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RESEARCH ARTICLE

Affordability of household water services across the United States

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Abstract

Households that cannot be able to afford their water bills may lose access to drinking water and wastewater services. This study seeks to quantify how many households may struggle to pay for water services across 787 of the largest drinking water providers located within each state of the United States. Household water affordability is the ability for a household to pay for basic water services without undue hardship. Here, we select 6,000 gallons per month (22.7 m^3/mo) as sufficient to meet basic needs and define undue hardship as spending more than 4.6% of household income (one day of labor each month) to pay for water services. Monthly bills are combined with census income data based on service area boundaries to determine how many households are spending more than 4.6% of their income on water services. We find that basic water services are unaffordable for 17% of the households (28.3 million persons) in this study. The median, or representative community, has one in seven households spending more than 4.6% of their income paying for water services. We developed a data visualization tool to allow users to explore how affordability challenges change across different volumes of water usage and levels of financial hardship (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-united-states). This research shows that household water unaffordability is not a localized problem but rather is a challenge experienced by households in communities across the nation.

Introduction

In the United States, most households gain access to water services (drinking water and wastewater) through water service providers (also referred to as "utilities"). The costs of infrastructure, treatment, operations and maintenance required to provide safe, reliable water services are primarily covered by the utility, with minimal subsidies or assistance from the federal or state governments. Utilities generate revenue to pay the costs of providing water service by treating water as a commodity and charging their "customers" (including residential households) for access to potable water and the removal of wastewater. When water is functionally treated as a commodity, failure to pay for services can result in loss of access to water. Loss of

access, particularly for disadvantaged households and communities, can exacerbate already dire situations that lead to eviction, removal of children, and undermining the health of families and whole neighborhoods [1–4]. Bill nonpayment causes the utility, in turn, to lose revenue necessary for continued operations while also potentially increasing overall costs (e.g. costs incurred by providing customer assistance programs, staff time expended to shut off and reinitiate water services, or collect delinquent bills).

In recent years, organizations such as the U.S. Water Alliance, American Water Works Association (AWWA), and the Environmental Protection Agency (EPA) have called attention to household water affordability as an economic, environmental, and equity concern [3, 5–7]. Household water affordability (hereafter referred to as "water affordability") refers to the ability of an individual household to pay for basic water needs–drinking, cooking, cleaning, and sanitation–without undue hardship. Two simultaneous occurring trends–the increased cost of water services and a widening income gap–have driven a growing concern over water affordability. First, the cost of providing water services has risen at nearly triple the rate of pre-2022 inflation. Several factors have contributed to the rise in costs, including replacement of aging infrastructure, expanding regulations, and reductions in federal and state financial support to water providers [8–10]. At the same time, the income gap between high-income earners and low-income earners has widened, particularly as lower wages have stagnated, leaving low-income households with less buying power now than in previous decades [11, 12]. The COVID-19 pandemic exacerbated this trend [13]. Rising costs amidst stagnating wages means that a larger proportion of household income is needed to pay for water services. Indeed, a 2022 AWWA utility survey found that the primary financial challenges faced by utilities were rising costs and inflation, followed by rates and affordability [14]. The financial challenges of utilities become the financial realities for their rate payers when utilities are primarily dependent on revenue from customers within their service area to meet their capital and operational expenses.

Developing an appropriate approach for addressing water affordability challenges requires understanding the scale of the challenge [15], particularly whether affordability challenges are widespread or localized to particular states, geographic regions, or communities. Here, the extent of the water affordability challenge is empirically quantified across the United States by collecting rate structures and income data from 787 utilities serving the largest communities within each state. Assuming a monthly household use of 6,000 gallons of water, we estimate that 17% of households may experience a financial burden paying for water services, spending more than a day of labor paying for services. Between 5% and 26% of households experience unaffordable water services depending on the volume of water used to estimate bills and the level of financial burden determined to be acceptable. This study uses rate and service area data from hundreds of utilities to estimate the breadth of affordability challenges within a flexible framework to adjust how affordability is defined and how sensitive affordability metrics are to changes in the definition (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-united-states).

Materials and methods

Experimental design

Comparing water affordability across utilities can only be approximated and not directly measured for two primary reasons. First, data relevant to affordability and its impacts on households have not been collected systematically at a national scale [15]. The relevant data include rates or tariffs, household bills, household water use, arrearages, shut-offs, and details about the existence and enrollment of customer assistance programs. Utilities may have these data,

but they are often nonpublic to protect customer privacy. Furthermore, each utility may have different definitions or standards that make comparison across utilities infeasible [15]. In the absence of these data, affordability studies typically combine surveyed water bills with census data to estimate the financial burden for households in the community, i.e. what percentage of household income is needed to pay for water services [6, 16–22]. This approach can only indicate the financial burden and not whether households are able to pay for services, or what sacrifices they must make in order to do so.

The second limitation relates to the subjectivity inherent in defining household water affordability. Any analysis of affordability must define (a) how much water is needed for basic water services, (b) what constitutes an undue financial hardship, and (c) against what level of household income should be evaluated to determine if rates are affordable, since utilities generally apply the same rates across a customer class (i.e., low-income, minimum wage, or median household income) [6, 17, 18, 20].

To date, general agreement on affordability metrics and thresholds does not exist. A growing number of studies have developed and proposed affordability metrics [16–22], each of which uses different volumes of water, different measures of financial hardship or burden, and different levels of household income. Since the definition of water affordability is subjective, we calculated affordability metrics across a range of water usage and levels of financial burdens to capture the potential range of affordability challenges. We developed an approach that looks at the affordability for all households, thereby eliminating the subjective criteria of selecting a representative household income (e.g., median or 20th percentile household income of the community).

In this study, we present the results for a household using 6,000 gallons per month (gal/mo) (22.7 m^3/mo) to meet basic needs and consider water is affordable when households spend less than a day of labor (4.6% of income) paying for water services. The average indoor per capita water use in the U.S. is 83 gallons (0.31 m^3) per day [23], meaning a 2.4-person household (the average U.S. household consists of 2.65 persons [6]) would use the 6,000 gal/mo considered in this analysis. This volume falls within the range of other studies on affordability, which use volumes from 4,000 gal/mo [20] to 12,000 gal/mo [16]. The selected level of financial burden (4.6%) is aligned with recommendations from the EPA [24] (4.5% of income) and Teodoro [18] (a day of labor for minimum wage earners). While these were the choices the authors made for this paper, others may have different criteria or values of interest. Accordingly, the authors developed an interactive visualization tool (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-united-states) that allows users to select their own definitions of basic water usage (volume) and undue financial hardship (percent of income) for applying the analyses presented in this paper.

Data sources

The affordability analysis required three types of data: (1) service area boundaries, (2) water service rates (drinking and wastewater), and (3) census data for each water system provider.

Identifying water system providers. The water service sector is highly fragmented, with some communities receiving drinking water, wastewater, and stormwater services from a single provider (i.e., utility or system) and other communities receiving these services from numerous different providers (e.g., a community may have a single drinking water provider and several wastewater providers serving different areas of that community). The drinking water service areas were the primary geographic unit of analysis within which we estimate total water bills (drinking water and the average wastewater bill). We refer to the service area and the households contained as "communities."

There are more than 48,500 drinking water service providers, estimated to serve between 87% [23] ad 95% [25] of the U.S. population. While the majority (91%) of drinking water providers serve fewer than 10,000 persons, the largest 9% of providers serve 83% of persons reliant on centralized services [25]. This study focuses on the drinking water providers serving the greatest number of persons in each state as identified using EPA's Safe Drinking Water Information System (SDWIS) [25]. Data were collected for the largest utilities in each state to maximize the number of households considered in estimating the extent of household affordability challenges and, by considering all 50 states, to understand how affordability varied due to different state legislation and regulations that shape rate structures and economic well-being [26] and influence the ability to pay for services [27].

We began by including all drinking water utilities serving a community of more than 100,000 persons, which are classified as "very large" utilities. Since we wanted to include several utilities for each state to represent a diversity of rate structures and locations, we expanded this selection to include all drinking water utilities serving a community with more than 50,000 persons in states with fewer than 10 very large utilities. If a state still had fewer than ten drinking water utilities represented, we included all utilities serving communities with more than 25,000 persons. More than a third of the population was represented in each state, except for Vermont, Maine, and Michigan due to population dispersion and reliance on private wells. For these three states, we include drinking water utilities serving as few as 10,000 persons. In all, 820 retail drinking water utilities were identified.

Service area boundaries. The geographic service area boundaries for the identified drinking water service providers were obtained for 14 states [28], with partial boundaries in five additional states. We used municipal boundaries as a proxy based on geographic information from each drinking water utility provider's website for states where public service area boundaries were not available (Table A in S1 Text). We used state-provided municipal boundaries where available (21 states) and census places for the remaining states, with the methodology for creating service areas from municipal boundaries described in Patterson et al. [29]. Service area boundaries were available or created for 796 of the initial 820 communities. The missing boundaries were county and district systems that did not provide sufficient geographic information to accurately identify their service area.

Water service rates. We manually collected drinking water and wastewater rate structures for each utility through online searches, prioritizing rates provided on utility websites. We used the resulting rates database to calculate total household water service bills for different volumes of water use [20]. There is considerable variation among rate structures; however, most consist of a fixed service charge, a commodity charge based on the volume of water used, and surcharges added to cover particular costs associated with debt, capital expenses, purchased water, or consent decrees. We were able to water and wastewater rates data for 787 of the 796 communities with service area boundaries. The rates database does not account for customer assistance programs (CAPs), which provide financial assistance to households that cannot afford their water bills. While CAPs provide assistance, few utilities provide sufficient detail to incorporate CAPs into the study (i.e., cap rate structures and discounts are not provided online), nor the information to know how many eligible households receive assistance [30, 31].

Drinking water providers may also provide wastewater services; however, these can be distinct utilities. We identified and included 1,130 wastewater utilities that intersected the 787 drinking water utilities and would contribute to the drinking water bills paid by residents within the communities. The average wastewater bill was calculated when multiple wastewater providers were located within a single drinking water service area.

Table 1. Population served by the largest cities in each region. State values provided in Table A in S1 Text.

Region	(A) Total Population (Millions)	(B) Population Served by Centralized Water Systems (Millions)	(C) Population in Study Communities (Millions)	(C)/(A) Percent of Total Population Represented (%)	(C)/(B) Percent of Population Served Represented (%)	Number of Communities Represented
Pacific Northwest	34.3	28.9	18.2	53.0	63.0	90
Great Plains	5.2	4.4	2.3	44.3	52.1	31
Southwest	54.1	52.1	33.2	61.3	63.6	120
Mid-South	14.2	11.8	5.8	41.1	49.2	39
Southeast	69.5	59.5	33.6	48.3	56.5	172
Midwest	43.3	40.8	22.1	51.1	54.2	92
Mid-Atlantic	39.7	31.7	20.7	52.2	65.3	80
Northeast	66.2	54.3	24.9	37.7	45.9	163
National	326.6	283.5	160.9	49.3	56.7	787

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Census data. The U.S. Census Bureau's five-year ACS survey (2015–2020) provided the population and number of households in each income bracket at the geographic scale of block groups.

Communities included

The 787 communities cover 160.9 million persons (49.3% of the U.S. population) (Table 1). States were grouped into eight geographic regions for ease of reporting (Fig 1), with between 38% (Northeast) and 61% (Southwest) of the regional population represented by the included communities.

Analysis

Numerous studies have developed water affordability metrics [6, 16–22]. Each approach requires researchers to make assumptions regarding the quantity of water appropriate to meet basic needs and the level of spending that constitutes undue financial hardship. Here, we estimate the monthly cost of water services as the summation of the cost of water and wastewater services for 6,000 gal/mo (22.7 m^3/mo). If a single drinking water system is served by multiple wastewater providers, we calculate a spatially weighted average bill representing the total costs of drinking water and wastewater services for the community [20].

The Income Dedicated to Water Services (IDWS) [20] method estimates the proportion of households experiencing different levels of financial burden paying water bills. For example, consider a household with a total monthly water service bill of $100. Such a household would be required to spend $1,200 per year on water services. If this household earns an annual income of $120,000, the household would dedicate 1% of its annual income to pay the annual water cost of $1,200. However, for another household in the same community with an annual income of $30,000 the same annual cost would represent 4% of the household income. For a household earning $12,000 annually, the water service bill would represent 10% the annual income (Fig 2A). At each level of financial burden selected (e.g. 1%, 4%, or 10%), the percent of households earning less than the required income (e.g., $120,000, $30,000, $12,000, respectively) is estimated from census data. We create an IDWS curve for each community by calculating the percent of households whose incomes fall below the level indicated by different financial burdens (Fig 2B).

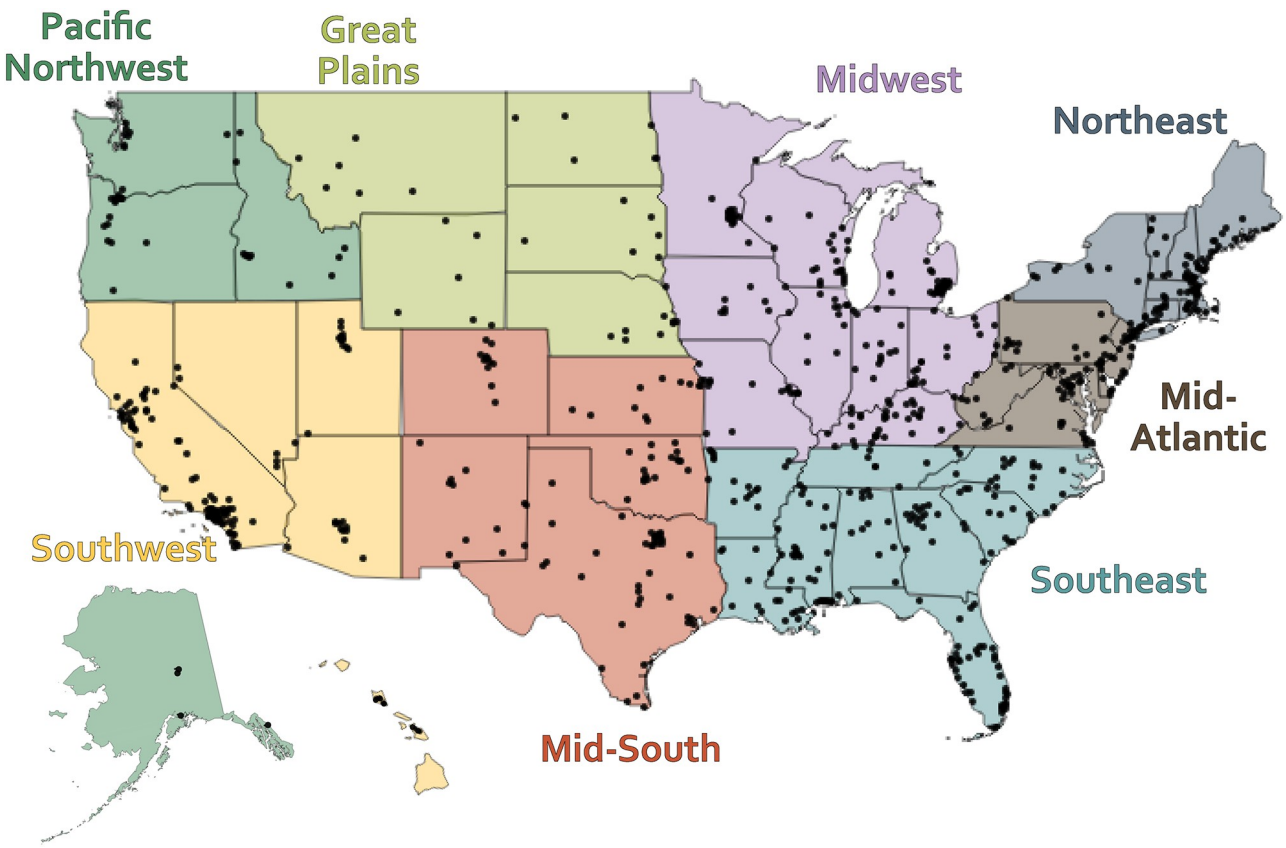

Fig 1. Location of communities in this study by state and geographic region. State shapefile is from the U.S. Census Bureau through the tidycensus R package (https://rdrr.io/cran/tidycensus/man/state_laea.html).

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We selected a percent of income along the IDWS curve (corresponding to a financial burden as described above) to represent an undue financial hardship (i.e., the amount of income at which services become unaffordable; Fig 2C). Here, we chose one day of labor dedicated to paying for water services per month (4.6% of monthly income) to distinguish between affordable and unaffordable services. This guideline is similar to that used by EPA [24] (4.5% of income) and Teodoro [18] (a day of labor for minimum wage earners). This cross-section of the IDWS provides the proportion of households spending more than one day of labor each month to pay for water services in the study communities. The measure we derive captures the breadth of the affordability challenge, i.e., how widespread is unaffordability within a community. We refer to this as the "pervasiveness of unaffordability." The cost of water services is compared alongside the pervasiveness of unaffordability (percent of households in a community paying more than one day of labor for water services, Fig 2D). We calculate the pervasiveness of unaffordability within the median community, along with the total percent of households considered to have unaffordable water (i.e. the sum across communities within this study).

We also estimate the percent of households experiencing unaffordable water services across a range of water usage (from 4,000 to 8,000 gal/mo, 15.1 to 30.3 m^3/mo), equivalent to a 2 to 4-person household using between 50 and 100 gallons (0.2 and 0.4 m^3) per person per day). This range represents the likely range of volumes considered "reasonable use" for many households given an average per capita water use of 83 gallons (0.31 m^3) per day in the U.S. [23]. We

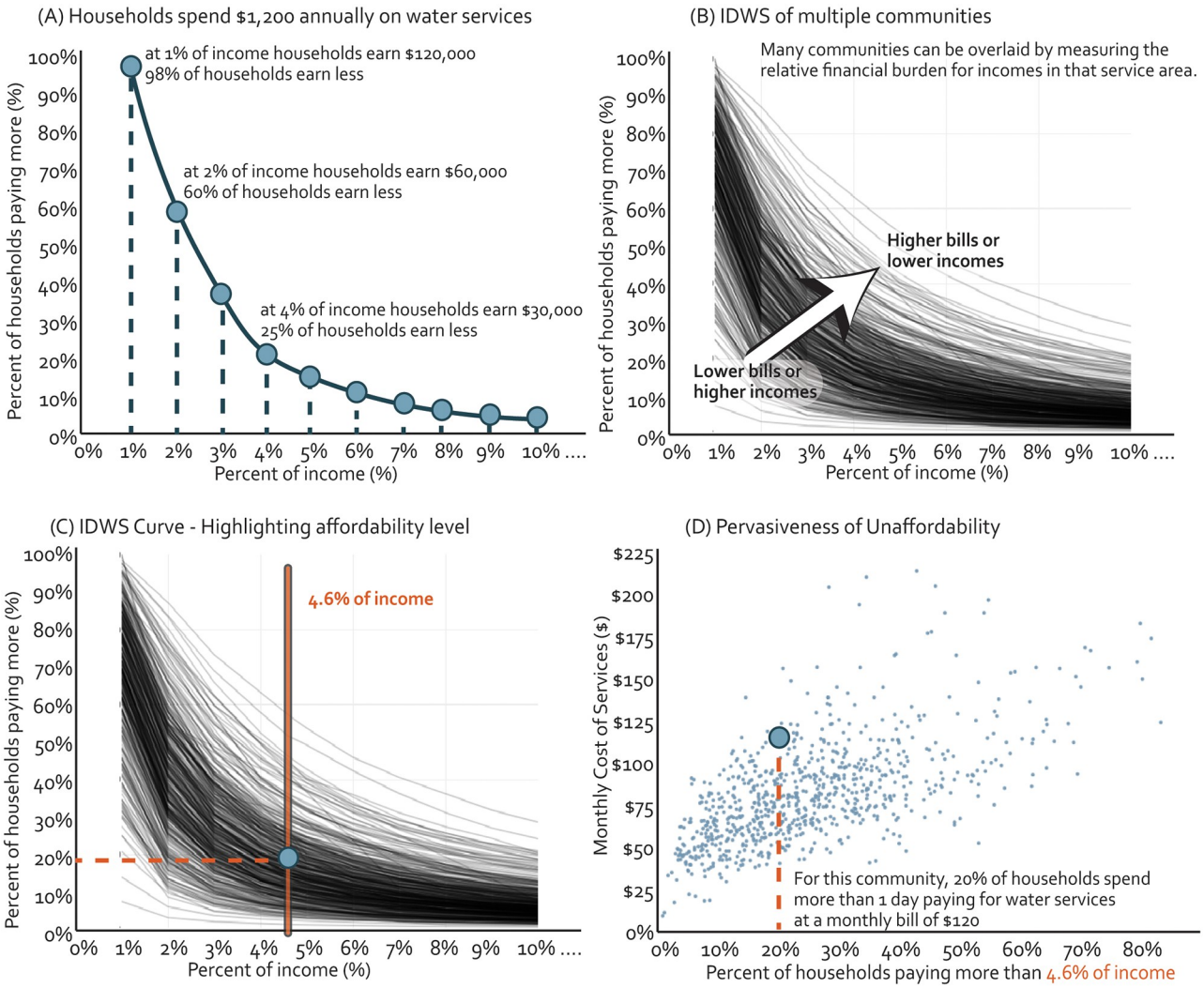

Fig 2. Income Dedicated to Water Services (IDWS) to pervasiveness of unaffordability. (A) IDWS provides a continuum of the financial burden of households (from 1% to 10% of annual income) for each community, (B) The affordability of water services in each community is summarized across a range of incomes by a single curve, with multiple IDWS curves representing a number of different communities, (C) A financial burden was selected to represent undue hardship; 4.6% of income or one day of labor per month. (D) A cross-section of the IDWS (percent of households spending more than 4.6% of income–x-axis) with the monthly cost of water services (y-axis).

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explore the sensitivity of results using different definitions of financial hardship ranging between 4% and 10% of household income (i.e. a little less than a day of labor to a little over two days of labor each month).

Statistical analysis

This study prioritized large utilities; however, previous studies have noted that smaller utilities are more likely to experience more affordability challenges than larger utilities [17, 18]. To assess the potential for bias due to reliance on larger utilities, we replicate the analysis with the complete rates database from Patterson & Doyle [20]. This database contained 3,845 communities of all sizes, but in fewer states and with older rates data, (68% of rates collected prior to 2022). In the following discussion, we retained EPA's utility size categorization, and we used two-sided t-tests to assess if there were significant differences in monthly bills and

pervasiveness of unaffordability between utilities of different sizes (i.e. different number of customers and therefore revenue generation potential).

Results

Costs and affordability of water services

When assuming 6,000 gallons of usage (22.7 m^3), the median water service bill is $77/mo, ranging from as low as $12/mo for a community in New York where wastewater services were embedded in the property tax to as high as $217/mo for a community in California. Water service bills for half of communities (the 25th to 75th percentile) range from $64/mo to $99/mo (Fig 3B). There is considerable variability in the costs of water services between communities as well as between geographic regions. The median monthly bill by region ranges from $68 in Great Plains to $95 in the Pacific Northwest and $96 in the Mid-Atlantic (Table 2). Of the regions with higher median monthly bills, the Mid-Atlantic generally has more expensive water services than other regions, while the Pacific Northwest has a handful of communities with very expensive water services. The Great Plains and Mid-South have the lowest median bills (less than $72/mo) and relatively small variability between communities (Fig 3).

In this study, 17.1% of households (28.3 million persons) have unaffordable water services when defined as spending more than one day of labor each month paying for services (4.6% of income) and using 6,000 gal/mo (22.7 m^3/mo) to meet basic needs. Within the median community, 15.3% of households–one in seven households–have unaffordable water services by that definition (Table 2; Fig 3), ranging from 1.2% to 58.5% households in a utility. While there is some correlation between monthly bills and unaffordability (spearman correlation = 0.62), there is large variation in the pervasiveness of unaffordability for similar monthly bills dependent on the income distributions of households in the service area. For example, within $1 of the median monthly bill, the pervasiveness of unaffordability ranges from 6.5% to 36% of households (Fig 3B). Affordability is affected not just by the cost of water services but also by the income distribution of the community [32].

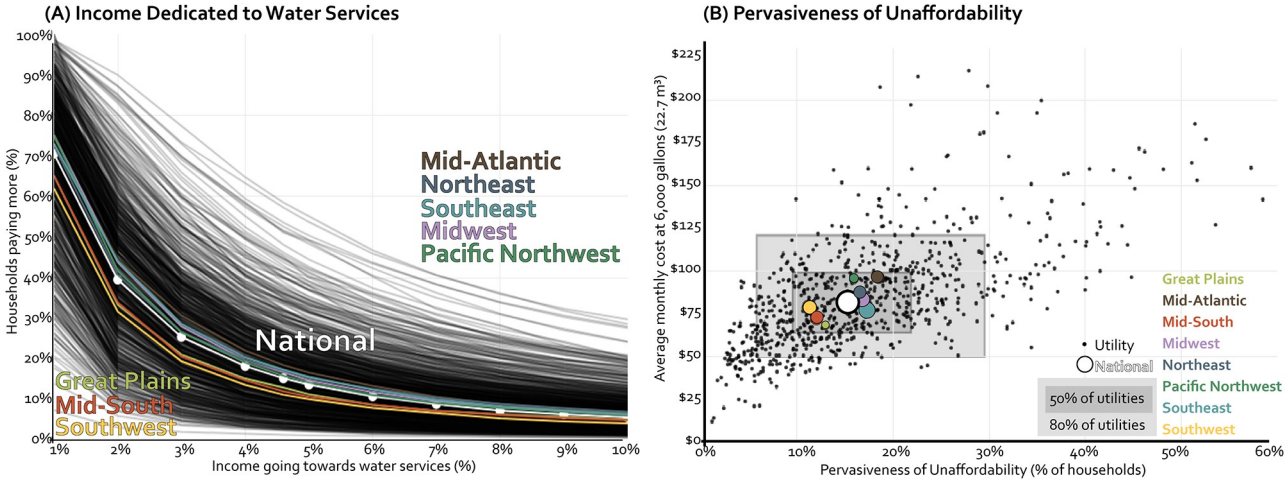

Fig 3. National, regional, and community IDWS and pervasiveness of unaffordability. (A) IDWS provides a continuum of the financial burden of households (from 1% to 10% of annual income) for each of the 787 communities (x-axis) with the percent of the population spending more on water services (y-axis). (B) A financial burden of 4.6% of income was selected from the IDWS to plot the percent of households in each community spending more than 4.6% of their income on water services (x-axis) with monthly bills (y-axis). The size of the national and regional points corresponds to the number of communities represented. The boxes represent the 25-75th percentile range (50% of utilities are located within the inner box) and the 10th to 90th percentile range (80% of communities are located within the outer box).

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Table 2. Median poverty prevalence, incomes, bills, and the pervasiveness of unaffordability for communities in each region. State median values are found in Table B in S1 Text.

Region	State Poverty Prevalence (%)	Community Poverty Prevalence (%)	Community Annual Median Household Income ($)	Community Annual Low-Income ($)	Median Total Monthly Bill ($)	Pervasiveness of Unaffordability (%)
Pacific Northwest	26.2	25.2	71,300	35,600	95	15.9
Great Plains	27.5	26.8	62,000	30,100	68	13.0
Southwest	29.0	29.3	78,900	40,800	79	11.2
Mid-South	31.6	32.8	61,900	31,900	72	12.0
Southeast	33.4	32.2	58,800	28,700	77	17.4
Midwest	28.4	31.2	58,900	29,200	83	16.7
Mid-Atlantic	24.3	24.7	71,300	35,400	96	18.5
Northeast	25.4	28.3	74,900	34,500	87	16.6
All regions	29.1	29.8	65,400	32,400	77	15.3

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As described above, we replicated our analysis for all communities in the Patterson & Doyle [20] database (n = 3,845 systems) with rates collected from 2019 to 2022 from utilities of various sizes. We found that communities with fewer than 10,000 persons (n = 1,967) were significantly more expensive and had a significantly higher pervasiveness of unaffordability (p-value $< = 0.001$) (Table 3) than the larger systems in this study. This suggests that the extent of the unaffordability challenge is greater for the individuals served by smaller systems.

The Income Dedicated to Water Services (IDWS) metric quantifies the pervasiveness of unaffordability at different levels of financial burden (Fig 3A). This study focuses on a financial burden of 4.6%; however, if a financial burden of 2% was considered, more than 1 in 3 households struggle with affordability (ranging from 33% in the Great Plains to 44% in the Southeast). Alternatively, if costs are considered unaffordable at 7% of income, then fewer than 1 in 10 households experience unaffordable water services (6.6% in the Southwest to 10.7% in the Mid-Atlantic). The importance of the financial burden considered to be affordable decreases after 1.5 to 2 days of labor (~7% to 9.2% of income, shown by the tapering of the IDWS curve as the percent of income increases), with smaller incremental changes in the pervasiveness of unaffordability as the threshold increases.

Regionally, the percent of households within a community earning less than 200% of the federal poverty level ranges from 25% to 33%, with higher poverty in southern states (Table 2). Household incomes are higher in the Southwest region than other regions in the U.S., resulting in fewer households with unaffordable water services. The two regions with the most expensive monthly bills (Pacific Northwest and Mid-Atlantic) have populations with similar incomes but different unaffordability experiences. The higher median bill in the Pacific Northwest is driven by a few communities with expensive services (Fig 4), while many communities in the Mid-Atlantic generally have more expensive water services and therefore higher levels of

Table 3. Median bill and pervasiveness of unaffordability based on the size of the community served. Categorization of communities is based on EPA's categories of system size. The table provides statistical differences (p-value $< = 0.01$) in t-tests between systems of different sizes for bills and pervasiveness.

System Size	Persons Served	Number of communities	Median bill at 6,000 gal/mo (22.7m^3/mo)	Median pervasiveness of unaffordability (%)
Very Large	> 100,000	430	84^{medium, small,}$	15.3%^{small}
Large	10,001–100,000	2,155	83^{medium, small}$	13.9%$^{medium, small}$
Medium	3,300–10,000	959	91^{very large, large}$	15.5%$^{large, small}$
Small	500–3,300	1,088	89^{very large, large}$	18.8%$^{very large, large, medium}$

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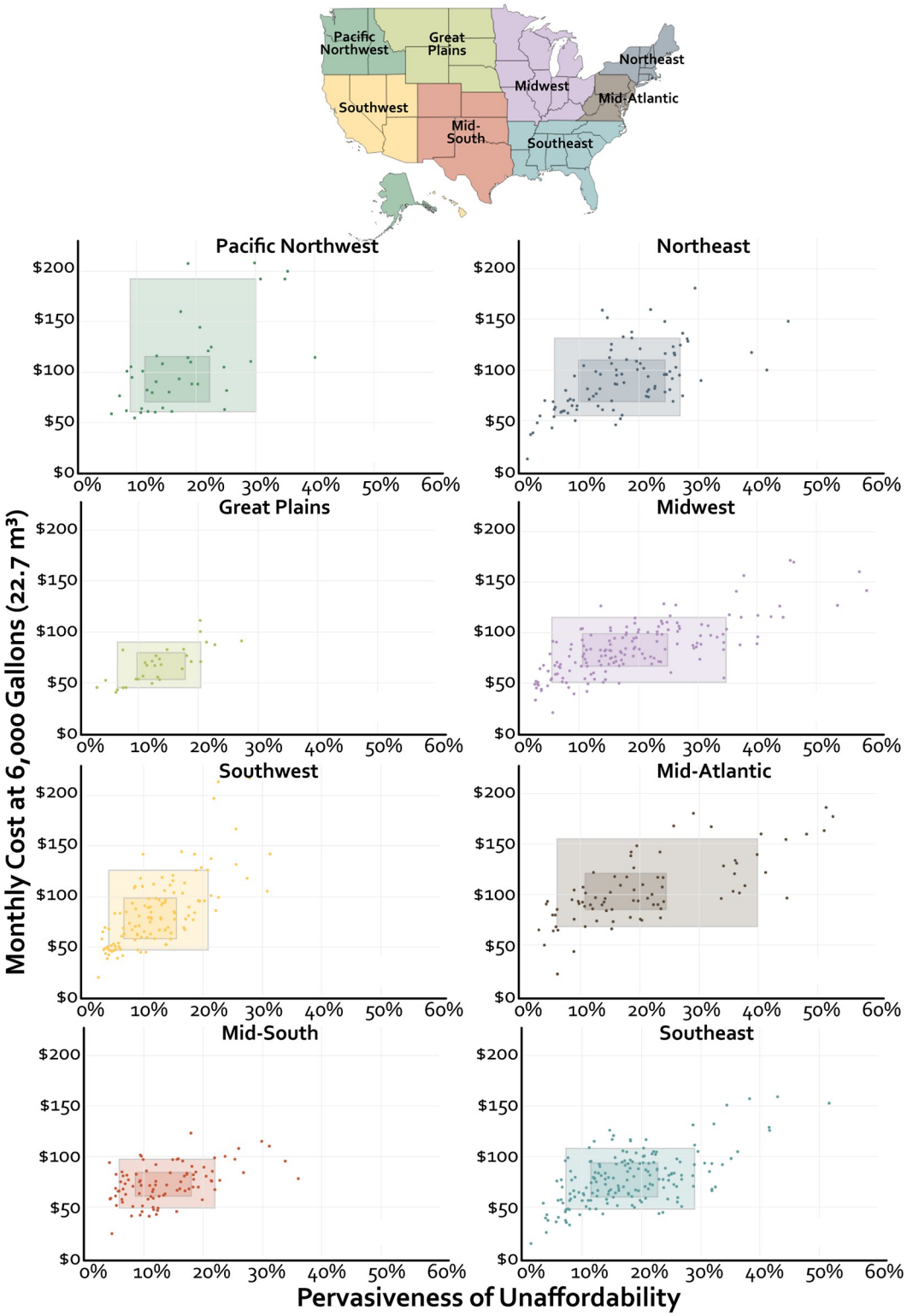

Fig 4. Regional variation in bills and the pervasiveness of unaffordability. The boxes represent the 25-75th percentile range (50% of utilities are located within the inner box) and the 10th to 90th percentile range (80% of communities are located within the outer box). State shapefile is from the U.S. Census Bureau through the tidycensus R package (https://rdrr.io/cran/tidycensus/man/state_laea.html).

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unaffordability. The Southwest, Mid-South, and Great Plains typically have less expensive services and lower pervasiveness of unaffordability compared to eastern regions (Fig 3). The Southeast and Midwest regions have bills comparable to the Southwest region; however, more of the population in the Southeast and Midwest have lower incomes, resulting in higher levels of unaffordability.

Robustness of results for different assumptions

The volume of water needed to meet basic needs also affects water affordability estimates. Both the cost of services and pervasiveness of unaffordability are more sensitive to the volume of water used in the eastern regions of the U.S. than in the western regions. For example, the total cost of water services increases by $4 per unit of water (1,000 gallons (3.8 m^3)) in the Southwest and $8 per unit in the Pacific Northwest and Great Plains, while total water service costs increase by more than $10 per unit in all eastern regions (Fig 5A). The steeper increase in costs with more water usage, combined with the relatively high poverty in these same regions, leads to greater changes in the pervasiveness of unaffordability as water usage increases. The pervasiveness of unaffordability increases with water use at more than twice the rate in eastern regions with an average of 2.7% per 1000 gallons (3.8 m^3) compared with an average of 1.3% in western regions (Fig 5B). By 8,000 gal/mo (30.3 m^3), more than 1 in 5 households in eastern regions are considered unaffordable, with higher concentrations in the Midwest and Mid-Atlantic (Fig 5C).

Discussion

The median (i.e., representative) community has 15.3% of households spending more than one day of labor paying for 6,000 gal/mo (22.7 m^3/mo; Table 2, Fig 3), resulting in an estimated

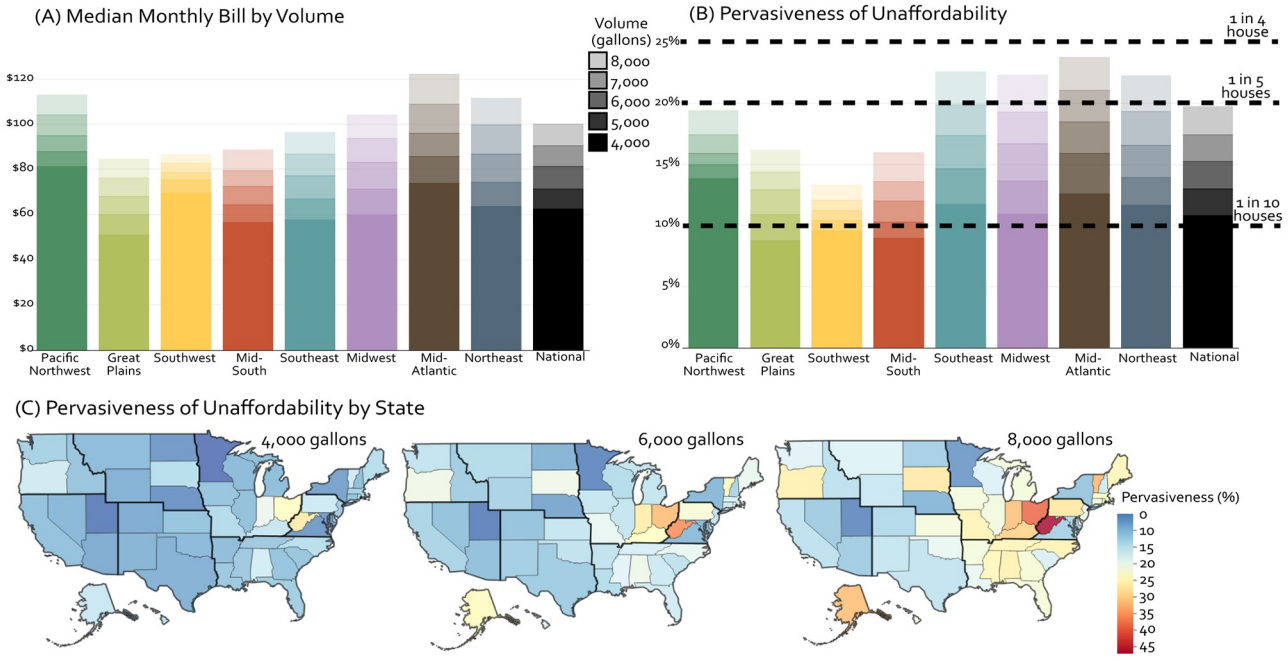

Fig 5. Sensitivity of costs and affordability results to the volume of water considered sufficient for basic needs. (A) Change in median monthly bill by region for different volumes of water usage. (B) Sensitivity of the pervasiveness of unaffordability to changes in the monthly bill (A). (C) State-level pervasiveness of unaffordability at 4,000 gal/mo (15.1 m^3/mo), 6,000 gal/mo (22.7 m^3/mo), and 8,000 gal/mo (30.3 m^3/mo) of usage. State shapefile is from the U.S. Census Bureau.

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Table 4. Recent studies exploring the affordability of water services for different households, including the present study.

Study	Rates Year	Number of Utilities	Scale	Water Use	Metric(s)	Result(s)
[16]	2014	296	National	12,000 gal/mo (45.4 m^3/mo)	• Percent of households with median income < $32,000; the income needed for median bill to represent 4.5% of household income.	• 11.9% of households earn < $32,000 and are likely to spend > 4.5% of their income on water services.
[18]	2019	414	National	6,200 gal/mo (23.5 m^3/mo)	• Percent of disposable income that the 20th quintile household spends on water services	• 12.4% of the disposable income of a 20th quintile income household is spent paying for water services
					• Number of hours a single minimum wage earner must work to pay for water services	• 10.1 hours of minimum wage labor per month
[20]	2019–2021	1,791	CA, NC, PA, TX	-4,000 gal/mo (15.1 m^3/mo)	• Percent of utilities with the median household income spending > one day paying for services	• 1.2% of utilities had median income households spend > one day of labor
				- 4,000 gal/mo (15.1 m^3/mo)	• Percent of utilities with low-income households spending > one day paying for services	• 65.8% of utilities had low-income households spend > one day of labor
				-4,000 gal/mo (15.1 m^3/mo)	• Number of hours a single minimum wage earner must work to pay for water services	• 10 hours of minimum wage labor per month
				-2,000–12,000 gal/mo (7.6–45.4 m^3/mo)	• Percent of households spending > 5% of income paying for water services	• 12% (at 2,000 gal/mo) to 35% (at 12,000 gallons) of households spend > one day of labor
[21]	2019	594	NJ	Variable; 40 gal/person/ day (0.2 m^3)	Households spending > 10% of disposable income on water services	• 20.6% of households spend > 10% of disposable income on water services
This study	2021	787	National	6,000 gal/mo (22.7 m^3/mo)	Households spending > one day of labor paying for services	• 15.3% of households in the median utility spend > one day of labor

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28 million persons experiencing water service unaffordability across all communities in this study. The approach we take here differs from previous studies (Table 4) which have focused on the financial hardship (percent of income) experienced by specific financial subsets of the community (e.g. median household income, 20th percentile household income, and minimum wage earners) [16–19]. Our study specifically explores the breadth of affordability challenges across households of all incomes using spatially explicit data (service area of the drinking water provider rather than aggregated to the county level) [20, 29].

We evaluated the robustness of household affordability estimates by using a range of definitions of undue hardship and varying the volume of water needed to meet basic needs. We explored definitions of undue hardship from 4% to 10% of income. This range is based on recommendations for the residential indicator used in EPA's financial capability assessments [6–7, 33], which include metrics for assessing the level of financial impact on households resulting from rate increases needed to make infrastructure investments to address regulatory concerns. The population categorized as experiencing unaffordability with a definition of hardship at 4% of income was 2.7 times greater than when defining hardship as 10% of income.

To assess the robustness of household affordability estimates relative to water usage volume, the pervasiveness of unaffordability was estimated at a range of "reasonable" volumes of water to meet basic household needs (4,000 to 8,000 gal/mo or 15.1 to 30.3 m^3/mo). The number of persons categorized as experiencing unaffordable services was 1.7 times greater at 8,000 gal/mo (30.3 m^3/mo) than at 4,000 gal/mo (15.1 m^3/mo). In all, our results from a sample representing half of the population in the U.S. suggest that between 8.7 million to 41.9 million persons within the communities in this study experience unaffordable water services (Table 5). These estimates are solely for households within the communities in this study and does not

Table 5. Sensitivity of affordability to the volume of water and definition of undue hardship. Estimated persons (in millions) with unaffordable water services at different volumes of water and levels of financial burden. Shading represents the selection used in this study.

		Volume of water to meet basic needs				
		4,000 gallons (15.1 m^3)	5,000 gallons (18.9 m^3)	6,000 gallons (22.7 m^3)	7,000 gallons (26.5 m^3)	8,000 gallons (30.3 m^3)
Income dedicated to water services becomes an undue hardship at:	4% of income (0.9 days of labor)	24.3	28.6	33.0	37.4	41.9
	4.6% of income (1 day of labor)	20.8	24.6	28.3	32.3	36.2
	5% of income (1.1 days of labor)	19.0	22.4	25.9	29.5	33.1
	7% of income (1.5 days of labor)	13.0	15.4	17.9	20.4	23.0
	10% of incomes (2.2 days of labor)	8.7	10.3	12.0	13.7	15.5

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extrapolate to account for individuals who experience unaffordable water services in communities that were not included in this study.

We found household water affordability challenges in all utilities, states, and regions of the U.S. In every community, there are households with unaffordable water services even when using the most conservative definitions of undue hardship and volumes of water usage. While unaffordable water services are not geographically limited to specific states or regions (Fig 4C), there are regional concentrations of unaffordability challenges in eastern regions, particularly within West Virginia, Ohio, and Indiana (Fig 5). Moreover, eastern regions also experience faster increases in the costs of water services as water use increases than do regions in the western US (Fig 4B), despite greater water scarcity in the western U.S.

Robustness and limitations

This analysis represents the rates of single-family residential homes and may not be representative of the rates that renters experience (e.g., some utilities use multi-family or commercial rates for apartments), which requires a level of data not readily available and beyond the scope of this project. For practical purposes and consistency, this study prioritizes exploring an analysis of rates data for the same year (2022) for the largest communities in each state and does not include smaller systems (i.e., those serving fewer than 10,000 persons). In the replicated analysis using the database from Patterson & Doyle [20], we found that Small and Medium systems (Table 3) have higher costs (~$6 more per month) than Large and Very Large systems. Small systems have a higher pervasiveness of unaffordability compared to other system sizes (2.4 to 4.3% more households) (Table 3). In short, the results from this study, based on Large and Very Large systems, are conservative. If data were included for smaller systems, the proportion of households with water affordability challenges would likely increase rather than decrease. Additionally, our analysis does not account for households that provide their own services through wells, septic systems, water hauling, etc. which account for 5 to 13% of the population [23, 25], of which between 1.1 million [34] and 2 million [3] persons do not have access to centralized or domestic water services. Households without access to water services are not necessarily rural, with nearly half located in the 50 largest metropolitan areas of the U. S. [34], all of which had communities included in this study.

Policy implications

Anecdotally and empirically, many households have difficulty paying for water services; however, the means for ensuring affordable water services are less clear. The water services sector is plagued by systemic challenges, many of which are beyond to the ability of a utility to address on their own. Drivers of unaffordable water services include low household incomes, increased regulatory costs, increased energy costs, aging infrastructure, population loss, climate change, and the rising costs of capital associated with finance [10, 35]. These are broad, systemic challenges, suggesting that unaffordable household water services (along with water quality violations that are more prone to occur when infrastructure investments are deferred) are a symptom of more far-reaching, underlying drivers affecting water service providers [35–38]. While it is crucial to create a safety net for households that are unable to pay their water bills in the short-term, such as utility customer assistance programs or the recent federal Low-Income Household Water Assistance Program (LIHWAP; https://www.acf.hhs.gov/ocs/programs/lihwap), these programs only address the symptoms of the challenge–that costs are too high for some residential incomes. Addressing the drivers of high costs, as well as income disparities that underlie poverty and drive water affordability challenges, will require approaches that incorporate finance, governance, equity, and span from the local to the state and federal scale [15].

Addressing water system shortfalls at the state and federal scale is not new in the U.S. Fifty years ago, a nationwide study by the US Public Health Service (USPHS) found that 41% of public water systems surveyed did not meet drinking water quality guidelines. This affected 2.5 million people (14% of their study population) with 360,000 persons receiving drinking water from a potentially dangerous water supply [39–41]. The USPHS study was the "first real attempt to determine, on a nationwide basis, the efficacy of current practices in water treatment and to assess future prospects for maintaining safe, high quality drinking water" [39, pg ii]. Further, the USPHS concluded that while most people were receiving safe water, several million persons were reliant on contaminated water, revealing a need to give focused attention to the broad problems of water supply, beyond the scale of individual utilities, to ensure drinking water is safe for consumption [39]. This 1970 report provided the impetus and the groundwork for nationwide drinking water regulation, which was realized in the 1974 Safe Drinking Water Act. Similar reports were the impetus for the 1972 Clean Water Act [42]. The breadth of exposure to unaffordable water services we documented (17% of households in the study or 28.3 million persons) is comparable to the breadth of exposure to unsafe drinking water half a century ago (14% of households in their study [39]).

Similarly, and more recently, researchers sought to understand the extent of lead service lines in water systems after acute crises in Flint, MI drew national attention. A 2016 study estimated 6.1 to 10.2 million lead service lines existed across the U.S. [43]. Legislators considered this scale of potential impact to be prevalent enough to justify updating the Lead and Copper Rule and to dedicate financial resources through the 2021 Infrastructure Investment and Jobs Act [44]. Contaminated drinking water and lead service lines have direct public health impacts, as can unaffordable water services if the inability to pay for water services results in loss of access through shut-offs.

While the majority of households in the U.S. have clean water and can afford the costs of basic water services, millions do not. Similar to the context for drinking water a half-century ago, or for lead service lines over the past decade, challenges to affording water services is experienced by many households in communities across the U.S. Further, the drivers of unaffordable water services extend beyond the boundaries and control of the individual utilities providing water services since the financial health of water service providers is tied to the

financial health of the customers they serve [10]. If the breadth of unsafe drinking water led to the 1974 Safe Drinking Water Act and the breadth of lead service line exposure led to more stringent regulations and prioritization in the 2021 Infrastructure Investment and Jobs Act, perhaps a national strategy for water affordability is also warranted [15].

Supporting information

S1 Text. Text contains two tables providing state-level descriptions of Table 1 (Table A in S1 Text) and Table 2 (Table B in S1 Text).
(DOCX)

S1 Data. Anonymized dataset of utilities used to create Figs 3–5.
(CSV)

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