# Geographies of insecure water access and the housing–water nexus in US cities

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**Safe, reliable, and equitable water access is critical to human health and livelihoods. In the United States, an estimated 471,000 households or 1.1 million individuals lack a piped water connection and 73% of households are located in cities, close to networked supply. In this study, we undertake a nationwide analysis of urban water access in the United States, with the aim of explaining the drivers of infrastructural inequality in the 50 largest metropolitan areas. Drawing on statistical analysis and regression modeling of census microdata at the household scale, our analysis reveals spatial and sociodemographic patterns of racialized, class-based, and housing disparities that characterize plumbing poverty. Among unplumbed households, we show that households headed by people of color are almost 35% more likely to lack piped water as compared to white, non-Hispanic households. Precarious housing conditions are an equally strong predictor: Renter-occupied households in the 50 largest US metros were 1.61 times more likely than owner-occupied households to lack piped water. We argue that insecure domestic water access in the United States should be understood as a housing issue that reflects structural inequalities of race and class, particularly in cities with widening wealth gaps. The article concludes with a call for research and action at the intersection of water provision, housing, and social inequality—a paradigm we call the housing–water nexus.**

household water insecurity | infrastructure | housing | sustainability | cities

Safe, reliable, and universal water access is critical to human health and livelihoods, a principle enshrined by the United Nations Human Right to Water and Sanitation and government policies in contexts as diverse as South Africa to the state of California. Despite progress toward United Nations Sustainable Development Goal 6—the goal of water and sanitation for all by 2030—an estimated 785 million people worldwide still lack basic water access in their homes (1). A lack of reliable water access hinders essential practices like drinking and cooking (2, 3); causes physical ailments such as dehydration, injury, and diarrhea (4–6); triggers stress, anxiety, and mental health problems (7–13); and impedes basic hygiene practices—such as frequent and thorough hand-washing—that are essential to good health and disease prevention (14–16). Transmission of highly contagious diseases, such as COVID-19, can be accelerated simply because people do not have secure access or adequate supply of tap water at home (17, 18).

Water insecurity and access problems are not confined to the global South. New and emerging research indicates alarming problems of insecure water access, quality, affordability, and trust experienced by households in Canada and the United States, despite sophisticated water governance systems and a history of ostensibly "universal" network coverage (19–23, 23, 24). We find that, in the United States, one of the world's wealthiest nations, an estimated 1,121,100 people (±25,500 margin of error [MOE]) lacked a household piped water connection between 2013 and 2017. While the proportion of US households without piped water access is small (0.3%) relative to the national population, the total number of people living in plumbing poverty is equivalent to the nation's seventh largest city—a population roughly the size of San José, California.

Who (and where) is left behind in the promise of universal water provision? In the United States, households without secure water access are more likely to be low-income, nonwhite, renter, and immigrant (21, 24–29). Nationwide, research suggests that water access problems are greater in certain types of housing (24, 30). In California, for example, mobile home parks are more likely to incur poor access, service shutoffs, and health-related violations than any other kind of housing stock (31). People without stable or conventional shelter routinely experience punitive barriers to water and sanitation access, forcing them to rely on dangerous, expensive, or unsafe options (32–35). Barriers to safe water access in the United States are further compounded by problems of aging and deteriorating infrastructure (36), unaffordable water bills and high shutoff rates (27, 37), and impaired water quality (25, 29, 38, 39). The water poisoning crisis in Flint, Michigan—set into motion by fiscal austerity measures adopted by an underfinanced and debt-leveraged municipal government—suggests that water provision to largely Black and brown communities has been devalued and subordinated to the goals of fiscal solvency in ways that exacerbate social inequalities and threaten lives (20, 40–42).

In this study, we undertake a nationwide analysis of urban water access in the United States. Cities are important sites of inquiry, as the United States is an urbanized nation. We take the central lesson of Flint—that certain populations are being left behind in water provision—and examine the character and prevalence of infrastructural inequality across the top 50 largest

## Significance

**Secure water access is a fundamental human right. Our study reveals disparities in piped water access in urban areas in the United States. From 2013 to 2017, we find that an estimated 1,121,100 people (±25,500) in the United States had insecure water access, with nearly one-half (47%) located in the 50 largest metropolitan areas. Unplumbed households in cities, on balance, are more likely to be headed by people of color, earn lower incomes, live in mobile homes, rent their residence, and pay a higher share of their gross income toward housing costs. We offer clear evidence that gaps in urban water access are neither random nor accidental but underpinned by precarious housing conditions and systemic social and racialized inequality.**

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metropolitan areas in the United States, where more than one-half of the national population lives. Specifically, we used a multivariate weighted logistic regression model to predict whether a household has piped water access (the dependent variable), using microdata collected by the US Census Bureau in their annual American Community Survey (ACS) survey. Our research identifies the housing–water nexus as a crux of infrastructural inequality and worthy of urgent policy attention.

In so doing, this study breaks ground in two main ways. First, we take a data-driven approach to identify the social and geographic dimensions of infrastructural inequality. Water access refers to how water is physically delivered or obtained (1). Piped water is the least costly method to transport and deliver water in densely populated areas—thus, service provision should be, in theory, readily available and fully universalized in cities. Our study probes this assumption and advances insights on the urban and demographic aspects of household water insecurity in US metropolitan areas, including some of the most affluent cities in the world.

Second, we introduce the housing–water nexus as a way to understand the entrenched nature of urban water insecurity. Our model posits a theory of household water insecurity as a relational condition that is produced, in part, by racialized wealth gaps that are expressed through the unequal geographies of housing. Water and housing should be understood as fundamentally interlinked sectors that do not exist outside of the institutionalized and systemic practices of racial capitalism. Specifically, we argue that disparities in secure water access in US cities are produced at the juncture of housing policy, water management, and entrenched social inequality—the housing–water nexus, a paradigm of future research and action.

## Results

**Water Access Is an Urban Problem.** Who and where are the plumbing poor in the United States? Between 2013 and 2017, we show that 471,000 households (±5,600) lacked a piped water connection in the United States, with the majority (73%) located in metropolitan areas and nearly one-half (47%) in the 50 largest metropolitan areas, a figure that tracks closely with the national population distribution (87% urban; 13% rural). Within the 50 largest metros, an estimated 220,300 (±5,700) households or 514,000 (±17,600) individuals lacked piped water access in their homes (Table 1).

Plumbing poverty is unevenly distributed across the country, with prominent clusters in large urban areas and certain regions (Fig. 1). Regions where unplumbed households are higher in absolute numbers include the urbanized corridor along the Eastern/Mid-Atlantic seaboard, the upper Midwest and Rust Belt, greater Appalachia, south-central Florida, Texas (including its major cities and the South Texas region), the lower Mississippi Delta/Louisiana Bayou, the Four Corners region (including the Hopi Reservation and Navajo Nation), most of Alaska, and major West Coast cities.

Unplumbed households are present in all major US cities (Fig. 2), but the problem is most acute for Sunbelt cities in the South and West. For example, 19 out of the top 50 metropolitan areas exceed the all-metro average rate (0.3%) for no piped water access (Fig. 2 and Table 1). Out of these 19 metros, 7 are located in the South, 7 are in the West, and the remaining 4 are split evenly across the Midwest and Northeast regions of the United States.

In contrast to the case of Flint—a city with struggling finances and a low tax base—we find that some of the most affluent cities in the United States have the highest shares of plumbing poverty (Table 1). Out of the 50 largest metropolitan areas, San Francisco has the highest proportion of households and individuals without piped water (0.9%, ±0.1%), followed by Portland (Oregon), Milwaukee, San Antonio, and Austin. In terms of total numbers, the New York metropolitan area is home to the largest number of individuals without piped water access, at 65,000 people in total (±5,100), followed by the Los Angeles metropolitan area with 44,200 people (±4,400), and the San Francisco metropolitan area with 27,400 people (±3,300).

**The Housing–Water Nexus.** What household conditions and characteristics are linked to insecure water access? Compared with the overall US population, we find that unplumbed households are more likely to be headed by people of color, earn lower incomes, live in mobile homes, rent their residence, and pay a higher share of their gross income toward housing costs (Table 2). Within the 50 largest US metropolitan areas, nearly 40% of households are headed by people of color (39.3 ± 0.1%). Among urban households without piped water, however, more than one-half of households (52.9 ± 1.3%) are headed by people of color. Put differently, more than 5 in 10 unplumbed households are headed by individuals of color, despite making up a collective fewer than 4 in 10 households among the top 50 largest metros.

Our findings show that unplumbed households are more likely to lack the financial resources or housing tenure to improve their plumbing conditions (Table 2). In the 50 largest US metropolitan areas, the median household income among all households ($65,000 ± $200) is almost double that of unplumbed households ($33,200 ± $1,400). Cost-burdened households pay more than 30% of their gross income to housing costs (e.g., rent or mortgage), as defined by the US federal government. While just over one-third of urban households in the United States are cost-burdened, nearly half (48.2 ± 1.4%) of unplumbed households are cost-burdened. Finally, our analysis shows that 39.8% (±0.1%) of all households in the United States rent their homes compared to 61.4% (±1.5%) of unplumbed households. In other words, renter-occupied households represent 4 in 10 of all households in the largest urban areas; among households without piped water access, more than 6 in 10 are renters.

**Modeling Household Trends.** Our initial foray revealed racialized and class-based disparities in household water access in US cities. To investigate the housing–water nexus in greater depth, we developed a statistical model to elicit social, demographic, and housing trends of water access across the 50 largest US metros (Table 3). Conceptual development of the model is discussed in detail at the end of this article (*Methods*). Briefly, we used a multivariate weighted logistic regression to predict whether a household has piped water access (the dependent variable), which is measured as "complete plumbing" by the US Census Bureau. Complete plumbing is currently defined as 1) piped hot and cold water, and 2) a bathtub or shower, all located within the housing unit and used only by occupants. To form the theoretical basis of our model, we started with a set of demographic, socioeconomic, and housing-specific variables that are conceptually relevant and statistically significant in shaping water access in high-income countries, as reported by emerging literature in this area (21, 22, 24, 26, 27, 30, 39, 43–46).

Our model posits a theory of insecure water access as a relational condition that is produced, in part, by racialized wealth gaps and unequal geographies of housing. This approach advances calls to specify the "social relations of access" (47) and improves methodological efforts in two ways (43, 47). First, our model adds three indicators that capture the contextual and geographic environment of unplumbed households. Specifically, we incorporate the cost-burdened status of each household, as well as income inequality and racial segregation as fixed effects in the model. Income inequality, as measured by the Gini coefficient, is a measure of wealth in relation to poverty (and vice versa); the index of dissimilarity measures racial segregation; and cost-burdened status (using the Housing and Urban Development

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**Table 1. Number of households and people without piped water in 50 largest US metros**

| | Households | | | | Individuals | | | |
|---|---|---|---|---|---|---|---|---|
| Metro area | Estimate | MOE (±) | Share, % | MOE (±), % | Estimate | MOE (±) | Share, % | MOE (±), % |
| San Francisco | 14,787 | 1,375 | 0.9 | 0.1 | 27,395 | 3,289 | 0.6 | 0.1 |
| Portland | 4,801 | 933 | 0.6 | 0.1 | 10,064 | 2,573 | 0.5 | 0.1 |
| Milwaukee | 3,341 | 891 | 0.5 | 0.1 | 8,673 | 2,555 | 0.6 | 0.2 |
| San Antonio | 3,370 | 684 | 0.5 | 0.1 | 10,098 | 2,086 | 0.5 | 0.1 |
| Austin | 3,130 | 709 | 0.4 | 0.1 | 7,904 | 2,156 | 0.4 | 0.1 |
| Cleveland | 3,743 | 758 | 0.4 | 0.1 | 8,814 | 2,299 | 0.4 | 0.1 |
| Los Angeles | 17,586 | 1,283 | 0.4 | 0.0 | 44,159 | 4,427 | 0.3 | 0.0 |
| Memphis | 1,814 | 508 | 0.4 | 0.1 | 4,100 | 1,239 | 0.3 | 0.1 |
| New Orleans | 1,854 | 442 | 0.4 | 0.1 | 3,661 | 954 | 0.3 | 0.1 |
| New York | 26,931 | 1,849 | 0.4 | 0.0 | 65,049 | 5,060 | 0.3 | 0.0 |
| Phoenix | 6,219 | 799 | 0.4 | 0.0 | 16,353 | 2,111 | 0.4 | 0.0 |
| Seattle | 5,389 | 964 | 0.4 | 0.1 | 9,840 | 2,044 | 0.3 | 0.1 |
| Nashville | 2,302 | 540 | 0.4 | 0.1 | 4,852 | 1,502 | 0.3 | 0.1 |
| Sacramento | 2,952 | 549 | 0.4 | 0.1 | 7,856 | 2,013 | 0.4 | 0.1 |
| Houston | 8,056 | 1,141 | 0.4 | 0.1 | 20,259 | 4,065 | 0.3 | 0.1 |
| Boston | 7,713 | 1,042 | 0.4 | 0.0 | 14,750 | 2,109 | 0.3 | 0.0 |
| Richmond | 1,660 | 551 | 0.4 | 0.1 | 3,262 | 1,231 | 0.3 | 0.1 |
| Riverside | 4,691 | 745 | 0.4 | 0.1 | 12,348 | 2,462 | 0.3 | 0.1 |
| Pittsburgh | 3,572 | 795 | 0.3 | 0.1 | 7,191 | 1,712 | 0.3 | 0.1 |
| Miami | 7,151 | 835 | 0.3 | 0.0 | 18,936 | 2,498 | 0.3 | 0.0 |
| Detroit | 5,490 | 930 | 0.3 | 0.1 | 11,560 | 2,203 | 0.3 | 0.1 |
| Providence | 1,368 | 415 | 0.3 | 0.1 | 2,999 | 911 | 0.3 | 0.1 |
| Birmingham | 1,299 | 459 | 0.3 | 0.1 | 3,046 | 1,268 | 0.3 | 0.1 |
| Buffalo | 1,559 | 393 | 0.3 | 0.1 | 2,641 | 807 | 0.2 | 0.1 |
| San Diego | 2,502 | 483 | 0.3 | 0.1 | 4,765 | 1,206 | 0.2 | 0.1 |
| Cincinnati | 1,907 | 505 | 0.3 | 0.1 | 4,680 | 1,654 | 0.2 | 0.1 |
| San Jose | 2,225 | 600 | 0.3 | 0.1 | 5,881 | 2,036 | 0.3 | 0.1 |
| Columbus | 3,397 | 773 | 0.3 | 0.1 | 7,971 | 2,564 | 0.3 | 0.1 |
| St. Louis | 3,348 | 675 | 0.3 | 0.1 | 7,110 | 1,806 | 0.2 | 0.1 |
| Louisville | 1,450 | 400 | 0.3 | 0.1 | 3,221 | 951 | 0.3 | 0.1 |
| Salt Lake City | 1,808 | 488 | 0.3 | 0.1 | 3,667 | 1,191 | 0.2 | 0.1 |
| Virginia Beach | 1,697 | 518 | 0.3 | 0.1 | 3,918 | 1,436 | 0.2 | 0.1 |
| Atlanta | 5,783 | 1,044 | 0.3 | 0.1 | 16,637 | 3,877 | 0.3 | 0.1 |
| Kansas City | 2,350 | 578 | 0.3 | 0.1 | 4,788 | 1,235 | 0.2 | 0.1 |
| Oklahoma City | 1,497 | 451 | 0.3 | 0.1 | 3,567 | 1,344 | 0.3 | 0.1 |
| Las Vegas | 2,095 | 513 | 0.3 | 0.1 | 6,390 | 1,890 | 0.3 | 0.1 |
| Baltimore | 2,800 | 479 | 0.3 | 0.0 | 6,004 | 1,258 | 0.2 | 0.0 |
| Dallas-Fort Worth | 6,651 | 911 | 0.3 | 0.0 | 16,395 | 2,523 | 0.2 | 0.0 |
| Denver-Boulder | 3,612 | 730 | 0.3 | 0.1 | 6,989 | 1,464 | 0.2 | 0.0 |
| Philadelphia | 6,056 | 930 | 0.3 | 0.0 | 13,529 | 2,553 | 0.2 | 0.0 |
| Chicago | 9,105 | 1,145 | 0.3 | 0.0 | 22,255 | 3,185 | 0.2 | 0.0 |
| Raleigh-Durham | 1,752 | 485 | 0.3 | 0.1 | 3,220 | 959 | 0.2 | 0.1 |
| Minneapolis-St. Paul | 3,556 | 767 | 0.3 | 0.1 | 7,301 | 2,177 | 0.2 | 0.1 |
| Washington, DC | 5,314 | 810 | 0.2 | 0.0 | 14,910 | 2,697 | 0.3 | 0.0 |
| Tampa | 2,853 | 482 | 0.2 | 0.0 | 6,475 | 1,286 | 0.2 | 0.0 |
| Charlotte | 2,155 | 494 | 0.2 | 0.1 | 5,268 | 1,408 | 0.2 | 0.1 |
| Hartford | 1,068 | 356 | 0.2 | 0.1 | 2,583 | 1,056 | 0.2 | 0.1 |
| Jacksonville | 1,268 | 426 | 0.2 | 0.1 | 2,910 | 1,048 | 0.2 | 0.1 |
| Indianapolis | 1,633 | 425 | 0.2 | 0.1 | 3,594 | 1,141 | 0.2 | 0.1 |
| Orlando | 1,607 | 449 | 0.2 | 0.1 | 4,157 | 1,123 | 0.2 | 0.0 |
| Top 50 US metros | 220,267 | 5,697 | 0.3 | 0.0 | 513,995 | 17,578 | 0.3 | 0.0 |

Urban areas are ranked (in descending order) according to share of households without piped water. Data source: US Census Bureau.

federal benchmark) captures housing costs relative to urban setting. These variables add explanatory traction to describe the household in relation to broader social contexts.

Second, we develop a model that tests the relational aspects of water access while avoiding the ecological fallacy, a common source of statistical bias and error in social science research. In census data, sociodemographic information is collected at the individual or household level and then aggregated to larger geographies to protect respondent confidentiality. Problems are introduced when individual-level inferences are made from ecological correlations at lower- or higher-order geographies (24). In other words, findings that are valid at one geographic level (e.g., counties) may not hold as true for another level (e.g., census tracts) (24). Our approach sidesteps ecological inference issues by making the household the geographic unit of analysis—and not census tracts or blocks—meaning we can draw accurate inferences about urban water access at the household level (24).

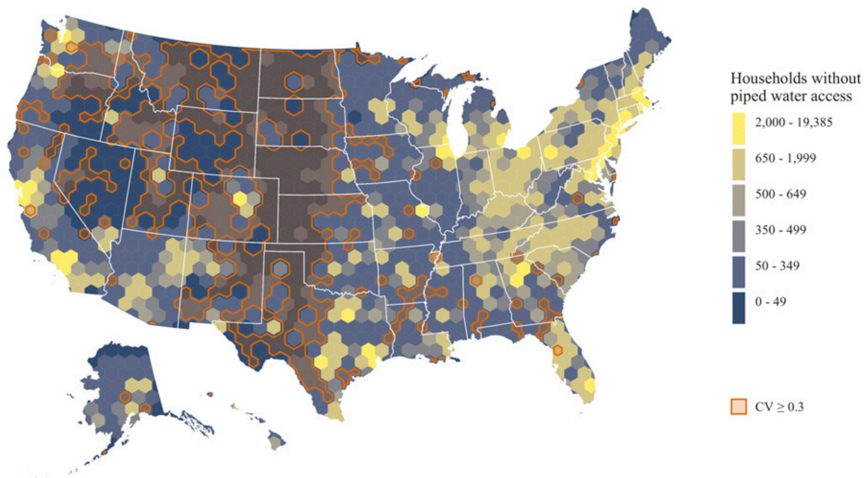


**Fig. 1.** Households without piped water access in the United States, 2013 to 2017. This hex map depicts the spatial distribution of households without piped water access, with lighter colors indicating areas with higher numbers of unplumbed households. Shaded areas (in orange) indicate that sampling error is large relative to the estimate, due to the relatively small number of unplumbed households. Data source: US Census Bureau.



Results of the model indicate that certain covariates are statistically significant predictors of a lack of household water access in US cities (Table 3). Holding all other variables constant, households headed by people of color are 1.34 (e ^ 0.292) times more likely (1.25, 1.43 CI) to lack complete plumbing than households headed by white, non-Hispanic individuals across the 50 largest US metros. In other words, urban households headed by people of color are almost 35% more likely (25–43% CI) to lack piped water compared to white, non-Hispanic households.

Income is an equally important predictor to race. Households with incomes twice the area median are 1.35 times (i.e., 1.003 ^ 100) less likely (1.29, 1.45 CI) to lack piped water. This relationship suggests that lower-income households are more susceptible to a lack of piped water access—regardless of differences in housing characteristics, race, and regional wealth.

Income inequality is a highly significant predictor of plumbing poverty. For every 10% increase of a metro subarea's Gini coefficient, households are 1.49 times (i.e., 1.041 ^ 10) more likely (1.41, 1.58 CI) to lack complete plumbing. In other words, neighborhoods with higher rates of income inequality—relative to the metropolitan area as a whole—are more likely to be plumbing poor.

Housing conditions, specifically housing tenure and type, emerged as statistically significant predictors of plumbing

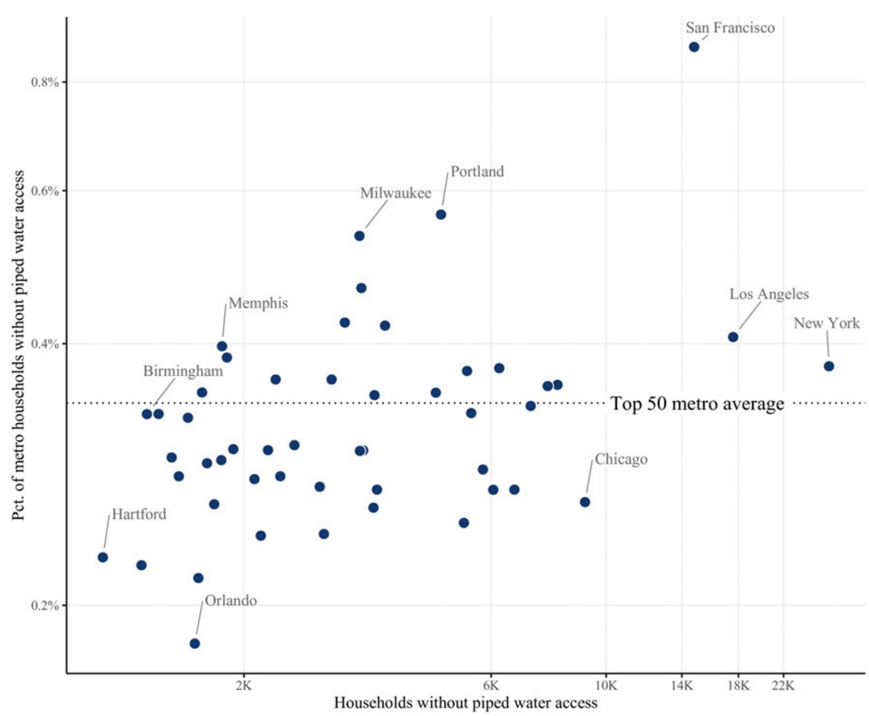


**Fig. 2.** Plumbing poverty in the top 50 largest US metropolitan areas. Urban areas are plotted by share (percentage) of households without piped water access (*y* axis) against total number of households without piped water (*x* axis), adjusted by a log transformation. The dashed horizontal line represents the average share of unplumbed households in the 50 largest metros. Data source: US Census Bureau.

**Table 2. Characteristics of urban US households without piped water**

| | All households | Households without piped water |
|---|---|---|
| People of color | 39.3% (±0.1%) | 52.9% (±1.3%) |
| Median household income | $65,014 (±$180) | $33,152 (±$1,412) |
| Cost burdened | 36.2% (±0.1%) | 48.2% (±1.4%) |
| Mobile home | 2.6% (±0%) | 5.2% (±0.6%) |
| Renter | 39.8% (±0.1%) | 61.4% (±1.5%) |

Percentages include all households ($n$ = 64,435,664) and households without piped water ($n$ = 220,267) in the 50 largest US metropolitan areas. Data source: US Census Bureau.

poverty. Renter-occupied households in the 50 largest US metros were 1.61 times more likely (1.50, 1.72 CI) than owner-occupied households to lack piped water access. Mobile home households are 1.89 times more likely (1.67, 2.13 CI) to lack piped water access than households residing in other structure types. Together, these findings underscore the racialized and class-based dimensions of water access across urban areas in the United States, which are experienced through precarious housing conditions.

Cost-burdened status is a statistically nonsignificant predictor of household water access. One potential explanation is that a majority of unplumbed households are renters, and these results signal that housing unaffordability is subsumed by rental status. Millions of renters live on the knife-edge of housing precarity. In the midst of the COVID-19 pandemic crisis, for example, one-third of renters across the United States missed their April 2020 rent payment. Future research at the housing–water nexus should clarify interactions between tenure, affordability, cost-burdened status, rental regulations, and secure household water access.

Racial segregation did not emerge as a statistically significant predictor in our all-metro model. Nonetheless, we recognize that racist segregation policies and practices have shaped cities in different ways across the United States (48). Future research should explore key differences and probe disparities among cities and regions, by modeling results separately for each of the geographies.

## Discussion

In the United States, an estimated 471,000 households or 1.1 million individuals lack a piped water connection and 73% of households are located in cities, close to networked supply. The spatial and sociodemographic patterns of plumbing poverty reveal that urban water insecurity is a relational condition reflecting disparities of race and class. To date, however, urban water management and security are largely framed as a supply issue. In contrast, our results develop an alternative conceptual paradigm—the housing–water nexus—that theorizes gaps in urban water access as a product of structural inequality, as neither random nor accidental but social and systemic in nature.

What factors are important in explaining the housing–water nexus? In the largest US cities, plumbing poverty is produced by racialized wealth gaps that are expressed through the unequal geographies of housing. Altogether, households headed by people of color are almost 35% more likely to lacked piped water as compared to white, non-Hispanic households. Equally important, our analysis shows that precarious housing conditions and income inequality are equally important predictors of plumbing poverty. Renter-occupied households in the 50 largest US metros were 1.61 times more likely than owner-occupied households to lack piped water access. Unplumbed households are more likely to earn lower incomes, live in mobile homes, and pay a higher share of their gross income toward housing costs. While previous research has advanced incremental insights about insecure water access in specific US regions or housing sectors (19, 25, 26, 39, 42, 42), our research nests these insights in the context of the country's largest metros.

Plumbing poverty, in short, flourishes in the gaps and silences between urban housing and water policy and management. Future research should explore these dynamics in greater depth across different cities and regions. Ethnographic and case study research is necessary to provide grounded explanations for how insecure water access is produced; why it persists; and how local residents cope with service gaps and transform local institutions. Why, for example, does the San Francisco metro region lead the nation in terms of plumbing poverty? What specific housing practices and policies lay the foundations for insecure water access? Spatial analysis and quantitative research—such as multilevel modeling methods—are also important to help identify key trends over time and space. Why do some cities outperform others in terms of water access? Finally, the integration of additional metropolitan water utility or housing attributes—such as housing unit type or size and year built—from other datasets (e.g., the American Housing Survey) could add greater explanatory depth and nuance to the housing–water nexus.

Policy action is urgently needed to stem the tide of plumbing poverty. Our research suggests that cities are prime sites of infrastructure investment and coverage, simply because most unplumbed households live in the nation's cities. Rural areas have

**Table 3. Results of the plumbing poverty logistic regression model**

| | B | SE | | Lower | Odds Ratio | Upper |
|---|---|---|---|---|---|---|
| Intercept | −7.929 | 0.151 | | | | |
| People of color | 0.292 | 0.034 | * | 1.253 | 1.339 | 1.432 |
| Household income | −0.003 | 0 | * | −1.004 | −1.003 | −1.003 |
| Percent of income spent on housing or rent | 0 | 0.001 | | | | |
| Mobile home | 0.634 | 0.062 | * | 1.669 | 1.885 | 2.129 |
| Renter | 0.474 | 0.035 | * | 1.5 | 1.606 | 1.72 |
| Gini coefficient (PUMA) | 0.04 | 0.003 | * | 1.035 | 1.041 | 1.047 |
| Index of dissimilarity (PUMA) | 0.001 | 0.001 | | | | |

Negative odds ratios indicate the decline in likelihood for every unit change in the covariate. Nagelkerke value is 2.3%. The asterisk signals that predictors are significant at the 95% confidence level. Data source: US Census Bureau.

higher shares of incomplete water access; however, the sheer number of unplumbed households in metropolitan areas—65,000 individuals (±5,100) in the New York City metro region alone—makes water security a profoundly urban challenge in the United States. Nationally, one in five (17.3%) US households without piped water access (81,000 total) live in the 10 largest metros. Improving infrastructure coordination and subsidizing costs for connection in these particular cities, for example, would make a significant impact in meeting SDG targets and improving public health outcomes. Without tap water, how do you wash your hands? In a global health pandemic such as COVID-19, the difference between secure and insecure water access—starting with those 65,000 unplumbed New Yorkers—is a matter of life and death.

A framework for future policy action at the housing–water nexus should emphasize cross-sectoral cooperation among metropolitan and state institutions, where most household-level water regulations and decisions are made. Coordinated policy and data sharing efforts should be prioritized between local water providers and housing officials. In most US cities, the responsibility of public water and sewerage provision tends to stop at the street level—with the homeowner responsible for costs of connecting individual residences to mains. However, such infrastructure costs may be prohibitive for low-income households; impossible for renters; and difficult for either water utilities or housing agencies to track, monitor, or enforce. Our research exposes persistent service gaps and racialized disparities that are unevenly produced at the local scale.

## Conclusion

Secure water access is a fundamental human right and critical element of sustainable and healthy communities. Without universal water access, efforts to limit the spread of infectious diseases—such as COVID-19—will undermine global health and benefit certain populations over others (17). Our study reveals persistent disparities in piped water access in urban areas in the United States, a finding that is strongly linked to precarious housing conditions and racialized wealth gaps. We offer compelling evidence that gaps in urban water provision are created at the juncture of housing and water sectors: a paradigm we call the housing–water nexus.

Our estimates of plumbing poverty are conservative—a troubling fact. The US Census Bureau routinely undercounts renters, the homeless, and people of color (49)—demographics that are disproportionately plumbing poor. Therefore, our baseline likely misses hundreds or possibly thousands of unplumbed households. For example, people experiencing homelessness routinely face extreme conditions of water and toilet insecurity (32, 34), and their population is growing in cities, especially areas without affordable housing. On a single night in 2019, almost 568,000 people experienced homelessness in the United States, with more than one-third (37.2%) residing in unsheltered locations (50). Given the undercount issues, a more likely scenario is that 2 million people in the United States regularly lack piped water—a population size greater than the nation's capital.

The global North is not immune to problems of water equity and access. In projecting forward from our model, we expect plumbing poverty to stagnate or worsen in cities of the United States. Since the 2008 recession, trends in the US housing sector include declining rates of homeownership (from 67.5 to 64.8% nationwide), corporate incursion and financialization of the rental market, rising rates of median rent (as incomes remain flat), and a sizeable portion of renter households that remain cost-burdened (51, 52). In light of such trends, we expect conditions of water access to deteriorate, especially in cities—such as San Francisco, Portland, and Los Angeles—with widening wealth gaps and increasingly unaffordable housing. Future research and policies for sustainable water access must directly address social inequality at the housing–water nexus if the global dream of "water for all" is to be realized in the United States.

## Methods

**Data Source and Code Availability.** The household data used in this research are from the 2013 to 2017 5-y combined ACS Public Use Microdata Sample from the US Census Bureau. Microdata are available for public download on the US Census Bureau website. The smallest unit of geography for which household data are available is the Public Use Microdata Area (PUMA), a census-defined area of roughly 100,000 to 200,000 individuals.

We developed an approach that uses customized metropolitan geographies, which are better suited for longitudinal geographic analysis as they standardize the boundaries of metropolitan areas through time (53). The US Office of Management and Budget defines Metropolitan Statistical Areas (MSAs) using counties (and county equivalents) that contain the following: 1) a densely settled urbanized area with a population of at least 50,000, and 2) adjacent areas that are socially and economically integrated with the urban core. A limitation of using MSAs is that some may include peri-urban (rural) populations at the fringe of metropolitan areas. At the same time, MSA definitions are drawn to capture the regional and socioeconomic connectivity across conurbations (or "urban areas"). We have made our customized MSA definitions available for public download and use in a citable format (53).

Statistical analysis of census microdata and the creation of spatial data visualizations were conducted in R using open-source packages, freely available on the internet. Census tables and boundary shapes were acquired using the "tidycensus" and "tigris" packages. Spatial joins and areal interpolations of household data were accomplished using the "sf" package. Data cleaning, transformation, and visualization were performed using the "tidyverse" packages. All R code developed by the authors are available for download and use in a citable format (53).

**Summative Statistics.** Household conditions and characteristics were first explored using descriptive statistics. We include both the statistical estimate and the corresponding statistical uncertainty (i.e., MOE) for households with and without piped water. All differences between variables are statistically significant at the 95% confidence level.

**Regression Model.** We used multivariate weighted logistic regression to predict whether a household has piped water access, using microdata collected by the US Census in the ACS, their largest annual statistical survey. The US Census Bureau has asked residents about their household water access—known as the "plumbing question"—since 1940. The Bureau currently defines "complete plumbing" as 1) piped hot and cold water, and 2) a bathtub or shower, all located within the housing unit and used only by occupants. A plumbed household may be connected to a community water source, a well, or municipal network. In other words, the plumbing variable only describes infrastructure access and does not discriminate between different water sources or types. Following the design of a previous study (24), our model uses the likelihood (i.e., logistic probability) that a household lacks complete plumbing as the dependent variable.

To develop the model, we started with a set of independent variables that capture household income, race/ethnicity, and housing type (21, 22, 24, 30, 39, 44, 45). In line with two household water access models at the national scale (24, 30), we began with two household predictors (race/ethnicity of the head of household; household income) and two housing-specific variables (housing tenure and housing type). Our model improves on previous nationwide studies that analyze household water access by incorporating three additional measures: income inequality, cost-burdened status, and racial segregation. The final list of independent variables included the following:

- Race/ethnicity: a binary nominal variable, indicating whether the head of household is a person of color (22, 24, 39, 44, 45).
- Median household income: ratio of household income to the area's median household income (24, 27). Value was centered by subtracting 100 from the ratio.
- Cost-burdened: a continuous measure of owner/renter costs as a share of household income. Cost-burdened households pay more than 30% of their gross income to housing costs, as defined by the US Department of Housing and Urban Development.
- Housing tenure: a binary nominal variable, measures whether the household is owner- or renter-occupied (24).
- Housing type: a binary nominal variable, indicates whether the household resides in a mobile home (24, 30, 31).

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- Racial segregation: a continuous variable that measures racial segregation across space using the index of dissimilarity, which calculates the extent to which particular racial groups are clustered across space. The index of dissimilarity reports a value from 0 to 1, with 1 representing complete segregation and 0 indicating near-perfect integration (54).
- Income inequality: a continuous variable, measured by the Gini coefficient of the PUMA, the largest spatial unit available to estimate household microdata. The Gini coefficient reports a value from 0 to 1, with 0 representing perfect income equality and 1 indicating complete income inequality (54).

Educational attainment and citizenship status were eliminated from model development due to issues of multicollinearity (e.g., education with income) and high nonresponse rates for the citizenship question. Other potential predictors—such as water service shutoffs or utility ownership—were not incorporated due to inconsistent and unreliable data, and the absence of a harmonized database. For example, information about utility ownership must be scraped from individual websites or volunteered by water service providers (27, 55).

**MOE.** The US Census Bureau conveys sampling error in ACS estimates with an MOE statistic. A limitation of working with sample-derived ACS data are that statistical uncertainty increases as sample size and geographical unit decreases. In following expert recommendations (56), we report MOE values where possible. We convey statistical reliability using a statistic called the coefficient of variation (CV). The CV is a ratio of sampling error (i.e., SE) to the statistical estimate, with the result multiplied by 100. In this study, we consider CV values between 0 and 12% as reliable, between 12 and 30% as moderately reliable, and values above 30% as unreliable.

**Spatial Data Visualization.** We created the hex map (Fig. 1) in R by interpolating county-level household totals to a nationwide hex-bin layer. We used a standard proportional areal interpolation function and created an overlapping statistical uncertainty layer by calculating the CV, derived from the combined MOE by counties.

Fig. 1 is an improved data visualization, for several reasons. In previously published maps (see refs. 18 and 21), the use of census tracts as spatial units (each tract consists of roughly 4,000 to 6,000 people) meant that expansive rural tracts with high shares of unplumbed households (but low overall population) were visually overrepresented. Equivalent urban tracts—which tend to be smaller, as urban populations are denser—disappeared completely from the maps. Fig. 1 reduces spatial bias, incorporates sampling error, and improves interpretation of geographic data by incorporating principles of universal map design and appropriate colorway schemes.

**Data Availability.** The metropolitan geographic definitions and codes for "Geographies of insecure water access and the housing-water nexus in US cities" have been deposited in the University of Arizona Research Data Repository (https://arizona.figshare.com/articles/dataset/Metropolitan_Geographic_Definitions_and_Code_for_Geographies_of_Urban_Water_Access_and_Infrastructural_Inequality_in_U_S_Cities_/12456536).

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