Measuring water affordability and the financial capability of utilities

Lauren A. Patterson1 © | Martin W. Doyle1,2

1Nicholas Institute for Environmental Policy Solutions at Duke University, Durham, North Carolina, USA
2Nicholas School of the Environment, Duke University, Durham, North Carolina, USA

Abstract

The cost of providing water services is increasing, placing greater financial burdens on individual households and utilities. Five metrics were calculated at multiple volumes of water usage and were applied to 1791 utilities, estimating bills from 2020 rates data, to gauge financial burdens in four states. More than a fifth of the population in 77% of utilities was experiencing poverty, suggesting widespread poverty is a major contributor to utility financial capability challenges. The Income Dedicated to Water Service metric was developed to understand how many households share a similar financial burden, exploring both the depth and prevalence of affordability challenges. Depending on water use, a tenth to a third of households work more than a day each month to afford water bills. This approach and an interactive visualization tool bring greater transparency to understand the scale of affordability and financial capability challenges (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard).

KEYWORDS

affordability metrics, data transparency, finance, rates, utilities

1 | INTRODUCTION

Water affordability challenges are increasing in the United States as the cost for providing water services is becoming more expensive for both water service providers (hereafter “utilities”) and their customers (Beecher, 2020; Colton, 2020; Goddard et al., 2021; Payne, 2021; Teodoro & Saywitz, 2020). Affordability challenges existed prior to the COVID-19 pandemic, but the pandemic accelerated and amplified the “Water Affordability Crisis” (Mack & Wrase, 2017) as many households lost employment and nonresidential customers decreased operations. In 2017, 4 out of 10 households in Philadelphia had water debt (Nadolny, 2017). By 2020, a survey of 12 large utilities alone found that more than 1.5 million households owed US$1.1 billion in past-due water bills (Walton, 2020). The inability for households to pay for water services can result in shut-offs, financial penalties, and arrearages that deepen the problem (Dig Deep & US Water Alliance, 2019; Walton, 2020). The inability for households to afford their water services also has negative financial impacts on the utility, which primarily relies on their customers (households and businesses) to pay for operations, maintenance, and infrastructure.

Local utilities reliance on their customers to cover the costs of operations has grown over time. The price for providing water services has historically been artificially low because the federal government subsidized building the current infrastructure through grants and low-
interest funding in the 1970s and early 1980s. The subsidies were designed to be temporary and to cover the initial 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). However, the cost remained prohibitive to many local utilities. The federal government transitioned funding from grants to low-interest or no-interest loans, with the federal contribution steadily diminishing but not ceasing (Copeland, 2019). As the federal government decreased funding, utilities became primarily responsible for financing water service infrastructure as well as operations (Greer, 2020; Tomer et al., 2019; US Water Alliance, 2017). By 2017, state and local governments were responsible for 96% of water utility financing (CBO 2018; Copeland, 2019; Greer, 2020) with local utilities generating revenue by charging rates for services and/or establishing taxes. This means that over time, the financial health of local water utilities has become more dependent on the financial health of the local community (Spearing et al., 2020). The ability for a community (commercial, industry, institutions, and households) to pay their water utility(ies) costs in terms of infrastructure, operations, maintenance, and financing (e.g., debt service) is referred to as the financial capability of the utility.

Since the early 2000s, water utilities have increased rates faster than inflation to cover rising costs needed for infrastructure repair and replacement (i.e., the “infrastructure gap” [AWWA, 2001]), addressing negative externalities (e.g., climate change and emerging contaminants), and meeting regulatory requirements with the expansion of regulations to protect public health (Beecher, 2020; Greer, 2020). The costs of providing water services have increased by 5% annually in recent decades (4.7% from 1996 to 2016 [Bunch et al., 2017] and 5.1% from 2014 to 2018 [AWWA, 2019a]). At the same time, an “income gap” emerged as incomes increased for high income earning families faster than for low-income families (CBO, 2020) with the median household income (MHI), adjusted for inflation, increasing by 0.44% (1996–2016) to 2.72% (2014–2018) annually (Federal Reserve Economic Data, 2020). 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. This “affordability gap” reflects the widening difference between the costs of providing water services and the ability to pay for those 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, Michigan provides a stark example, where nearly 40% of the population lives below the federal poverty threshold, yet water rates increased by over 400% since 2000 (Lakhani, 2020).

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. Low-income households, those with incomes in the lowest 20th percentile, already spend 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 minimum wage earners work 10 hr each month to pay for water services (Teodoro & Saywitz, 2020). 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 United States (Horowitz et al., 2020), lead to commensurate disparities in the fiscal health of local utilities (Smull et al., 2021; Spearing et al., 2020). 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. 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 affordability gap affects both utility financial capability and household affordability. However, potential solutions to address affordability challenges across the community may differ from those addressing individual households. These distinctions are important and necessary to understand both household affordability and financial capability challenges.

1.1 Household affordability and financial capability metrics

A plethora of metrics have been developed to assess financial capability and household affordability (e.g., Davis & Teodoro, 2014; Raucher et al., 2019; Teodoro, 2018). The US Environmental Protection Agency (EPA) developed the earliest metric in the mid-
1980s 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). Most utilities are legally required to charge the same rates within a customer class. The EPA does not check to ensure rates are affordable for each household, but whether rates are affordable for a representative income in the community (e.g., median or low-income households). EPA considered utilities to have sufficient financial capability for compliance with the Clean Water Act if average household water bills (combined drinking water and wastewater) were less than 4.5% of the MHI. Importantly, this metric was designed to be one of several indicators to determine utility financial capability (EPA, 1995, 1997). However, this metric has often been conflated with (and improperly used as an indicator of) household affordability (Teodoro & Saywitz, 2020).

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; NAPA, 2017; Raucher et al., 2019; Teodoro, 2018; Teodoro & Saywitz, 2020). There are a growing number of metrics based on assessing the financial burden for the 20th percentile income (i.e., low-income) instead of the median income household (Raucher et al., 2019; Teodoro, 2018). 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 the community. A third representative of the community that is often explored when assessing household affordability is the financial burden on single-earning minimum wage households using the Minimum Wage Hours metric (Teodoro, 2018).

The above metrics all focus on the financial burden of a representative household within the community (minimum wage, low-income, and median income households). However, none of these metrics provide insight into the prevalence of financial burden. The authors developed the income dedicated to water services (IDWS) metric to explore different slices of financial burden (e.g., 5% of a household’s income spent on water services) to estimate how many households are burdened at that level (e.g., 12% of households spend 5% or more of their income on water services).

Lastly, there are metrics focused solely on the financial capability of the community. For example, the poverty prevalence (PP) indicator quantifies the percentage of the community below 200% of the federal poverty level (FPL). By setting aside the costs of water services, the PP indicator emphasizes only the potential financial capability of the community. However, the metric uses federal poverty criteria and does not account for differences in the cost of living among states and regions.

While there are studies that develop and compare affordability metrics (Raucher et al., 2019; Teodoro, 2018; Teodoro & Saywitz, 2020; Van Abs & Evans, 2018), 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; each metric provides different insights into the affordability gap, and in combination, provide a more holistic perspective.

### 1.2 Objectives

This paper introduces 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, this 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, the IDWS metric was developed to understand the distribution of affordability challenges within a utility. This is the first metric the authors 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 made open and accessible to expand water affordability research.

This approach was applied to 1791 utilities located in four states—California (CA), North Carolina (NC), Pennsylvania (PA), and Texas (TX). This analysis combined census, utility service area boundary, and rates (drinking water, wastewater, and stormwater) data to calculate multiple metrics at different volumes of water usage. These four states were chosen because they had statewide service area boundaries and represented a wide variety of climates, populations, and utilities.

The authors also created an interactive data visualization tool to enable greater transparency around water affordability and financial capability within and across utility service areas at different volumes of water use (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard). Finally, the results are presented using previously recommended thresholds to provide context to frame the conversation. The authors 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, the number of days of labor required to pay for services were used with more days of labor indicating greater affordability challenges.

This 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.

2 MATERIALS AND METHODS

2.1 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.

2.1.1 Service area boundaries

This study used the drinking water service area boundaries for four states: California (https://gispublic.waterboards.ca.gov/portal/home/item.html?id=fbba842bf134497c9d611ad506ec48cc), North Carolina (https://about.us.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 nonpublic 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. The authors relied on the available spatial boundaries from these four sources and did not adjust or correct perceived spatial boundary inaccuracies. No statewide wastewater or stormwater service area boundaries were found for this study (see below).

2.1.2 Rates data

There is not a publicly available data set 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 are not always made available. 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; Rothstein et al., 2021). 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 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.

Rates data were collected through online searches, prioritizing locating rates on the official website of a utility. The data were entered into a standardized spreadsheet. 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, purchased water, or consent decrees). When rates were not located online, the utility was included in the metadata with “not found” in the column listing the website source. However, only utilities with rates data for both drinking water and wastewater services were included in the analysis.

Importantly, the rates database does not capture customer assistance programs (CAPs) designed to provide short-term assistance for customers struggling to pay their bills; however, these programs are increasingly being used to address chronic water affordability needs.
An estimated 31%–37% of utilities offer any type of CAPs (AWWA, 2019b; EPA, 2016; 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%–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. In addition, the rates data only represent single-family households and do not account for multi-family or rental units with different rates structures.

### 2.1.3 Census data

The spatial data for census tracts and block groups came from the US Census Bureau. The historic population (1990, 2000, 2010) and income (2000) data came from the University of Minnesota's IPUMS National Historical GIS data (Manson et al., 2020), where data are standardized across block groups over time. The population, household, income, and PP of census tracts and block groups were obtained from the Census Bureau’s 5-year american community 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), MHI (B19013_001), and the number of households within each income bracket (B19001 group).

Census tract data for calculating PP included the number of households surveyed (S0101_C01_001) that were below the 200% FPL (S1701_C01_042). The only affordability metric reliant on census tract data was PP. The same PP was applied 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 using a simple area-weighted method described below (included in the online visualization, but not analyzed further here).

### 2.1.4 Utilities included in this study

For this study, rates data were obtained for 1957 utilities, of which 1825 had both drinking water and wastewater rates. There were 34 utilities with missing service area boundaries, resulting in 1791 utilities where both water and wastewater rates were identified within the service area (Table 1). Stormwater rates were identified for 195 utilities (10.8%). The population of utilities in this study ranged from 25 (Harris County Municipal Utility District, Texas) to over 4 million (Los Angeles Department of Power and Water, California). The utilities in this data set served between 65% (Texas) and 92% (California) of each state's total population. Overall, 44% of the utilities in this study were large or very large (serving over 10,000 persons), 25% were medium (serving 3301–10,000 persons), and 32% were small or very small (serving 3000 or less persons). This study includes most large and very large utilities in these states, but medium and smaller utilities are underrepresented because of missing rates data. This may result in under-stating the scale of affordability challenges since price is often negatively correlated with utilities size (i.e., smaller utilities tend to charge higher prices; Teodoro, 2018; Teodoro & Saywitz, 2020).

### 2.2 Analytical approach

Affordability metrics strive to answer two questions (1) what is enough water? and (2) what constitutes undue financial hardship (Goddard et al., 2021; Raucher et al., 2019; Teodoro, 2018)? The typical amount of water considered “enough” for indoor domestic water use in the United States is 50 gal per person per day (Bowne et al., 1994; Raucher et al., 2019; Teodoro & Saywitz, 2020). However, the amount of water used (and billed) varies by household size, age of household, appliance efficiency, irrigation needs, and so on. Previous studies of water affordability used different volumes of monthly water consumption such as 5000 gpm (Van Abs & Evans, 2018), 6200 gpm (Teodoro & Saywitz, 2020), 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 gal per person per day, resulting in an average use of 4030 gpm. However, the average per capita water use in the United States is 82 gal (https://www.epa.gov/watersense/statistics-and-facts), which is considerably more than other countries. Rather than selecting a single volume, bills and affordability metrics were calculated for no water use to 16,000 gpm at increments of 1000 gpm. This allows users to select the volume of water most representative of their residential community 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 IDWS. Most affordability metrics provide some
guidance as to what constitutes undue hardship. The authors 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 (Teodoro, 2018).

2.2.1 | Estimating monthly household bills

Household bills were quantified as the sum of fixed charges, usage charges, and surcharges. Bills also could vary by location within the 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 North Carolina, 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 this 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 utilities, current municipal boundaries were intersected with service area boundaries to estimate which households were billed inside or outside rates. 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, North Carolina provides water to those living inside the Greensboro municipal limits as well as outlying areas (Figure 1). Those living inside city limits were assigned inside monthly rates, which has an estimated monthly bill of $46 for 4000 gpm of use, while those living outside of the city were assigned outside rates (with an estimated monthly bill of $110 for 4000 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.

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

For example, the North Penn Water Authority (Figure 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 Souderton at 4000 gpm. No wastewater rates were identified for two townships. The mean wastewater bills within the drinking water utility service area were calculated where there was missing data and a lack of spatial wastewater service areas. In addition, 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

| TABLE 1 Description of utilities included in the study and the percentage of state population covered |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 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                         | 2871                        | 22.1                       | 15,898                        | 36.2                                       | 91.6                                              |
| North Carolina                | 415                         | 1962                        | 21.2                       | 3656                          | 7.1                                        | 67.7                                              |
| Pennsylvania                  | 330                         | 1883                        | 17.5                       | 8263                          | 9.8                                        | 76.6                                              |
| Texas                         | 412                         | 4616                        | 8.9                        | 5468                          | 18.8                                       | 64.8                                              |
| All data                      | 1791                        | 11,332                      | 8.4                        | 9300                          | 71.9                                       | 78.3                                              |

Note: The total number of utilities is based on EPA Safe Drinking Water Information System data (https://www.epa.gov/enviro/sdwis-model).
different drinking water rates in its service area, with Sellersville having lower rates. The sum of the mean drinking water bill and mean wastewater bill resulted in an estimated total bill of $65 that was applied throughout North Penn Water Authority (Figure 2).

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

2.2.2 Calculating metrics for block groups

Five metrics were calculated 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). The following metrics, plus a new metric—IDWS—described after Table 2, were calculated:

- **Traditional**: measures the financial burden of a representative income (median or 50th percentile) in the community by assessing the portion of income spent on water services for the community’s MHI (EPA, 1995, 1997). This metric is designed for financial capability assessments.

- **Household burden (HB)**: measures the financial burden of a representative income (20th percentile) 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) (Raucher et al., 2019). This metric is designed for financial capability assessments.
### TABLE 2  Metrics considered in this study (HH is households)

| Metric                                      | Description                                                                 | Formula                                                                                                             | Policy usage                                      |
|---------------------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| Poverty prevalence (PP)                     | Percent of households below 200% of FPL. Measures the ability of the community to finance utility costs. | $\frac{\text{HH surveyed below 200\% FPL}}{\text{HH surveyed}}$                                                      | Utility financial capability assessment           |
| Traditional                                 | Percent of median household income paying for water services. Measures the financial burden for a representative income in the community. | $\frac{\text{Annual HH bill} (\$)}{\text{Median HH income} (\$)}$                                                  | Utility financial capability assessment           |
| Household burden (HB)                       | Percent of 20th percentile household income paying for water services. Measures the financial burden for a representative income in the community. | $\frac{\text{Annual HH bill} (\$)}{\text{Lowest quintile HH income} (\$)}$                                      | Utility financial capability assessment           |
| Framework                                   | Combines HB and PP together. Measures the ability of the community to pay and the financial burden for low-income households. | See Table 3                                                                                                         | Utility financial capability assessment           |
| Minimum wage hours                          | Number of hours worked at minimum wage paying for water services. Measures the financial burden for a representative income in the community. | $\frac{\text{HH bill} (\$)}{\text{Minimum wage} \times \text{h}}$                                                   | Household affordability assessment               |
| Income dedicated to water services (IDWS)   | Percent of households in a utility spending x% of income on water services. Measures the prevalence of different financial burdens in the community. | $\frac{\sum (\text{HH with income} < \text{HH Bill} (\$) \times \text{Percent income to water})}{\text{Total HH}}$ | Household affordability assessment               |

*Note: The IDWS, a new metric, is described in detail in the table.
Abbreviation: FPL, federal poverty level.*
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 50 random incomes were generated within that range) and then calculating 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).

- **Minimum wage hours**: measures the financial burden for a single-family minimum wage earner based on the number of hours 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 a higher minimum wage that is not captured here and may change the results of this metric. This metric is used for household affordability assessments.

- **PP**: portion of households within a service area at or below 200% of the FPL (Raucher et al., 2019) (note that this metric is purely derived from census data and does not consider the costs of providing water services or variations in the cost of living within the nation). This metric is used for financial capability assessments.

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).

What constitutes an “undue hardship” is a values-based question and various organizations and individuals have offered different thresholds to provide context for when prices may cause undue hardship. For example, 4.5% of the MHI going to water services has been considered affordable for the community when using the Traditional metric (EPA, 1995, 1997). The initial suggestion for the HB metric was 7% and 10% as indicators that the rates are becoming less affordable for the community (Raucher et al., 2019). Recommendations for PP thresholds suggests that 20% indicates relatively low amounts of poverty, between 20% and 35% indicates moderate amounts of poverty, and greater than 35% indicates high amounts of poverty (Raucher et al., 2019). Teodoro (2018) offered a general “rule of thumb” for policymakers that a four-person household’s basic monthly water and wastewater services bill should not require more than 8 h at minimum wage to be considered affordable.

While these thresholds exist, determining what constitutes “enough” water and “undue” hardship are value-based judgments. Here, results are presented using the number of days of labor required each month as a consistent and intuitive way to provide context to the financial burden shown by the minimum wage hours, traditional, and HB indicators. A day of labor is roughly equivalent to 4.6% of a household’s monthly income. In addition, a proposed (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 3). The authors adopted similar categories of describing burden levels (i.e., low to very high) using the recommended thresholds for PP and the percent of income representing each subsequent day of labor for the HB.

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 financial capability results using the recommended thresholds for the Traditional and HB metrics.

### TABLE 3
Framework combining household burden (HB) and poverty prevalence (PP) to reflect that water services become increasingly burdensome and unaffordable as HB and PP increase

| Household burden by days of labor | Poverty prevalence  |
|----------------------------------|---------------------|
|                                  | <20%                | 20%–35%            | >35%               |
| >2 days (>9.2%)                  | Moderate-high       | High               | Very-high          |
| 1–2 days (4.7%–9.2%)             | Low-moderate        | Moderate-high      | High               |
| <1 day (4.6%)                    | Low                 | Low-moderate       | Moderate-high      |

*Source: Adapted from Raucher et al. (2019).*
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, census block groups and tracts were intersected with service area boundaries. Since census and service area boundaries do not perfectly align, affordability metrics were weighted by the percent of area that intersected 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 (Figure 3). Only one block group was located completely inside the service area boundary of the Hillsborough utility (the remaining overlapped by 0.4%–76%), while the most overlap with a census tract was 55%.

2.2.3 | Calculating metrics for the utility

Block group metrics were aggregated to the service area using a recommended weighting method (Raucher et al., 2019). Here, the number of households was adjusted based on the percent of the block group within the service area (Figure 4). For example, if a block group had 100 households, but only 45% of the block group was within the service area, then the number of households was adjusted from 100 to 45. Next, the total number of adjusted households in the service area was summed and used to weight the metric scores in each block group. For example, in Figure 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 (e.g., an HB score of 4 times 9% gives a score of 0.36). The sum of the metric in each block group becomes the overall metric for the utility.

Adjusted household = Percent of block group in service area \times number of households

Block group weight\_i = \sum \frac{\text{Adjusted Households}}{\text{Adjusted Households}}, \text{where } i \text{ is an individual block group.}

Service area HB score = \sum \text{HB} \times \text{block group weight}, \text{where } i \text{ is an individual block group.}

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 metric for each block group and utility, as well as to estimate the change in population, MHI, and LQI by block group within utility service area boundaries between 2000 and 2019.

2.2.4 | Income dedicated to water services

Most metrics consider the financial burden on a representative income in the community—the LQI or MHI—and assess whether an undue hardship is present 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 experience a low or high financial burden. This metric pivots the question to allow utilities to explore the percent of households sharing different levels of undue hardship. Since the metric can explore several levels of “undue hardship” simultaneously, a distribution could be created to ask, “What proportion of income dedicated to water services is acceptable for what proportion of customers” (Figure 5)? The advantage of this approach is that it does not require selecting a threshold and it provides information on both the breadth and depth of affordability challenges as a continuum.

The continuum of income dedicated to paying for water services was quantified 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 (Figure 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. The number of households estimated to earn less than that amount in a service area could be calculated using census data. For example, the North Penn Water Authority has 2175 (3.9% of total) households earning less than $11,243, thus generating the data point of 3.9% of

![Figure 4](image1.png)  
**FIGURE 4** Aggregating block group metrics to a single metric for the utility. Individual block group household burden (HB) scores were weighted by percent overlap with the utility service area to develop a utility HB score

![Figure 5](image2.png)  
**FIGURE 5** Income dedicated to water service (IDWS) metric. (a) IDWS curve for a single utility. (b) Overlaying an individual utility IDWS curve with other utilities
households spend more than 7% of their income on water services. Combining the burden (% of income spent on water services) with the prevalence (percentage of households spending that much or more) constructs the IDWS for a particular utility (Figure 6).

This method was repeated to estimate the annual income needed for water services to account for 1%–20% of income (Figure 6). Next, incomes were randomly generated for the total number of adjusted households (Figure 4) within each census income bracket. Each income within the bracket was given an equal probability of being sampled with replacement allowed (meaning the same income could appear twice). The randomly generated incomes in each bracket were combined to create a distribution of household incomes in the service area. Finally, the total number of households that earned less than the household income needed for water service bills to account for some percentage of their annual income was counted (Figure 6).

The table in Figure 6 is 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, summary descriptions for collections of utilities can also be estimated (e.g., the median utility; Figure 5b). This approach is not suitable for utilities that serve a small fraction of a single block group; utilities whose service area covered less than 15% of all intersecting block groups were not included (removing 246 utilities).

2.2.5 | Example of metrics calculated for a single utility

This approach calculates each metric for a selected volume of water providing information regarding the community financial capability and household affordability for representative incomes in the community (minimum wage earners to MHI). For example, North Penn Water has a 13% PP (Table 4). At 4000 gal, the financial burden for different slices of the community were: 1.6 h of labor to pay for water services for the median-income household, 3.5 h for the low-income household, and 9 h for a single minimum wage earner. Lastly, 5.3% of households in the utility spend a little more than a day of labor (8.6 h or 5% of income) paying for water services.
2.3 Limitations

There are several limitations and assumptions made around the data. First, rates data were manually collected and are 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). Stormwater utilities were more difficult to locate because they are often embedded within a different department (such as public works or transportation), not present on the website (as some water and wastewater rates are not present on websites), or are embedded within property taxes. The number of stormwater utilities in our study was compared with a survey conducted by Campbell (2020), showing between 72% (CA) and 133% (PA) of stormwater utilities were included. Campbell (2020) notes their survey may be incomplete, allowing for the presence of more stormwater utilities in our rates database. Appendix S1 contains more information about how rates data were collected and quality control. The authors note that rates were more often available online for larger utilities; smaller utilities may not have a website or may not provide rates data online. The results are biased toward the experience of medium to very large utilities.

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 the authors assumed the service areas were commensurate. However, in Pennsylvania, the geographic footprint and administration of drinking water and wastewater services differed. Here, the mean of wastewater bills within the service area of the drinking water utility was used. 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, the average of the estimated bills was used, with the exception of inside-outside rates, although there was not confirmation 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 using on-site treatment (i.e., septic systems). In these instances, homeowner costs to maintain a septic system were estimated (relevant for 28 utilities in Pennsylvania). It may be preferable to exclude these utilities in the future or provide affordability metrics for water services 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 estimate 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.

Fourth, minimum wage hours were calculated using the minimum wage of the state; however, there seem to be few local governments that have adopted higher minimum wages (45 were listed by the https://www.epi.org/minimum-wage-tracker/). This approach will overestimate the minimum wage hours for those localities (only influencing results for California). In addition, none of the metrics account for variability in the cost of living between locations.

Finally, the data collected here are accurate for a specific moment in time. Utilities update rates and change service area boundaries. Residents move and the incomes change. In this study, the authors used the most recently available service area boundaries and 2019 census income data. The rates database has been created over time and the authors collect metadata on the year rates were last collected.

3 RESULTS

There were 1791 utilities with rates and service area data included at the time of this study. All results can be
examined through an interactive dashboard, which visualizes metrics, water rates, and demographic characteristics for different volumes of usage (https://nicholasinstitute.duke.edu/water-affordability/water-affordability-dashboard). The dashboard is 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 Texas and for larger utilities overall (Figure 7). However, the median income decreased for 35% of utilities in California, 44% in Pennsylvania, 49% in Texas, and 70% of utilities in North Carolina. Further, low-income customers experienced a decrease in adjusted income in 54% of utilities (with the median change ranging from 0% in Texas to −7.2% in North Carolina). No discernable trajectories were evident by utility size; however, this may reflect that only utilities providing rates online are included in this database (i.e., missing data are not random with more very small and small utilities not being represented here).

3.1 | Price 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 gpm (Figure 8). The median wastewater bill ranged from $27 at zero usage (reflecting fixed charges only) to $76 at 16,000 gpm. The median total household bill was $51 without any water usage, increasing to $188 at 16,000 gpm. Less than 2% of utilities (27 utilities) exceeded $200 per month at 4000 gpm, 11% of utilities by 8000 gpm, 31% of utilities by 12,000 gpm, and 54% of utilities by 16,000 gpm.

Most water services included a fixed charge and a usage charge; however, the portion of the monthly bill derived from these components (and surcharges) varied tremendously for similar water usage (Figure 9). It was more common for wastewater services to have a single fixed charge (46% of wastewater utilities compared to 6% of drinking water utilities). For drinking water utilities, the median percent of the fixed bill decreased from 89% at 1000 gpm to 21% of the bill at 16,000 gpm. The median percent of the fixed bill for wastewater utilities decreased from 100% of the bill at 1000 gpm to 32% of the bill at 16,000 gpm.

3.2 | Affordability metrics at 4000 gpm

Since the volume of water used directly affected the costs of services, and by extension affordability, the metrics are first compared assuming 4000 gpm, which is near the 4030 gpm recommended by Raucher et al. (2019). The sensitivity of these metrics to changes in volume of water used is then explored. Using 4000 gpm, the combination of metrics provided several distinct insights. First, 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 this study, 77% have a moderate or higher PP and 37.5% had a high PP (Table 3, Figure 10). Indeed, 143 utilities (8%) are serving communities where more than half of the households are below 200% of FPL.

Second, the financial burden for different representative households in the community was compared. The financial burden for the median household was typically less than half a day of labor. The financial burden increased for the low-income household to 0.5–1.4 days of labor. The household with a single minimum-wage earner (based on the state minimum wage) experienced the highest financial burden, spending 0.8–1.6 days of labor per month at 4000 gpm. The median household bill for water services at 4000 gpm was $77 per month, requiring nearly 10 h of labor at minimum wage to pay monthly bills (Figure 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 4000 gpm (Table 5). Utilities in California required fewer hours (median of 7.3 h) largely because the state’s minimum wage is $12/h compared to the $7.25/h used by the other states in this study. Utilities in Texas required a median of 9.4 h 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 h of labor per month, respectively.

Third, the Traditional and HB metrics were highly correlated ($r^2 = .95$, 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, the financial burden varies. The authors found 34.2% of utilities served a community where a low-income household spent

![Figure 8](image_url)
more than a day of labor to pay for services (Table 4). In contrast, only 1.2% of utilities served a community where more than a day of labor was required for median households to pay for water services at 4000 gpm.

Fourth, block group metrics showed considerable variation within utilities. The 1791 utilities intersected 47,479 census block groups, with each utility comprised of between 1 and 2779 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 to see the financial capability of block groups and providing greater granularity on how poverty, rates, and household incomes combine within a utility. Utilities classified with a Low HB at the scale of the entire service area often contained few individual block groups with a Moderate or High HB (Table 6). Utilities with an HB classified as Moderate to High at the service area scale had greater diversity in block group HB classifications.

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 (Figure 1). For example, for Greensboro, NC, the entire utility had a PP of 34% with minimum wage earners spending nearly 11 h to pay monthly bills (Figure 11c). The affordability burden framework (Table 2) indicated the utility as a whole had a low-moderate burden driven by PP (Figure 11c). Within the utility, however, there was clear spatial variability in the affordability framework: 94 of the block groups, particularly those located northwest of the city center, had lower burden than block groups located near the city center (Figure 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.

### 3.3 Income dedicated to water services

The previous metrics provide a snapshot of affordability at a particular income level while the IDWS metric shows the breadth of burden 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, 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 (Figure 12). At the most extreme, 45% of households in one utility spent more than 7% of their income on water services at 4000 gpm (a utility in North Carolina where 49% of the population earned less than 200% of the FPL). 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 (Figure 12); however, the sources of this variability are beyond the scope of this paper.

### Table 5 Percent of utilities classified by days of labor needed to pay for water services for their respective metric at 4000 gpm

| Metric                                      | Days of labor or percent of community | Percent of utilities | Measures                                      | Policy usage                        |
|---------------------------------------------|---------------------------------------|----------------------|-----------------------------------------------|-------------------------------------|
| Minimum wage hours (state minimum wage)     | <1 day                                 | 32.4                 | Financial burden for a representative income in the community | Household affordability Assessment |
|                                             | 1–2 days                               | 60.7                 |                                               |                                     |
|                                             | >2 days                                | 6.8                  |                                               |                                     |
| Traditional (median; 50th percentile income)| <1 day                                 | 98.8                 | Financial burden for a representative income in the community | Utility financial capability assessment |
|                                             | 1–2 days                               | 1.2                  |                                               |                                     |
|                                             | >2 days                                | 0.0                  |                                               |                                     |
| Household burden (HR; 20th percentile income)| <1 day                               | 65.8                 | Financial burden for a representative income in the community | Utility financial capability assessment |
|                                             | 1–2 days                               | 31.5                 |                                               |                                     |
|                                             | >2 days                                | 2.7                  |                                               |                                     |
| Poverty prevalence (PP; below 200% FPL)     | <20%                                   | 23.0                 | The ability of the community to finance utility costs | Utility financial capability assessment |
|                                             | 20–35%                                 | 39.5                 |                                               |                                     |
|                                             | >35%                                   | 37.5                 |                                               |                                     |

Note: A day of labor is equivalent to 4.6% of monthly income. The exception is poverty prevalence, whereby recommended thresholds were used (Raucher et al., 2019).

Abbreviation: FPL, federal poverty level.

### Table 6 Comparison of household burden (HB) metric for utility service areas and their corresponding block groups at 4000 gal

| 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                           |
| 1–2 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                           |

Note: For example, for the 65.8% of utilities had an HB requiring less than a day of labor at the utility-wide scale, 83% of block groups within those utilities had an 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 representing the number of days of labor at the utility-scale.
As noted above, many communities experienced a moderate burden to cover the costs of water services provided by utilities regardless of water usage because of PP (Figure 10). The financial burden for low-income households was less than a day of labor at 88% of utilities when no water is used (Figure 13a; Table 2). As water usage increased, the financial burden increased (utilities move vertically with HB; while PP remained constant since not based on water usage) (Figure 13a–c); the number of utilities with low-income households spending more than a day of labor nearly tripled between 0 gpm (12% of utilities) and 4000 gpm (34% of utilities). Similarly, the number of utilities with low-income households spending more than 2 days of labor doubled for each thousand gallons of water from 2000 (0.8% of utilities) to 6000 gpm (8.6% of utilities) (Figure 13d).

The amount of water needed for basic use is a function of household size. A single-person household using 50 gpd would use 1500 gpm; at this volume, fewer than 19% utilities in this study required more than a day of labor (15 utilities required more than 2 days). However, a four-person household would use 6000 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 (Figure 13d).

Minimum wage earners would need to spend more than 30 days (i.e., a month of labor) to pay for water services over the course of a year when using 4000 gpm for 19 utilities. As water use increased the amount of labor...
hours needed to pay for water services rapidly grew such that by 6000 gpm (~50 gpd for a four-person household), minimum wage earners would spend more than 30 days (a month) each year working to pay for water services at 8% of utilities (Figure 14). By 10,000 gpm, minimum wage earners would spend more than a month each year working to pay for water services at 32% of utilities. 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 (e.g., Teodoro & Saywitz, 2020). This is one part of the equation as even those utilities with identical costs may have dramatically different financial capability depending on the characteristics of the community served. For example, the same monthly bill of $80 could be a low financial burden in an affluent community, while a high financial burden in a low-resourced community (S3 File).

FIGURE 12  Income dedicated to water services (IDWS) results at 4000 gpm 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. CA, California; NC, North Carolina; PA, Pennsylvania; TX, Texas

FIGURE 13  Changes in financial capability by water usage. The burden for the residential community to cover the costs of water service at (a) 0 gpm, (b) 4000 gpm, and (c) 8000 gpm. Only (d) HB changes with volume, while PP remains constant (not shown). HB, household burden; LQI, lowest quintile income; PP, poverty prevalence
The effect of increasing water use on affordability was also evident using the IDWS. Doubling the volume of water used from 4000 to 8000 gpm, the percent of homes spending more than 5% of their income on water services increased from a median of 12%–19% of households in the community (Figure 15). The breadth of households ranged from 5% at 4000 gpm to 8% at 8000 gpm when looking at the percent of households spending more than 10% of their income on water services.

4 | DISCUSSION

4.1 | 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 United States in terms of utility financial capability and household affordability (Goddard et al., 2021; Raucher et al., 2019). Standardizing these metrics has been challenging because defining what constitutes enough water (volume of water used), when is the cost an undue hardship, and for whom varies by community. Rather than advocating for one metric, several metrics were calculated across a range of water usage and provided context for hardship in terms of the number of days of labor needed to pay water bills each month for different representative incomes in the community. 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 PP metric is based solely on census data and demonstrated that many utilities serve communities experiencing widespread poverty (Figures 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 (Goddard et al., 2021; Spearing et al., 2020). In these situations, changing rates or establishing CAPs will not change poverty levels. These utilities might need to look toward other solutions that reduce utility costs, build non-operating revenues, hire and bid locally to stimulate economy, or increase economies of scale (i.e., different forms of regionalization or privatization).

In contrast, the Minimum Wage Hours metric was greatly influenced by rate structures, volume of water used by households, and the minimum wage. Even at 4000 gpm, households relying on a single minimum wage earner typically must work 1–2 days per month to pay for water services (Figures 10 and 14) while low-income and median-income households spend less time working to pay the same bills (Figure 10). Teodoro and Saywitz (2020) found minimum wage earners spent more than a day of labor (10.1 h) paying for water services at 6200 gpm. Our results were comparable, finding minimum wage earners spent 11.7 h per month at 6000 gpm in the median utility. The increased hours could be explained by the growing costs of water services, exploration of different utilities, and differences in the minimum wage of that state or locality. Teodoro and Saywitz (2020) used the minimum wage for utilities in their jurisdiction, which may be above the minimum wage set by the state, which is what was used in this study. The importance of higher minimum wages to reduce the financial burden is highlighted by comparing the median utility labor hours in CA (8.2 h at 6000 gpm with an hourly minimum wage of $12) compared with NC (15.2 h at the federal minimum wage of $7.25).

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. At low volumes, Minimum Wage Hours increased by less than an hour per month from 0 to 2000 gpm, but consistently increased by an hour per 1000 gpm above that volume. The slower increase in Minimum Wage Hours for the first 2000 gpm is likely because many utilities included the first several thousand gallons in the fixed charge; that is, the monthly bill remains the same at lower volumes until the volume of water used exceeds minimum volume included in the fixed fee. Teodoro and Saywitz (2020) found an increased reliance by utilities on fixed costs than volumetric charges, which has implications on the ability for a low-income customer to reduce their water bill. For example, 43% of drinking water rates, and 82% of wastewater rates did not have a usage charge at 2000 gpm. By 4000 gpm, 92% of drinking water rates, and 43% of wastewater rates had a usage charge, thus increasing sensitivity to the volume of water used.

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 parity (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). Even the term “customer” suggests water services are providing an economic good for those who can afford to pay. In addition to rate structures, efforts to help households conserve water and providing CAPs are common solutions for utilities seeking to address affordability challenges for individual households.

The affordability framework measures the financial capability for the community to afford proposed costs of financing capital and operations. While PP placed many utilities into moderate burden levels for affordability (Tables 3 and 4), the HB resulted in utilities with more prevalent poverty to shift from moderate to high affordability burdens as water usage increased (Figure 13d). No utilities with a PP below 20% shifted into a Moderate-High affordability burden until more than 4000 gpm of water were used (Figure 13b,c) 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 3000 gpm of water use (Figure 13d). This 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 6; Figure 11).

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

The median-income, low-income, and minimum wage incomes estimate the financial burden for represented incomes 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 financial 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, in our study, 8% of households spend more than 7% of their income on water services in the median utility (Figure 12). Cardoso and 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. At 2000 gpm, the median utility had 12% of households spending more than 5% of their income (8.6 h of labor) on water services, while at 3000 gpm 14% of households spent more than 5% of their income on water services. By 6000 gpm, more than 21% of households in the median utility spent more than 5% of their income on water services. When this metric was applied to the 12,000 gpm used by Colton (2020) then 35% of households are spending more than 5% 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.

5 | 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 (Colton, 2020; Goddard et al., 2021; Mack & Wrase, 2017; Teodoro & Saywitz, 2020). In addition, many of these studies prioritized certain geographies (e.g., Goddard et al. (2021) focused on California and Van Abs and Evans (2018) focused on New Jersey or were limited to certain utility sizes because of data availability (medium or larger utilities such as in Teodoro & Saywitz, 2020). This 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 PP). More nuanced understandings of affordability challenges enable us to design policy responses that best fit the needs of particular communities.

Making water affordability more transparent is important to improve our understandings of the scale of affordability challenges across and within utilities (Figure 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., CAPs). 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 challenges). The water affordability tool and the open data and open-source code approach developed in this study may help to bring 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) CAPs, (4) water efficiency programs to reduce usage, and (5) crisis relief to protect households from shutoffs (including the newly launched Federal Low Income Household Water Assistance Program; https://www.acf.hhs.gov/ocs/programs/lhhwap). It is important to
consider how to collect data that demonstrates the effectiveness of these different solutions in addressing affordability challenges.

Finally, the 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 (2019–2021). In the future, the authors hope to work with other organizations to develop tools for utilities to directly update their service area boundaries and provide updated water service rates data, thus increasing the number of utilities included, improving rate accuracy, and keeping the data up-to-date and relevant. Future work is needed to incorporate non-residential water users (i.e., commercial, industrial) to better understand the sensitivity of these water users to affordability challenges and their impact on overall utility financial capability.

ACKNOWLEDGMENTS
Spring Point Partners funded this work through their Delta Water Innovators program. Kyle Onda provided guidance on developing the rates databases and Erika Smull provided review of the scripts written to calculate rates and affordability. The work led by Megan Mullin and Katy Hansen to develop updated shapefile boundaries for the state of North Carolina sparked our initial curiosity and interest in developing a statewide approach to explore affordability. This manuscript benefited from detailed reviews by Manny Teodoro, John Mastraccio, Peter Grevatt, and Sri Vedachalam. The performance of the dashboard benefited from work done by Don’t Panic Labs.

CONFLICT OF INTEREST
The authors declare no conflict of interest, whether real, potential, or perceived.

AUTHOR CONTRIBUTIONS
Lauren A. Patterson: Conceptualization; data curation; formal analysis; investigation; visualization; methodology; writing – original draft; writing – review and editing.
Martin W. Doyle: Conceptualization; supervision; funding acquisition; writing – review and editing.

DATA AVAILABILITY STATEMENT
The data and code that support the findings of this study are openly available in the Duke Research Data repository: https://doi.org/10.7924/r4862k514. The live version of data (expanded to include additional states and utilities and updated with more recent rates) that is used in the dashboard is available from our github repository: https://github.com/NIEPS-Water-Program/water-affordability with a CC-BY license.

ORCID
Lauren A. Patterson https://orcid.org/0000-0002-7512-7845

REFERENCES
AWWA. (2001). Reinvesting in Drinking Water Infrastructure: Dawn of the Replacement Era. https://www.tucsonaz.gov/files/water/docs/Dawn_of_the_Replacement_Era.pdf
AWWA. (2019a). Water and wastewater rate survey book (p. 77). ISBN: 9781625763365. https://www.awwa.org/AWWA-Articles/rate-survey-water-cost-increases-outpacing-other-us-goods-and-services
AWWA. (2019b). State of the water industry report. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/2019_STATE%20OF%20THE%20WATER%20INDUSTRY_post.pdf
Baird, G. M. (2010). Water affordability: Who’s going to pick up the check? AWWA, 102(12), 16–23. https://doi.org/10.1002/j.1551-8833.2010.tb11358.x
Beecher, J. A. (2020). Policy note: A universal equity-efficiency model for pricing water. Water Economics and Policy, 6(3), 29. https://doi.org/10.1142/S2382624X20701001
Bowne, W. C., Naret, R. C., & Otis, R. J. (1994). Alternative wastewater collection systems manual. EPA Office of Wastewater Enforcement and Compliance.
Bunch, S., Cort, K., Johnson, E., Elliot, D., & McMordie, K. (2017). Water and wastewater annual price escalation rates for selected cities across the United States. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. Report EOE-EE1670. https://www.energy.gov/sites/prod/files/2017/10/f38/water_wastewater_escalation_rate_study.pdf
California State Water Resources Control Board. (2020). Regionalization approach – Step by step. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/regionalization.html
Campbell, W. (2020). Western Kentucky University stormwater utility survey. SEAS Faculty Publications. Paper 3. https://digitalcommons.wku.edu/sea_faculty_pubs/3
Cardoso, D. S., & Wichman, C. J. (2020). Water affordability in the United States (Working Paper). https://www.diegoscardoso.com/research/water_affordability_US#:~:text=Descriptive%20statistics%20suggest%20that%2013.8,on%20water%20and%20service.
Colton, D. (2020). The affordability of water and wastewater services in twelve U.S. cities: A social, business and environmental concern. The Guardian, 88 pp. https://www.theguardian.com/environment/2020/jun/23/full-report-read-in-depth-water-poverty-investigation
Congressional Budget Office. (2018). Public spending on transportation and water infrastructure, 1956 to 2017. https://www.cbo.gov/publication/54539
Congressional Budget Office. (2020). The distribution of household income, 2017. https://www.cbo.gov/system/files/2020-10/56575-Household-Income.pdf
Copeland, C. (2019). Funding for EPA Water Infrastructure: A fact sheet. Congressional Research Service Report R43871. https://crsreports.congress.gov/product/pdf/R/R43871
Davis, J. P., & Teodoro, M. P. (2014). Financial capability and affordability. In G. Raffelis (Ed.), *Water and wastewater financing and pricing* (4th ed.). Taylor & Francis.

Dig Deep and US Water Alliance. (2019). Closing the water access gap in the United States: A national action plan (p. 85). http://uswateralliance.org/sites/uswateralliance/files/publications/Closing%20the%20Water%20Access%20Gap%20in%20the%20United%20States_DIGITAL.pdf

Doyle, M. W., Patterson, L. A., Smull, E., & Warren, S. (2020). Growing options for shrinking cities. *JAWWA*, 112(12), 56–66. https://doi.org/10.1002/awwa.1634

Environmental Finance Center at UNC-Chapel Hill and the North Carolina League of Municipalities. (2018). 2018 North Carolina water and wastewater rates report. https://efc.sog.unc.edu/sites/default/files/2018/NCLM_EFC_Annual_Rates_Report_2018.pdf

Environmental Protection Agency. (1984). Financial capability guidebook. EPA 000-R-84-101. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000UIW8.TXT

Environmental Protection Agency. (1995). Interim economic guidance for water quality standards. EPA 832-B-95-002. https://www.epa.gov/sites/production/files/2016-03/documents/econworkbook-complete.pdf

Environmental Protection Agency. (1997). Combined sewer overflows – Guidance for financial capability assessment and schedule development. EPA 832-B-97-004. https://www.epa.gov/sites/production/files/2015-10/documents/csofc.pdf

Environmental Protection Agency. (2016). Drinking water and wastewater utility customer assistance programs. https://www.epa.gov/sites/production/files/2016-04/documents/dw-ww_utilities_cap_combined_508.pdf

Federal Reserve Economic Data. (2020). Real median household income in the United States. https://fred.stlouisfed.org/series/MEHOINUSA672N

Goddard, J. J., Ray, I., & Balazs, C. (2021). Water affordability and human right to water implications in California. *PLoS One*, 16(1), e0245237. https://doi.org/10.1371/journal.pone.0245237

Greer, R. A. (2020). A review of public water infrastructure financing in the United States. *WIREs Water*, 7, e1472. https://doi.org/10.1002/wat2.1472

Horowitz, J. M., Igielnik, R., & Kochar, R. (2020, September 1). Most Americans say there is too much economic inequality in the U.S., but fewer than half call it a top priority. Pew Research Center. https://www.pewsocialtrends.org/2020/01/09/trends-in-income-and-wealth-inequality/

Lakhani, N. (2020). Detroit suspends water shutoffs over Covid-19 fears. *The Guardian*. https://www.theguardian.com/us-news/2020/mar/12/detroit-water-shutoffs-unpaid-bills-coronavirus

Mack, E. A., & Wrase, S. (2017). A burgeoning crisis? A nationwide assessment of the geography of water affordability in the United States. *PLoS One*, 12(4), e0176645. https://doi.org/10.1371/journal.pone.0176645

Manson, S., Schroeder, J., Van Riper, D., & Ruggles, S. (2020). IPUMS National Historical Geographic Information System: Version 14.0. http://doi.org/10.18128/D050.V14.0

Nadolny, T. L. (2017, September 7). For low-income residents, Philadelphia unveiling income-based water bills. *The Philadelphia Inquirer*. https://www.inquirer.com/phillyphilly/news/politics/city-for-low-income-residents-philadelphia-unveiling-income-based-water-bills-20170620.html

National Academy of Public Administration. (2017). *Developing a new framework for community affordability of clean water services*. NAPA.

Payne, H. (2021). Unservice: Reconceptualizing the utility duty to serve in light of climate change. *University of Richmond Law Review*, 56, Seton Hall Public Law Research Paper, 52 pp. https://ssrn.com/abstract=3796398

Pennsylvania Department of Environmental Protection. (2009). State water plan principles. https://www.dep.pa.gov/Business/Water/PlanningConservation/StateWaterPlan/Pages/2009-Update.aspx

Pierce, G., El-Khattabi, A. R., Gmoser-Daskalakis, K., & Chow, N. (2021). Solutions to the problem of drinking water service affordability: A review of the evidence. *WIREs Water*, 8, e1522. https://doi.org/10.1002/wat2.1522

Raucher, R., Rothstein, E., & Mastracchio, J. (2019). Developing a new framework for household affordability and financial capability assessment in the water sector. Report prepared for the American Water Works Association, National Association of Clean Water Agencies, and the Water Environment Federation. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/DevelopingNewFrameworkForAffordability.pdf?ver=2020-02-03-090519-813

Rothstein, E., Isaac Berahzer, S., Crea, J., & Matichich, M. (2021). Affordability and equity considerations for rate-setting. *JAWWA*, 113(7), 36–47. https://doi.org/10.1002/awwa.1766

Smull, E., Patterson, L. A., & Doyle, M. W. (2021). Rising market risk exposure of municipal water service providers in distressed cities. *Journal of Water Resources Planning and Management*, 13. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001506

Spearin, L., Osman, K. K., Faust, K. M., & Armanios, D. E. (2020). Systems vary, affordability should not: Trends of water sector affordability based on city attributes. *ASCE Construction Research Congress 2020*. 10 pp. https://doi.org/10.1061/9780784482858.068

Teodoro, M. P. (2018). Measuring household affordability for water and sewer utilities. *JAWWA*, 110(1), 13–22. https://doi.org/10.5942/jawwa.2018.110.0002

Teodoro, M. P., & Saywitz, R. R. (2020). Water and sewer affordability in the United States, 2019. *JAWWA Water Science*, 2, e1176. https://doi.org/10.1002/aws2.1176

Texas Water Development Board. (2020). Water service boundary viewer overview. https://www3.twdb.texas.gov/apps/WaterServiceBoundaries/Home/Overview

Tomer, A., Kane, J. W., Fishbane, L. (2019). To fix our infrastructure, Washington needs to start from scratch. Brookings Institute Report. https://wwwbrookings.edu/research/to-fix-our-infrastructure-washington-needs-to-start-from-scratch/

US Water Alliance. (2017). An equitable water future: A national briefing paper. http://uswateralliance.org/sites/uswateralliance.org/files/publications/uswa_waterequity_FINAL.pdf

Van Abs, D. J., & Evans, T. (2018). Assessing the affordability of water and sewer utility costs in New Jersey. Final Report to Jersey Water Works. 98 pp. https://www.danvanabs.com/uploads/3/8/1/3/38131237/van_abs_and_evans_2018.09.09_phase_1_ assessing_water_sewer_utility_costs.pdf

Vedachalam, S., & Dobkin, R. (2021). H2Affordability: How water ill assistance programs miss the mark. Environmental Policy Innovation Center Report. 40 pp. http://policyinnovation.org/wp-content/uploads/H2Affordability_AssistancePrograms.pdf
Walton, B. (2020, August 5). Millions of Americans are in water debt. *Circle of Blue Article*. https://www.circleofblue.org/2020/world/millions-of-americans-are-in-water-debt/

**SUPPORTING INFORMATION**
Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article**: Patterson, L. A., & Doyle, M. W. (2021). Measuring water affordability and the financial capability of utilities. *AWWA Water Science*, e1260. https://doi.org/10.1002/aws2.1260