Exploring the Affordability of Water Services within and across Utilities

Abstract

The cost of water services in the United States is increasing along with water affordability challenges. We developed an open approach that calculates five affordability metrics at multiple volumes of water usage (from 0 to 16,000 gallons per month) using rates data from 2020 at the scale of census block groups and service areas. We applied this approach to 1,791 utilities in four states. We found 77% of utilities had more than 20% of their population below 200% of the federal poverty level, suggesting widespread poverty is a major contributor to affordability challenges. Depending on how much water a household uses, our results suggest a tenth to a third of households are working more than a day each month to afford their water bills. We developed an interactive visualization tool to bring greater transparency to water affordability (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard) that can be expanded to further increasing our understanding of water affordability.

Research Impact Statement

Developing an open approach to quantify and visualize water affordability provides insight on the scope and drivers of affordability.

INTRODUCTION

In 2017, nearly 29% of the world's population did not have safe, reliable drinking water and 46% did not have access to safely managed sanitation (UNICEF & WH, 2019). The United Nation's 6th Sustainable Development Goal is for all people to have access to safe and affordable drinking water by 2030 (United Nations 2018). One component of being able to access water services is the ability for households to afford the costs of those services. In the United States (U.S.), the focus of this study, 1.4 million persons did not have access to water services in 2014, of which many were located in low-income regions (Dig Deep & US Water Alliance 2019). Indeed, the lack of access to water services in the U.S. is more likely due to affordability challenges than physical infrastructure as more than 1.5 million households in 12 large utilities owed $1.1 billion in past-due water bills (Walton 2020). In many states and localities, shutoffs are used to remove these households from access to water services until those bills are paid, thus directly linking affordability to access (Dig Deep & US Water Alliance 2019; Walton 2020).

Water affordability and access challenges are increasing in the U.S. as the cost for providing water services is becoming more expensive for both water service providers (hereafter "utilities") and their customers (Teodoro & Saywitz 2019; Beecher 2020; Colton 2020; Goddard *et al.* 2021; Payne Forthcoming). Initially, the federal government subsidized a portion of the modern water service infrastructure through grants and low interest funding. As the federal government has decreased funding, utilities have become primarily responsible for financing water service infrastructure as well as operations (US Water Alliance 2017; Tomer *et al.* 2019; Greer 2020). Most utilities generate revenue by charging customers for water services and/or establishing taxes (if the utility has taxing authority). Thus, the financial capability of a utility is a function of the number of customers and those customers' financial health. That is, the ability to finance local water utilities has become more dependent on the financial characteristics of the local community (Spearing *et al.* 2020).

In recent decades, water utilities have increased the cost of services faster than inflation to cover rising operational costs in addition to infrastructure repair and replacement costs (Beecher 2020; Greer 2020). Households with moderate or high incomes can typically afford to pay for water services as rates increase; however, low-income households may struggle to pay bills as costs rise. At the utility scale, utilities serving a higher portion of low-income households will have greater difficulty generating sufficient revenues through their customer base without creating undue hardship. Teodoro & Saywitz (2019), for instance, have shown that households with incomes in the lowest 20th percentile are already spending an average of 16.5% of their disposable income (income remaining after paying for other essential services like housing, energy, and food) on water services, and that minimum wage earners must work 10 hours per month to pay for water services. Additional increases in water rates may require households to make tradeoffs with other basic living expenses (e.g., rent, electricity, food). Increasing water rates, coupled with the growing geographic economic disparity in household income and wealth in the U.S. (Horowitz *et al* 2020), lead to commensurate disparities in the fiscal health of local utilities (Smull *et al.* Forthcoming). Utilities serving declining or struggling communities may also need to make tradeoffs based on what they can afford: servicing debt, ensuring updated infrastructure and service quality, or maintaining affordable rates (Doyle *et al*. 2020).

The financial capability of a community refers to the ability for a community (commercial, industry, institutions, and households) to pay for their water utility(ies) costs in terms of infrastructure, operations, maintenance, and financing (e.g., debt service). In the U.S., large federal subsidies were provided in the 1970s and early 1980s to cover the financing and infrastructure costs needed for utilities to adopt the treatment technology required to comply with new regulatory requirements (e.g., Clean Water Act (1972) and the Safe Drinking Water Act (1974)) (CBO 2018). The subsidies were designed to be temporary, with local utilities growing their financial capability to cover not only operations and maintenance, but also infrastructure and debt. However, the cost remained prohibitive to many local utilities so the federal government transitioned funding from grants to loans, with the federal contribution steadily diminishing, but not ceasing (Copeland 2019). By 2017, state and local governments were responsible for 96% of water utility financing (CBO 2018; Copeland 2019; Greer 2020), and as local communities have moved towards paying full costs, the costs have been ultimately transferred onto their customers, exacerbating household affordability challenges.

Household affordability refers to the ability for a household to pay for the basic water services needed for drinking, cooking, cleaning, and sanitation without undue hardship. Household affordability has become more tenuous as the costs of providing water services have increased at about 5% annually in recent decades (4.7% for 1996 – 2016 (Bunch *et al.* 2017); 5.1% from 2014 – 2018 (AWWA 2019a)). In contrast, the median household income, adjusted for inflation increased at a much slower annual rate (0.44% from 1996-2016 and 2.72% from 2014-2018, https://fred.stlouisfed.org/series/MEHOINUSA672N). The slower increase in income compared to water bills raises deep concerns for the ability of low-income, fixed income, or other economically disadvantaged groups to afford basic water services. While there may be a willingness to pay more to maintain and ensure access to water, the ability of many households to do so may be limited (Baird 2010; Mack & Wrase 2017). Detroit, MI provides a stark example, where nearly 40% of the population lives below federal poverty threshold, yet water rates increased by over 400% since 2000 (Lakhani 2020).

Affordability metrics

A plethora of metrics has been developed to assess the financial capability of the community and household affordability (e.g. Davis & Teodoro 2014; Teodoro 2018; Raucher *et al.* 2019). The earliest metric – which has been co-opted as an affordability metric (although never it's intended design) – was developed by the U.S. Environmental Protection Agency (EPA) in the mid-1980's. This metric sought to determine whether a utility under consent decree had the financial capability to pay for the proposed solution, part of which included the financial impact to households if the utility raised rates to pay for the solution (EPA 1984). In other words, are the rates affordable for a representative income in the community (e.g. median or low-income households)? EPA considered the solution affordable if the proposed rate increase resulted in average household water bills (combined drinking water and wastewater) being less than 4.5% of the median household income (MHI). Importantly, this metric was designed to be used as one of several indicators to determine the utility financial capability, recognizing the added financial burden on households. However, this metric has often been conflated with (and improperly used in isolation as an indicator of) household affordability.

Recently, the use of MHI has received considerable scrutiny, in part because it does not capture impacts on low-income residents, who are most sensitive to water affordability challenges (Mack & Wrase 2017; Teodoro 2018; Teodoro & Saywitz 2019; Raucher *et al.* 2019). To better quantify affordability for low-income households, a growing number of metrics are based on the 20th percentile income (i.e., low-income) instead of the median income (Teodoro 2018; Raucher *et al.* 2019). For instance, the recently proposed Household Burden indicator (Raucher *et al*. 2019) uses the portion of income needed to pay a water bill based on the 20th percentile income. However, these metrics are not strictly looking at household affordability as much as whether the rates are affordable for a representative low-income household in a community.

There are metrics focused solely on the financial capability of the community. For example, the Poverty Prevalence indicator, which quantifies the percent of the community below 200% of the federal poverty level (FPL). By setting aside the costs of water services, the Poverty Prevalence indicator emphasizes only the potential financial capability of the community. Alternatively, there are metrics focused solely on household affordability, such as Minimum Wage Hours (Teodoro 2018), which assesses the number of hours needed at minimum wage to pay for water services, setting aside the composition of household incomes in the community.

While there are studies that develop and compare affordability metrics (Teodoro 2018; Van Abs & Evans 2018; Teodoro & Saywitz 2019; Raucher *et al.* 2019), these studies aggregate results across many utilities and do not allow for exploration of nuances among or within individual utilities. Further, no metric is perfect; they each provide different insights into overall water affordability, and in combination, provide a potentially more holistic perspective.

Objectives

We developed a systematic approach that enables the exploration of multiple affordability metrics within and across utilities. This work has three main contributions beyond the results provided in this paper. First, our approach allows for a granular exploration of affordability across a large number of utilities in an open and transparent way that is repeatable and expands the work done in previous studies. Second, we developed an additional metric to understand the distribution of affordability challenges within a utility – the Income Dedicated to Water Service. This is the first metric we are aware of that assesses how many households share a similar affordability burden; thereby showing both the prevalence of affordability challenges (how many households) at a particular level of hardship (percent of income going to water services). Third, the rates data and code to replicate this analysis are open and accessible to expand water affordability research.

We applied this approach to 1,791 utilities located in four states – California (CA), North Carolina (NC), Pennsylvania (PA), and Texas (TX). Our analysis combined census, utility service area boundary, and rates (drinking water, wastewater, and stormwater) data to calculate multiple affordability metrics at different volumes of water usage. We chose these four states because they had water service area boundaries (a key data requirement) and represented a wide variety of climates, populations, and utilities.

We also created an interactive data visualization tool to enable greater transparency as it allows users to examine how affordability changes within and across utility service areas at different volumes of water use (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard). Finally, we summarize results. Some results are presented using previously recommended thresholds to provide context to frame the conversation. We fully recognize that thresholds are fraught with challenges, as they can be interpreted as fixed boundaries rather than general guidelines for interpretations. However, they also provide useful classifications for communication and guidance as to when metrics may indicate affordability challenges. When possible, we simply used the number of days of labor required to pay for services with more days of labor indicating greater affordability challenges.

Our approach relies on publicly available data and open-source software; thus, allowing the analysis to be continually updated and applied to more utilities as data become available. However, while the rates data were public, they required substantial efforts to collect and curate. All scripts use open source software (Rcran and Javascript) to enable transfer of this method to other locations that have service area boundaries and rates data.

MATERIALS AND METHODS

Data

The affordability analysis requires three types of data: (1) service area boundaries, (2) water service rates (drinking, wastewater, and stormwater), and (3) census data.

Service area boundaries.

In this study, we selected and obtained water service area boundaries for four states: California (https://data.ca.gov/dataset/drinking-water-water-system-service-area-boundaries), North Carolina (https://aboutus.internetofwater.dev/layers/aboutus_data:geonode:PWS_NC_20190), Pennsylvania (http://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=1090), and Texas (https://www3.twdb.texas.gov/apps/WaterServiceBoundaries). California uses digital service area boundaries to build multi-utility scoping projects around mutual aid agreements and regionalization (CASWRCB 2020). In Pennsylvania, the State Water Plan requires service area boundaries to determine non-public water supply areas and assess the population served (PADEP 2009). Similarly, the Texas Water Development Board created a statewide public water system service area mapping application to update utility boundaries to inform regional and state water planning, particularly projecting population and water demand, as well as to estimate populations not served by public water systems (TWDB 2020). North Carolina's water supply boundaries were updated in 2019 by a team of students at Duke University to aid the state in local water supply planning and emergency response to drought. States have different processes for creating and maintaining boundaries and different levels of accuracy. We relied on the available spatial boundaries from these four sources and did not adjust or correct perceived spatial boundary inaccuracies. We could not locate any statewide wastewater or stormwater service area boundaries when those services were separated from drinking water utilities (see below).

Rates data.

There is not a publicly available dataset for water service rates, although there are groups regularly collecting rates data from utilities through surveys (e.g. https://efc.sog.unc.edu/utility-financial-sustainability-and-rates-dashboards and https://github.com/California-Data-Collaborative/Open-Water-Rate-Specification). However, the underlying raw data is not available (only calculated bill estimates). Adding to this challenge, there is large diversity in rate structures as each utility is trying to balance several goals including cost recovery, revenue stability, conservation, regulatory compliance, equity across customer classes, and administrative simplicity (Beecher 2020). Differences in priorities and state regulations have led to a plethora of rate structures. For example, some utilities have a single, uniform rate structure for all customers, while others provide different rates based on meter size or customer class (e.g., residential, commercial, industrial). In addition, some utilities have varying water rates based on location within the service area (e.g., inside or outside of a municipal boundary, distribution type, and elevation zones). California had particularly complex rates, with some utilities creating customized water budgets based on previous winter use and property characteristics. All of these variations make it challenging to develop a standardized rates database.

We collected rates data through online searches, prioritizing locating rates on the official website of a utility. We created a standardized spreadsheet for data entry. Rate structures often consisted of several components: service charges (a fixed or constant amount charged each month, hereafter referred to as “fixed charge”), commodity charges (amount varies based on usage or household size, hereafter referred to as “usage charge”), and surcharges (extra charges added to the bill, often to cover particular costs associated with debt, capital expenses, or consent decrees). When we were unable to locate rates online, we included the utility in our metadata and placed “not found” in the column listing the website source. However, without rates data for both drinking water and wastewater services, these utilities are not included in the dashboard or analysis.

Importantly, the rates database does not capture customer assistance programs (CAPs) designed to make water more affordable for low-income customers. An estimated 31% to 37% of utilities offer any type of CAPs (EPA 2016; AWWA 2019b; Vedachalam & Dobkin 2021). Furthermore, few utilities report CAPs rates and most require individuals to opt-in (i.e. low-income households or senior citizens are not automatically enrolled), resulting in less than 10 to 15% of eligible households benefiting from these programs (Vedachalam & Dobkin 2021). Thus, it is not possible to discern the scale of CAPs within a utility, precluding our ability to incorporate these programs into a generalizable analysis and approach. While households benefiting from CAPs will receive some financial relief, no affordability metrics currently account for CAPs. The data would need to be collected and future research undertaken to understand how CAPs influence affordability.

Census data.

The spatial location of census tracts and block groups came from the U.S. Census Bureau. The historic population (1990, 2000, 2010) and income (2000) data came from University of Minnesota's IPUMS National Historical GIS data (Manson *et al.* 2020), where the data are standardized across block groups over time. The population, household, income, and poverty prevalence of census tracts and block groups were obtained from the Census Bureau's 5-year ACS survey (2014-2019). Block groups were the finest spatial resolution available to estimate household income affordability, including total population (B01001_001), total households (B19001_001), median household income (B19013_001), and the number of households at each income bracket (B19001 group).

Census tract data for calculating poverty prevalence included the number of households surveyed (S0101_C01_001) that were below the 200% federal poverty level (S1701_C01_042). The only affordability metric reliant on census tract data was poverty prevalence. Since block groups fit within tracts, we applied the same poverty prevalence to all block groups within a tract. Census data were used to quantify population trends, age, race, income, unemployment, and building age within each service area (included in the online visualization, but not analyzed further here).

Utilities included in this study.

For this study, we obtained rates data for 1,957 utilities, of which 1,825 had both drinking water and wastewater rates. There were 34 utilities had missing service area boundaries, resulting in 1,791 utilities where we could identify both water and wastewater rates within the service area (Table 1). We identified stormwater rates for 195 utilities (10.8%). The population of utilities in this study ranged from 25 (Harris County Municipal Utility District, TX) to over 4 million (Los Angeles Department of Power and Water, CA). The utilities in our dataset served between 65% (Texas) and 92% (California) of each state's total population. Overall, 44% of the utilities in our study are large or very large (serving over 10,000 persons), 25% are medium (serving 3,301 to 10,000 persons), and 32% are small or very small (serving 3,000 or less persons).

Table 1. Description of utilities included in the study and the percent of state population covered. The total number of utilities is based on EPA Safe Drinking Water Information System data (https://www.epa.gov/enviro/sdwis-model). California and Texas do not include many very small, small, or medium utilities at this time.

State	Number of Utilities in Study	Number of Utilities in State	Percent of Utilities in Study	Median Population of Utilities	Population Served by Utilities (millions)	Portion of State(s) Population Represented by Utilities (%)
California	634	2,871	22.1	15,898	36.2	91.6
North Carolina	415	1,962	21.2	3,656	7.1	67.7
Pennsylvania	330	1,883	17.5	8,263	9.8	76.6
Texas	412	4,616	8.9	5,468	18.8	64.8
All Data	**1,791**	**11,332**	**8.4**	**9,300**	**71.9**	**78.3**

Analytical approach

Affordability metrics strive to answer two questions (1) what is enough water and (2) what constitutes undue financial hardship (Teodoro 2018; Raucher *et al.* 2019; Goddard *et al.* 2021)? The typical amount of water considered "enough" for indoor domestic water use in the U.S. is often set at 50 gallons per person per day (Bowne *et al.* 1994; Teodoro & Saywitz 2019; Raucher *et al.* 2019). However, the amount of water used (and billed) varies based on household size, age of household, whether appliances are low-flow, irrigation needs, and so on. Previous studies of water affordability used different volumes of monthly water consumption such as 5,000 gallons per month (gpm) (Van Abs & Evans 2018), 6,200 gpm (Teodoro & Saywitz 2019), and 12,000 gpm (Mack & Wrase 2017). A recent joint report of several water utility organizations (Raucher *et al.* 2019) recommended assuming 2.65 persons per household at 50 gallons per person per day, resulting in an average use of 4,030 gpm. However, the average per capita water use in the U.S. is 82 gallons (https://www.epa.gov/watersense/statistics-and-facts), which is considerably more than other countries. Even the 50 gallon recommendation is at the upper end of the optimal amount considered necessary to ensure public health (26.4 to 52.8 gallons per person per day) (WHO 2017 Table 5.1). Rather than selecting a single volume, we calculated bills and affordability metrics for no water use to 16,000 gpm at increments of 1,000 gpm. This allows users to select the volume of water most representative of their residential community (including household size) and to assess the sensitivity of affordability metrics to water usage.

The definition of undue financial hardship is often described in terms of the acceptable share of a household's income dedicated to water services. Most affordability metrics provide some guidance as to what constitutes undue hardship. Here, we do not subscribe to a recommended threshold but provide context by referring to how many days of labor were required to pay for water services (a day of labor is equivalent to 4.6% of monthly income). This concept is intuitive with the basic understanding that more time spent paying for water services suggests greater affordability challenges.

Estimating monthly household bills.

Household bills were quantified as the sum of fixed charges, usage charges, and surcharges. Bills also could vary by location, as there were many instances when utilities charged different rates to different regions within their service area, often based on distribution type (pump or gravity), location (closer or farther away), elevation, or the consolidation of new systems with specific debt service or capital expenditure needs. In NC, 76% of water and wastewater utilities in this study charged residential customers different rates depending on if a customer was located inside or outside of a utility's political jurisdiction or municipal boundaries (EFC & NCLM 2018). These geographically variable rates are often referred to as “inside” or “outside” rates, with inside rates being typically lower than outside rates.

Inside and outside rates were common for utilities in our study, and when present, often resulted in very different bills. For example, in North Carolina the median outside bill was 72% higher than the inside bill, ranging from as little as 0.4% higher to as much as 272% higher. Both Texas (161 utilities) and California (54 utilities) also had utilities with inside and outside rates, but the difference in bills was smaller than in North Carolina. In Texas, the median outside bill was 29% higher, while in California the median outside bill was 9% higher.

Since inside and outside rates resulted in very different bills and were relevant for 29% of our utilities, we estimated which households were billed these rates by intersecting current municipal boundaries with service area boundaries. Households located within the municipal boundary were assigned inside rates, while households outside of the municipal boundary (but inside the service area) were assigned outside rates. For example, Greensboro, NC provides water to those living inside the Greensboro municipal limits as well as outlying areas (Fig 1). Those living inside city limits were assigned inside monthly rates, which has an estimated monthly bill of $46 for 4,000 gpm of use, while those living outside of the city were assigned outside rates (with an estimated monthly bill of $110 for 4,000 gpm). Assuming that current municipal boundaries reflect inside and outside charges is an assumption made in lieu of spatially defined rate zones from utilities. For utilities with inside and outside rates, and where there were known stormwater services, stormwater rates were only applied inside the municipal boundary because stormwater services are often provided by municipalities and not water utilities.

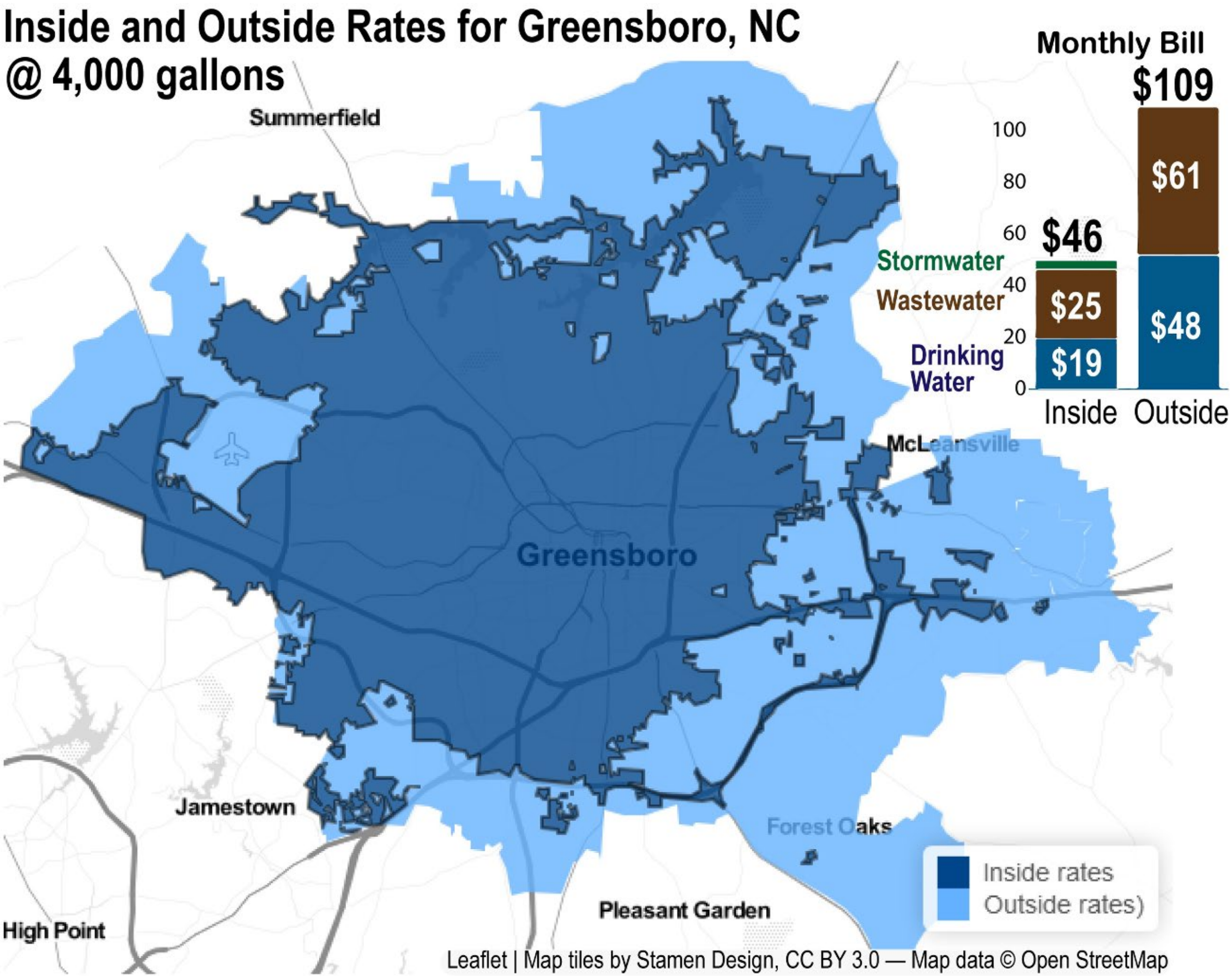


Fig 1. **Inside-Outside Rates**. Inside (municipality) and outside (service area outside of the municipality) for Greensboro, NC with the associated inside and outside rates resulting in different monthly bills (inset graph on right).

Wastewater services may be provided by the same entity as drinking water; however, Pennsylvania and California often had separate authorities providing drinking water and wastewater. When multiple wastewater providers served customers in the service area of a drinking water utility, we calculated the mean of wastewater bills, and applied that bill to all customers within the drinking water service area.

For example, the North Penn Water Authority (Fig 2) provided drinking water services to all or portions of 10 municipalities; yet each municipality had its own wastewater utility with rates ranging from as low as $20 per month in Lansdale to as much as $58 per month in Soulderton at 4,000 gpm. No wastewater rates were identified for two townships. In these instances, given missing data and lack of spatial wastewater service areas, we calculated the mean wastewater bills within the drinking water utility service. Additionally, some utilities charge different rates for different portions of the service area, requiring us to calculate a mean drinking water bill. For example, the North Penn Water Authority charges different drinking water rates in its service area, with Sellersville having lower rates. We took the sum of the mean drinking water bill and mean wastewater bill to estimate a total bill of $65 that was applied throughout North Penn Water Authority (Fig 2).

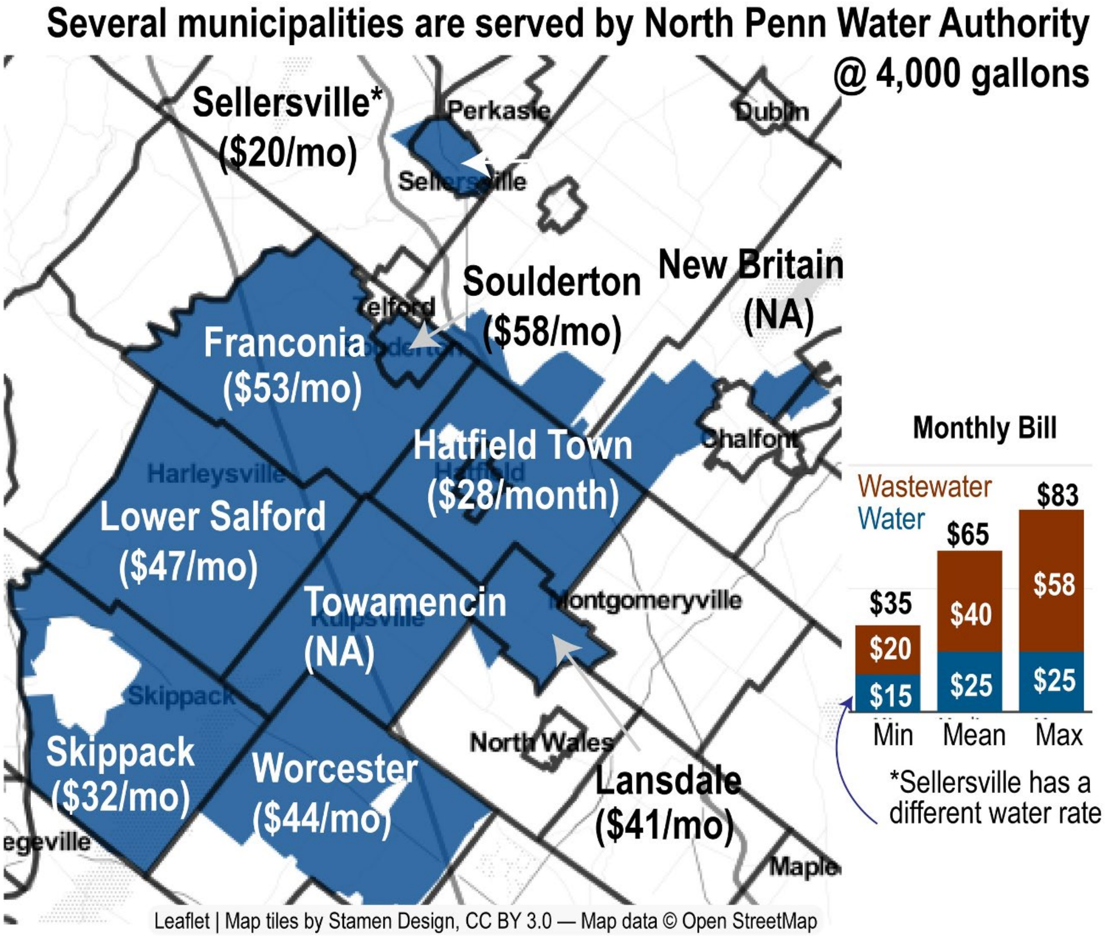


Fig 2. Averaging bills within a service area. The North Penn Water Authority (blue) intersects 10 municipalities, many of which provide their own wastewater services. We calculated the bill for each township and took the mean to get a single estimated bill that we applied across the service area of the drinking water utility; however, there is a wide range in estimated bills depending on location.

Different spatial boundaries and inside/outside rates were present for hundreds of utilities in our study, but were generally sufficiently consistent for us to use systematic approaches to standardize rates for analysis. However, a few complex rate structures required additional assumptions (see S1 File).

Calculating affordability metrics for block groups.

We calculated a set of affordability metrics across the hundreds of utilities studied here and could be generated for utilities nationwide (Table 2) using broadly available public data (i.e., service area boundaries, census data, rates). Specifically, we calculated:

- **Traditional**: measures the financial capability of the community by assessing the portion of income spent on water services for the community's median household income (MHI, 50th percentile of household incomes in the utility) (EPA 1995; EPA 1997).
- **Household Burden (HB)**: measures the financial capability of the community by assessing the portion of income spent on water services for the community's lowest quintile income (LQI; 20th percentile of household incomes in the utility). This metric reflects the financial burden of relatively low-income households in the utility (Raucher *et al.* 2019). The LQI was estimated by randomly generating incomes for the number of households present within each income bracket (i.e., if there were 50 households in the $20,000 to $25,000 income bracket then we generated 50 random incomes within that range) and then calculate the LQI of the randomly generated incomes of all brackets. Previous work has shown this approach to be robust and comparable to assuming all households earn the median income of each bracket (Cardoso & Wichman 2020).

- **Poverty Prevalence (PP)**: portion of households within a service area at or below 200% of the federal poverty level (note that this metric is purely derived from census data and does not consider the costs of providing water services) (Raucher *et al.* 2019).
- **Minimum Wage Hours**: number of hours worked at minimum wage needed to pay for water services (Teodoro 2018). North Carolina, Pennsylvania, and Texas adopted the federal minimum wage ($7.25, which was set in 2009), while California had a higher minimum wage of $12.00 set in 2019. Local governments may provide for a higher minimum wage that is not captured here and may significantly change the results of this metric.

While there are other metrics that could be calculated (e.g., the Weighted Average Residential Index and the Affordability Ratio), they require greater granularity of data, such as actual household bills or disposable income, that are difficult to obtain across a large number of utilities, particularly smaller utilities (Davis & Teodoro 2014; Raucher *et al.* 2019).

Table 1: Metrics considered in this study (HH is households). The IDWS, a new metric, is described in detail below.

Metric	Description	Formula	What it measures
Poverty Prevalence (PP)	Percent of households below 200% of FPL	$\frac{HH\ Surveyed\ below\ 200\%\ FPL}{HH\ Surveyed}$	Community Financial Capability
Traditional	Percent of median household income paying for water services	$\frac{Annual\ HH\ Bill\ (\$)}{Median\ HH\ Income\ (\$)}$	Community Financial Capability
Household Burden (HB)	Percent of 20th percentile household income paying for water services	$\frac{Annual\ HH\ Bill\ (\$)}{Lowest\ Quintile\ HH\ Income\ (\$)}$	Community Financial Capability
Minimum Wage Hours	Number of hours worked at minimum wage paying for water services	$\frac{HH\ Bill\ (\$)}{Minimum\ Wage\ (\frac{\$}{hr})}$	Household Affordability
Income Dedicated to Water Services (IDWS)	Percent of households in a utility spending x% of income on water services	$\frac{\sum(HH\ with\ Income < \frac{HH\ Bill\ (\$)}{Percent\ Income\ to\ Water})}{Total\ HH}$	Household Affordability

Affordability is concerned with defining what constitutes an “undue hardship”. Each of these metrics provides some threshold to provide that context. For example, the Traditional metric suggests that if less than 4.5% of the MHI is going to water services then the rates are affordable for the community (EPA 1995; EPA 1997). The HB metric suggests 7% and 10% as indicators that the rates are becoming less affordable for the community (Raucher *et al.* 2019). PP thresholds suggest less than 20% indicates relatively low amounts of poverty, between 20 to 35% indicates moderate amounts of poverty, and greater than 35% indicates high amounts of poverty (Raucher *et al.* 2019). The general assessment for minimum wage hours is that a four-person household’s basic monthly water and wastewater services bill should not require more than 8 hours at minimum wage to be considered affordable (Teodoro 2018).

While these thresholds exist, determining what constitutes “enough” water and “undue” hardship are value-based judgments. Instead, we present the results using the number of days of labor required each month as a consistent and intuitive way to provide context to the increasing affordability challenges for the Minimum Wage Hours, Traditional, and Household Burden indicators. A day of labor is roughly equivalent to 4.6% of a household's monthly income. Additionally, a proposed water affordability framework (Raucher *et al.* 2019) combined HB and PP to understand the financial capability of the community to pay for water services by defining burden levels in terms of a low financial burden to a very high financial burden (Table 2). We adopted similar categories of describing burden levels (i.e. Low to Very High) using the recommended thresholds for Poverty Prevalence and the percent of income representing each subsequent day of labor for the Household Burden.

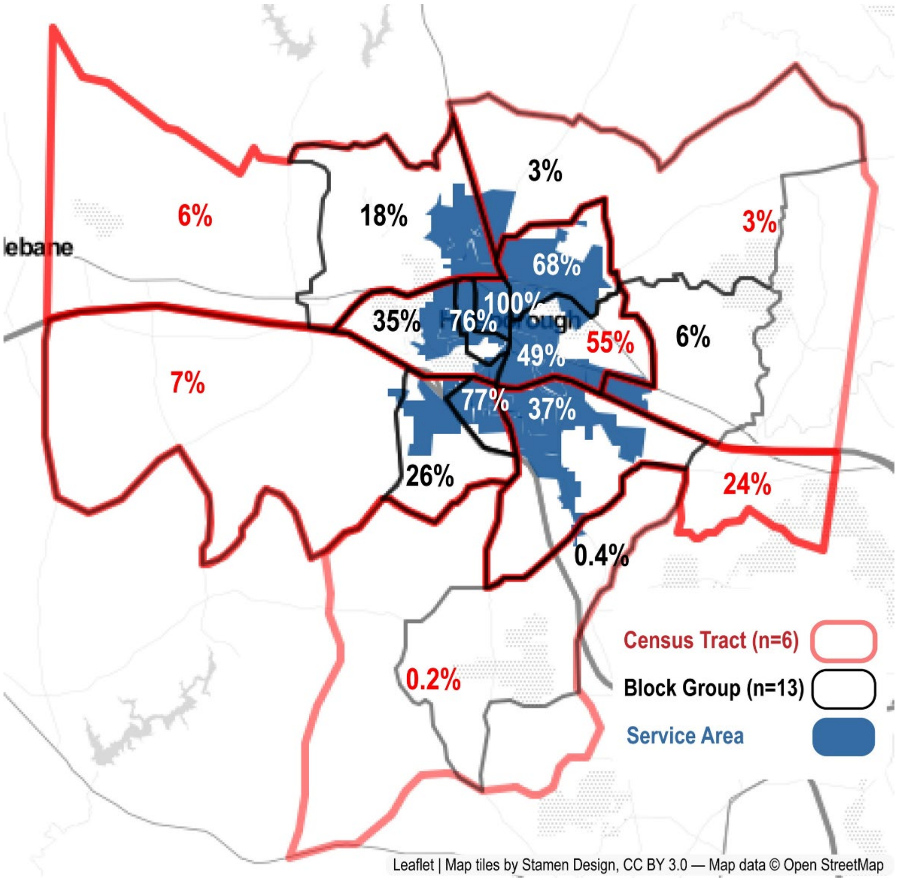
Table 2. Affordability framework combining Household Burden (HB) and Poverty Prevalence (PP) to reflect that water services become increasingly burdensome and unaffordable as HB and PP increase. Adopted from (Raucher *et al.* 2019).

Household Burden by Days of Labor	**Poverty Prevalence**		
	< 20%	**20 to 35%**	**> 35%**
> 2 days (> 9.2%)	Moderate-High	High	Very-High
1 – 2 days (4.7 to 9.2%)	Low-Moderate	Moderate-High	High
< 1 day (4.6%)	Low	Low-Moderate	Moderate-High

There is some correlation between HB and PP as the distribution of income in the community influences the income for the lowest quintile; the greater the prevalence of poverty in a community, the lower the 20% of household income (LQI) and the greater the burden of paying for water services. While thresholds provide useful constructs for assessing affordability, such thresholds should be held loosely as the difference between a utility with 19% PP (low) and 21% PP (moderate) is minute. S2 File contains a comparison of affordability results using the recommended thresholds for the Traditional and Household Burden metrics.

Linking census data to service areas for income and poverty variables used by affordability metrics.

To develop affordability metrics at the block group and utility scale, we intersected census block groups and tracts with utility service area boundaries. Since census and service area boundaries do not perfectly align, we calculated the percent of area that intersected to weight affordability metrics when aggregating metric scores for the utility. This allows block groups fully in the service area to have greater weight than block groups only partially within the service area. For example, Hillsborough, NC is a rural community that intersects 6 census tracts and 13 block groups (Fig 3). Only one block group was located completely inside the service area boundary of the Hillsborough utility (the remaining overlapped by 0.4 to 76%), while the most overlap with a census tract was 55%.



Leaflet | Map tiles by Stamen Design, CC BY 3.0 — Map data © Open StreetMap

Fig 3. Overlapping service area and census boundaries. Hillsborough, NC service area intersected portions of 6 census tracts and 13 block groups. We show the percent of the census tract (red) and block group (black) overlapping the service area.

Calculating affordability metrics for the utility.

Block group affordability metrics were aggregated to the service area using a recommended weighting method (Raucher *et al.* 2019). Here, we adjusted the number of households based on the percent of the block group within the service area (Fig 4). For example, if a block group had 100 households, but only 45% of the block group was within the service area, then we adjusted the number of households from 100 to 45. Next, we summed the total number of adjusted households in the service area. We then weighted the affordability metric scores in each block group based on the total number of households in the service area. For example, in Fig 4, the block group with 45 households represents 9% of all households in the weighted service area (468 households). The Traditional, HB, and PP scores in each block group are multiplied by the weighted block group ratio (for example, an HB score of 4 times 9% gives a score of 0.36). The sum of the affordability metrics in each block group becomes the affordability score for the utility.

$$Adjusted\ Household = Percent\ of\ Block\ Group\ in\ Service\ Area\ \times Number\ of\ Households$$

$Block\ Group\ Weight_i = \frac{Adjusted\ Households_i}{\sum Adjusted\ Households}$, where i is an individual block group.

$Service\ Area\ HB\ Score =\ \sum_i\ HB\ X\ Block\ Group\ Weight$, where i is an individual block group.

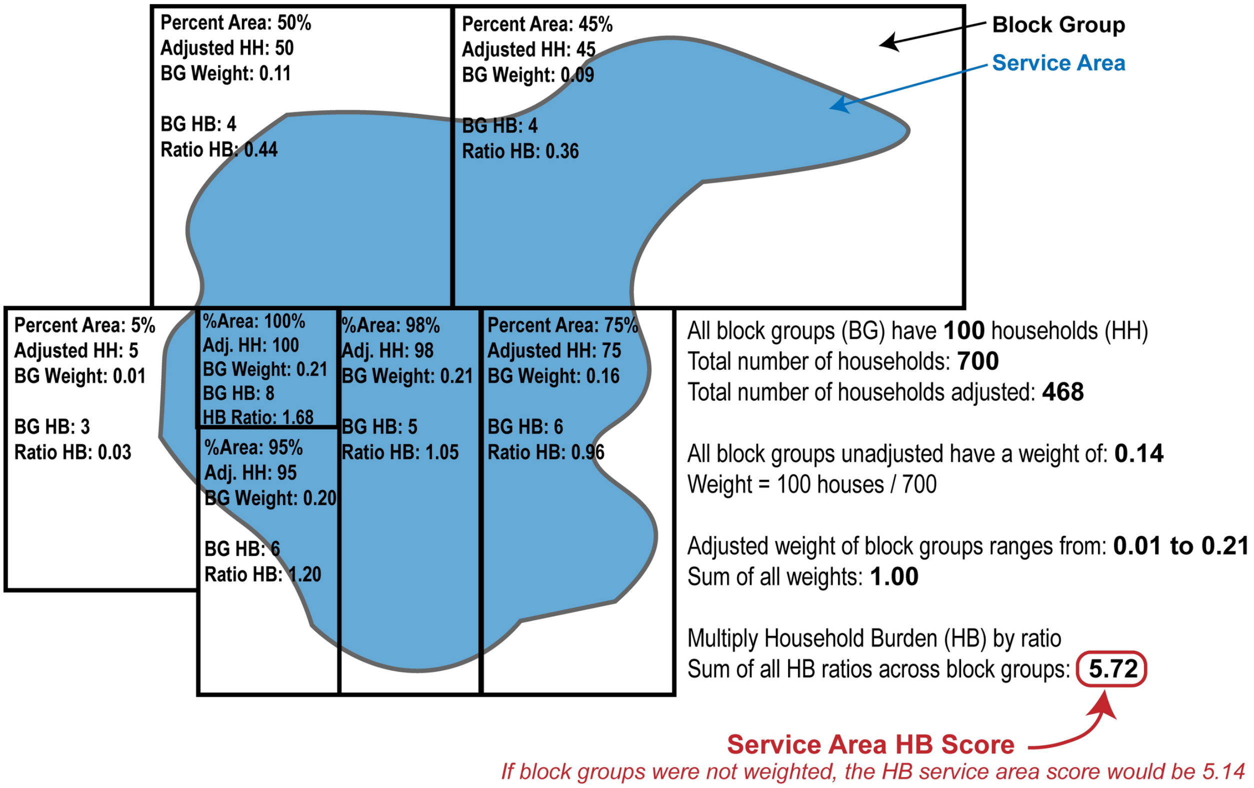


Fig 4. Aggregating block group metrics to a single metric for the utility. Individual block group HB scores were weighted by percent overlap with the utility service area to develop a utility HB score.

Utilities with inside-outside rates often had block groups bisected by the municipal boundary. Here, the percent of the block group located inside were assigned inside bills and the percent of the block group located outside were assigned outside bills. The same weighting method was applied to estimate a single affordability metric for each block group and utility. We also used this weighting approach to estimate the change in population, MHI, and LQI by block group within utility service area boundaries between 2000 and 2019.

Income Dedicated to Water Services (IDWS).

Most metrics consider affordability at a specific income level – the LQI or median – and assess affordability based on pre-identified thresholds of income needed for water services (e.g., 4.5%, 7%, 10%). However, these approaches do not quantify how many customers have a low or high financial burden to pay for water services. We sought to pivot the question to allow utilities to explore the distribution of affordability in their service area by asking, "*What proportion of income dedicated to water services is acceptable for what proportion of customers in a utility"* (Fig 5)? The advantage of this approach is that it does not require selecting a threshold and it provides information on both the financial capability of households, as well as the relative burden imposed by water rates across the entire population served by the utility.

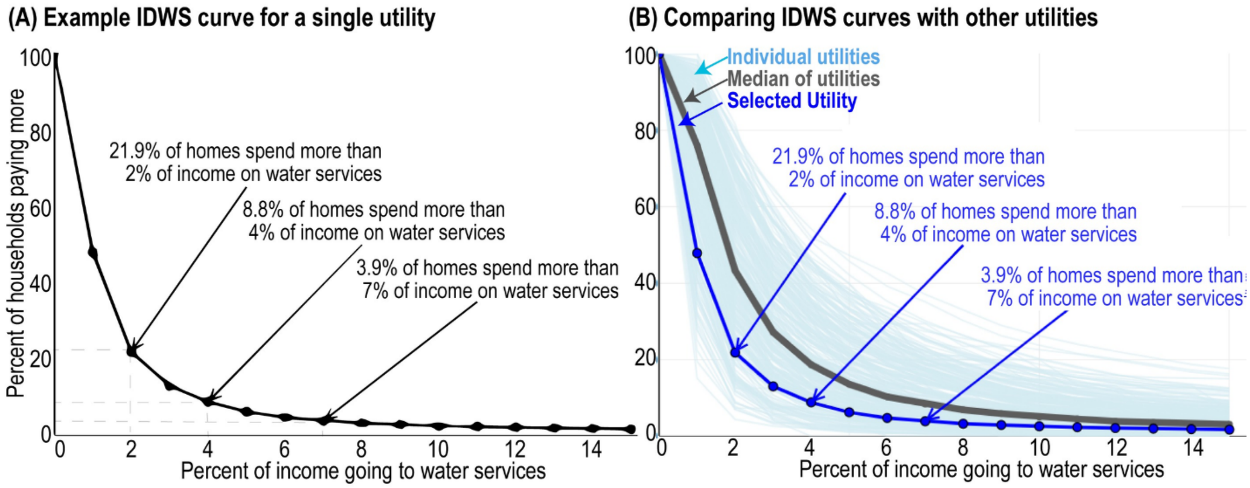
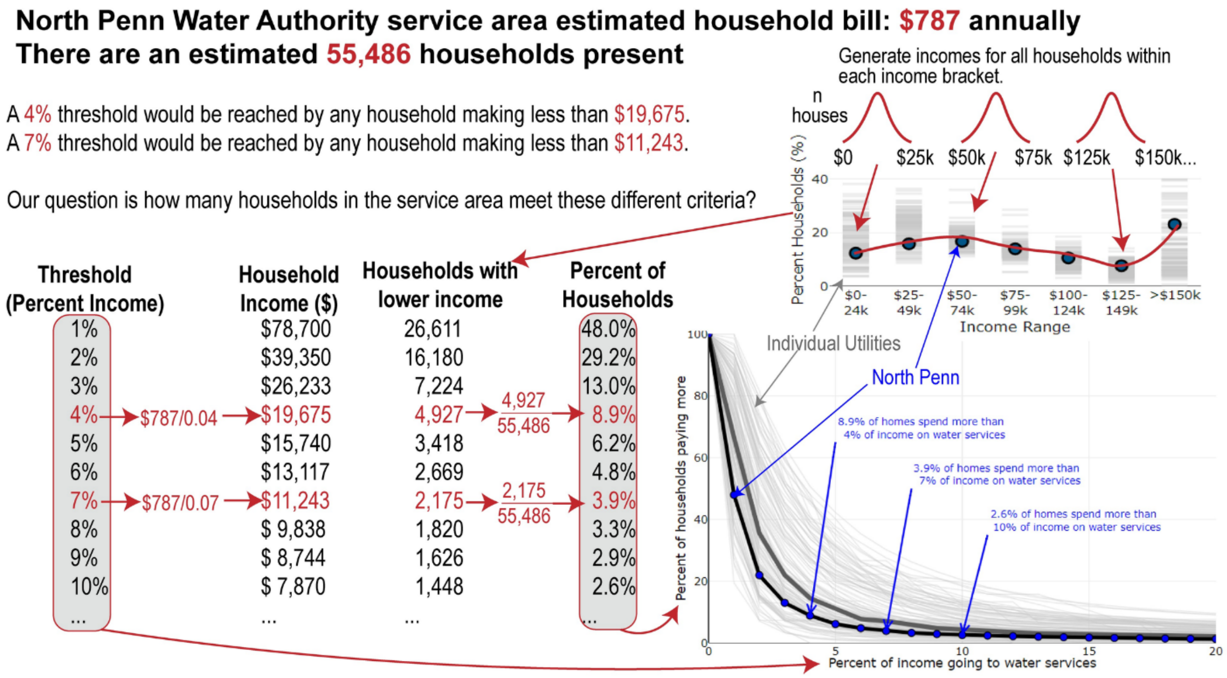


Fig 5. Income Dedicated to Water Service metric. (A) IDWS curve for a single utility. (B) Overlaying an individual utility IDWS curve with other utilities.

We quantified the continuum of income dedicated to paying for water services by dividing the annual household bill by a percentage to identify the income required for the household to spend 1%, 5%, 10%, etc. of their income on water services. For example, if the estimated annual water bill is $787 (Fig 6), and we wanted to know what income would be needed for that bill to account for 7% of household income, we would divide 787/0.07 to find that a household earning $11,243 annually would spend 7% of their income on water bills. We then quantify the number of households estimated to earn less than that amount in a service area using the census data. For example, the North Penn Water Authority has 2,175 (3.9% of total) households earning less than $11,243, thus generating the data point of 3.9% of households spend more than 7% of their income on water services. Combining the burden (x% of income spent on water services) with the prevalence (percent of households spending that much or more) constructs the IDWS for a particular utility (Fig 6).



North Penn Water Authority service area estimated household bill: $787 annually
There are an estimated 55,486 households present

A 4% threshold would be reached by any household making less than $19,675.
A 7% threshold would be reached by any household making less than $11,243.

Our question is how many households in the service area meet these different criteria?

Threshold (Percent Income)	Household Income ($)	Households with lower income	Percent of Households
1%	$78,700	26,611	48.0%
2%	$39,350	16,180	29.2%
3%	$26,233	7,224	13.0%
4%	$19,675	4,927	8.9%
5%	$15,740	3,418	6.2%
6%	$13,117	2,669	4.8%
7%	$11,243	2,175	3.9%
8%	$ 9,838	1,820	3.3%
9%	$ 8,744	1,626	2.9%
10%	$ 7,870	1,448	2.6%
...	...	...	...

Generate incomes for all households within each income bracket.

8.9% of homes spend more than 4% of income on water services

3.9% of homes spend more than 7% of income on water services

2.6% of homes spend more than 10% of income on water services

Fig 6. Schematic showing how IDWS is calculated. The North Penn Water Authority serves ~55,486 households with an estimated annual bill of $787 at 4,000 gpm. We calculated the annual income (second column of table) needed for water services to account for some percent of income (first column of table). We then calculated the percent of houses earning less than that income (third and fourth column of table) based distribution of households by census income brackets (upper right chart).

We repeated this method to estimate the annual income needed for water services to account for 1 to 20% of income (Fig 6). Next, we summed the total number of adjusted households (Fig 4) within each census income bracket and randomly generated an income for each household within that bracket. We then combined these incomes to create a distribution of household incomes in the service area. Finally, we counted all households that earned less than the household income needed for water service bills to account for some percentage of their annual income (Fig 6). The first and last columns of the table in Fig

6 are plotted to visualize how many households spend more than some percentage of their annual income on water related services. This approach allows us to generate a single, continuous curve that represents how many households within a utility share a similar financial burden to pay for services. Moreover, by generating such curves for many utilities, we can also generate summary descriptions for collections of utilities (e.g., the median utility; Fig 5B). This approach is not suitable for utilities that serve a small fraction of a single block group and we did not include those utilities whose service area covered less than 15% of all intersecting block groups (removing 246 utilities).

Limitations

There are several limitations and assumptions made around the data. First, the rates data were manually collected and subject to transcription error, particularly for utilities that are billed by multiple entities (e.g., municipality owns the infrastructure but another authority treats and distributes water). We also are not sure how many municipalities have stormwater bills that were missed in our search or are embedded in property taxes.

Second, spatial boundary data only existed for drinking water utilities. The majority of utilities in this study in California, North Carolina, and Texas provided both drinking water and wastewater services and we assumed the service areas were commensurate. However, in Pennsylvania, the geographic footprint and administration of drinking water and wastewater services differed. Here, we took the mean of wastewater bills within the service area of the drinking water utility. Better spatial wastewater data would improve the accuracy of bill estimates for block groups. Similarly, spatial boundary data did not include distinctions of locations where different rates applied. Again, we used the average of the estimated bills, with the exception of inside-outside rates, although we could not confirm that current municipal boundaries were used by all utilities to distinguish inside and outside rates.

Third, some communities with drinking water services did not have wastewater services, with households relying on on-site treatment (i.e., septic systems). In these instances, we estimated homeowner costs to maintain a septic system (relevant for 28 utilities in PA). It may be preferable to exclude these utilities in the future or provide affordability metrics for water and wastewater separately.

Fourth, this approach is less robust for utilities with a very small service area. Some utilities represent less than 1% of a single block group. The metrics approach estimates affordability for the income composition of the block group; however, it is unknown how accurately the composition of such small utilities represents the composition of the overall block group.

Finally, because utilities may change their water rates, we provide the last date a selected utility's rates were updated on our website (between 2020 and 2021). We are in the process of creating tools that would allow the underlying data and affordability tool to be updated.

RESULTS

There were 1,791 utilities with rates and service area data included at the time of this study. All results can be examined through the use of an interactive dashboard, which visualizes metrics of affordability, water rates, and demographic characteristics for different volumes of usage (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard). The dashboard is continually being updated as new data become available. All results presented here are based on analysis of data available as of June 2021.

For 76% of utilities in this study, the number of customers grew over the past two decades, particularly those located in TX and for larger utilities overall (Fig 7). However, the median income decreased for 35% of utilities in California (CA), 44% in Pennsylvania (PA), 49% in Texas (TX), and 70% of utilities in North Carolina (NC). Further, low-income customers had a decrease in adjusted income in 54% of utilities (with the median change ranging from 0% in TX to -7.2% in NC). When exploring trajectories by utility size, there were slight but not significant differences in population and income trajectories.

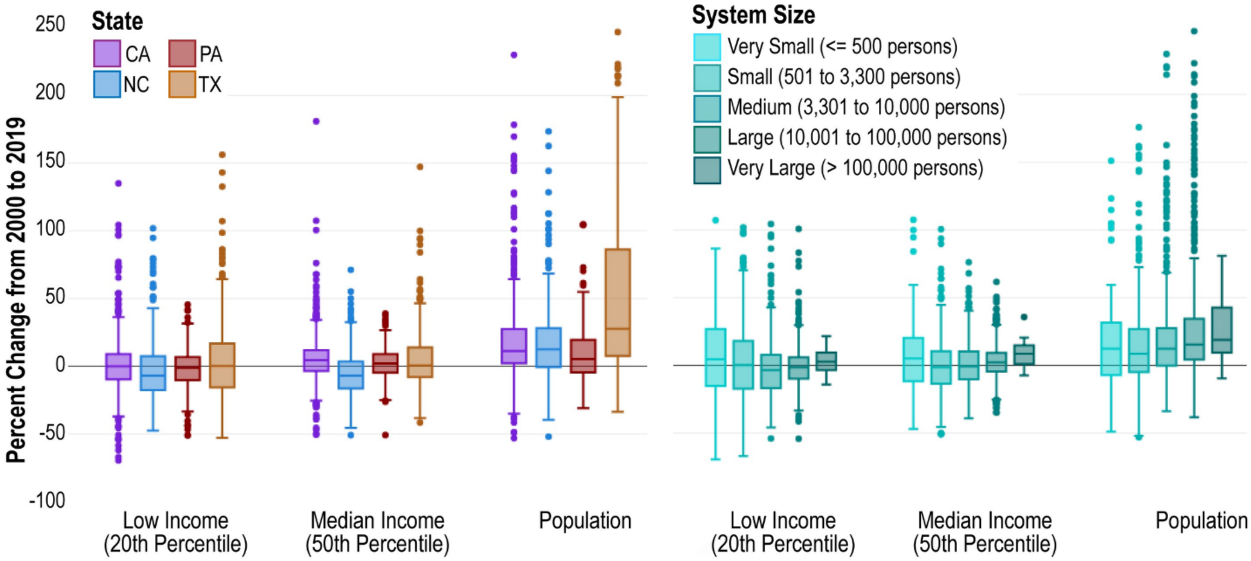


Fig 7 Change in income and population for utilities over time. Change in income and population by (Left) state and (Right) utility size from 2000 to 2019. Income is adjusted to 2019 dollars.

Cost of water services.

There was considerable variability in utility rate structures, which created variability in how sensitive water bills were to the volume of water used. Overall, the median monthly drinking water bill ranged from $22 with zero usage to $105 at 16,000 gallons per month (gpm; Fig 8). The median wastewater bill ranged from $27 at zero usage to $76 at 16,000 gpm. The median total household bill was $51 without any water usage, increasing to $188 at 16,000 gpm. Twenty-seven utilities exceeded $200 per month at 4,000 gpm, 11% of utilities by 8,000 gpm, 31% of utilities by 12,000 gpm, and 54% of utilities by 16,000 gpm.

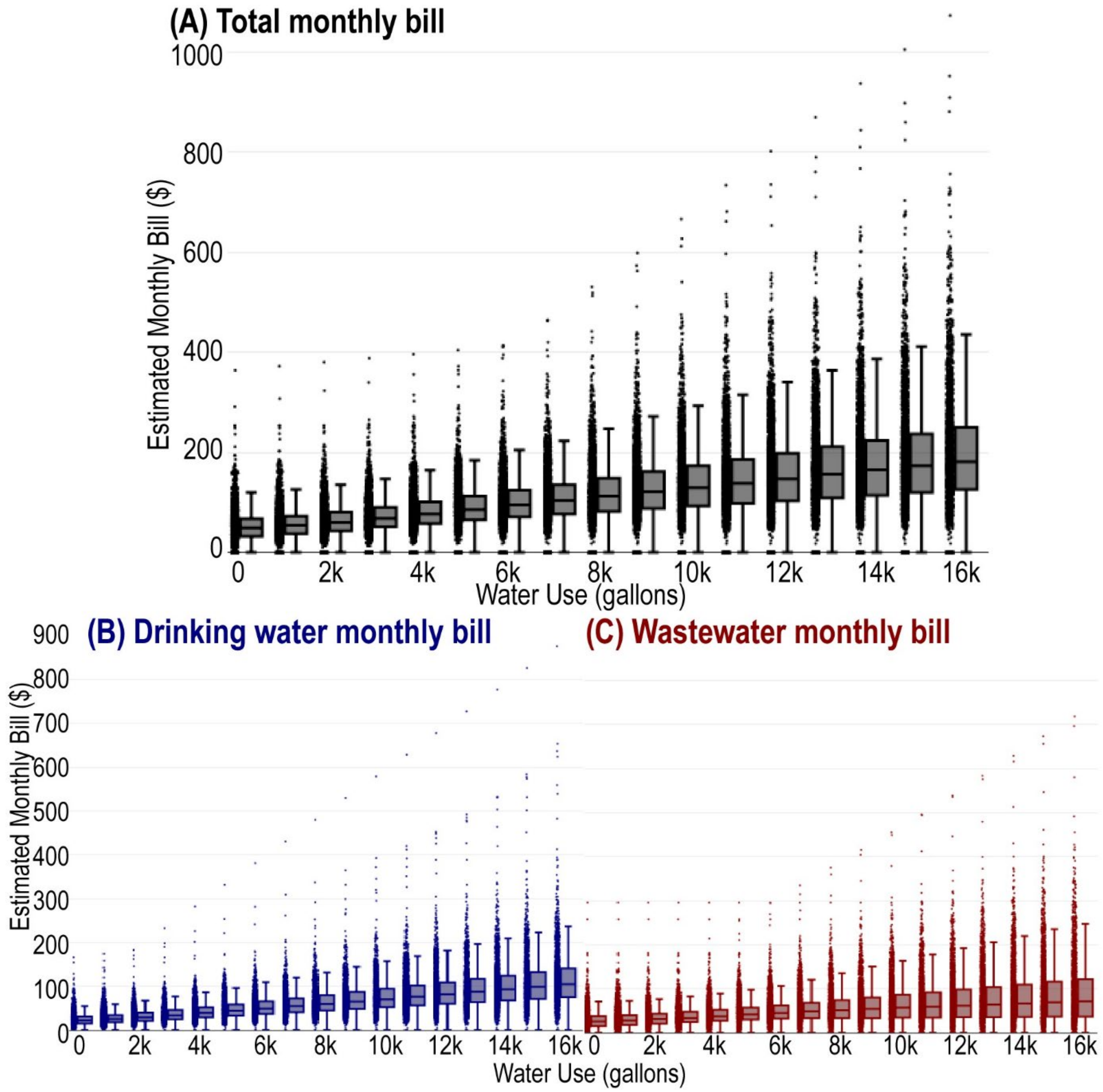


Fig 8. Monthly bills by water usage. Total (A), drinking water (B), and wastewater (C) estimated monthly bills by monthly water usage.

Most water services included a fixed charge and a usage charge; however, the portion of the monthly bill derived from these components (and surcharge) varied tremendously for similar water usage (Fig 9). It was more common for wastewater services to have a single fixed charge (46% for wastewater compared to 6% for drinking water). For drinking water, the median percent of the fixed bill decreased from 89% at 1,000 gpm to 21% of the bill at 16,000 gpm. The median percent of the fixed bill for wastewater decreased from 100% of the bill at 1,000 gpm to 32% of the bill at 16,000 gpm.

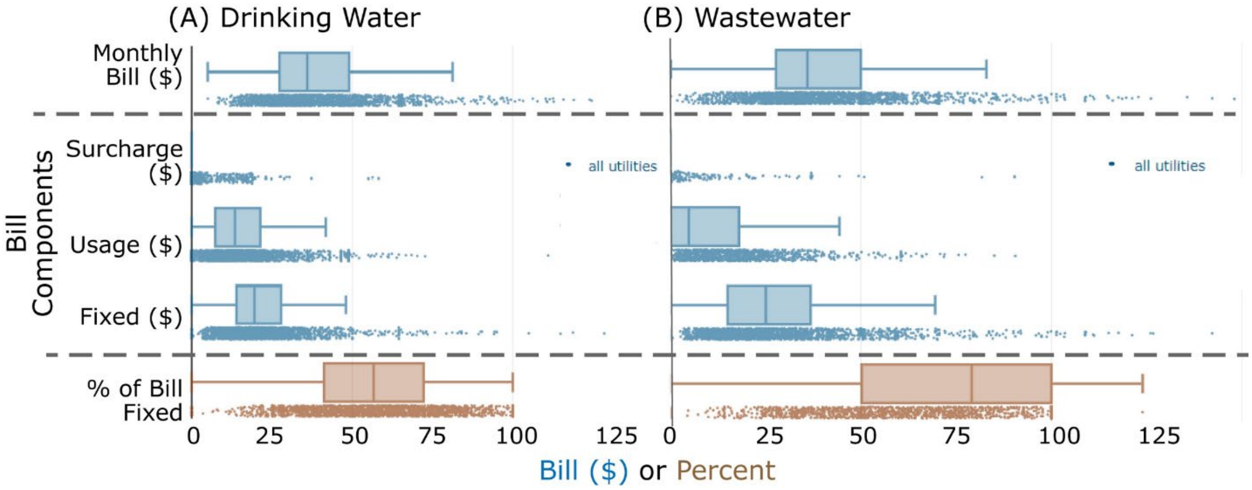


Fig 9. Components of monthly bills. (A) Drinking Water and (B) Wastewater monthly bills, their components, and the percent of the bill that is fixed at 4,000 gpm for utilities in this study. Note that the percent of the fixed bill exceeded 100% for one utility wastewater bill due to averaging bill components across multiple service areas within the utility with very different rate structures.

Affordability metric comparisons at 4,000 gpm.

Since the volume of water used directly affected the costs of services, and by extension affordability, we first compare affordability metrics assuming 4,000 gpm, which is near the 4,030 gpm recommended by Raucher et al. (2019). We then explore the sensitivity of these metrics to changes in volume of water used. Using 4,000 gpm, the combination of affordability metrics provided several distinct insights. First, Poverty Prevalence (PP), which is the only metric not dependent on water usage, indicated that many utilities have widespread poverty in their service area with a median PP of 30%. For utilities in our study, 77% have a PP greater than 20%, 37.5% have a PP greater than 35% (Table 3, Fig 10), and 143 utilities (8%) are serving communities where more than half of the households are below 200% of FPL.

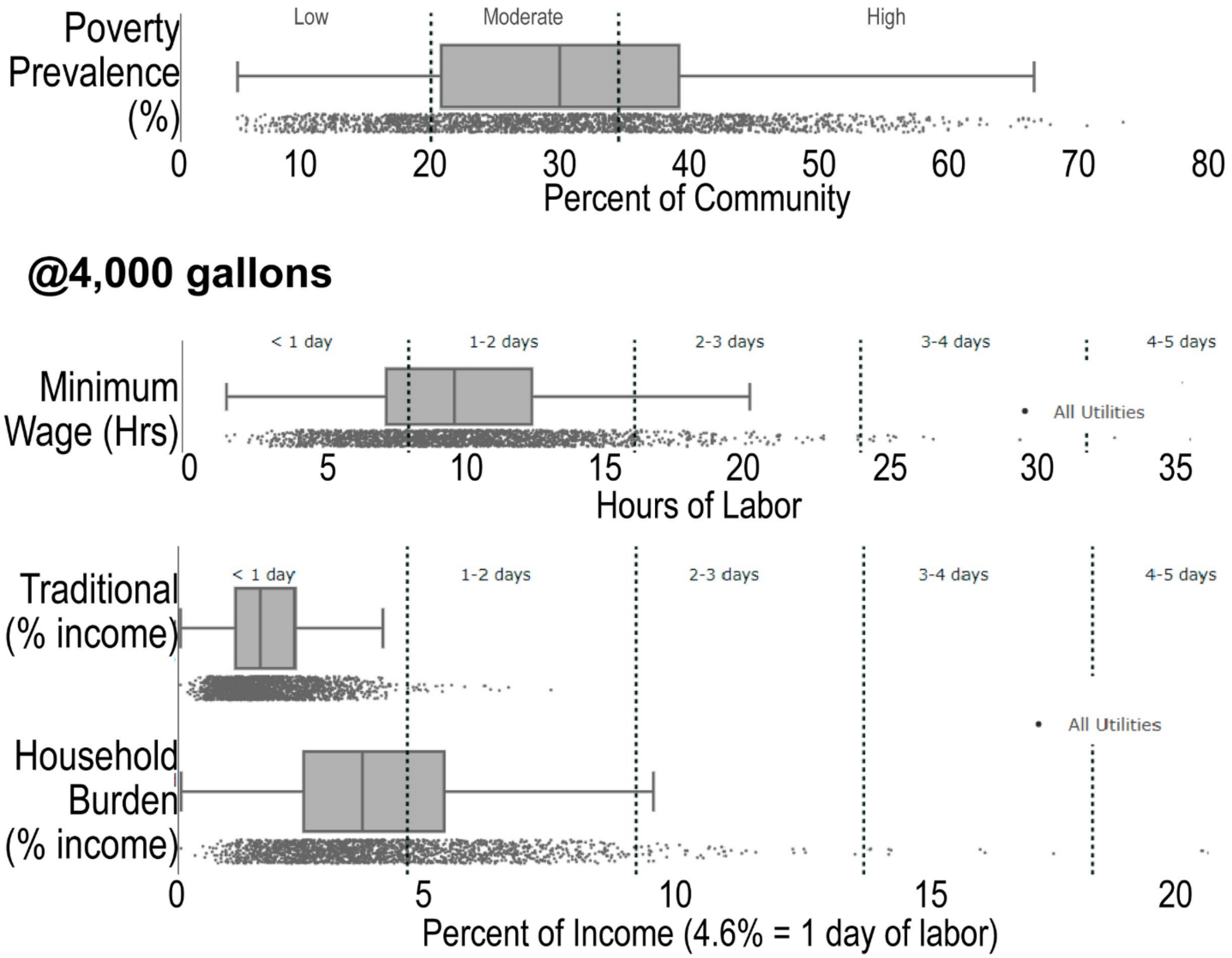


Fig 10. **Range of metric scores for four affordability metrics at 4,000 gallons of water usage per month**. Note that the x-axis scale for poverty prevalence is different. The recommended thresholds (Table 3) for PP and the days of labor for the other metrics are provided for context. Note that 4.6% of income is equivalent to a day of labor each month.

Second, Minimum Wage Hours – the only metric focused on solely household affordability – indicated that many minimum wage earners spend more than a day of labor per month to afford a low volume of water. The median household bill for water services at 4,000 gpm was ~$77 per month, requiring a median of nearly 10 hours of labor at minimum wage to pay monthly bills (Fig 10). Further, 67% of utilities in this study required more than a day of labor at minimum wage each month to pay for water services at 4,000 gpm (Table 3). Utilities in California required fewer hours (median of 7.3 hours) largely because the state's minimum wage is $12/hr compared to the $7.25/hr used by the other states in this study. Utilities in Texas required a median of 9.4 hours per month because their average monthly bill was often lower (median of $67) relative to the other states. Utilities in North Carolina and Pennsylvania required a median of 11.6 and 11.8 hours of labor per month, respectively.

Table 3. Percent of utilities classified by days of labor needed to pay for water services for their respective metric at 4,000 gpm. Note that a day of labor is equivalent to 4.6% of monthly income. The exception is Poverty Prevalence, whereby we used recommended thresholds (Raucher *et al.* 2019).

Metric	**Days of Labor or Percent of Community**	**Percent of utilities**	**Measures**
Minimum Wage Hours	< 1 day	32.4%	Household Affordability
	1-2 days	60.7%	
	> 2 days	6.8%	
Traditional	< 1 day	98.8%	Financial Capability
	1-2 days	1.2%	
	> 2 days	0.0%	
Household Burden (HB)	< 1 day	65.8%	Financial Capability
	1-2 days	31.5%	
	> 2 days	2.7%	
Poverty Prevalence (PP)	< 20%	23.0%	Financial Capability
	20-35%	39.5%	
	> 35%	37.5%	

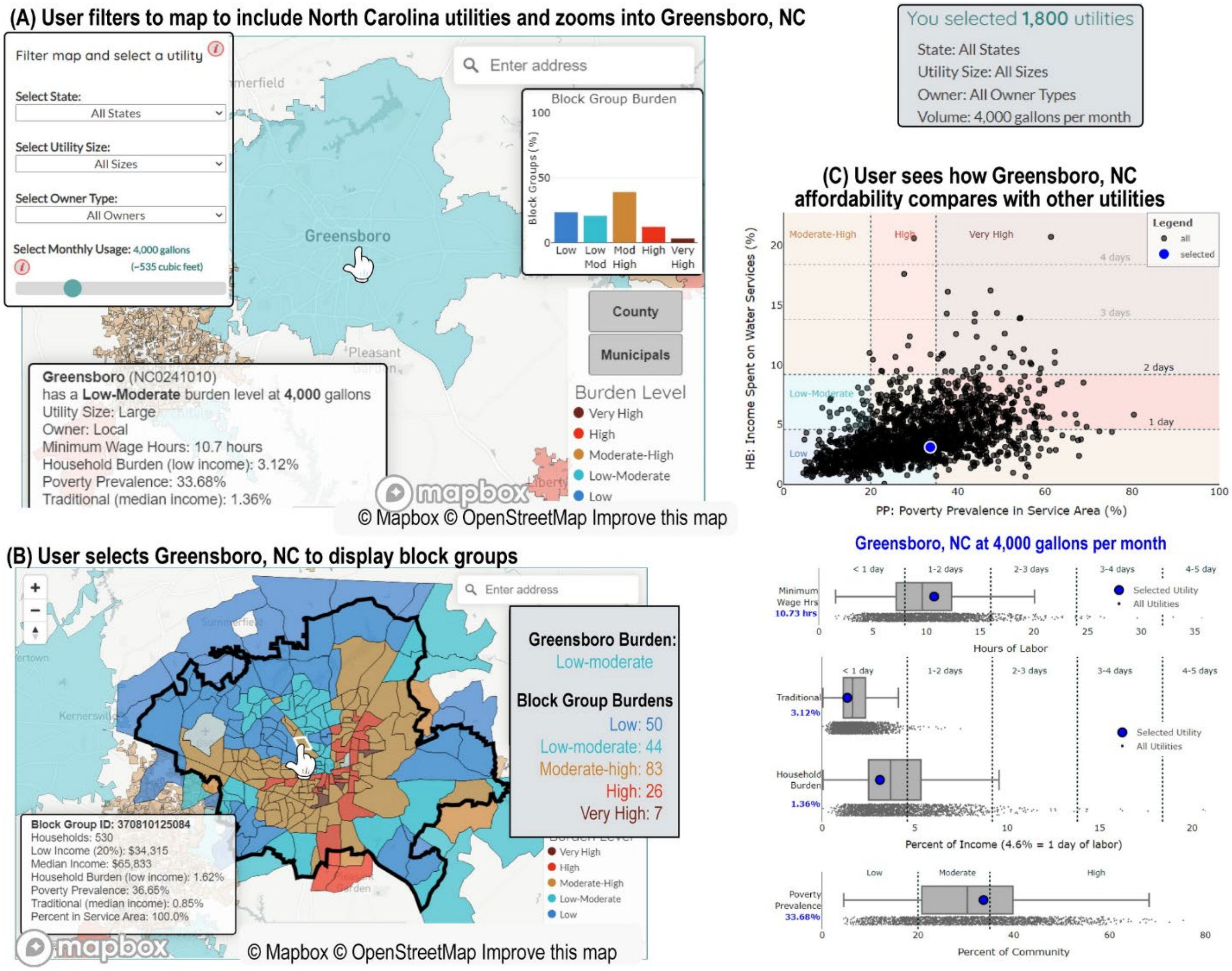
Third, the Traditional and HB metrics measuring the financial capacity of median income and low-income households in the community to pay for water services was highly correlated (r2 = 0.95, pearson). SI File 2 contains additional information comparing the Traditional and HB metric with their recommended thresholds. While there is strong correlation between the two metrics, we found the HB metric to be more sensitive to low-income households with 34.2% of utilities requiring more than a day of labor for households to pay for services (Table 3). This is in contrast to the Traditional metric where only 1.2% of utilities required more than a day of labor from median households at 4,000 gpm.

Fourth, block group metrics showed considerable variation within utilities. The 1,791 utilities intersected 47,479 census block groups, with each utility comprised of between 1 and 2,779 block groups (median number of block groups in a utility = 9, mean = 32). The Traditional and HB metrics were calculated at the census block group scale, thus providing greater granularity on how rates and household incomes combine within a utility. We found that utilities classified with a Low HB at the scale of the entire service area often contained a few individual block groups with a Moderate or High HB (Table 4). Utilities with a HB classified as Moderate to High at the service area scale had greater diversity in block group HB classifications.

Table 4. Comparison of Household Burden (HB) metric for utility service areas and their corresponding block groups at 4,000 gallons. For example, for the 65.8% of utilities had a HB requiring less than a day of labor at the utility-wide scale, 83% of block groups within those utilities had a HB requiring less than a day of labor, 14.5% 1-2 days of labor, and 2% more than 2 days of labor. Shaded cells represent the percent of block groups matching the number of days of labor of the utility.

Days of labor each month to afford water bill based on HB	Percent of utilities	Percent of block groups needing < 1 day	Percent of block groups needing 1-2 days	Percent of block groups needing > 2 days	Percent of block groups unknown
Less than 1 day	65.8	82.7	14.5	2.0	0.9
1 to 2 days	31.5	44.6	42.0	12.3	1.0
More than 2 days	2.7	16.2	39.8	42.4	1.3

The distribution of affordability by block group primarily reflected the distribution of household income, and where applicable, the presence of inside and outside rates relative to current municipal boundaries (Fig 1). For example, for Greensboro, NC, the entire utility had a poverty prevalence of 34% with minimum wage earners spending nearly 11 hours to pay monthly bills (Figure 11C). The affordability burden matrix (Table 2) indicated the utility as a whole had a low-moderate burden, driven by poverty prevalence (Fig 11C). Within the utility, however, there was clear spatial variability in affordability burden: 94 of the block groups, particularly those located northwest of the city center, had lower burden than block groups located near the city center (Fig 11B). That is, households near the city center had lower incomes and would be expected to struggle more to pay for water services than those in the northwest region of the service area.


(A) User filters to map to include North Carolina utilities and zooms into Greensboro, NC

Filter map and select a utility
Select State: All States
Select Utility Size: All Sizes
Select Owner Type: All Owners
Select Monthly Usage: 4,000 gallons (~535 cubic feet)

Greensboro (NC0241010)
has a **Low-Moderate** burden level at **4,000** gallons
Utility Size: Large
Owner: Local
Minimum Wage Hours: 10.7 hours
Household Burden (low income): 3.12%
Poverty Prevalence: 33.68%
Traditional (median income): 1.36%

You selected 1,800 utilities
State: All States
Utility Size: All Sizes
Owner: All Owner Types
Volume: 4,000 gallons per month

(B) User selects Greensboro, NC to display block groups

Greensboro Burden: Low-moderate
Block Group Burdens
Low: 50
Low-moderate: 44
Moderate-high: 83
High: 26
Very High: 7

Block Group ID: 370810125084
Households: 530
Low Income (20%): $34,315
Median Income: $65,833
Household Burden (low income): 1.62%
Poverty Prevalence: 36.65%
Traditional (median income): 0.85%
Percent in Service Area: 100.0%

(C) User sees how Greensboro, NC affordability compares with other utilities

Greensboro, NC at 4,000 gallons per month

Fig 11. Maps and charts of affordability metrics. (A) Map shows the affordability burden for utilities in North Carolina. (B) The affordability burden for block groups within the Greensboro utility. (C) Greensboro (blue dot) is plotted alongside other utilities (here, utilities in North Carolina) when looking at affordability metrics.

Income Dedicated to Water Services (IDWS).

The previous metrics provide a snapshot of affordability at a particular income level while the Income Dedicated to Water Services (IDWS) metric shows the breadth of impact along a continuum (i.e., how many households spend what percent of income on water services). There was wide variability in the

IDWS of utilities in this study, as well as some variability between states. When taken collectively, the IDWS indicated that, for the median utility in our dataset, 16.4% of households spent more than 4% of their income (0.9 days of labor) on water services, while 7.7% of households spent more than 7% of their income (1.5 days of labor) on water services (Fig 12). At the most extreme, 45% of households in one utility spent more than 7% of their income on water services at 4,000 gpm (a utility in NC where 49% of the population earned less than 200% of the federal poverty level). At the other extreme, 15 utilities had less than 1% of households spending more than 7% of their income on water services (these utilities often had both low poverty and low costs). There was also variability in utilities between states (Fig 12); however, the sources of this variability are beyond the scope of this paper.

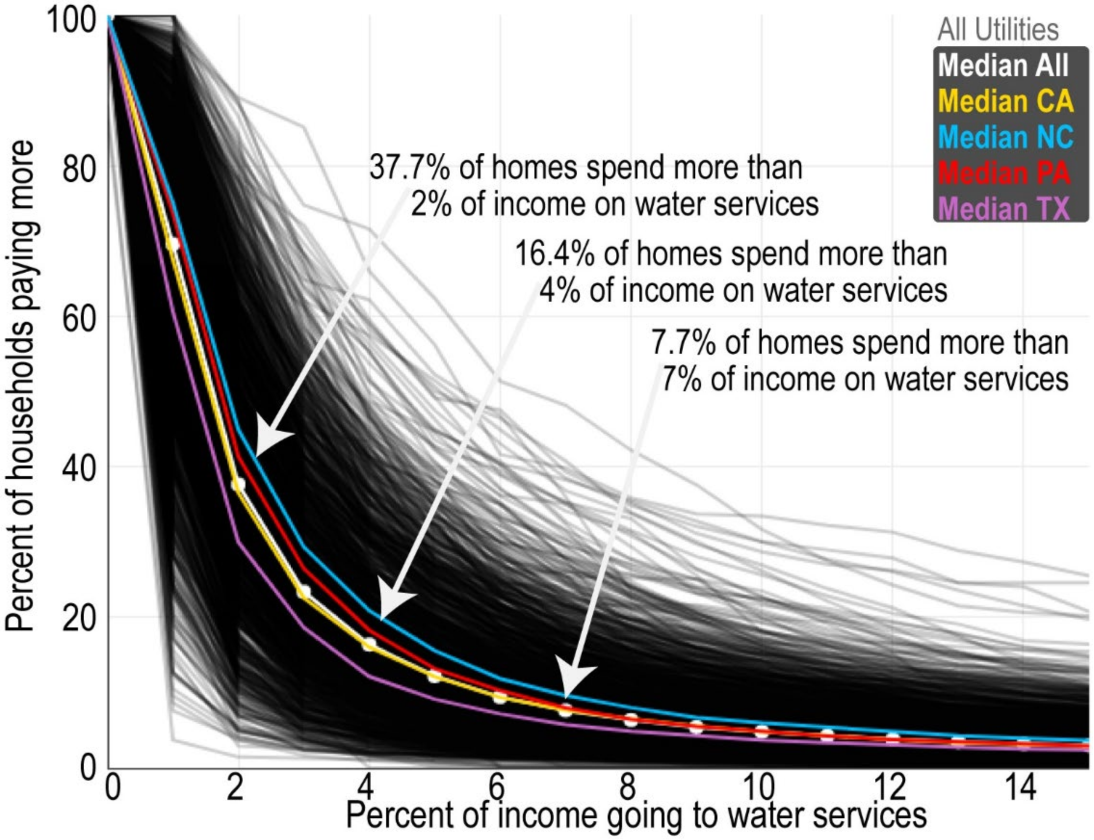


Fig 12. **IDWS results at 4,000 gallons for utilities in the study.** Each utility shows the proportion of households in the community spending more than some percent of their income on water services.

Sensitivity of affordability metrics to water usage.

As noted above, many utilities had a moderate affordability burden regardless of water usage because of poverty prevalence (Fig 10). We found 88% of utilities required less than a day of labor for low-income households when no water is used (Fig 13A; Table 2). As water usage increased, the burden increased (utilities move vertically with HB; while PP remained constant since not based on water usage) (Fig 13A-C); the number of utilities requiring low-income households to spend more than a day of labor nearly tripled between 0 (12% of utilities) and 4,000 gpm (34% of utilities). Similarly, the number of utilities requiring low-income households spending more than 2 days of labor doubled for each thousand gallons of water from 2,000 (0.8% of utilities) to 6,000 gpm (8.6% of utilities) (Fig 13D).

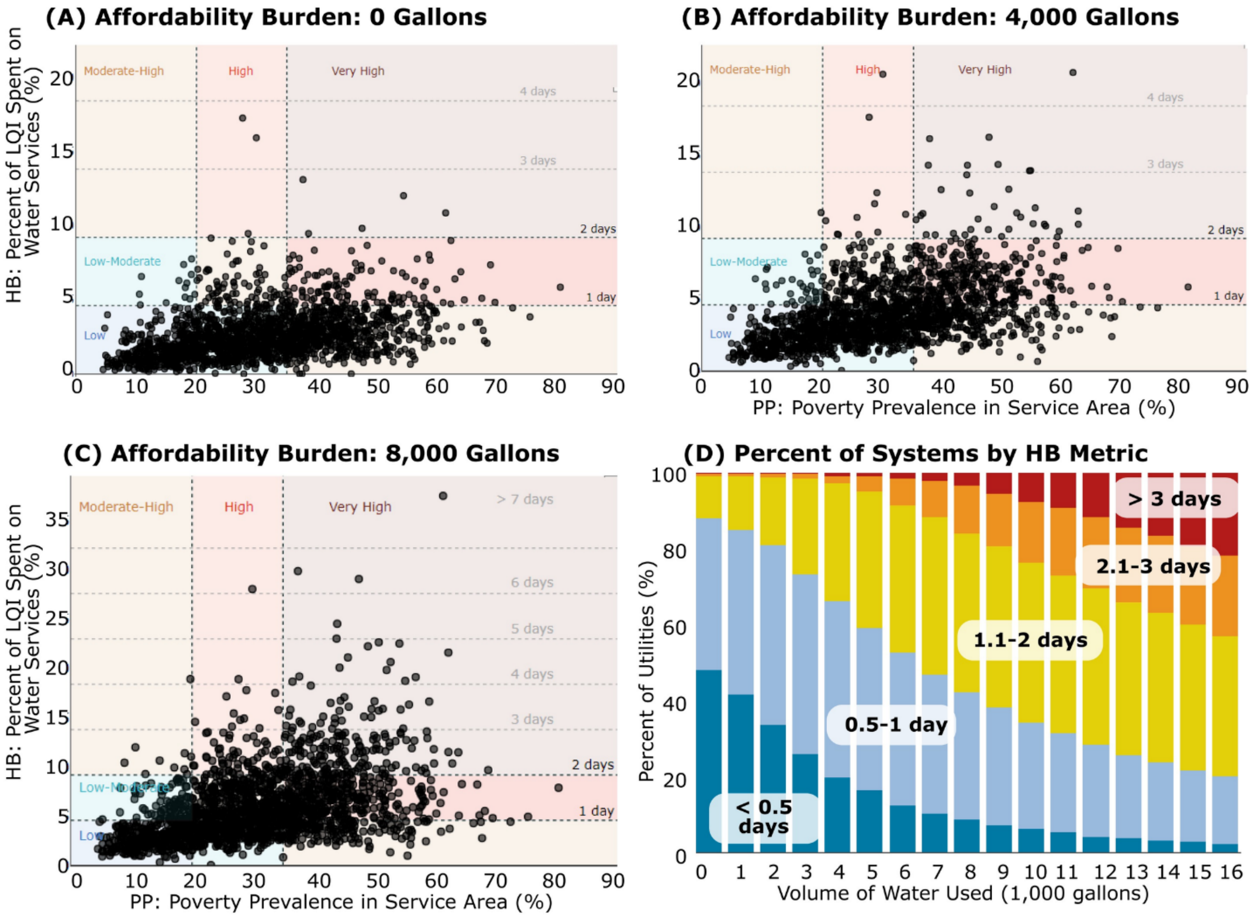


Fig 13. **Changes in affordability by water usage.** Affordability Burden at (A) 0 gpm, (B) 4,000 gpm, and (C) 8,000 gpm. Only (D) HB changes with volume, while PP remains constant (not shown).

The amount of water needed for basic use is a function of household size. A single-person household using 50 gallons per day would use 1,500 gpm; at this volume, fewer than 19% utilities in our dataset required more than a day of labor (15 utilities required more than 2 days). However, a four-person household would use 6,000 gpm; at this volume, 551 utilities (58%) required more than a day of labor while 76 of utilities (8%) required more than 2 days of labor (Fig 13D).

Nineteen utilities required more than 30 days of labor each year at minimum wage to pay for water services at 4,000 gpm. As water use increased, however, the amount of labor hours needed to pay for water services rapidly grew. For example, at 6,000 gpm (~50 gallons per day for a 4-person household), 8% of utilities required more than 30 days to pay for water services each year (Fig 14), and at 10,000 gpm, 32% of utilities required more than 30 days per year at minimum wage to pay for water services. By 16,000 gpm, 55% of utilities required more than a month of labor per year at minimum wage to pay for water services, and 14% required 2 months of labor per year. The immense variability in minimum wage hours by utilities at all volumes reflects the importance of rate structures on affordability. This is one part of the equation as even those utilities with identical costs may have dramatically different affordability burdens depending the characteristics of the community served. For example, the same monthly bill of $80 could be a low financial burden for households in an affluent community, while a high financial burden in a low-resourced community (S3 File).

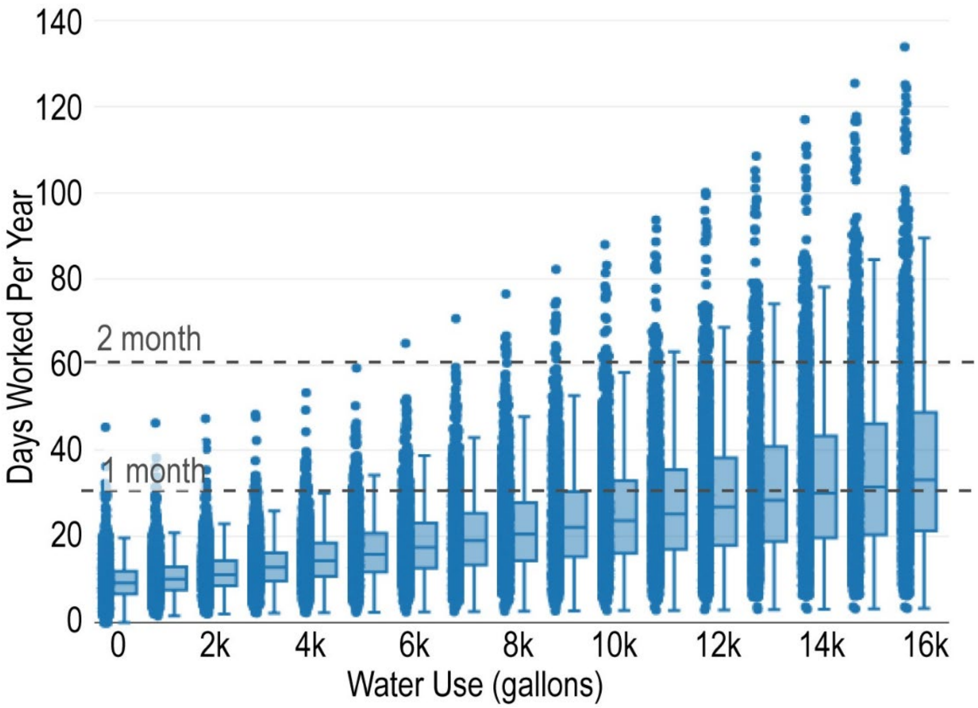


Fig 14. Changes in minimum wage hours by water usage. The number of days a minimum wage worker must labor to pay for water services each year based on monthly water consumption.

The effect of increasing water use on affordability was also evident using the IDWS. Doubling the volume of water used from 4,000 to 8,000 gpm, the percent of homes spending more than 5% of their income on water services increased from a median of 12% to 19% of households in the community (Fig 15). Similarly, the breadth of households grew from 5% to 8% when looking at the percent of households spending more than 10% of their income on water services.

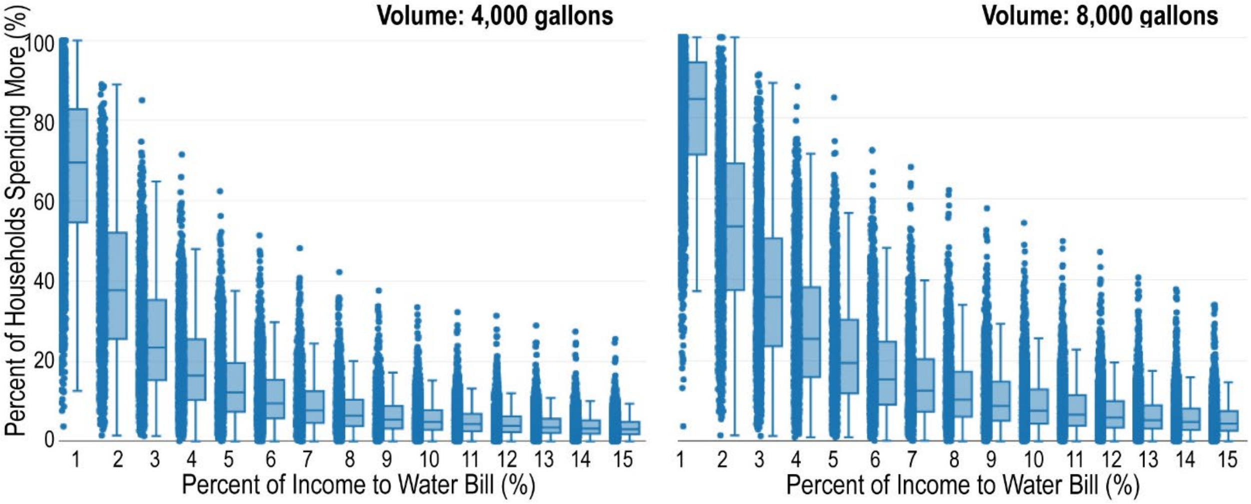


Fig 15. Change in IDWS by water usage. Percent of households spending more than 1 to 15% income on water services at 4,000 gpm (Left) and 8,000 gpm (Right). For example, at 4,000 gpm 12% of households spent more than 5% of their income on water services.

DISCUSSION

Affordability metrics provide different insights and collectively give better understanding.

In the last decade, several metrics were developed to understand different aspects of water affordability in the U.S. in terms of the financial capability of utilities and household affordability (Raucher *et al.* 2019; Goddard *et al.* 2021). These metrics are intended to identify what constitutes enough water (volume of water used) and undue hardship to pay for basic water services. Rather than advocating for one metric, we calculate several metrics across a range of water volumes and provide context for hardship in terms of the number of days of labor needed to pay water bills each month. We found each metric provided different insights, and in combination, can provide a more comprehensive understanding of water affordability challenges for utilities and households.

For example, the Poverty Prevalence metric is based solely on census-based data (no water rates or usage data), but demonstrated that many utilities are experiencing widespread poverty (Figs 10 and 13). Regardless of water rates or usage, deep poverty can make affording water services a challenge for households, and simultaneously create financial capability challenges for a utility: if a large portion of the population served by a utility is low income, then the revenue potential for the utility will be constrained (Spearing *et al.* 2020; Goddard *et al.* 2021).

Similarly, Minimum Wage Hours was an informative metric, yet because it focused solely on household affordability, it was greatly influenced by both water rates set by the utility and the volume of water used by households. Our results demonstrate that regardless of the community composition, in a typical utility, those relying on minimum wage must work 1 to 2 days per month to pay for water services, even when households use relatively low amounts of water use (Figs 10 and 14). This metric was sensitive to the volume of water used, particularly as water use reached levels more typical of large households. At low volumes, Minimum Wage Hours increased by less than an hour per month from 0 to 2,000 gpm, but from 3,000 gpm onward, the median Minimum Wage Hours consistently increased by an hour per 1,000 gpm. The slower increase in Minimum Wage Hours for the first 2,000 gpm is likely because many utilities included the first several thousand gallons in the fixed charge. For example, 43% of drinking water rates, and 82% of wastewater rates did not have a usage charge at 2,000 gpm. By 4,000 gpm, 92% of drinking water rates, and 43% of wastewater rates had a usage charge, thus increasing sensitivity to the volume of water used.

This metric demonstrated that low-income households are quite vulnerable to the size of water bills and the amount of water used, and are particularly affected by rate structures. Low-income households pay comparatively more for water services because fee structures are often regressive (i.e. water bills account for a larger share of a low-income household budget compared to a high-income household budget) and cumulative across each water service (drinking water, wastewater, and stormwater) (Beecher 2020). This vulnerability highlights the significance of rate design to affordability, particularly when considering the difference in monthly water consumption between households of different sizes. The current paradigm of treating water as an economic good with rates striving to reach economic equity (everyone pays the same amount) could be reassessed in the context of affordability, so that low-income households do not spend a higher proportion of their budget on water services (e.g. Beecher 2020).

As such, results for Minimum Wage Hours showed the median utility in our study required minimum wage earners to spend 11.7 hours at 6,000 gpm to pay for water services, which is more than the 10.1 hours found in Teodoro & Saywitz (2019) for 6,200 gpm. The difference in results highlights both the growing costs of water services and the importance that minimum wages have on alleviating household affordability. Teodoro & Saywitz (2019) used the minimum wage for utilities in their jurisdiction, which may be above the minimum wage set by the state, which is what we used in this study. The importance of higher minimum wages is highlighted by comparing the median utility labor hours in CA (8.2 hours at 6,000 gpm with an hourly minimum wage of $12) compared with NC (15.2 hours at the federal minimum wage of $7.25).

The Traditional and Household Burden (HB) metrics measure the financial capability for the community to afford proposed costs of financing capital and operations. We found that while PP placed many utilities into moderate burden levels for affordability (Table 2 and 3), the HB resulted in utilities with more prevalent poverty to shift from moderate to high affordability burdens as water usage increased (Fig 13D). No utilities with a PP below 20% shifted into a Moderate-High affordability burden until more than 4,000 gallons of water were used (Figs 13B and 13C) and no utilities with a low PP had a High or Very High burden up to and including 16,000 gpm. The transition from a moderate to high affordability burden began to increase rapidly after the first 3,000 gallons of water use (Fig 13D). Our approach also takes advantage of the ability to calculate metrics at the block group scale to provide insight into how affordability challenges may be distributed within a utility (Table 4; Fig 11).

Importance of understanding how many households may have difficulty affording water services.

The Traditional and HB metrics each provide a single cross-section of the affordability burden (percent of income going towards water services) for a particular representative household income (i.e. MHI or LQI) in the community. While useful, these metrics provide limited insight on how many households experience different levels of affordability burden (Colton 2020; Goddard *et al.* 2021). The IDWS provides a method to quantify both the affordability burden (i.e. what percent of income is used to pay for water) and the breadth of impact (number of households at that burden level). For example, the median utility in our study would have 8% of their households spending more than 7% of their income on water services (Fig 12). Cardoso & Wichman (2020) adopted 4.5% as the acceptable percent of household income spent on water services, and found that 13.6% of households in their study spent more than 4.5% of their income on water services. Our approach does not allow a direct comparison (because they modeled the volume of water used by households), but our general results are consistent with theirs despite the different approaches. We found that at 2,000 gpm, the median utility had 12% of households spending more than 4% of their income on water services, while at 3,000 gpm 14% of households spent more than 4% of their income on water services. Importantly, however, by 6,000 gpm (a more realistic estimate for larger households), more than 21% of households in the median utility spent more than 4% of their income on water services. If we applied this metric to the 12,000 gpm used by Colton (2020) then 35% of households are spending more than 4% of their income on water services. That is, depending on how much water a household uses, between a tenth to a third of households are working a day or more each month to pay for water services.

CONCLUSIONS

Previous studies highlighted water affordability challenges by describing the aggregated, utility-scale results for a few volumes of water use at a specific threshold and reported findings across geographic regions or utility size (Mack & Wrase 2017; Teodoro & Saywitz 2019; Colton 202; Goddard *et al.* 2021). Additionally, many of these studies, due to data limitations, have prioritized certain geographies (e.g. states with data available such as Goddard *et al.* (2021) for California and for New Jersey (Van Abs & Evans 2018) or limited to certain utility sizes because of data availability (medium or larger utilities such as in Teodoro & Saywitz (2019)). Our work built upon these efforts by collecting rates data and developing a visualization tool that allows utilities (or any user) to explore affordability metrics within and across their utility. This approach allows utilities and regulators (e.g., state agencies or EPA) to avoid reliance on singular metrics or thresholds, as such reliance can overly simplify challenges and obscure which groups are affected by affordability or which causes are most relevant (e.g., rate structures, water usage, minimum wage standards, and/or poverty prevalence). More nuanced understandings of affordability challenges enable us to design policy responses that best fit the needs of particular communities.

Making water affordability measures transparent is important for utilities and households. Creating more transparency can improve our understandings of the scale of affordability challenges across utilities and the concentrations within utilities (e.g. Fig 11). Furthermore, the amount of water used by utilities and households varies for numerous reasons including infrastructure age, climate, household size, and so on. Calculating affordability metrics at multiple volumes is important for understanding the challenges facing any particular utility, as well as understanding the implications for rate structures adopted by utilities and the differential impact across income levels. Transparency in water affordability is also critical for informing potential interventions by state or federal governments, whether subsidies at the utility level (e.g., State Revolving Funds) or at the household level (e.g., Customer Assistance

Programs). A suite of affordability metrics is helpful for gaining better understanding of the challenges a utility is facing to assess what types of policy interventions may be most beneficial.

Affordable water services was a burgeoning crisis (Mack & Wrase 2017) prior to the COVID-19 pandemic with periodic, acute crises bringing these challenges to the public's attention (e.g. Flint, Michigan or the bankruptcy of Detroit and subsequent shutoffs). The COVID-19 pandemic has spurred on another acute water affordability crisis, this time nationwide, as the pandemic resulted in businesses closing and rising unemployment. Many households lost jobs, leading to additional financial hardship with the accrual of penalties from unpaid bills (household affordability challenges). At the same time, many states and utilities enacted shutoff moratoria, meaning that utilities lost revenue while having to create new practices and invest in new technologies to ensure workforce safety (utility financial capability). The water affordability tool and the open data and open-source code approach we developed here may help to bring some greater transparency and understanding to how water affordability has been impacted by the pandemic, and how communities, utilities, and households recover.

The combination of metrics and understanding what factors are driving affordability challenges can help with policy-making and choosing activities that will most directly address the underlying challenge. The primary activities utilities may take to address affordability challenges include (Goddard *et al.* 2021; Pierce *et al.* 2021): (1) consolidation and regionalization, (2) rate design changes, (3) customer assistance programs (including the newly launched Federal Low Income Household Water Assistance Program; https://www.acf.hhs.gov/ocs/programs/lihwap), (4) water efficiency programs to reduce usage, and (5) crisis relief to protect households from shutoffs.

Finally, our database, and online visualization tool (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard), represents a limited number of utilities, and reflects rates and demographic data during a particular period of time (2018 to 2021). Future versions of the dashboard will include the ability for utilities to directly update their service area boundaries and provide updated water service rates data, thus increasing the number of utilities included as well as most accurately representing rates. We also envision incorporating non-residential water users (i.e., commercial, industrial) to better understand and visualize sensitivity of these water users to affordability challenges as well, and their impact on overall water utility affordability.

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