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RESEARCH ARTICLE

Keep your head above water: Explaining disparities in local drinking water bills

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Abstract

Rising water bills across the U.S. underscore the need to understand the factors that contribute to disparities in local system bills. In this paper, we examine residential water bill amounts from 1,720 systems in four states in different regions of the U.S. (Arizona, Georgia, New Hampshire and Wisconsin) to (1) examine how local system bills at a constant consumption level (4,000 gallons per month or 15.14m3) for drinking water vary within and across states, as well as within combined metropolitan statistical areas (MSAs), and (2) study the relationship between local system bills and system-level characteristics. We find a high degree of similarity in median bill amounts between states but substantial variation within them at the MSA and local system scale. Our multivariate analysis suggests that municipally-owned systems are more likely to have lower water bills relative to for-profit systems, while factors such as purchasing water and having neighboring systems with high bills significantly correlate with higher water bills. Though we find that water systems with high levels of poverty tend to have higher water bills, our results also suggest that local systems that serve populations with higher levels of income inequality and higher proportions of non-White population tend to have lower water bills. These findings point to future research and data needs to better inform federal, state and local water affordability policy and underline the importance of examining and addressing water affordability at local scales.

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1. Introduction

Over the past decade, rising residential drinking water bills across the U.S. have raised concerns about households' ability to access safe and affordable drinking water services. These concerns have been accentuated further by the COVID-19 pandemic, which has laid bare many of the stark economic inequalities related to accessing water services. In the policy arena, concerns over high water bills have prompted regulators, policy makers and advocates to contextualize bill amounts in water system needs assessments. Local water systems are very fragmented compared to other utility providers; water bills have historically been, and largely remain, a local matter with some state oversight. Understanding local system-level

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characteristics that contribute to variation in water bill amounts can help inform household water affordability policies and address broader environmental justice efforts.

In this paper, we (1) examine how bill amounts at a constant consumption level (4,000 gallons per month or 15.14 m^3) for drinking water vary within and across states and by sub-state region—defined as combined metropolitan statistical areas (MSAs)—and (2) study the relationship between bills and system-level characteristics. We use the most recent data available on residential water bills from four states in different areas of the U.S. (Arizona, Georgia, New Hampshire and Wisconsin). We select these four states in part because of consistency in the most recent year of billing data available in states, consistency in available time periods of data across the states, metro area representation, and the presence of rate data for both drinking water and wastewater. These data are uniquely compiled and made available by the University of North Carolina's Environmental Finance Center (UNC EFC). Notably, the 1,721 water systems with available billing data in the UNC EFC database represents a near census of water systems with greater than 500 connections operating in the four selected states.

Contribution to scholarship

Our study contributes to the literature by examining how bills for drinking water vary within and across states and by sub-state region, defined in terms of combined metropolitan statistical areas (MSAs). Comparisons using these geographic units allow us to account for potential similarities in regulatory environment, climate, water source availability, and other factors that influence bill amounts. To our knowledge, only one previous study, Thorsten, Eskaf and Hughes (2009), takes a similar data collection approach with a near census of systems with available billing data across one entire state in the U.S [1]. Notably, they find that water systems' bills are significantly and positively correlated with bill amounts charged by other nearby systems. Chica-Olmo, González-Gómez and Guardiola (2013) take a similar study approach in Southern Spain and find similar results (2009) [1, 2]. This finding is somewhat intuitive; one might expect relative parity in price levels for an essential service such as drinking water, as is supported for other household staple goods and services.

Our use of a cross-state sample of systems with available billing data complements work by Teodoro and Saywitz, who report trends in drinking water and sewer affordability based on a nationally-representative sample of household water bills, and additional work in certain states by Teodoro [3–5]. Other recent studies analyzing water bills also identify multi-state or national trends in drinking water affordability over time [6–8]. Each of these studies has a slightly different focus and contribution to the literature; we discuss our findings in the context of these studies. One drawback of this literature is that studies either examine affordability in very large systems or use a convenience sample of systems.

Our study differs from other recent analyses in at least three key respects. First, our dataset of systems, as described below, represents nearly all systems that report billing data in four regionally diverse states across the U.S. where the most extensive data are available. This is valuable given that most studies which examine variation in water bills focus predominantly on large systems or small geographies, or use very limited data [9]. For instance, previous comparative bill work in North America is largely limited to individual metro areas—Los Angeles, Chicago, and British Columbia [10–12].

Second, we focus on explaining disparities in bill amounts rather than exceedances of any specifically defined affordability thresholds. We focus on bills to relate water affordability to the broader concept of water poverty, which provides a more holistic assessment of water access [13]. Previous literature acknowledges that water affordability is shaped by local community contexts and social inequalities [13, 14]. In particular, bill amounts interact with city, community, and household factors to influence water affordability and access [14]. We further differentiate our analysis from past studies by identifying bill amounts that are outliers at the low end and the high end of the state and MSA distributions, the former of which could suggest low system financial capacity and the latter of which could suggest customer affordability concerns. We use 4,000 gallons per month as our primary billing comparison point to capture a relatively modest level of household consumption. Prior research on affordability and conservation has also used this threshold for household consumption [7, 15].

Third, in addition to using available system characteristics, we collect data on water quality violations from the Safe Drinking Water Information System (SDWIS), available from the US Environmental Protection Agency, and customer base characteristics from the U.S. Census to jointly explore the relationship between these factors and billing levels for water to an extent beyond that in existing studies. Several studies have shown a relationship between race-ethnicity and water quality outcomes [16, 17]. The relationship between a system's technical, managerial, and financial (TMF) capacity, including its ability to respond to regulatory water quality violations, however, is much discussed and assumed in affordability conversations, but rarely documented empirically [18].

Preview of findings and policy implications

In this study, we find notable local-level variation in bills that differs based on system characteristics. We find that municipally-owned systems are more likely to have lower water bills relative to for-profit systems. Our results also suggest that systems that serve populations with higher levels of income inequality and higher proportions of Non-White population typically have lower water bills. Additionally, factors such as purchasing water and having neighboring systems with higher water bills significantly correlate with higher water bills.

Although our findings have implications for state and national drinking water system assessment efforts, the extent to which these results are generalizable across the U.S. is unclear. Collecting and analyzing bill data from additional states will be essential to assess national trends. Notwithstanding, this study fills a gap in the literature by comparing bill amounts across and within states, and examining the factors that drive variation in water bills across state boundaries [9]. It also calls attention to some system-level characteristics that drive some of the observed variation in bills. As such, the findings of this study provide insight for water system TMF capacity, local economic capacity, and affordability policies. This study also identifies future research and data collection needs to make those efforts more robust.

2. Data

We use data from UNC EFC's rates dashboard as our primary source of data. We combine these data with several other data sources. Notably, we collect additional data on water quality and demographics available from the U.S. EPA and U.S. Census Bureau, respectively. The matching process resulted in some reductions in the total water systems for which data was available, as detailed in Table 1 below. To obtain system-level information on water bills, water quality, and sociodemographics, three sources were combined (see subsections below). Systems lacking data from the source at each step (UNC EFC rate data, SDWIS water quality, and U.S. Census demographics) were removed from analysis, resulting in the final sample. A total of 1,721 systems in the four states contained monthly water or sewer bill data at the 4,000-gallon consumption level in the UNC EFC database—removing systems with only sewer bill data resulted in 1,637 systems. These systems were then matched to water quality violation data available in the U.S. EPA SDWIS database. A total of 1,558 systems had available water quality violation data; the final dataset sample contains water bill, water quality, system structure, and

Table 1. Summary of system data available combing across sources.

Data Type	Number of Systems	Description (Data Source)
Total Systems with Billing Data	1721	Systems with EFC bill data (UNC EFC)
Total Water Systems with Violation Data Available	1558	Systems with EFC bill data + violation data in SDWIS (SDWIS)
Total Water Systems with Rate, Violation, and Census Data Available	1558	All systems matched with a Census Designated Place (CDP). If no CDP is available, the system was matched to County area data.
Total Water Systems with CDP level Census Data	1373	
Total Water Systems with County level Census Data	185	

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customer sociodemographic data for these 1,558 systems. These systems were matched to U.S. Census demographic data based on the "primary Census Designated Place served" listed in the UNC EFC database. If no primary Census Designated Place (CDP) was available, the primary county served was identified from the SDWIS database. Merging census data with the UNC EFC data resulted in 1,373 systems with sociodemographic data at the CDP level and 185 systems with county-level sociodemographic data.

Water rates data

The UNC EFC dashboards are a unique and valuable set of water bill data. First, they are carefully compiled using a refined and well-tested data collection and standardization method. UNC EFC compiles these data primarily for benchmarking and comparison purposes between local systems in a given state. UNC EFC explicitly advises users to "compare [bills] with caution. High rates may be justified and necessary to protect public health." Though we acknowledge the validity of this statement, we also recognize that high rates may create affordability challenges for low-income households and in turn create different public health risks [19]. Second, even compared to other credible state-level and national-bill-level surveys (such as surveys conducted by AWWA-Raftelis and Circle of Blue) and dashboards (Duke's Nicholas Institute), the UNC EFC dashboards provide a near census of all systems with available billing data in a given state. The data contained in UNC EFC's dashboards effectively represent 80–90% coverage of all systems serving 500 or more people and historically have achieved the highest response rate of any such effort. The actual number of community water systems in each state is larger than the number reported in each UNC EFC dashboard (AZ = 742; WI = 1,034; GA = 1,725; NH = 710). This equates to 40% of all systems, but 86% of non "very small" systems serve a population of 500+ (GA = 1,100; WI = 541; AZ = 434; NH = 581). The 500-customer population threshold is the cutoff for EPA's "very small" system designation. Third, the dashboards also provide bill amounts for multiple levels of consumption; this provides a more accurate and consistent estimate of bills than estimates from water systems or household self-reporting. Lastly, they merge in additional valuable contextual information from several sources. This information includes system size, billing cycles, rate structures, and CDP.

As of late 2021, the UNC EFC currently had rates dashboards available for 18 states. All the dashboards employ very consistent, albeit not uniform, methodologies and some contain multiple years of data [20]. For the purposes of this study, we focus on data for Arizona, Georgia, New Hampshire, and Wisconsin (see Fig 1). The UNC EFC made available a near-standardized Excel spreadsheet version of data for each state analyzed, with the exception of Wisconsin. In each spreadsheet, data on most variables available in the online dashboards are available for

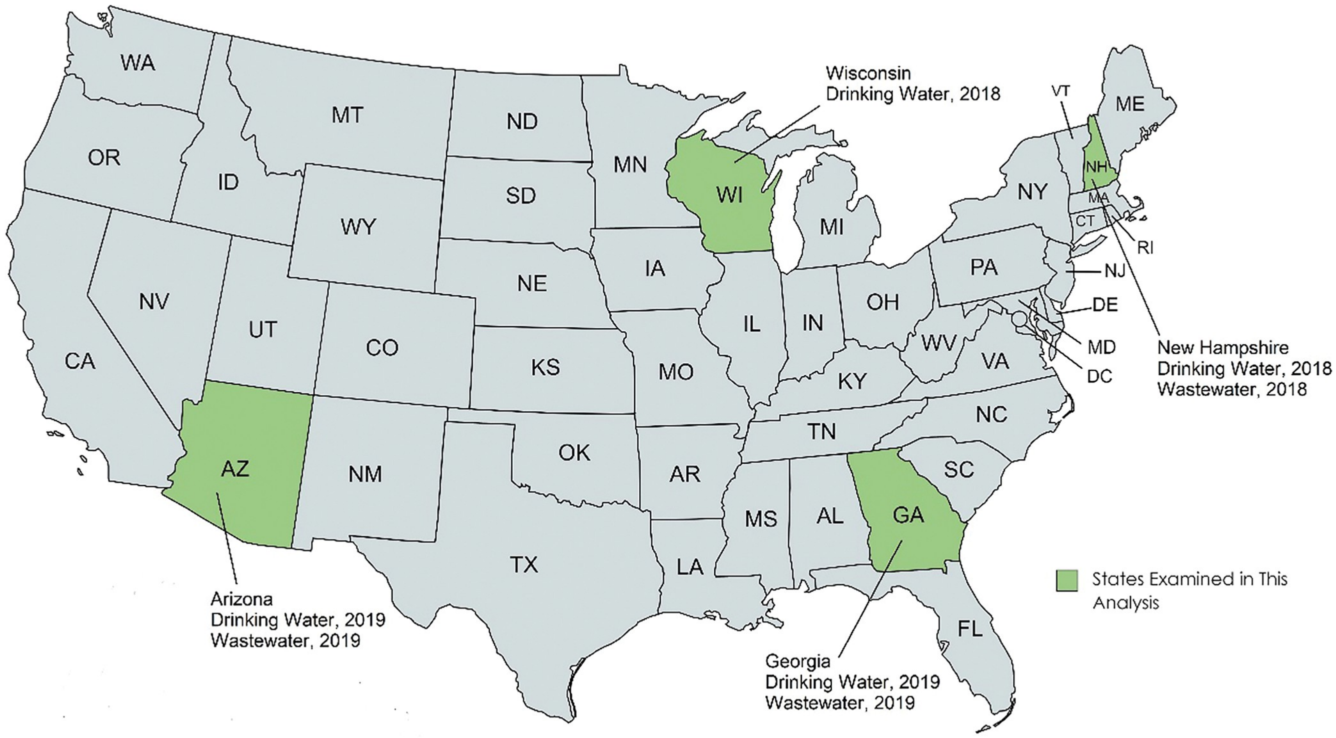

Fig 1. Four states included in this study and data available.

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each system, with one key exception. For Wisconsin, collecting data from the dashboard required manual scraping from PDF forms into Excel.

We focus our analyses on documenting the variation in bill totals at 4,000 gallons of consumption. We examine this variation within and across states and adjacent communities, defined in terms of metropolitan statistical areas (MSAs).

With respect to rate structures, a flat fee or charge refers to systems charging customers a single monthly amount regardless of water use. Uniform rates charge a single volumetric rate per unit of consumption (e.g., the rate is multiplied by monthly consumption). Uniform rates differ from block or tiered rates, in which the volumetric rate changes based on which 'block' of consumption a customer falls in. Increasing-block rates occur when the volumetric rate increases for customers in higher consumption levels, while decreasing block rates charge lower rates for customers with higher water usage. Many systems have bills that include a combination of flat fixed charges and volumetric charges. The flat fixed charge is often called a base charge in this situation, as it is assessed even for customers with no water usage, with volumetric charges (whether uniform or block rates) then included on top of this base charge.

There are clear differences in water rate structures for systems in each state. In Arizona, 73% of systems use increasing-block rate structures, whereas 78% of Wisconsin systems use decreasing-block rate structures, and 75% of New Hampshire systems use uniform rate structures. In Georgia, there is a more even split between uniform rate structures (47%) and increasing-block rates (48%). Flat and other rate structures are uncommon in all four states.

The bill amounts in the UNC EFC dataset reflect monthly-equivalent water bills for the various consumption points. Given that systems use billing structures with differing frequencies, the actual bills customers face in each system may be different. Notwithstanding, the monthly equivalents provide accurate estimates of the amount of monthly expenditure necessary for a household for comparative purposes.

There are significant differences in the method that water systems use for determining fixed charges across states. The majority of systems in Arizona calculate base pricing by meter size (67%), although some use constant pricing (32%). New Hampshire systems show a more even distribution between constant base pricing (48%), pricing by meter size (33%) and no base pricing (19%). Most systems in both Georgia and Wisconsin use constant base prices (84% and 99.7% respectively).

The median water bills at typical consumption points of 4,000 gallons per month are strikingly similar across states. Arizona, New Hampshire, and Wisconsin have nearly identical median water bills ranging $31-$33 whereas Georgia has consistently lower median bills at around $23.

The UNC EFC data also includes key data on water system characteristics, including how each system sources its water. Water systems are classified into three categories: groundwater, surface water, or purchased water. EFC obtains this information from the U.S. EPA's publicly-available SDWIS database. The U.S. EPA categorizes systems as surface water if any of their sources are surface water. Groundwater is the most common water source for water systems across all four states (85% in Arizona, 63% in Georgia, 67% in New Hampshire, 89% in Wisconsin). Purchased water and other sources are uncommon in Arizona (9%) and Wisconsin (4%) but more prevalent in Georgia (19%) and New Hampshire (26%).

The UNC EFC data also include information on ownership structure. System ownership includes four categories: for-profit, municipal, other government, and other. For-profit refers to private systems including investor-owned systems which, depending on the state and size of the system, may or may not be regulated by a state or state-level public systems commission. Municipal refers to city-owned and operated water or sewer systems; while "other government" refers to special districts, county authorities, or joint powers authorities, depending on the state. "Other" encompasses all other system types, particularly mutual water companies that do not fit in the for-profit, municipal, or other government categories. Not-for-profit (e.g., mutual and cooperative water companies), as classified in the EFC database, only accounted for 24 systems total. Due to the very small size of this category compared to the overall sample, these were combined with the 3 systems classified as 'other' into a single other category. The states exhibit similar makeups of ownership type diversity, except for Arizona. Over 50% of all systems in Georgia, New Hampshire, and Wisconsin are municipal; in contrast, 69% of systems in Arizona are for-profit and only 3% are municipal (see Fig A in S1 Text).

Water quality data

Given the lack of readily available water quality data from state-level databases, we queried the U.S. EPA's publicly-available SDWIS search function by state [21]. We then use the system names provided in the EFC database to identify and scrape data system by system [1, 8]. We only consider and scrape violation records data between the years of 2009 and 2020. To determine year of violation, we use the compliance period start date in the SDWIS data. As with rate data, SDWIS data on water violations and system characteristics must also be compared with caution, based on potential missing or incorrectly classified data [22].

For each system (referred to as community water systems in SDWIS) in each of the four states (1,558 systems- see Table 1), we collect and record each violation as an individual row in a spreadsheet to allow for maximum flexibility in analysis by violation type/time period per system. For analytical purposes, we define health-based compliance shortcomings (our primary water quality category of interest) in terms of Maximum Contaminant Level (MCL) violations, Lead Copper Rule exceedances, and treatment technique violations. We also include an additional measure of water quality compliance shortcomings that includes all "monitoring and reporting," "notification", and other miscellaneous violation types. The difference between compliance start and end dates captures length of time out of compliance during the time period of interest. But this was not used as a variable of interest in analysis given variability and degree of missingness in the quality of compliance date entry. While the original intention of the effort was to code the full detail of each violation, it quickly became impossible given some systems (especially in Arizona) have dozens of monitoring and reporting violations; we only coded full detail of each violation for systems with less than 5 violations. Combining these data allows us to study water quality in relation to other system characteristics which may be explored in future studies. In Supplementary Text 1, we provide bivariate correlations between water quality data and system-level characteristics. In this study, however, the primary outcome of interest is the residential monthly bill for water services.

In terms of health violations, most systems (1,158 of 1,558 systems) incurred no primary health-based violations from 2009 to 2020. Resulting health-based violation averages vary from 1 to 2 violations per system for all states, with the lowest average of 1.05 violations per system in Georgia and the highest average of 2.17 violations in Arizona. However, the median number of violations for systems in each state is 0, with several outliers (a maximum of 290 for one system in Wisconsin). Further analysis would be required to ascertain the extent of data limitations from SDWIS violation data. Observed differences in water quality compliance data across states may in part reflect actual compliance variation but also may reflect potential inconsistencies in state programs monitoring compliance or in the way in which violation data were coded and entered between states. Efforts were made to clean data to ensure unique violation entries, but SDWIS data should also be used with caution [22].

Demographic data

We obtain demographic data for each water system using CDP boundaries as the relevant geographic unit. Though geographic information system (GIS) shapefiles for water systems currently represent the best currently available approach (albeit still imperfect) to approximating water system boundaries, shapefiles are only available for the state of Arizona among the four states analyzed [23]. We explore our choice of using CDP boundaries relative to other potential approaches using shapefiles for Arizona (see Supplementary Text 2 for boundary comparisons). This approach follows Berazher et al. in their use of CDP boundaries for water systems in North Carolina [24]. We explored the possibility of using zip codes and geocoding address information but found these approaches to be inferior to our selected method. Using a single valid address for each system (i.e., geocoding) is not a reliable strategy given that the public-facing SDWIS is missing any address for some systems, and some of the addresses provided are out of county or even out of state P.O. boxes [22].

In addition to better approximating geographic boundaries, our use of CDP boundaries confers two additional benefits. First, the choice of CDP boundaries is consistent with collection efforts by the UNC EFC for some of its state dashboards, as well as other recent studies which evaluated similar alternatives [24]. Second, using CDP boundaries allows us to compile and approximately match income and race-ethnicity data from the U.S. Census to characterize the socioeconomic status of customer bases, as well approximate each system's total population, the proportion of population which is Non-White, its median household income, the proportion of its population under 100%, 150%, and 200% of poverty level, and the Gini Inequality Index, which is a measure of income inequality.

We collect socioeconomic data from the U.S. Census (American Community Survey 2015–2019, 5-year estimates) at both the CDP and county-levels: race, ethnicity, median household income, and poverty status. The ACS data for these variables were downloaded using the National Historical Geographic Information System (NHGIS) database [25]. Using these data, we create the following five variables: Non-White population proportion, Hispanic/Latino population proportion, median household income, and proportion of the population under 100% and 200% of the federal poverty level (FPL). We match these census variables to systems using the system's primary CDP, as listed on the UNC EFC dashboard or SDWIS. If the EFC dashboard did not provide a primary CDP/county or one that did not match census data (144 systems), the CDP was obtained from SDWIS. In the event the SDWIS CDP did not match available census data (35 cities), the primary county was used.

Census demographic data was matched to systems based on the primary location served. Where CDPs could not be obtained (no primary CDP served was noted in the UNC EFC data), we supplemented these data with the primary county served from SDWIS codes. We also ran a sensitivity test which excludes systems with county-matched data. We recognize substantial shortcomings with this approach; there is no perfect way to match system customer base demographic data to system boundaries. Any method to attribute population characteristics from the census to small water systems is likely to have a high degree of inaccuracy, given that the smallest census geography at which population characteristic data are available (the block group, serving between 600 and 3,000 people) is larger than any very small systems. For very small and some small systems, only manually-collected socioeconomic characteristic survey data will be sufficient.

3. Methodology and hypotheses

Regression model specifications

Our analysis provides basic descriptive statistics across states to look for general state-level and regional trends for water bills at the 4,000-gallon consumption level. We then estimate a linear model to examine what system-level characteristics most significantly influence water bills. We estimate our model using ordinary least squares linear regression to shed light on the contribution of different system characteristics, including ownership type, rate structure, and water source type to a system's monthly water bill.

To study the factors that influence bill amounts, we estimate the following linear model:

$$Y_i = \alpha + \beta X_i + \gamma_i + \epsilon_i$$

where the outcome of interest Y_i is the total monthly bill amount corresponding to 4,000 gallons of water for residential customers at the system-level. We choose 4,000 gallons as the relevant amount because we argue that it represents a level of consumption that meets the standard for modest indoor household use. In other words, 4,000 gallons allows for essential needs but does not extend to substantial discretionary use (i.e., outdoor irrigation). Monthly consumption of 4,000 gallons reflects roughly 45 gallons (0.17 m3) per capita per day for a three-person household, which represents modest use. The decision to use 4,000 gallons as our main outcome of interest is also motivated by the fact that all systems in the dataset had bill data at that level (some states lacked data at other consumption levels).

We acknowledge that essential indoor needs vary by household size; and some studies find indoor use to be greater in some U.S. metro areas than others [26]. Notwithstanding, our choice of 4,000 gallons is consistent with the range presented in affordability literature which examines bills for "reasonable" levels of consumption. Such previous studies examine consumption levels ranging from 3,000 gallons in North Carolina (Thorsten, et. al, 2009), to 3,740 gallons nationally (5 CCF, commonly used in AWWA-Raftelis surveys), 4,488 gallons in

California (Pierce, Chow and DeShazo, 2020), to up to 6,200 gallons for municipalities across the U.S. (Teodoro and Saywitz, 2020) [1, 4, 19].

The vector X_i represents the following system-level characteristics to explain variation in bills:

- water quality compliance:

○ total number of health-based violations (2009–2020)

○ total number of monitoring and reporting violations (2009–2020)

- socio-demographics of the customer base:

○ proportion of major racial ethnic groups

○ median household income,

○ proportion of population below federal poverty level

- nearest neighbors' cost (i.e., average bill for all other systems in the county of the system and systems in the counties contiguous to the system's county)
- system ownership type: municipal, other government type, private, or other
- system customer base size (i.e., approximated system service population)
- rate structure type: flat, increasing block, other block or uniform volumetric
- presence of a free monthly water allowance (i.e., binary variable where a 1 indicates system provides a baseline water allocation with the fixed charge)
- type of water source: groundwater, surface water, or purchased

Hypotheses

Each of the model specifications includes data on system-level characteristics hypothesized to affect water bills, based in part on similar studies cited in a recent U.S. Government Accountability Office (GAO) report [9]. Despite limited previous research on drivers of variation in bills, we draw on prior studies to generate hypotheses on the expected influence of the system-level variables on system bills.

Hypothesis 1: A review of multiple rate studies by the GAO suggests that public or quasi-public system ownership types (e.g., municipal, other government) will correlate with lower bills than for-profit systems [8, 9]. We anticipate that larger system customer base size will correlate with lower bill amounts based on potential economies of scale [10].

Hypothesis 2: We anticipate that higher nearest neighboring system bills will lead to higher bills, as local similarities to some extent reflect cost and political similarities [1, 2].

Hypothesis 3: We expect that purchased water sources will also lead to higher bills due to the costs of purchasing raw water which may be reflected in the bill price for customers, compared to systems with their own ground or surface water source rights. However, we note that we do not have data on source water quality, which may also impact bills. In particular, levels of salinity or contaminants may increase treatment costs [27]. Geographic or topographical factors can also influence costs of purchased water delivery [9].

Hypothesis 4: While limited, prior research in Michigan and North Carolina found higher bills faced by minority populations; if these trends extend beyond these states we would expect higher proportions of Non-White customer populations to correlate with higher water bills [28, 29].

Hypothesis 5: Finally, we expect household bills to be lower for systems that provide a free baseline allocation of water each month, as customers are not charged for this initial allocation that is a portion of the 4,000 gallons.

The vector γ_i represents geographic controls to assess intra-state variation. Including these fixed effects allows us to examine the influence of system-level characteristics on water costs while taking into account variation due to state location (state-level cost variation). We also estimate an additional specification which includes an additional set of fixed effects that represent local areas. As previously noted, we define local areas in terms of MSAs, using combined statistical areas where applicable. The last term in our model, ϵ_i, represents an error term that captures any remaining unexplained variation.

4. Cross-section variation in system level water bills

In this section, we explore cross-sectional trends in system-level deviation of water bills from the central tendency of local, state and national comparator groups described above. We define "local" in terms of metropolitan statistical areas (MSAs). Where applicable, we use combined statistical areas to account for arbitrary boundaries that separate contiguous MSAs. A little fewer than 25% of all systems considered in this study are not located within an MSA—we label these systems as "non-MSA" for the purposes of analysis and categorize them in a single group of rural systems within each state.

To gain a better understanding of the percentage of systems with high or low water bills, we compute the percentage of bills at "extreme values" at different spatial scales. We define relatively high bill values as above 200% of the average of the comparator group (e.g., MSA, state, or all systems) and relatively low bill values as below 50% of the average of the comparator group. We computed and compared deviations from central tendency within a metro area using medians as the reference point, and the results were largely similar. We also considered a method looking at top and bottom deciles within a metro area but found the artificial bounds this poses on the range of deviation to be less helpful than our primary method.

As shown in Table 2, these ratios are remarkably consistent, irrespective of using the mean bill of the local area, individual states, or the four combined states as the point of comparison. For instance, 8.4% of systems have water bills below 50% of the average of their MSA, whereas 9.1% have water bills below 50% of their state average, and 9.7% have water bills below 50% of the 4-state average. In fact, the distribution of relatively low and high values at each scale is fairly similar to a bottom-top decile approach for identifying values of potential concern.

On the other hand, we document major differences in the distribution of relatively low and high bills using the local area as a comparison group, both across states and by ownership type. As shown in Table 3, bill totals for systems in Wisconsin show the least variance within local areas by far. This difference may reflect the central regulation of ratemaking for all systems by the state's public service commission, a practice which does not occur in other states [30]. Georgia has the highest proportion of systems with relatively low bill values but the second

Table 2. Percentage of systems with extreme household water bills.

Comparison group	Below 50% of average (relatively low)	Above 200% of average (relatively high)
Local (MSA) average bill	8.6%	2.8%
State average bill	9.2%	2.6%
Average bill across all four states	10.1%	4.0%

Source: UNC EFC (2021)

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Table 3. Percentage of systems with extreme water bills by state and ownership type.

Comparison to local average bill	Below 50% of average (relatively low)	Above 200% of average (relatively high)
States		
Arizona	11.0%	3.7%
Georgia	14.4%	2.2%
New Hampshire	9.2%	3.7%
Wisconsin	3.3%	2.1%
Major Ownership Types		
For-profit	11.1%	3.6%
Municipalities	9.6%	3.8%
Other-governmental	8.8%	3.9%
All systems	10.1%	4.0%

Source: UNC EFC (2021)

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lowest proportion of relatively high values. Arizona and New Hampshire have similarly large proportions of relatively high bill values. New Hampshire has the second largest proportion of relatively low values.

Across the three main ownership types, clear trends emerge, especially in terms of relatively high bills. Municipalities are much less likely to have high bills compared to local neighbors and are slightly less likely to have relatively low values as well.

Fig 2 highlights the variation across metro areas for water bills at 4,000 gallons of monthly consumption to gain a better understanding of the distribution of water bills. The spread of each MSA is plotted and visually confirms the findings of on state-level and metro area-level variation in water bills. Despite similar median water bills across states, systems in Georgia have consistently lower mean bills compared to other states. Georgia also exhibits the fewest outlier systems with extreme bills within metro areas. Meanwhile, Arizona demonstrates the most spread of water bills both within and between metro areas compared to other states.

5. Results

In this section, we present the results from estimating our regression model to shed light on factors that explain variation in water bills at the system-level. We estimate two specifications that include different sets of fixed effects; the first specification includes controls for the state where a water system is located while the second controls for the MSA in which the system is located.

In our primary set of results, presented in Tables 4 and 5, we exclude systems with socio-demographic characteristics that are not matched to CDP areas (i.e., County information). In Table 4 we estimate a version of our model using the federal poverty limit as a measure of poverty whereas in Table 5 we use Gini index to capture income inequality. In Supplementary Text 3, we estimate several additional versions of our model as sensitivity checks, including versions of the model that include all water systems. The results from these additional analyses support our main set of results in Tables 4 and 5. In Supplementary Text 4, we estimate our main model restricting the data to water systems in Arizona to explore the effect of matching systems to CDP (Table A in S4 Text) as compared to water system boundaries (Table B in S4 Text). The results of these regressions qualitatively support those shown in the Tables 4 and 5, though point to the need to better ascertain water system boundaries.

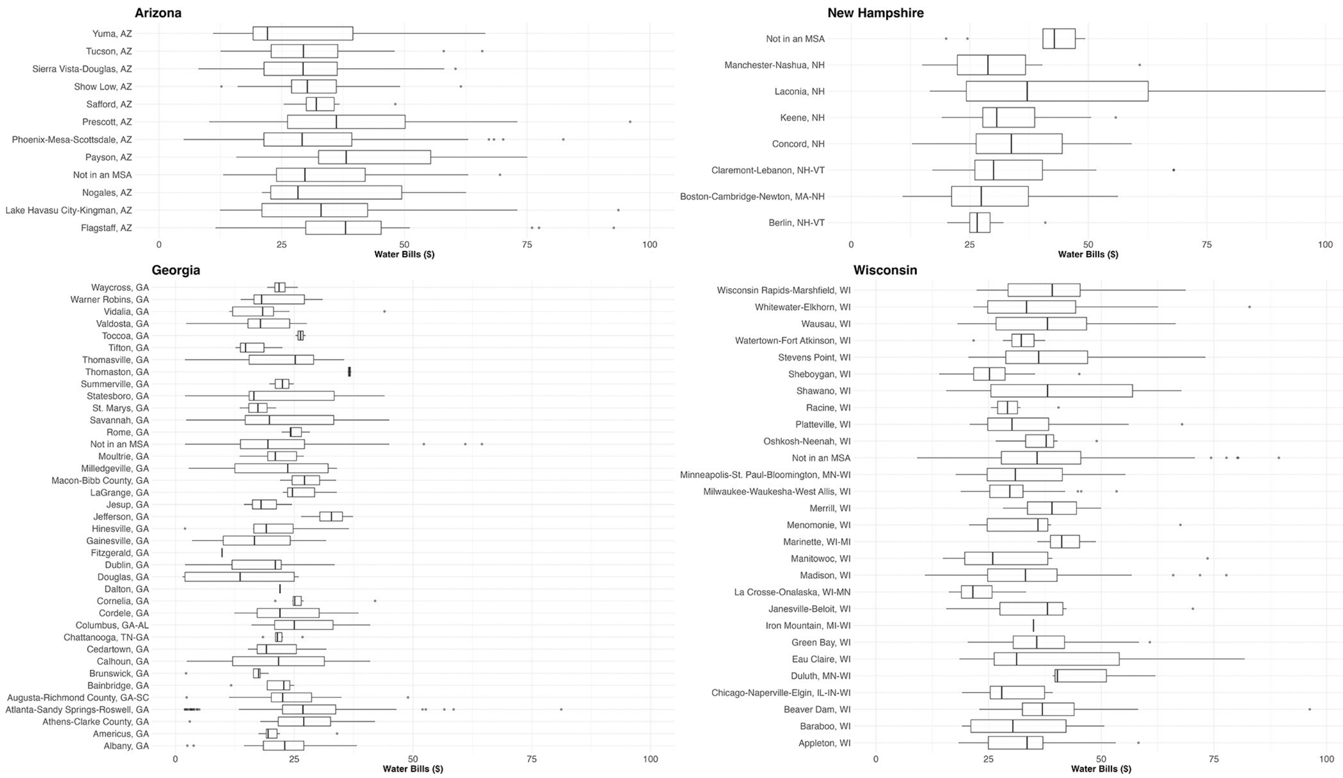

Fig 2. Distribution of water bills at 4,000 gallons per month by metropolitan statistical area in each state. Notes: Data for the figure is derived from UNC EFC (2021).

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We find that several factors we include in the model are significant in explaining variation in the cost of water. Significant correlates include nearest neighbors' bills, ownership type (municipal as compared to for-profit), monthly allowances, service population, income inequality, percentage of Non-White population, and source water (purchased as compared to the baseline of groundwater). Significant correlates do not vary between the model controlling for state location and the model controlling for metro area location, except with respect to the presence of tiered rate structure.

Influence of system characteristics

In support of Hypotheses 2 and 5, water bills are significantly higher among systems where neighboring systems charge more for water and significantly lower for systems that provide a baseline monthly allocation of water [1, 2]. Table 4 demonstrates that, when controlling for state location (fixed effects) and holding all else constant, a $1 increase in the average monthly bill for 4,000 gallons by neighboring systems will predict a $0.80 increase in average monthly bill for a system. Meanwhile, the presence of a baseline monthly allocation of water (some water provided without charge) predicts a decrease of $4.73 for a system's monthly bill level for 4,000 gallons, holding all else constant. These effects are slightly stronger when the local MSA of a system is controlled for instead of the state in Table 5 ($0.96 increase and $4.94 decrease for an increase in neighboring water bills or a monthly allowance respectively). Additionally, municipal systems tend to levy significantly lower water bills than for-profit systems (the baseline of for-profit systems is not included as a variable in the model to enable comparison) [6]. The "other" category for government ownership type was not a significant correlate

Table 4. Correlates of water bills at 4,000 gallons using gini index.

	Water Bill Amount 4k Gallons	
Cost of 4k Gallons in Neighboring Systems	0.852*** (0.087)	0.778*** (0.238)
Ownership: Municipality	-3.933** (1.806)	-4.409** (1.952)
Ownership: Other	1.506 (3.475)	0.973 (3.335)
Ownership: Other Government Type	-1.308 (2.150)	0.180 (2.367)
Includes Monthly Baseline Allowance	-3.485*** (0.936)	-3.833*** (1.148)
Total Health-Based Violations	0.057 (0.080)	0.056 (0.090)
Total Monitoring and Reporting Violations	-0.003 (0.006)	-0.005** (0.006)
Proportion Population Non-White	-1.525 (2.318)	-2.223 (3.349)
Gini Inequality Index	-5.795** (5.954)	-0.138 (8.069)
Service Population (Standardized)	-1.181** (0.392)	-1.145*** (0.426)
Rate Structure: Flat	1.490 (3.609)	3.312 (5.264)
Rate Structure: Increasing Block	-1.168** (1.548)	-1.849** (1.852)
Rate Structure: Other block type	-1.089 (2.016)	-2.385** (2.765)
Rate Structure: Uniform Volumetric	-0.499 (1.374)	-2.201** (1.539)
Source: Purchase	2.436** (1.159)	2.483** (1.368)
Source: Surface	0.374 (1.298)	0.795 (1.576)
Constant	7.902** (4.568)	12.726** (10.279)
Spatial FE	State	MSA
Observations	1,308	946
R2	0.274	0.245
Adjusted R2	0.263	0.185

Note: Robust standard errors clustered at the water system level are in parentheses. Service populations are standardized by demeaning then normalizing using standard deviation. *p<0.1; >**p<0.05; >***p<0.01

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in the model compared to the for-profit system type baseline. In support of Hypothesis 1, a larger service population is associated with significantly lower bills. We also find that water systems that purchase water sources have significantly higher bills than systems with groundwater sources, which supports Hypothesis 3. This is demonstrated by the values in Table 4 and 5; all else constant, when a system purchases water as its main source, the model predicts an increase in the monthly water bill for 4,000 gallons of $1.78 or $2.14 depending on fixed effects (controlling for a system's state or MSA respectively).

The presence of a tiered water rate structure is also significantly negatively correlated with bill amounts in the model. While further research is required to assess the reasons behind this

Table 5. Correlates of water bills at 4,000 gallons usage using federal poverty limit.

	Water Bill Amount 4k Gallons	
Cost of 4k Gallons in Neighboring Systems	0.868*** (0.094)	0.782*** (0.238)
Ownership: Municipality	-4.362** (1.813)	-4.944** (1.972)
Ownership: Other	0.915 (3.485)	0.205 (3.406)
Ownership: Other Government Type	-1.686** (2.165)	-0.367 (2.394)
Includes Monthly Baseline Allowance	-3.467*** (0.939)	-3.757*** (1.15)
Total Health-Based Violations	0.055 (0.078)	0.051 (0.085)
Total Monitoring and Reporting Violations	-0.003 (0.006)	-0.005** (0.006)
Prop. Population Non-White	-1.682 (2.659)	-2.722 (4.502)
Proportion Population under 100% of Federal Poverty Limit	2.294 (4.474)	10.198** (7.175)
Service Population (Standardized)	-1.212** (0.409)	-1.161** (0.444)
Rate Structure: Flat	1.57 (3.629)	3.809** (5.361)
Rate Structure: Increasing Block	-0.939 (1.558)	-1.447** (1.887)
Rate Structure: Other block type	-1.02 (2.016)	-2.26** (2.74)
Rate Structure: Uniform Volumetric	-0.518 (1.38)	-2.238** (1.542)
Source: Purchase	2.495** (1.173)	2.598** (1.373)
Source: Surface	0.213 (1.291)	0.653 (1.562)
Constant	4.943** (3.912)	10.969** (8.894)
Spatial FE	State	MSA
Observations	1,310	948
R2	0.272	0.245
Adjusted R2	0.261	0.186

Note: Robust standard errors clustered at the water system level are in parentheses. Service populations are standardized by demeaning then normalizing using standard deviation. *p<0.1; > **p<0.05; > ***p<0.01

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trend, this does follow prior research that finds increasing block rates for water may improve water affordability [31]. Often increasing block rates include a 'lifeline' or lower rate for lower levels of consumption, thus modest levels of usage (e.g. our selected threshold of 4,000 gallons) may result in lower bills than the same usage under certain flat or decreasing block rate structures [32]. In the regression models, the use of an increasing block rate structure predicts a system will have a $2.44 or $2.85 decrease in monthly bill when controlling for state or MSA system location respectively (all else constant).

Influence of demographic variables

However, higher income inequality, which is highly correlated with a greater proportion of Non-White population (see Supplementary Text 1), is significantly associated with lower bill amounts. Higher Non-White population in our model is significantly associated with lower bills, contrary to our expectation (Hypothesis 4) after controlling for other factors. Table 4 demonstrates that, holding all else constant, a 1% increase in the proportion of Non-White population served by a water system predicts a decrease of $6.38 or $6.27 in the system's monthly water bill for 4,000 gallons, when controlling for the system's state and MSA respectively.

Influence of water quality and monitoring variables

We did not find evidence of water quality violations, either health or procedural, influencing bill totals. We do note, however, that the proportion of Hispanic/Latino residents served by a system is significantly positively correlated with more health violations (see results of bivariate correlations in Table 1 in S1 Text). This finding echoes existing research regarding potential inequities in water quality by race and ethnicity [23]. Similarly, we do not find significant associations between health-violations and system size (i.e., service population). The relationship is positive and non-significant, despite evidence that smaller system size predicts more health violations than much larger systems [10, 33]. Further research is required to better assess the relationship between water quality and bills; as noted above, there may be differences in how systems and regulators monitor, report, and enforce water quality violations among states which may impact the data and ultimate correlations.

6. Discussion

Review of results and contributions

In this study, we compile data on water system bills from four states to analyze variation in local bills at modest levels of consumption (4,000 gallons). We then examine characteristics of systems and water bills across the four states selected for analysis: Arizona, Georgia, New Hampshire, and Wisconsin. Though median bill amounts for drinking water are similar across all four states, we find major differences in bills within regional and local areas, influenced by system-specific characteristics.

We find large variation in bill amounts at each geographic scale that we analyzed, including within MSAs. Variation in water bills across systems can in part be explained by system ownership type, size, water source, rate structure, and the bills of neighbors, as well as race-ethnicity and income inequality of customers. Municipal ownership type, larger service population, and a baseline monthly allowance of water all predict systems with lower bills, supporting hypotheses from existing studies. Additionally, we find that, as hypothesized, higher bills of nearby systems and using purchased water as the main water source predicts higher bills for a system. Our results suggest that water systems with high levels of poverty have higher water bills. Counter to our expectations, including evidence from previous studies, our results also suggest that local systems that serve populations with higher levels of income inequality and higher proportions of non-White population typically have lower water bills. These relationships, however, appear to be relatively weak statistically, and thus deserve further scrutiny. Overall, our finding that some system characteristics are strongly correlated with water bills has important implications for policy interventions in the context of evaluating systems' TMF capacity, as well as customer affordability, and community environmental justice outcomes.

Limitations and future directions

Much of the variation in bills, however, remains unexplained in our modeling. One potential reason for the unexplained variation is limited water system-specific data. Comparisons with existing available data sources require 'caution' [20, 22]. We could not capture all drivers of water costs nor could we consider historic drivers of water rates since our bill data is derived from a single point in time. Other potentially interesting variables, suggested by Teodoro and Saywitz and the UNC EFC, for example, are not readily available for collection and matching at the local system level but may be collectible for pilot analyses for individual or small groups of states [4, 34]. These include system capital replacement rates; receipt of general fund, state, or federal assistance; physical and uncollectible non-revenue water levels; customer class composition ratios; staffing levels and compensation; and quality treatment requirements. Recent efforts by researchers have resulted in the Municipal Drinking Water Database (MDWD) which may prove useful for capturing such variables at the water system level [35]. The MDWD contains variables on water system revenues, expenditures, and capital outlay, although initial review finds numerous systems in the UNC EFC database missing from the MDWD. A null finding regarding water quality compliance and bills, despite multiple specifications, also deserves further exploration, particularly to understand links between water affordability and access to safe, clean water. With respect to water quality, another avenue for future research would include a comparison of pre and post pandemic situations as several recent studies have observed that water quality improved during periods when lockdown measures were in place [36–40].

Our study expands upon previous work examining variation in water bills at the state and metro-specific levels and provides additional insight which can inform future policy efforts. This study does not, however, provide definitive answers on the best metrics to compare intra-MSA bill variation at the low or high end, or factors contributing to this variance. Local water bill amounts have historically been, and largely remain, a local matter with some state oversight. While we find consistent averages across states, we find very high levels of bill variation at the local and regional scales. Significant variation in bill amounts, as opposed to water quality—where the Safe Drinking Water Act imposes common minimum standards—is inevitable and may be justifiable. Most of the correlates of high bills which we identify are not conducive to direct policy reforms. Notwithstanding, extreme disparities may justify policy efforts from states to promote consolidation, evaluate TMF capacity, provide customer assistance, or implement rate revision guardrails. Regardless of the extent to which policymakers seek to intervene to address local bill disparities, understanding this variation is an important step in the context of affordability and larger environmental justice efforts.

7. Conclusion

Overall, our analysis helps fill an ongoing gap in national studies of water bills that consider the influence of system-level, local, and regional factors on water system TMF and customer affordability, as well as helps inform ongoing efforts to expand data collection and needs analysis efforts nationally. Broad implications of the study include, first, that lifeline rates and inclining block rates can help address water affordability challenges. Second, when developing a state or federal low-income water affordability or assistance program, policy makers must account in their program design for the huge variability in local water bills. Third, consolidation of small water systems may, in appropriate cases and with robust community engagement and buy-in, help reduce bills for essential water service. Fourth, when privatization of a publicly-owned water system is under consideration, there must be a careful consideration of impacts on water bill affordability. Fifth, state oversight of local water rates may contribute to greater equity in water expenditures across communities. Sixth, understanding bill amounts can help state and federal agencies prioritize communities for receipt of financial and technical assistance.

Last, but not least, the results from this study motivate an effort to expand the states included in data collection and analysis. We selected the four states based on data collection method and timing consistency, as well as geographic diversity within the U.S. However, the four states we examine differ in terms of climate and geography and have substantially different metropolitan area profiles. More importantly, these states cannot be considered representative of the entire U.S. Though expanding to include additional states with UNC EFC-collected data appears feasible, it appears highly unlikely that other national association and states' ad hoc system bill collection efforts, such as in California and New Jersey, will be consistent, accurate, or extensive enough to be included in a master dataset. A unified database on residential household system bills would be useful, perhaps by combining rates dashboard efforts by the UNC EFC—which still offer by far the most coverage, reliability and flexibility of any multi-state source—with more recent efforts such as those at Duke's School of the Environment [7]. Reforms to address SDWIS data and include bills may also be a unique opportunity to create a more comprehensive database of water systems [22]. While we recognize several ongoing efforts may yield great progress along these fronts, in terms of improved understanding of water system structures and governance, ongoing and future national and multi-state analyses could greatly benefit from better national system spatial location information and more efficient ways to incorporate SDWIS data [9].

Supporting information

S1 Text. Water system ownership and correlations with local factors.
(DOCX)

S2 Text. Comparison of methods to match water system boundaries.
(DOCX)

S3 Text. Multivariate regression sensitivity analyses.
(DOCX)

S4 Text. Arizona only models.
(DOCX)

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