bracket pay 8.1% of annual income on water and sewer bills

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 an average combined water and sewer bill equal to 8.1% 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 1.7% 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 0.4%. This analysis reveals that the vast majority of households facing unaffordable water service are concentrated in the lowest income deciles.

3.4 Water and sewer bills are regressive, but less so, when compared with annual expenditure data

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, Mathur, & Metcalf, 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 3, 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.

3.5 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 estimated consumption levels (see Materials and Methods). Some counties in the desert Southwest display high levels of unaffordable CWSBs, 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 greater 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 three large urban areas: Atlanta, GA, Chicago, IL, and Portland, OR. 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.

3.6 Water affordability concerns are significantly correlated with select community characteristics

We conduct a statistical analysis to test whether any associations between the proportion of households in a block group with unaffordable water and sewer service are statistically significantly correlated with socioeconomic or other community characteristics. To develop conditional statistical tests of 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).

Conditional correlation coefficients are presented in Table 3, along with bootstrapped 95% confidence intervals, between the proportion of households facing unaffordable CWSBs and select socioeconomic variables. 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 0.600 [0.573, 0.626; 95% CI] percentage points increase in the number of households above the affordability threshold. Additionally, we find a significant positive relationship between water affordability concerns and the proportion of black households within a community (0.033 [0.012, 0.053; 95% CI]) even after controlling for poverty levels. However, no significant relationship was found between affordability and the proportion of Hispanic residents (0.016 [-0.017, 0.049; 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 -0.494 [-0.715, -0.272; 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 -0.0049 percentage point decrease in affordability concerns. Additionally, 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 conclude that water affordability is 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 (7.677 [4.634, 10.719; 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 0.077 percentage point increase in affordability concerns. A second variable captures the proportion of a typical 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 (0.079 [0.018, 0.393; 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. We do not, however, find a significant relationship between the prevalence of unaffordable water and 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.

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

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. 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 relatively wealthy households. All affordability programs are assumed to be administered at the county level. The total size of the programs is equivalent and set equal to the dollar amount needed to cover the 50% rate discount option. The average-income tax increase is 0.1 percentage points and the average lump-sum transfer is $34.6 per month. We assume general equilibrium changes (e.g., changes in labor supply) in response to small income changes are negligible. Additionally, we abstract from costs associated with policy implementation.

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. 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.

We compare the effectiveness of different program combinations in Figure 6. 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. 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 the combined water and sewer bill for each policy. All policies substantially reduce the total bill 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 relatively wealthier households increases total 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 above the 4.5% affordability threshold from 11.0% to 6.7% if funded by rate increases and from 9.8% to 5.6% if funded by income taxes. Interestingly, rate-reduction programs funded by a price increase evaluated at a 2.0–3.0% affordability threshold can actually worsen outcomes relative to the status quo. 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, 2014)) 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. 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 perform a sensitivity analysis on these parameters in the Supporting Information. Because rate reductions distort marginal incentives for households to consume water more than do income transfers, low-income water customers consume more water as a result of affordability policies directed at making water 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

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 seven households spend more than 4.5% of their annual household income on water and sewer service, and that affordability concerns are positively 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, however, does have several limitations. Here, we outline these limitations and discuss detailed robustness checks that explore the implications of these limitations 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 S6), 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 on 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 S7). 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.

Our affordability framework has several attractive features for policymaking. First, we note that all proposed affordability metrics rely on judgments about what is essential consumption and what defines low-income customers. Our framework is no different in that regard. But, we do not contend that using a threshold of 4.5% of income to determine affordability is inherently wrong. This threshold is an arbirtary judgment of what is deemed affordable, just like all other affordability metrics proposed for water and other goods. What we do contend is that this threshold should not be applied to the median household in a given geography. If policymakers believe that a household spending more than 4.5% of income is unaffordable, our analysis provides a rigorous framework to estimate the number of households above that threshold based on publicly available data at a broad scale. Second, if a policymaker believes 3% or 6% is a preferable threshold, our framework is easily adaptable to inform and account for that decision, as illustrated in Figure 2. Third, we also provide a framework for estimating water consumption (and, thus, water bills) by adjusting average consumption for demographic and economic differences across representative households. Additionally, our framework easily permits, and is robust to, alternative assumptions about what is "essential" consumption (Table S5).

Two other limitations are worth noting. First, 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 useful for the scope 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. Additionally, 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 incomes. 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.

In sum, we provide evidence of the widescale water-affordability burden on low-income households. By assembling a novel data set covering 45% of the US population, we estimate that approximately 1 in 7 (13.6%) households in our sample have water and sewer expenditures that exceed 4.5% of their annual household income. We also show that redistributive programs that do not distort marginal incentives to consume water can be effective policy options. Our analysis provides a consistent framework to evaluate the extent of the water affordability burden and policies ameliorate its worst consequences as municipalities and regulators grapple with policies to fund water infrastructure improvements equitably.

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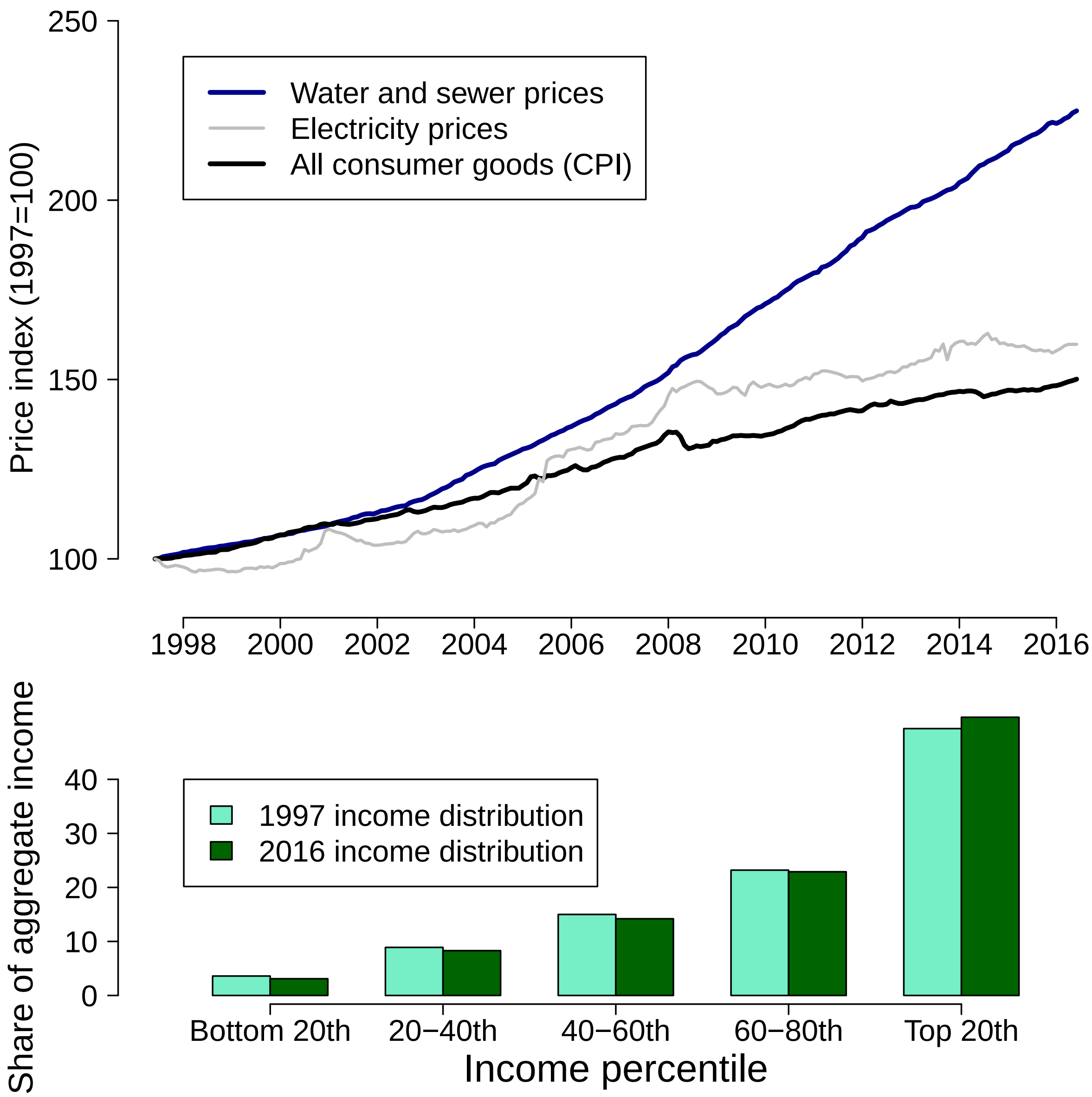

Figure 1: U.S. price indexes and income distribution over time. **Top Panel:** Monthly price (U.S. city average, all urban consumers, seasonally adjusted) for all consumer goods, electricity, and water and sewer. Series begins in December 1997 (=100). Water and sewer price index includes trash collection. *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.

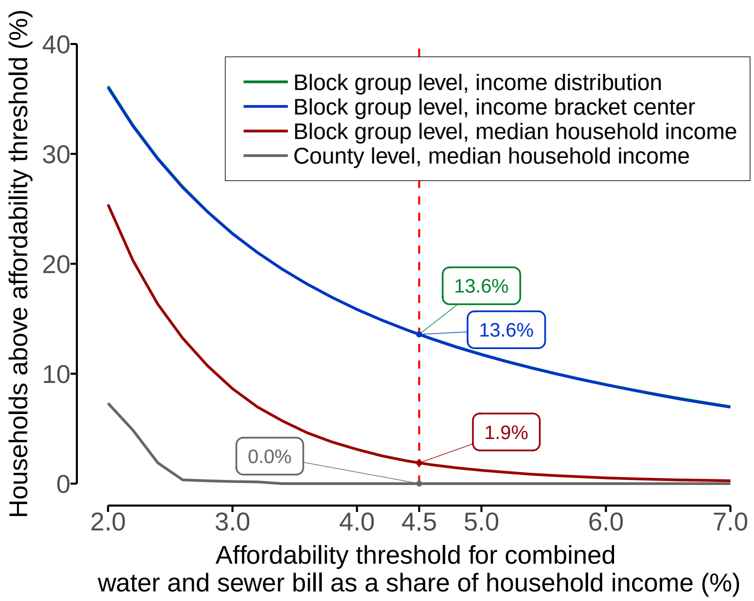

Figure 2: Proportion of households above affordability threshold based on water and sewer expenditure-shares of income, based on varying degrees of income data resolution.

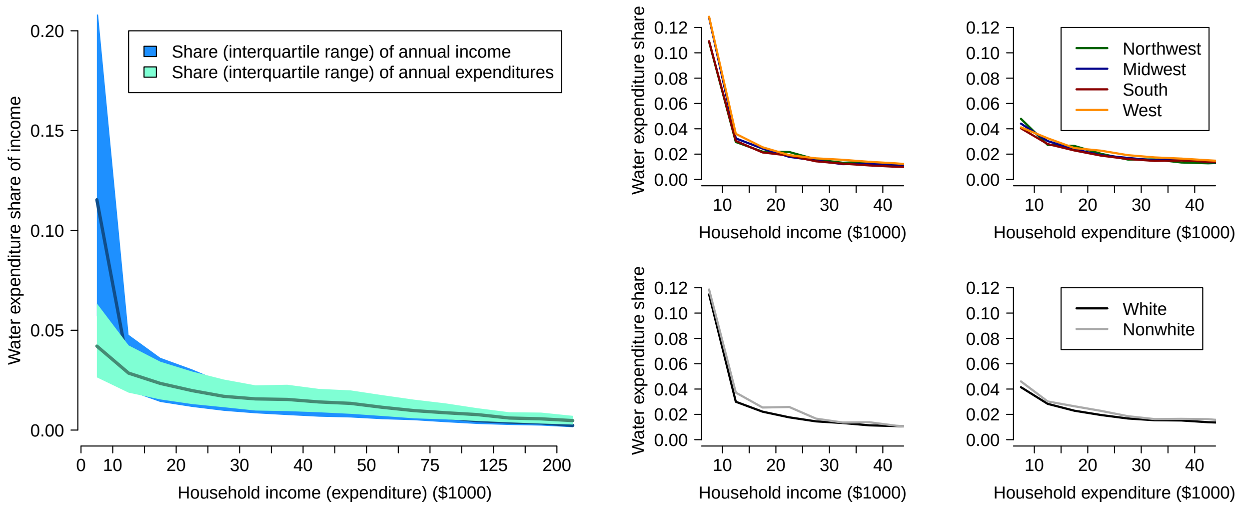

Figure 3: Incidence of US water bills using Consumer Expenditure Survey data. **Left panel:** Median annual water expenditure share (solid lines) and 25th–75th percentile range (shaded regions) as a proportion of annual household income or total annual household expenditures. Annualized water expenditures 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.

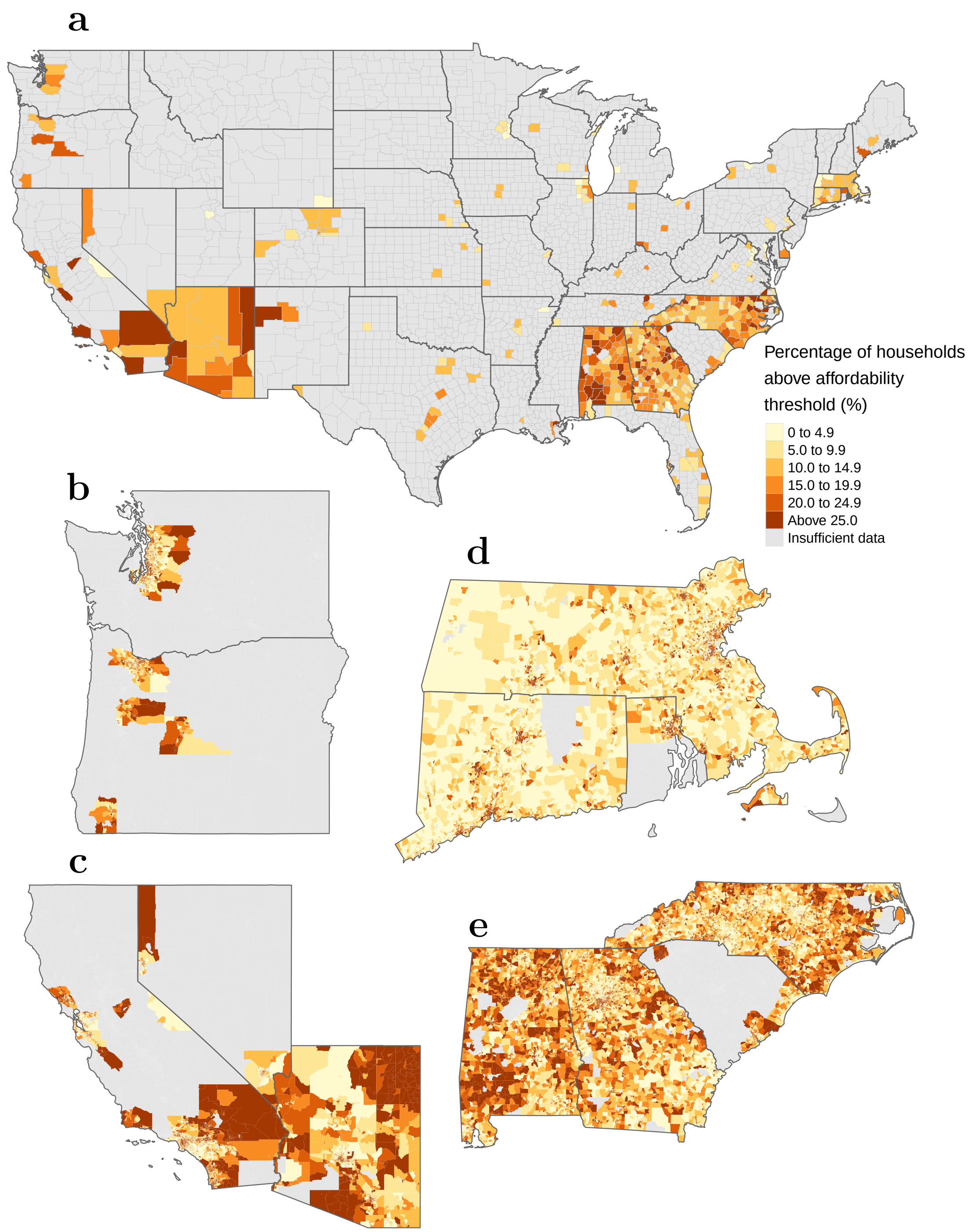

Figure 4: **Geographic distribution of water affordability using estimated levels of consumption to calculate combined water and sewer bills.** Shaded colors show the percentage of households within each county (in **a**) and Census block group (in **b–e**) that have combined water and sewer bills above 4.5 percent of annual household income.

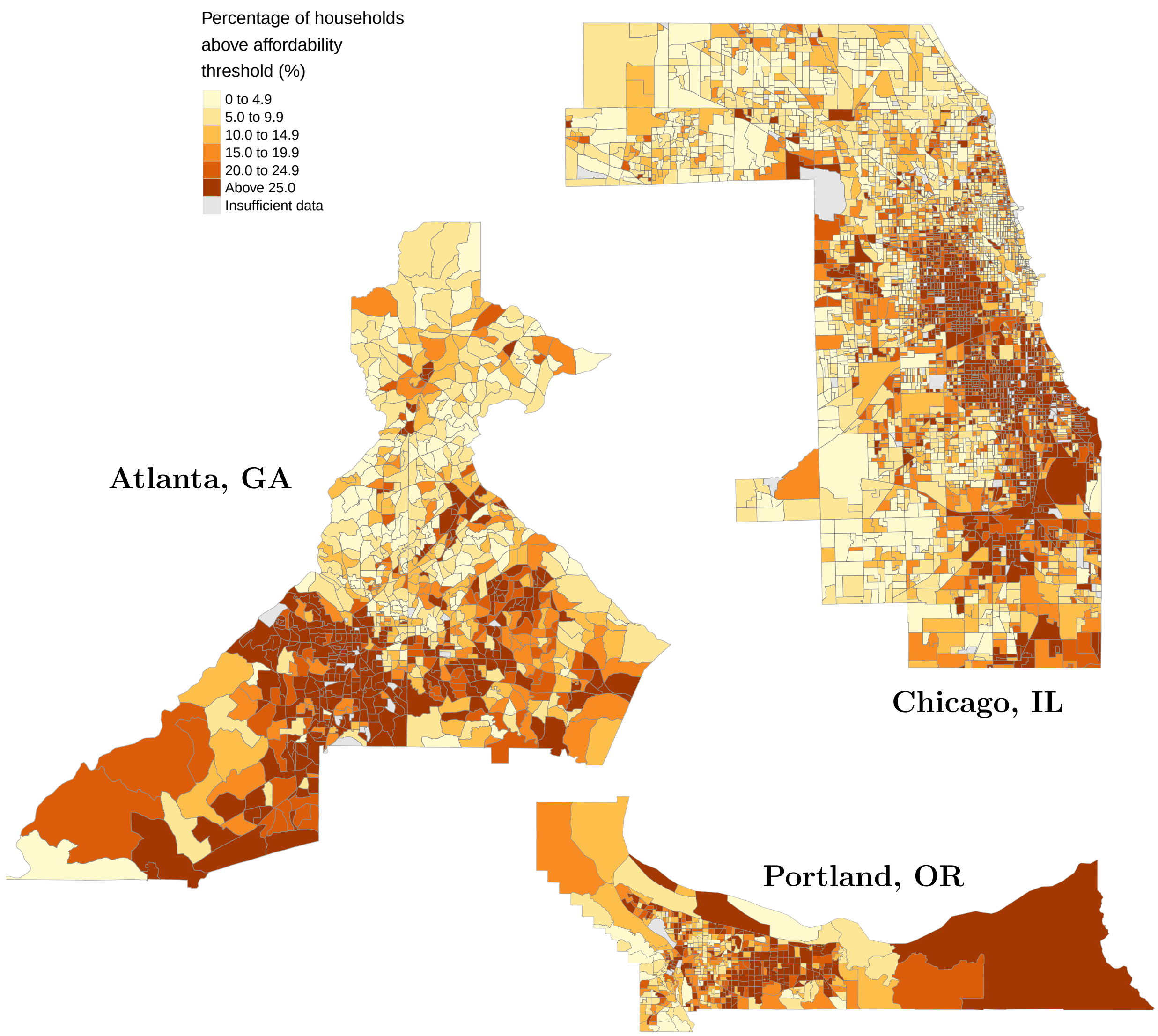

Figure 5: Geographic distribution of water affordability in block groups within urban areas. Results are presented for Atlanta, GA (DeKalb and Fulton counties), Chicago, IL (Cook county), and Portland, OR (Multnomah county). Shaded colors show the percentage of households within each Census block group that have combined water and sewer bills above 4.5 percent of annual household income. Combined water and sewer bills are based on estimated levels of consumption.

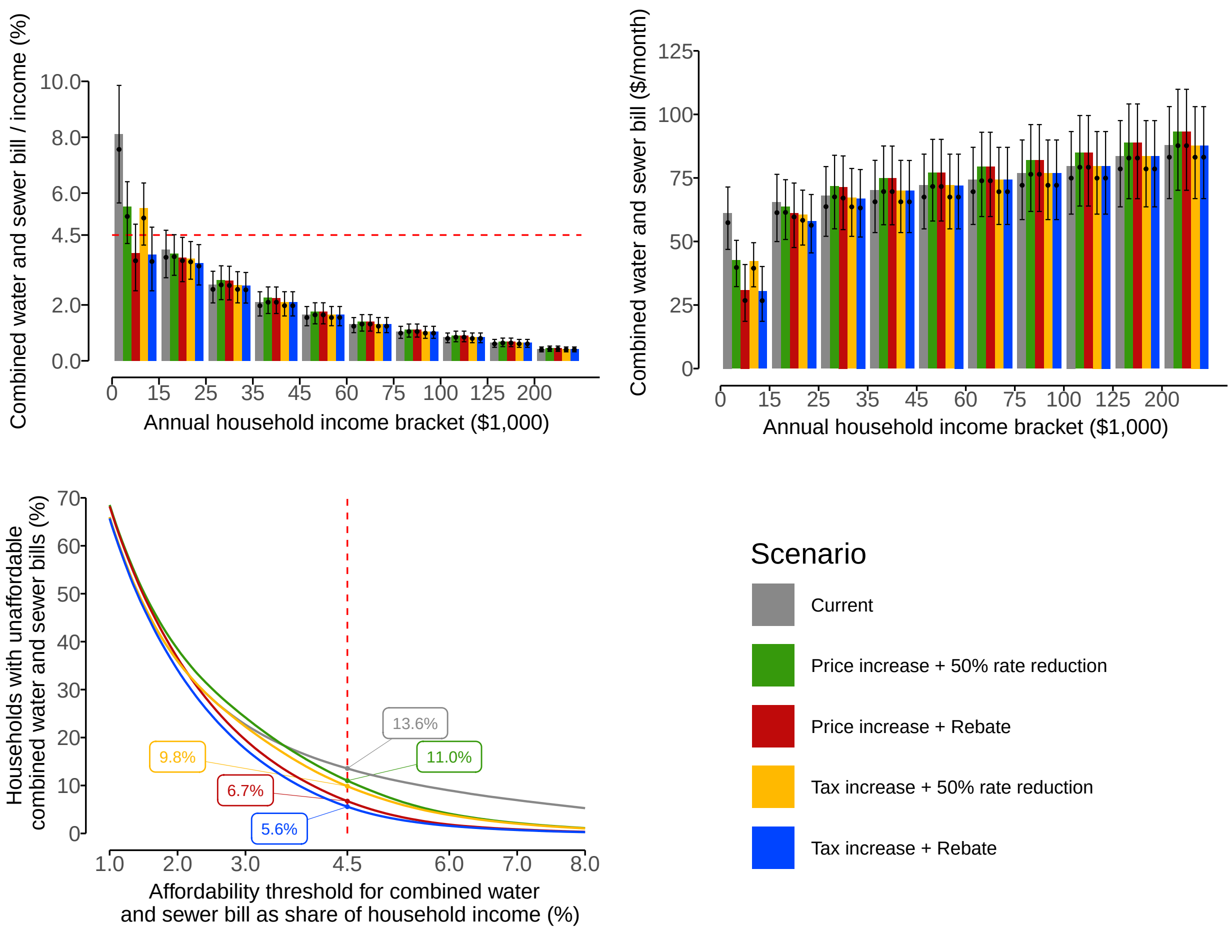

Figure 6: Results of program simulations. **Top left panel:** Average expenditure shares on water and sewer service by income bracket for business-as-usual and each policy option. **Top right panel:** Combined water and sewer bill by income bracket for business-as-usual and each policy option. **Bottom 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**[a]	**Estimated consumption**[b]	**Estimated**	**50 gppd**	**100 gppd**
County	Median household income	Average	0.00%	0.00%	0.09%
Block group	Median household income	Income-adjusted	1.88%	0.79%	4.83%
Block group	Income bracket center	Income-adjusted	13.57%	10.03%	18.54%
Block group	Income distribution	Income-adjusted	13.58%	10.10%	18.54%

[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 center" measures incomes at the midpoint of income brackets evaluated at the block-group level; and (iii) "Income distribution" represents the 16-node income distribution with interpolation between nodes evaluated within Census block groups.

[b]We use two consumption metrics: (i) "Average" consumption levels are estimated (see Materials and Methods, sample average estimated consumption is 78.1 gppd); (ii) "Income-adjusted" consumption levels adjust for household income levels using an income elasticity of 0.1 for the relevant income metric. Consumption levels of 50 and 100 gallons per person day (gppd) are fixed across all households.

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	8.1%
$15,000 to $24,999	4,988	9.6%	21.0	4.0%
$25,000 to $34,999	4,899	9.4%	30.5	2.7%
$35,000 to $44,999	4,620	8.9%	39.4	2.1%
$45,000 to $59,999	6,036	11.6%	51.0	1.7%
$60,000 to $74,999	5,092	9.8%	60.8	1.3%
$75,000 to $99,999	6,361	12.3%	73.0	1.1%
$100,000 to $124,999	4,517	8.7%	81.7	0.9%
$125,000 to $199,999	6,013	11.6%	93.3	0.6%
$200,000 and over	3,468	6.7%	100.0	0.4%

[a]Income distribution data are obtained from the U.S. Census 2016 5-Year American Community Survey and defined at the block-group level.
[b]Combined water and sewer bills (CWSB) are estimated.

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

	Coef.	Asymp. SE	Bootstrap SE	Bootstrap 95% CI
log(Population density) (Persons/Sq. mi)	-0.4935	0.0289	0.1129	[-0.7147,-0.2722]
Average household size (Persons)	1.7333	0.0795	0.3939	[0.9612, 2.5054]
log(Volumetric rate at 5–10 ccf) (USD/1,000 gallons)	7.6766	0.1246	1.5523	[4.6342, 10.7191]
Base charge relative to CWSB at essential level (%)	0.0785	0.0026	0.0310	[0.0177, 0.1393]
Households below poverty level (%)	0.5998	0.0042	0.0135	[0.5734, 0.6262]
Households between 1 and 2× poverty level (%)	0.1478	0.0036	0.0123	[0.1236, 0.1719]
Median gross rent relative to income (%)	0.0988	0.0036	0.0076	[0.0839, 0.1137]
Occupied units that are rented (%)	0.0257	0.0019	0.0076	[0.0108, 0.0405]
Median age of housing unit (Years)	0.0129	0.0021	0.0118	[-0.0103, 0.0361]
Population identified as Black/African American (%)	0.0325	0.0020	0.0103	[0.0124, 0.0526]
Population identified as Hispanic/Latino (%)	0.0159	0.0025	0.0168	[-0.0170, 0.0488]
Constant	-32.2983	0.6462	8.9454	[-49.8310,-14.7655]
State fixed efects			Yes	
Climate zone fixed efects			Yes	
Observations			76240	
R^2			0.6466	
F-statistic			2322.96	

[a]Dependent variable is the percentage of households in a block group above the 4.5 percent water affordability threshold calculated with estimated consumption levels. The mean of the dependent variable is 15.78 and its standard deviation is 13.93. Summary statistics for other variables are presented in the Supporting Information. Bootstrapped confidence intervals should be used for inference. See Supporting Information for detailed variable definitions and a description of the bootstrap. All variables are defined at the block-group level.

Supporting Information

The Supporting Information is structured as follows. Section A describes the sources of data and outlines the steps in assembling our data set. Section B formalizes the regression analysis and policy simulations. Section C presents additional results for socioeconomic and demographic factors at select US region. Section D examines how sensitive our results are to key parameters in the model. Section E performs robustness checks by considering alternative specifications for our estimations. Finally, F compares our approach to alternative metrics in the literature.

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 and water use

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

[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.

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 software 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.

The EFC dashboards do not report average residential water consumption by utilities. However, this information is needed to estimate affordability based on current consumption. To address this issue, we predict average consumption using ordinary least squares with parameters estimated from the AWWA data set. The details of the estimation procedure are described in the Section B.

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 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 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 a distribution of water consumption, 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 identify their race as Black or African American alone.
3. The percentage of the block group population that identify 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 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

[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.

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 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

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

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:

$$w_{ibc} = \bar{w}_c \left(\frac{y_i}{\bar{y}_c} \right)^{\epsilon_y}, \tag{S1}$$

where $\epsilon_y = 0.1$ is the constant income elasticity (Havranek et al., 2018). Letting $\bar{h}_{bc}$ denote the average household size in block group b, the household's monthly consumption of water is given by

$$W_{ibc} = 30\bar{h}_{bc} w_{ibc} = 30\bar{h}_{bc} \bar{w}_c \left(\frac{y_i}{\bar{y}_c} \right)^{\epsilon_y}. \tag{S2}$$

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:

$$\hat{\phi}_{ibc} = \Phi_c\left(\hat{W}_{ibc}\right) = \Phi_c\left(\bar{h}_{cb} y_i^{\epsilon_y} \bar{y}_c^{-\epsilon_y} \hat{\bar{w}}_c \hat{\nu_c}\right). \tag{S3}$$

Hence, the annual share of income corresponding to the CWSB is

$$\hat{s}_{ibc} = \frac{12\hat{\phi}_{ibc}}{y_i}. \tag{S4}$$

B.2 Regression analysis and bootstrapping

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

B.2.1 First stage: predicting average water and sewer expenditure.

The AWWA data set provides the average household water consumption by utility, W_u, whereas the EFC does not. The first step, then, is to use W_u to (i) calculate the county average water consumption per capita, $\bar{w}_c$, and (ii) use $\bar{w}_c$ 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:

$$\begin{aligned} \log(\bar{w}_c) = \quad & \beta_0 + \beta_1 \log(Pop_c) + \beta_2 \log(\bar{y}_c) + \beta_3 BaseCharge_c + \beta_4 \log(Rate5_c) + \\ & + \beta_5 \log(Rate10_c) + \textstyle\sum_{z \in Z} \gamma_z 1(CZ_c = z) + \sum_{s \in S} \delta_s 1(State_c = s) + e_c, \end{aligned} \tag{S5}$$

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.

Using the estimated parameters in Equation S5, we predict $\hat{\bar{w}}_c$ for EFC counties. Consequently, we can only estimate $\hat{e}_c$ for counties in the AWWA set, but not for the ones in EFC. For the next stage, it will be helpful to express the exponential of the error term, $\nu = \exp(e_c)$, which allows us to write:

$$\log(\bar{w}_c) = \log\left(\hat{\bar{w}}_c\right) + \hat{e}_c \Rightarrow \bar{w}_c = \hat{\bar{w}}_c \hat{\nu}_c.$$

Summary statistics for the variables used in the first-stage regression are presented in Table S1. The estimation results of this stage are reported in Table S2. 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 first stage 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.

B.2.2 Intermediate step: 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 $U\left(\bar{h}_{bc}, \bar{y}_c, \hat{\bar{w}}_c, \hat{\nu_c}, t, \Phi_c, \mathbf{f}_{bc}\right)$, 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

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

B.2.3 Stage two: affordability and socioeconomic-demographic factors.

In this stage, we estimate the linear association between local unaffordability and various 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:

$$U\left(\bar{h}_{bc}, \bar{y}_c, \hat{\bar{w}}_c, \hat{\nu}_c, t, \Phi_c, \mathbf{f}_{bc}\right) = \hat{U}_{bc} = \mathbf{X}'_{bc}\Gamma + \sum_{z \in Z} \gamma_z 1(CZ_c = z) + \sum_{s \in S} \delta_s 1(State_c = s) + u_{bc}, \quad \text{(S6)}$$

where $1(CZ_c = z)$ and $1(State_c = s)$ are defined as in the first stage, and u_{bc} is the idiosyncratic error term.

A challenge in estimating the standard errors of the previous equation is the fact that $\hat{U}_{bc}$ is measured with error, $\hat{\nu}_{bc}$; the nonlinearity in $\hat{U}_{bc}$ restricts our ability to derive asymptotic properties of the estimators analytically. For this reason, we obtain standard errors by bootstrap. Resampling the variables in Equation S5 could lead to iterations in which certain states or climate zones would not have estimated coefficients; we implement residual bootstrap to avoid this problem. The procedure can be outlined in six steps:

1. Estimate Equation S5 to obtain the parameter vectors β, δ, γ and the predicted residuals. Rescale residuals to correct their variance: $\ddot{e}_{bc} = \left(\frac{n}{n-k}\right)^{1/2} \hat{e}_c$, where n is the number of observations and k the number of estimable parameters (MacKinnon, 2006). Let Θ denote the set containing all $\ddot{e}_{bc}$.
2. Calculate $\hat{\bar{w}}_c$ for all counties using the parameters estimated in Equation S5.
3. For each county, randomly draw $\tilde{e}_c$ from Θ and obtain $\tilde{\nu}_c = \exp\left(\tilde{e}_c\right)$.
4. For each block group, calculate $\tilde{U}_{bc} = U\left(\bar{h}_{bc}, \bar{y}_c, \hat{\bar{w}}_c, \tilde{\nu}_c, t, \Phi_c, \mathbf{f}_{bc}\right)$.
5. Estimate Equation S6 using sample $\left\{\tilde{U}_{bc}, X_{bc}\right\}$.
6. Obtain the empirical distribution of Γ by repeating steps 3-5 many times. In our application, we perform 1,000 bootstrap replications.

The generated distribution of Γ is used to calculate the standard errors of parameter estimates and form their respective confidence intervals.

Summary statistics for the variables used in the second stage are presented in Table S1. Section E discusses alternative one-stage estimations when the average water consumption is either observed or held at a fixed level.

B.3 Policy simulations

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 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 fair comparisons, 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 price change d and a constant price elasticity ϵ_p, the ratio of water consumption after and before the change is d^{ϵ_p}. Hence, following the notation defined in Section B, the expenditure on water services after a rate change d is given by:

$$\hat{\phi}_{ibc} = \Phi_c\left(\hat{W}_{ibc} d^{\epsilon_p}\right) = \Phi_c\left(\bar{h}_{bc} y_i^{\epsilon_y} \bar{y}_c^{-\epsilon_y} \hat{\bar{w}}_c \hat{\nu_c} d^{\epsilon_p}\right). \tag{S7}$$

The simulations assume a constant elasticity $\epsilon_p = -0.3$ (Dalhuisen et al., 2003). Thus, a price discount of 50% ($d = -0.5$) increases water consumption by about 23% and decreases water expenditure by approximately 38%. Similarly, Equation S3 is used to adjust consumption after changes in income due to transfers.

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.

C Water affordability and socio-economic-demographic factors in US regions

Our main regressions focus 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 S4 presents the estimates and bootstrapped standard errors for regional regressions, with summary statistics presented in Table S3. 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; this result is particularly salient for price covariates in New England and the Southwest due to higher correlation across block groups in fewer counties.

Although point estimates change across regions, the 95% confidence intervals of regional regressions contain the point estimate of the national regression in almost all cases; the exceptions are discussed below. Overall, poverty and water rates remain important determinants of water affordability in regional regressions, albeit with small variations. In New England, the results suggest that prices and poverty are relatively more important drivers of unaffordability; this is in line with higher water prices and lower poverty rates in this region. In the Southeast, where poverty rates are higher on average, the coefficients on poverty are smaller, and their respective 95% confidence intervals do not contain the point estimates for the national regression; however, poverty coefficients in the Southeast remain relatively large and statistically significant. For the Southwest, the coefficient on price is imprecisely estimated due to a large standard error; coefficients for poverty remain large and within the range of the national averages.

With greater standard errors, the coefficients on race/ethnicity covariates are not statistically significant, though point estimates may be even larger in certain regions. The only exception we observe is in the Southeast: a 10 percentage point increase in the proportion of Hispanic/Latino population in a block group is associated with a 1 percentage point decrease in water unaffordability. This result is in contrast with the national averages and illustrates how the mechanisms of demographic factors may play different roles across different regions.

D Sensitivity analysis

Two key parameters in our analysis are the income and price elasticities of household water consumption. 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 S2). To illustrate the impact of these parameters in our framework, we consider multiple scenarios with alternative combinations of elasticities.

In this sensitivity analysis, we take the lowest absolute value of elasticities to be zero; i.e., household water consumption does not change with income or prices. We discuss alternative scenarios for the upper absolute value of each elasticities in the subsections below. The first part of this section examines the effect of different income elasticities on our assessment of current unaffordability based on estimated consumption. The second part presents the results for program simulations under four combinations of elasticities.

D.1 Affordability assessment at the estimated consumption levels

To assess water affordability at the estimated level of consumption[S3], our model predicts the level of water consumption for a household. This prediction adjusts the household per capita consumption based on the county average, the household income relative to the county-average income, and the income elasticity (see Section B for details). In this setting, the income elasticity determines the spread of household per-capita water consumption around the average. A higher income elasticity results in a larger difference in per-capita consumption between households above and below the average income; a zero income elasticity results in all households consuming water at the county average.

Based on meta-analyses (Dalhuisen et al., 2003; Havranek et al., 2018), we consider four scenar-

[S3]The income elasticity assumption does not affect unaffordability metrics evaluated at the essential level of consumption (50 gppd) as these metrics use a fixed per capita consumption for all households.

ios for income elasticity: 0, 0.1, 0.4, and 0.7. The two last cases are based on higher point estimates and upper bounds of 95% interval confidence reported in the meta-analyses. We consider the values of 0 and 0.7 to be extreme cases, as they lead to rather unrealistic consumption patterns in our framework. With income elasticities equal to zero, there is no heterogeneity in water consumption within a county. With income elasticity at 0.7, low-income households adjust more aggressively, which results in approximately 29% of households consuming water below our assumed essential level of 50 gppd; for comparison, with elasticities of 0.1 and 0.4, the approximate percentages of households below 50 gppd are 7% and 20%.

Table S5 summarizes how different income elasticities affect the number of households facing unaffordable water when evaluated at different resolutions. Once again, we observe that metrics based on the median income greatly underestimate the number of households with unaffordable water, even at the block-group level. As shown in the third column, unaffordability metrics are higher when the income elasticity is zero, as poorer households are assumed to consume at the county average. The fifth column shows that a four-fold increase in the income elasticity from the baseline leads to a decrease in the unaffordability metrics of roughly 5.5 percentage points (or 33%) for the high-resolution cases; despite this change, the metrics in this column are in line with those using the essential level of consumption. Though metrics decrease even further when elasticity is 0.7 (column 6), we note that this comes as a result of poorer households consuming well below 50 gppd.

Complementing Table S5, Figure S3 shows the distribution of expenditure shares implied by each scenario; the distributions are calculated using the center of income brackets within each block group. The slope of the curves around the 4.5% cutoff point is approximately preserved, meaning that the relative magnitude of the differences presented in Table S5 is similar if we consider alternative affordability thresholds around 4.5% of income.

D.2 Program simulations

The outcomes of the affordability programs we simulate in our paper depend both the income and price elasticities. 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.

We consider four scenarios: two-by-two combinations of “low” and “high” magnitudes of each elasticity. The “low” case for both elasticities is zero. Following the previous subsection, we define the “high” case for income elasticity as 0.4. 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 S4 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.

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.

E Robustness checks

In this section, we explore two alternatives to the first-stage estimation. The first option is to restrict the sample to counties in which we observe the average per capita water consumption—most counties included in the AWWA survey. The second option is to rely on the assumption that per capita water consumption is fixed across all households. Both approaches avoid estimating levels of consumption, so that conditional correlations between water affordability and socio-economic-demographic factors can be estimated in one stage.

E.1 Estimation with observed average consumption

Panel A of Table S6 reports the results for the subsample in which we observe the average per capita water consumption. We note that most estimates are reasonably close to our main specification, with the possible exception of the effect for households identified as Hispanic. Nevertheless, the point estimates in Table S6 are all within the 95% confidence intervals reported in Table 3.

E.2 Estimation with fixed per capita consumption

Instead of estimating the current per capita water use, another possibility is to assume a fixed, uniform quantity ω for all households. Then, with w_{ibc} equal to ω for all households, we compute U^{ω}_{ibc}, the affordability metric under fixed water use. Finally, we estimate $U^{\omega}_{bc} = \mathbf{X}'_{bc}\mathbf{\Gamma} + u_{bc}$. As the assumption on ω replaces the first stage of the estimation procedure described above, the robust asymptoptic standard errors will be consistent under the usual regularity conditions.

We present results for two different assumptions on ω. The first choice is to set ω at 50 gppd, in which case we assess the conditional correlations between affordability of essential water services and socioeconomic factors. The second choice of ω assumes consumption at 100 gppd. Estimates for both cases are presented in Table S6, panels B and C. These results are qualitatively similar to our main specifications.

F 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.

F.1 National affordability assessment in Mack and Wrase

The study by Mack and Wrase (henceforth MW) published in 2017 is one of the first affordability assessments of water and sewer costs at the national level for the US (Mack & Wrase, 2017). 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 S5 presents the comparison between MW's approach and our assessment using estimated 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 13.6%. 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 22.7%.

Considering MW's original unit cost (gray line in Figure S5), 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 S6 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.

F.2 Local affordability assessments using alternative metrics

A recent 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.[S4] 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.[S5] In line with Teodoro's focus on basic consumption, our comparisons assume the essential level of consumption (50 gppd) and use interpolated local income distributions.

Table S7 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 (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 S7 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

[S4] Typically, disposable income is defined as after-tax income.

[S5] Our sample does not include New York, NY, Houston, TX, Indianapolis, IN, Washington, DC, and Detroit, MI.

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.

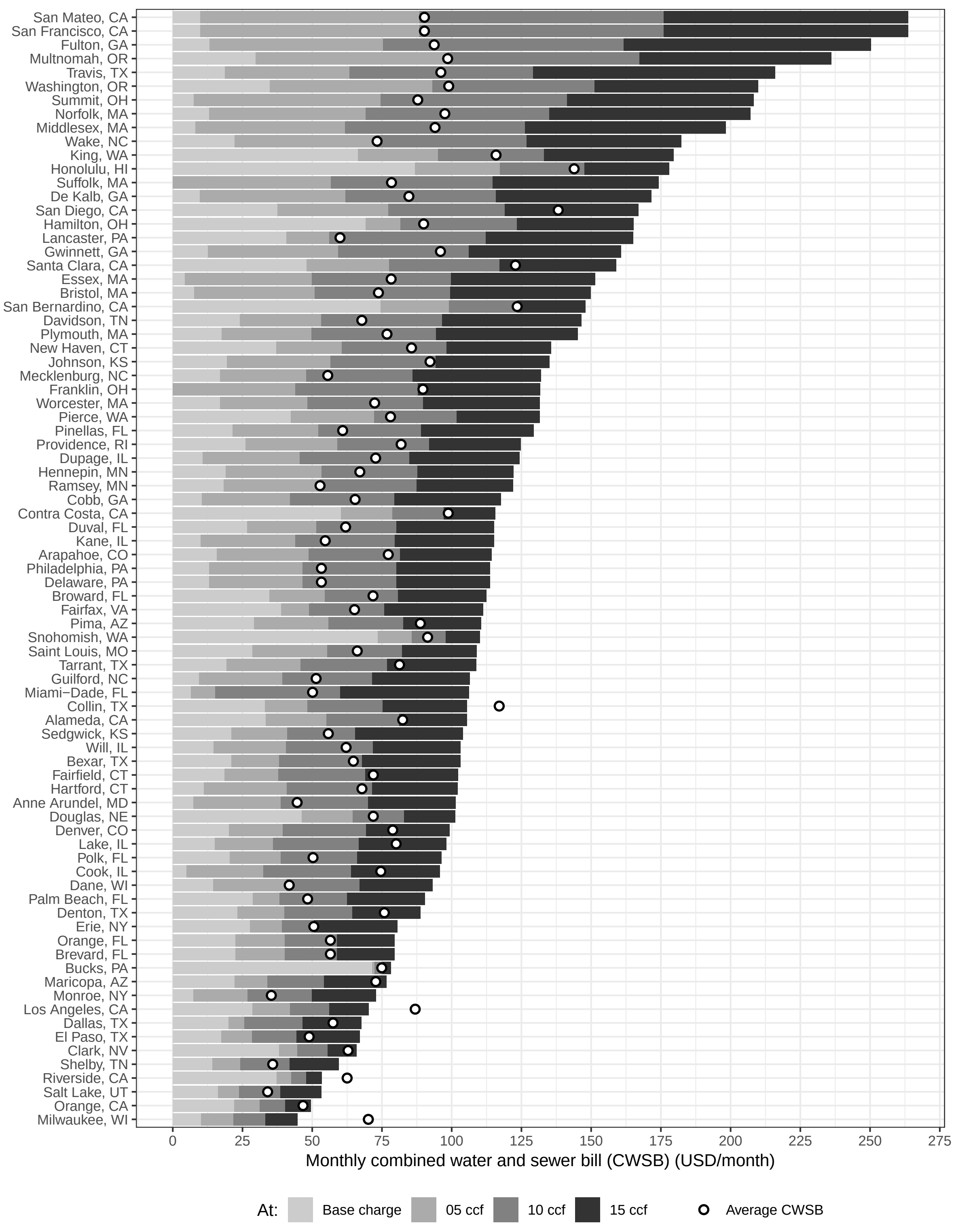

Figure S1: Combined water and sewer bills in counties with populations greater than 500,000. *Source:* Authors’ calculations from AWWA and EFC data.

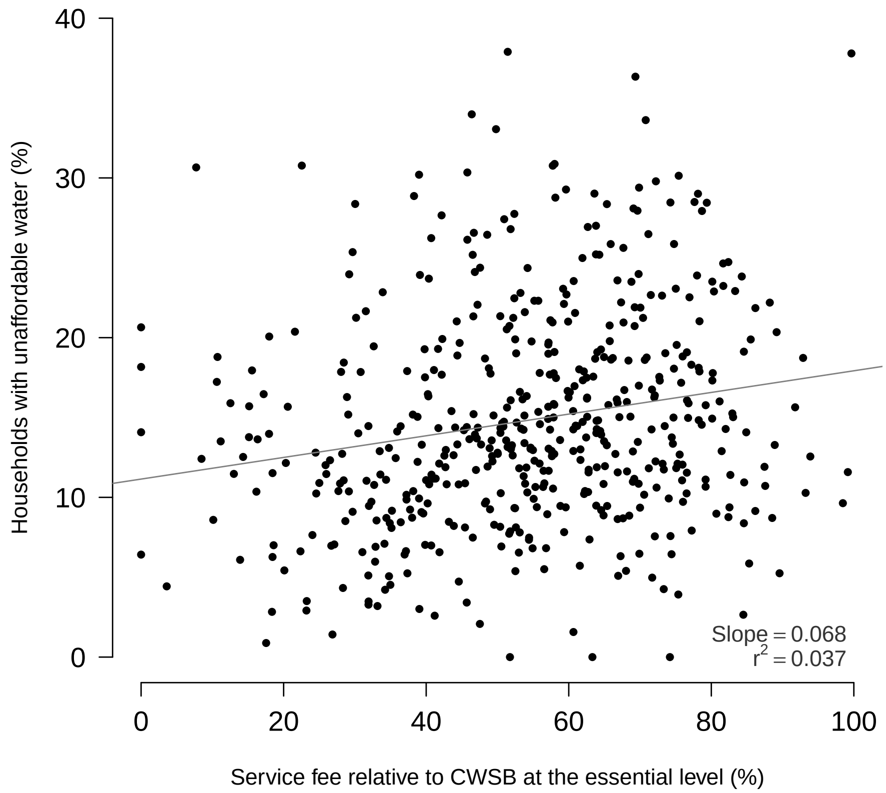

Figure S2: Correlation between the proportion of the combined water and sewer bill (CWSB) that is the fixed access fee (evaluated at 50 gppd) relative to the proportion of households with unaffordable water and sewer service within a county.

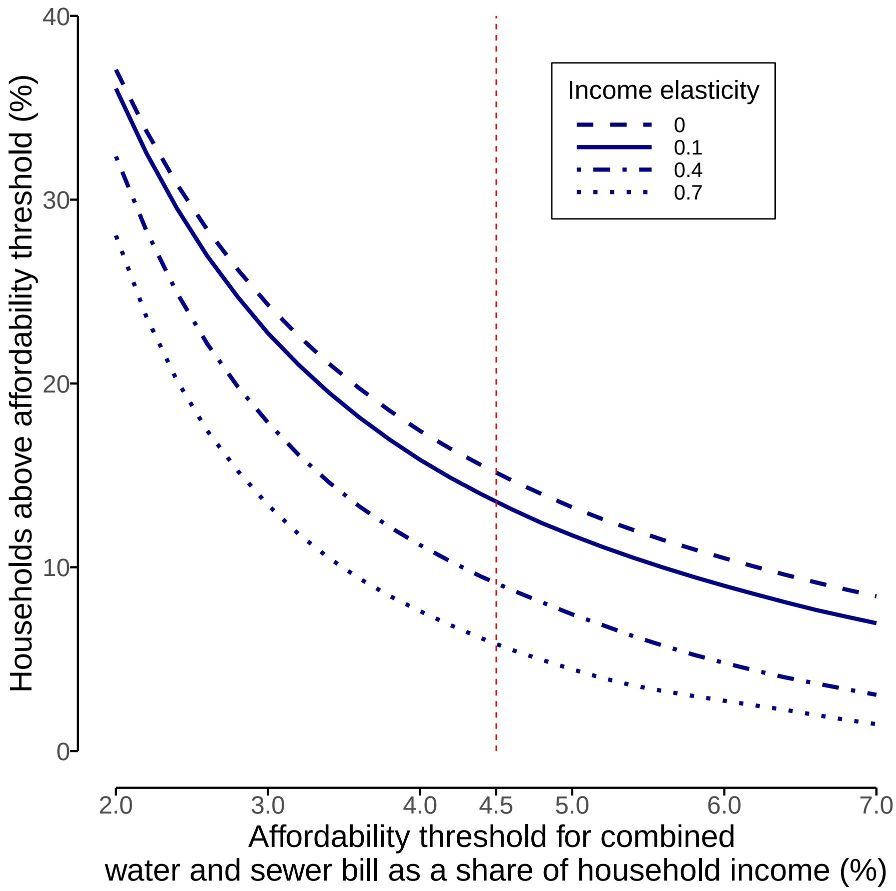

Figure S3: Proportion of households above the affordability threshold based on water and sewer expenditure-shares of income for different assumptions of income elasticity.

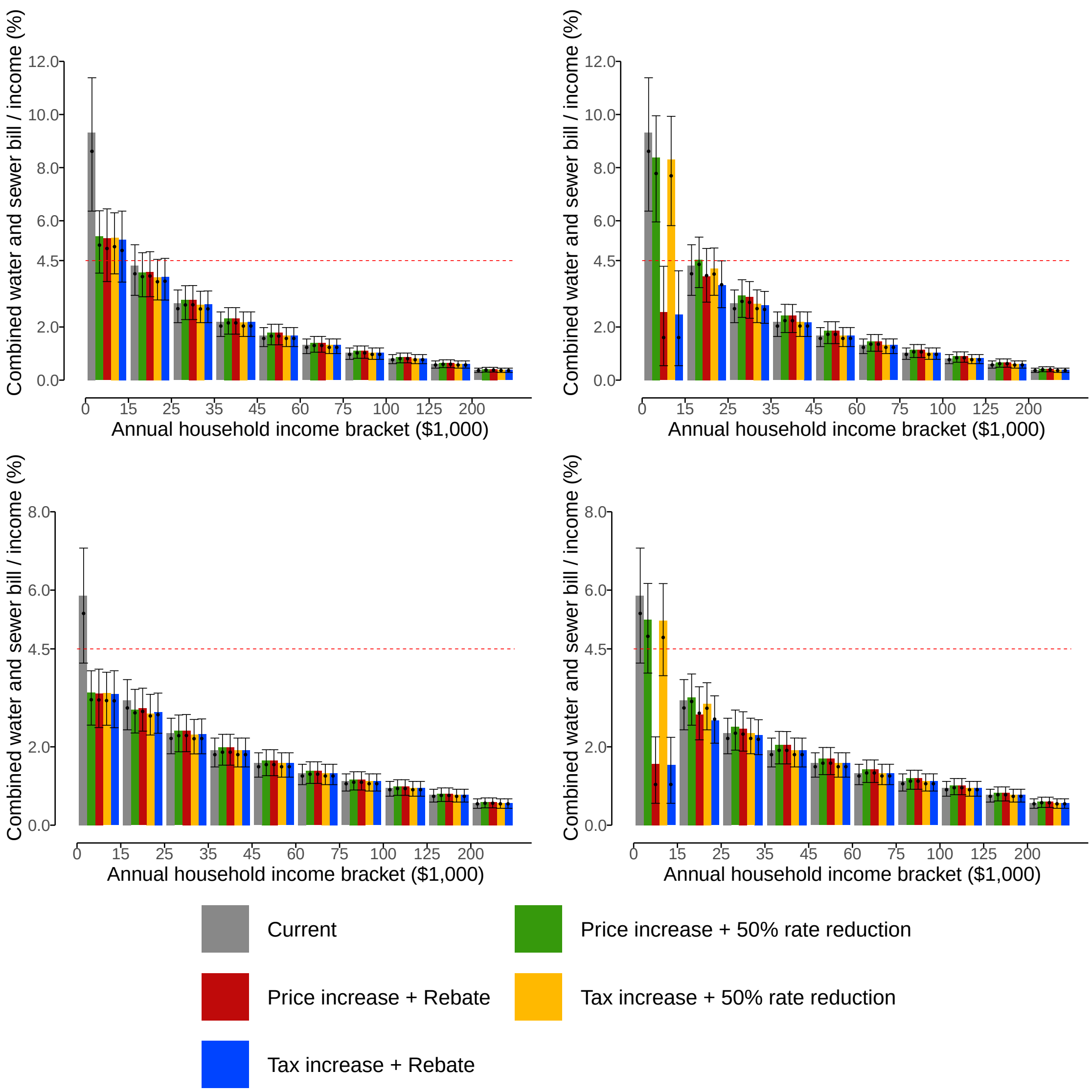

Figure S4: Average expenditure shares on water and sewer service by income bracket for business-as-usual and each policy option assuming different values of elasticities. **Top left panel:** Income elasticity = 0 and price elasticity = 0. **Top right panel:** Income elasticity = 0 and price elasticity = -0.8. **Bottom left panel:** Income elasticity = 0.4 and price elasticity = 0. **Bottom right panel:** Income elasticity = 0.4 and price elasticity = -0.8. In all bar charts, whiskers show the interquartile ranges and dots represent median values.

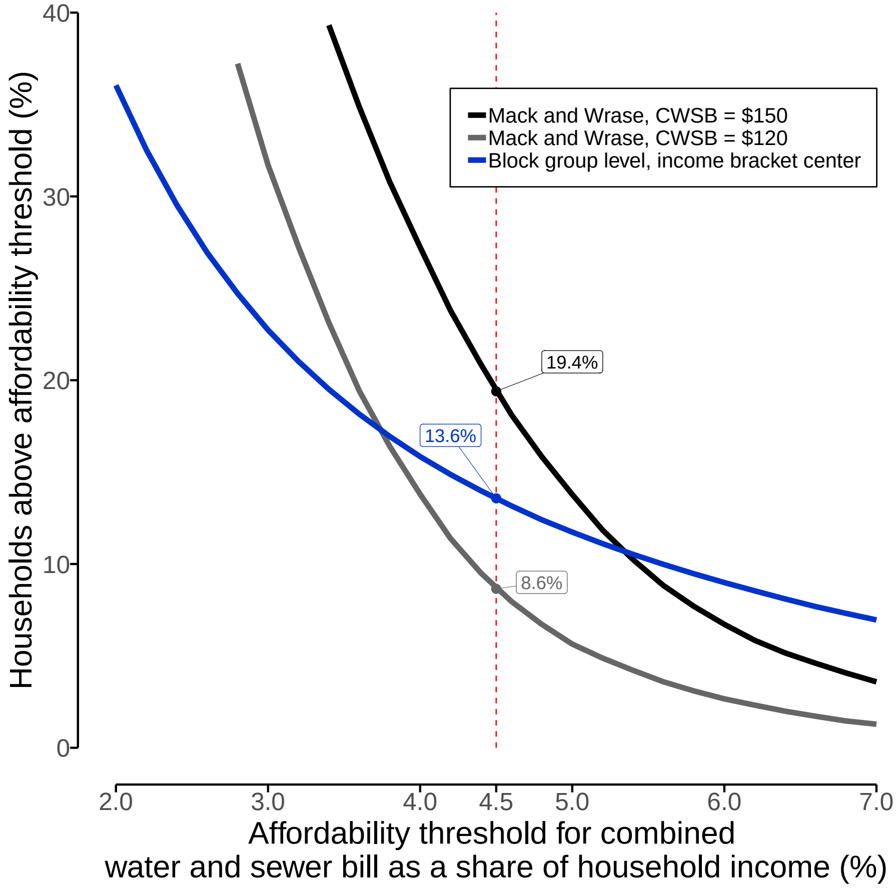

Figure S5: A comparison of the proportion of households above affordability threshold for Mack and Wrase's approach (MW) and our proposed method. The gray line follows MW, considers a unit cost of $0.01/gallon and a monthly combined water and sewer bill (CWSB) is $120 for all households in the sample. The black line uses an updated unit cost of $0.0125/gallon and a monthly CWSB of $150 for all households in the sample. The blue line considers estimated, income-adjusted consumption based on income bracket centers at the block-group level.

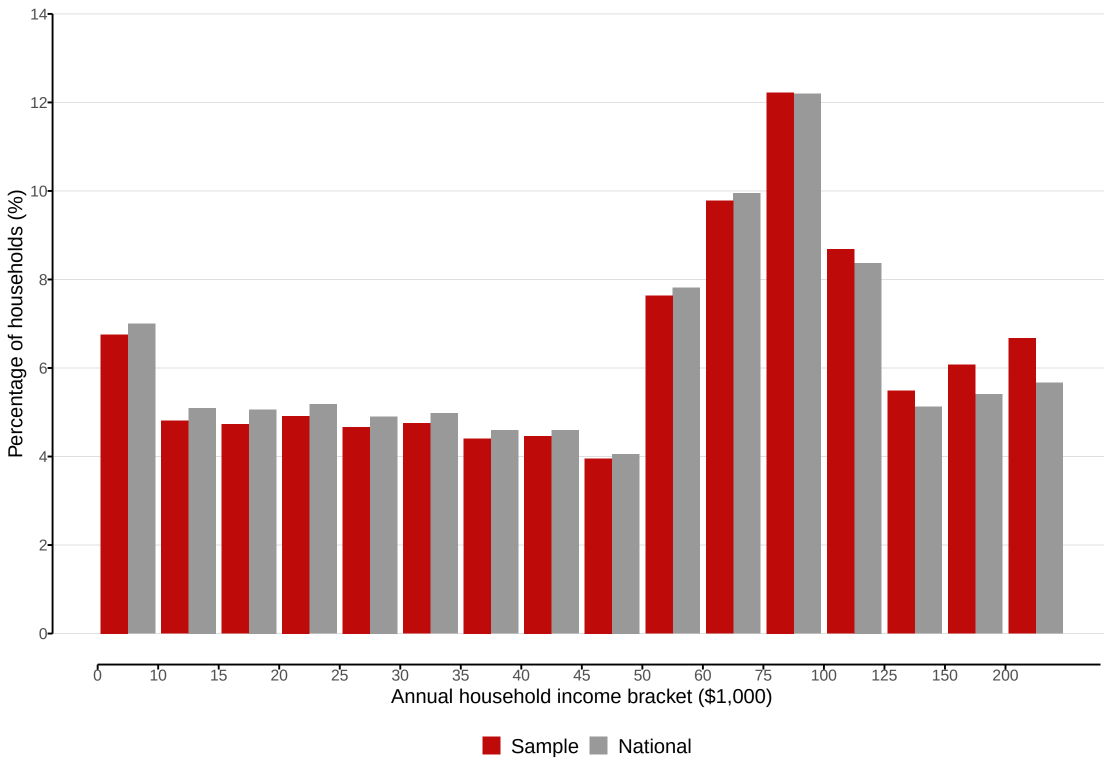

Figure S6: Household annual income distributions in our sample and for the entire United States. *Source:* US Census, American Community Survey.

Table S1: Summary statistics

Panel A: First-stage estimation[a]	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				

Panel B: Second-stage estimation[b]	Mean	Median	Min	Max	SD
Households above affordability threshold at estimated level (%)	15.78	11.97	0.00	100.00	13.93
Households above affordability threshold at essential level (%)	11.49	8.06	0.00	100.00	11.67
Households above affordability threshold at 100 gppd (%)	21.07	16.95	0.00	100.00	16.64
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				

[a] All variables are aggregated to the county level.
[b] Marginal prices are aggregated to the county level. All other variables are aggregated to the block group level.

Table S2: Results for the first-stage regression[a]

	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	

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

Table S3: Summary statistics for US regions[a]

(a) New England

	Mean	Median	Min	Max	SD
Households above affordability threshold at estimated level (%)	14.58	10.81	0.00	81.76	13.00
Households above affordability threshold at essential level (%)	10.74	7.41	0.00	77.94	10.70
Households above affordability threshold at 100 gppd (%)	21.77	17.75	0.00	90.64	15.91
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 estimated level (%)	15.29	12.19	0.00	96.00	12.93
Households above affordability threshold at essential level (%)	13.39	10.28	0.00	96.00	12.14
Households above affordability threshold at 100 gppd (%)	25.93	22.46	0.00	100.00	17.15
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 estimated level (%)	15.90	11.82	0.00	100.00	13.96
Households above affordability threshold at essential level (%)	9.68	6.36	0.00	100.00	10.67
Households above affordability threshold at 100 gppd (%)	18.69	14.23	0.00	100.00	16.07
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				

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

Table S4: Conditional correlations between water affordability and select socioeconomic characteristics for subsamples containing states in US regions[a]

	All regions Coef. (SE)	New England Coef. (SE)	Southeast Coef. (SE)	Southwest Coef. (SE)
log(Population density) (Persons/Sq. mi)	-0.4935*	-0.1005*	-0.4775*	-0.8586*
	(0.1129)	(0.3536)	(0.2295)	(0.3014)
Average household size (Persons)	1.7333*	2.1567*	3.2451*	1.1892
	(0.3939)	(0.9936)	(0.6257)	(3.088)
log(Volumetric rate at 5–10 ccf) (USD/1,000 gallons)	7.6766*	12.4559*	8.8374*	4.4855
	(1.5523)	(5.8052)	(1.9489)	(8.3736)
Base charge relative to CWSB at essential level (%)	0.0785*	0.0427	0.0758	-0.0357
	(0.031)	(0.0785)	(0.0454)	(0.2752)
Households below poverty level (%)	0.5998*	0.6412*	0.5381*†	0.6346*
	(0.0135)	(0.0454)	(0.0194)	(0.0294)
Households between 1 and 2× poverty level (%)	0.1478*	0.1159*	0.1013*†	0.1304*
	(0.0123)	(0.0395)	(0.0159)	(0.0307)
Median gross rent relative to income (%)	0.0988*	0.0665*	0.0797*	0.0961*
	(0.0076)	(0.0222)	(0.0099)	(0.0189)
Occupied units that are rented (%)	0.0257*	0.0242	0.032*	0.0101
	(0.0076)	(0.0161)	(0.0069)	(0.018)
Median age of housing unit (Years)	0.0129	-0.0318†	0.0324*	0.0187
	(0.0118)	(0.0183)	(0.0144)	(0.022)
Population identified as Black/African American (%)	0.0325*	0.0638	0.0175	-0.0126
	(0.0103)	(0.0476)	(0.0134)	(0.0332)
Population identified as Hispanic/Latino (%)	0.0159	0.0444	-0.1088*†	0.0122
	(0.0168)	(0.0413)	(0.0458)	(0.0349)
Constant	-32.2983*	-33.7254*	-33.6289*	-3.1786
	(8.9454)	(15.8409)	(8.4868)	(41.6757)
State fixed efects	Yes	Yes	Yes	Yes
Climate zone fixed efects	Yes	Yes	Yes	Yes
Observations	76240	6304	20411	9066
R^2	0.6466	0.7221	0.5962	0.6748
F-statistic	2322.96	1167.36	1368.27	1042.89

* denotes statistical significance at 5%. † indicates the 95% confidence interval does not contain the point estimates of the "All regions" regression.

[a] Dependent variable is the proportion of households above the 4.5% water affordability threshold within a block group. Bootstrapped standard errors in parentheses. Water affordability is calculated using reported consumption only. Marginal prices are aggregated to the county level. All other variables are aggregated to the block group level.

Table S5: 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 under different income elasticity assumptions

		Income elasticity			
Income metric[a]	**Estimated consumption**	ϵ_y **= 0**	ϵ_y **= 0.1**	ϵ_y **= 0.4**	ϵ_y **= 0.7**
Median household income	Income-adjusted	2.55%	1.88%	0.76%	0.36%
Income bracket center	Income-adjusted	15.14%	13.57%	9.11%	5.82%
Income distribution	Income-adjusted	15.14%	13.58%	9.08%	5.44%

[a]Results are presented for three income metrics: (i) "Median household income" represents median incomes at the block-group level; (ii) "Income bracket center" measures incomes at the midpoint of income brackets evaluated at the block-group level; and (iii) "Income distribution" represents the 16-node income distribution with interpolation between nodes evaluated within Census block groups.

Table S6: Conditional correlations between water affordability and select socioeconomic characteristics[a]

	(A) Observed consumption only			(B) Fixed consumption at 50 gppd			(C) Fixed consumption at 100 gppd		
	Coef.	SE	95% CI	Coef.	SE	95% CI	Coef.	SE	95% CI
log(Population density) (Persons/Sq. mi)	-0.5057	0.0358	[-0.5758, -0.4355]	-0.5067	0.0274	[-0.5604, -0.4530]	-0.8163	0.0308	[-0.8767, -0.7560]
Average household size (Persons)	1.5908	0.0892	[1.4159, 1.7657]	0.9252	0.0708	[0.7865, 1.0639]	1.9230	0.0815	[1.7632, 2.0827]
log(Volumetric rate at 5–10 ccf) (USD/1,000 gallons)	7.2115	0.1441	[6.9291, 7.4940]	8.4189	0.1116	[8.2002, 8.6377]	14.5106	0.1336	[14.2487, 14.7726]
Base charge relative to CWSB at essential level (%)	0.0711	0.0032	[0.0647, 0.0774]	0.1150	0.0026	[0.1100, 0.1200]	0.0867	0.0027	[0.0814, 0.0920]
Households below poverty level (%)	0.6079	0.0049	[0.5982, 0.6176]	0.4922	0.0042	[0.4840, 0.5005]	0.6976	0.0040	[0.6897, 0.7055]
Households between 1 and 2× poverty level (%)	0.1622	0.0041	[0.1541, 0.1703]	0.1002	0.0033	[0.0938, 0.1066]	0.2608	0.0038	[0.2534, 0.2682]
Median gross rent relative to income (%)	0.1053	0.0042	[0.0972, 0.1135]	0.0580	0.0034	[0.0514, 0.0646]	0.1215	0.0038	[0.1141, 0.1288]
Occupied units that are rented (%)	0.0232	0.0022	[0.0190, 0.0275]	0.0116	0.0017	[0.0082, 0.0150]	0.0196	0.0021	[0.0155, 0.0237]
Median age of housing unit (Years)	0.0096	0.0023	[0.0052, 0.0141]	-0.0048	0.0019	[-0.0086, -0.0011]	0.0069	0.0022	[0.0027, 0.0112]
Population identified as Black/African American (%)	0.0317	0.0024	[0.0270, 0.0363]	0.0188	0.0019	[0.0150, 0.0226]	0.0416	0.0020	[0.0377, 0.0456]
Population identified as Hispanic/Latino (%)	0.0129	0.0028	[0.0075, 0.0183]	-0.0231	0.0023	[-0.0275, -0.0186]	-0.0025	0.0025	[-0.0074, 0.0024]
Constant	-32.3545	0.8503	[-34.0210, -30.6881]	-28.5992	0.6017	[-29.7785, -27.4199]	-35.2743	0.6727	[-36.5928, -33.9557]
State fixed efects		Yes			Yes			Yes	
Climate zone fixed efects		Yes			Yes			Yes	
Observations		58400			76240			76240	
R^2		0.6554			0.5715			0.7280	
F-statistic		1880.71			1693.31			3398.06	

[a]Dependent variable is the proportion of households above the 4.5% water affordability threshold within a block group. Marginal prices are aggregated to the county level. All other variables are aggregated to the block group level.

Table S7: 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.