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RESEARCH ARTICLE

Disparities in disruptions to public drinking water services in Texas communities during Winter Storm Uri 2021

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Abstract

Winter Storm Uri of February 2021 left millions of United States residents without access to reliable, clean domestic water during the COVID19 pandemic. In the state of Texas, over 17 million people served by public drinking water systems were placed under boil water advisories for periods ranging from one day to more than one month. We performed a geospatial analysis that combined public boil water advisory data for Texas with demographic information from the 2010 United States Census to understand the affected public water systems and the populations they served. We also issued a cross-sectional survey to account for people's lived experiences. Geospatial analysis shows that the duration of boil water advisories depended partly on the size of the public water system. Large, urban public water systems issued advisories of intermediate length (5–7 days) and served racially diverse communities of moderate income. Small, mostly rural public water systems issued some of the longest advisories (20 days or more). Many of these systems served disproportionately White communities of lower income, but some served predominantly non-White, Hispanic, and Latino communities. In survey data, "first-generation" participants (whose parents were not college-educated) were more likely to be placed under boil water advisories, pointing to disparate impacts by socioeconomic group. The survey also revealed large communication gaps between public water utilities and individuals: more than half of all respondents were unsure or confused about whether they were issued a boil water advisory. Our study reinforces the need to improve resilience in public water services for large, diverse, urban communities *and* small, rural communities in the United States and to provide a clear and efficient channel for emergency communications between public water service utilities and the communities they serve.

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1. Introduction

Water is an essential resource that is unevenly distributed. For at least one month each year, two-thirds of the world's population experiences conditions of severe water scarcity [1]. As the climate changes, water scarcity will persist for many communities [2] and expand to new ones. Extreme weather events such as droughts and floods are also expected to increase in frequency and severity in the coming decades, creating further disruptions to water supply and accessibility. Droughts have triggered partial shutoffs of municipal water services in locations around the world. A prominent example is Cape Town, South Africa's municipal water crisis in 2018, when the city narrowly averted a total shutdown of municipal water services due to drought conditions and water management decisions [3]. Droughts place heavy pressure on surface water resources and, to a lesser extent, on groundwater resources, which are inherently more insulated against drought. Floods damage infrastructure and test the limits of water treatment technologies. Severe weather such as winter storms bring freezing temperatures that damage pipes and can also disrupt the power supply to water treatment facilities.

In the United States, 97% of the population has access to improved water [4], but supply was disrupted across Central and Gulf Coast states during Winter Storm Uri (February, 2021). The state of Texas experienced severe, but not unprecedented, cold temperatures in the teens and single digits in Fahrenheit (around -10 to -15˚C) [5]. Due to infrastructure damage, the storm left millions without power and water for days [6, 7]. The storm was estimated to have caused over 200 deaths and created about $100 billion in financial losses in Texas [8]. Over two out of three (69%) Texans lost electrical power at some point during the storm. Almost half (49%) reported losing access to running water, on average, for 52 hours [9]. Those with uninterrupted access to running water still reported that their water was unpotable for an average of 40 hours during the week of the storm (for example, they were issued a boil water advisory). More than half (56%) of those who lost potable water considered the loss to be extremely serious or very serious. Nearly half (45%) also experienced difficulties finding bottled water, rating this impact as very serious or extremely serious. For comparison, loss of cell phone service, difficulties obtaining food, and illness or injury to immediate family were all rated less serious in terms of impact [9]. Loss of domestic water disproportionately affects the health of vulnerable populations such as children, older adults, and low-income individuals [7]. The combination of winter weather, which made it difficult to use public transportation, and the ongoing COVID-19 pandemic hindered access to bottled water supplies, particularly for older adults and low-income individuals [7]. The loss of clean, domestic water also made it harder for households to follow World Health Organization (WHO) and United Nations Children's Fund (UNICEF) guidelines for handwashing, a key strategy to reduce the spread of the virus [10].

Amidst these factors, it is important to understand the effects of Winter Storm Uri on the public supply of drinking water. Winter Storm Uri was the largest known boil water event in U.S. history [11] and reflects the resilience of public water services in the region. Here, resilience is defined as "the ability to plan for, absorb, recover from, or more successfully adapt to actual or potential adverse effects" [12]. Existing analyses of this historic boil water event point to knock-on effects from power outages [6]. In a survey of large, mostly urban public water utilities, 85% lost power, impacting their ability to produce clean water [13]. Though many had backup generators, not all were operable due to low fuel supplies or cold temperatures. Additionally, water losses from burst pipes and leaks caused pressures to drop in many distribution systems below the regulatory minimum, triggering the issuance of boil water advisories to protect customers from pathogens that tend to infiltrate under low pressure [13]. By understanding which public systems were most affected and the contributing factors, new strategies can be implemented to increase the resilience of public drinking water systems under future weather extremes.

It is also important to identify communities that may be disproportionately vulnerable to disruption of services in order to prioritize equitable responses [14]. Across urban areas of the

United States, consistent disparities in piped water access have been linked to unpredictable housing conditions and racialized wealth gaps [15]. In peri-urban and ex-urban areas, municipal underbounding has excluded low-income neighborhoods and people of color from public water services altogether [16, 17]. Further, studies demonstrate that Black and Latino individuals, and generally those at lower income levels, have less access to clean water [18] and indoor plumbing [19]. In the specific case of Winter Storm Uri, multiple studies have identified disparities in utility outages across racial, ethnic, and income groups. For example, Nejat et al. [20] showed that communities with a great proportion of non-Hispanic White residents, single family homes, and greater income experienced a smaller share of lingering power outages after the storm. Grineski et al. [21] revealed through a survey that Black participants were more likely to experience longer water outages. By analyzing 311 calls for the Houston area, Lee et al. [22] showed that burst pipes were more severe for low-income and racial minority groups. Glazer et al. [11] examined power and water outages by county and compared them with an index of social vulnerability. Although there was no clear correlation between the length of boil water advisories and social vulnerability at the county level, they observed that some of the most impacted counties had greater percentages of non-English speakers and minority residents, apartment complexes, and mobile homes. They therefore suggested the need for a more granular analysis on a census tract level.

Here, we sought to understand the finer-scale impacts to Texas public water systems and identify groups that were most affected through two related studies: 1) a geospatial analysis of community public water systems that issued boil water advisories, and 2) a cross-sectional survey of individuals residing in Texas during February 2021. In the geospatial analysis, we used principal component analysis to test whether there was any relation between the length of the advisory (a measure of the recovery time for safe drinking water services after the storm) and various factors describing the public drinking water system. These factors included size or location of the public water system, severity of weather, and demographics at the *system level* (derived from mapping public census data onto each water system's service area). We also asked how the advisories impacted specific demographic groups at the *individual level* through the cross-sectional survey using both an analysis of covariance and a multivariate analysis of covariance on human subjects data. Drawing on the integrated findings from these two studies, we were also able to examine individual awareness of boil water advisories and explore communication gaps between public water providers and customers.

2. Method and materials

2.1. Geospatial analysis

To gather data on boil water advisories issued by public water systems, a request for information was placed with the Texas Commission of Environmental Quality (TCEQ) under the Texas Public Information Act. We limited the request to community public water systems, defined as those that have the potential to serve at least fifteen residential connections or twenty-five residents on a year-round basis [23], and excluded other public water systems such as schools, hospitals, and seasonal communities. Most of the Texas population (roughly 27 million people, or 93%) is served by community public water systems [24] and therefore is represented in the geospatial component of this study. Roughly 5% of Texans depend on private well water [25] and are not included in the geospatial analysis.

TCEQ provided a list of 2,080 community public water systems that reported issuing a boil water advisory related to Winter Storm Uri. The list includes the name of the public water system, a unique identifier code, the county, the issue date of the boil water notice, the rescind date of the boil water notice, the population served, and the number of connections served.

Retail service areas for community public water systems were obtained from the Texas Water Development Board's (TWDB) water service boundary viewer in November of 2021 [26]. It is worth noting that as of 2022, Texas is one of only 24 states with geospatial data products for community water system service area boundaries [27]. The Texas dataset includes 4,572 out of 4,641 community public water systems [28]. Fourteen of the 2,080 public water systems that issued boil water advisories did not have a service area polygon, so they were excluded from the analysis. The remaining 2,066 records were screened for completeness and to ensure that the dates of boil water advisories were consistent with Winter Storm Uri. A small number of records [28] were removed from the analysis because they were incomplete, or the reported advisory was not conclusively connected to Winter Storm Uri. The excluded records fit at least one of these exclusion criteria: 1) the reported advisory was issued and rescinded prior to Winter Storm Uri; 2) the reported advisory was issued before the storm hit, and local minimum temperatures never fell below freezing; 3) no rescind date was provided. In total, 2,038 public water systems were retained for analysis.

To relate information on boil water advisories to weather, daily climate summaries were retrieved from the National Oceanic and Atmospheric Administration (NOAA) from February 1, 2021 to February 28, 2021 for 360 weather stations in the state of Texas [29]. Some of the longest boil water advisories were not lifted until March, but the month of February fully encompassed the climatological phenomenon of Winter Storm Uri; thus, we restrict our investigation of the climatological phenomenon (for example, how long temperatures stayed below freezing) to February. A point feature class shapefile was created in ArcGIS for the weather stations with attributes containing the minimum and maximum recorded temperatures for each day in February. We also calculated the sum of the number of days in February that the maximum or minimum daily temperature was below freezing. Some stations had missing data for maximum and minimum temperatures on select days. No attempt was made to interpolate missing data because it is possible that data gaps are temperature-dependent or biased towards frozen temperatures. Our estimation of the number of frozen days is therefore conservative, meaning that the number of days below freezing may be underestimated, and the minimum daily recorded temperature may be overestimated. Weather data from the nearest station was attributed to each public water system using a spatial join with the nearest neighbor in ArcGIS.

Information on urban and rural households, population, race, and housing tenure were obtained for the state of Texas from the 2010 decennial United States Census using the R package tidycensus [30]. We opted for the 2010 census instead of the more recent 2020 census because the results of the 2020 decennial census and American Community Survey were impacted by the COVID-19 pandemic, and income data were only available as experimental estimates [24]. We acknowledge that Texas has experienced substantial growth and demographic change since 2010, which introduces additional uncertainty to our analysis. Medium income and its margin of error (MOE) were taken from the 2010 American Community Survey. The U.S. Census Bureau organizes data based on spatial hierarchy, ranging from states down to blocks, the smallest measurement scale. Income data are not available at the block level, but they are at the next largest block group level. Initial analyses showed that block group-level calculations compared well with block-level calculations for public water systems [31]. We, therefore, chose to analyze demographic information for block groups because there is simplicity and advantage to working at one consistent spatial level for demographic and income data.

In ArcGIS Pro, areas were calculated for both block groups and public water systems. Overlapping areas between the census block groups and public water systems were then used to compute aerially-weighted average demographics for each public water system. Further information is provided in Section 1 in S1 Text.

To explore relationships between public water system characteristics, we performed inferential statistical analyses, including Pearson correlation coefficients (which provide a measure of linear correlation between two variables) and principal component analysis (PCA) using MATLAB. The goal of PCA is to reduce the dimensionality of the data set by finding the combination of variables that best explain the total variance [32]. Variables that displayed strong positive skewness were logarithmically transformed (specifically, number of advisory days, service area, homes served, and median income). All variables were then scaled to have a mean of 0 and a standard deviation of 1. We chose 15 variables to be included in the final matrix of correlation coefficients, detailed in the Results. These variables were selected to represent a range of conditions (*meteorological*: extent and duration of freezing temperatures; *geographic*: latitude and longitude, degree of urbanization; *scale of the system*: size of service area and number of homes served; and *demographics*: race, ethnicity, homeownership, and income), with the goals of understanding which public water systems took the longest to recover, who was affected, and for how long. We explored different combinations of variables (e.g., minimum of daily minimum temperature versus minimum of daily maximum temperature; population served versus homes served; fraction of White individuals versus fraction of White families) and found negligible differences; duplicated variables were removed. Last, the dataset was subjected to PCA to test whether there were any underlying patterns in the public water systems that issued short or long boil water advisories. We removed the length of the boil water advisory as a variable from the analysis, so that public water systems were only described by geographic, meteorological, and demographic variables. We also chose to eliminate elevation, a variable strongly correlated with longitude and latitude, which was found in preliminary analysis to have a negligible effect on the amount of variance explained by the first two components in the PCA analysis, leaving a total of 13 remaining variables for the final statistical analysis.

2.2 Survey

We cross-sectionally surveyed 407 people who lived in Texas during Winter Storm Uri. We received IRB approval (#IRB2021-882) from Texas Tech University to conduct this study. Participants were asked to indicate their consent to participate in the first question on the survey, and we only collected data from individuals who indicated their consent on this question. Participants were permitted to skip any question in the survey they did not feel comfortable answering without penalty. Participants were recruited from January 2022—April 2022. We retained only those participants without missing data who could also be located and thus connected to public water system service areas in the geospatial analysis (N = 289). Of these, N = 23 people in our data set were not on public water systems at all, so we excluded these individuals from our analyses regarding public water systems. Thus, our final sample consists of N = 266 participants. Importantly, these individuals self-identify as 56% (149) female, 43% (114) male, 1% (2) non-binary, and .5% (1) preferred not to say. Regarding race and ethnicity, these individuals self-identify as 71% (188) White and Non-Hispanic, 21% (57) Latino or Hispanic, 3% (9) Asian or Pacific Islander, 4% (10) Black and Non-Hispanic, and 1% (2) who chose to write-in their responses (see Section 3 in S1 Text for details regarding how these categories were combined and how identities differ slightly from categories in the United States Census). Our sample is on average 22.88 years old (ranging from 18 to 80 years).

We associated participants with their public water system (if they lived in one) by asking them to provide a zip code and street address where they were living during the storm, or alternatively, two nearby cross-streets, if they were uncomfortable listing their street address. This information was provided by N = 266 participants. Using a Google Sheets plug-in called GeoCode, we generated longitude and latitude for each of these participants (Fig B in S1 Text) and performed a spatial join in ArcGIS to the feature class of public water systems. Because some participants provided nearby cross-streets rather than exact addresses, we experimented with including a 500-m buffer, which only affected the spatial join for 4 participants (thus, we did not use this buffer).

We asked participants a series of thirteen questions related to their access to clean water during Winter Storm Uri, their experiences with boil water advisories, electricity and Wi-Fi outages, and burst pipes or water damage due to the storm. Finally, we asked them a series of demographic questions related to their gender, race and ethnicity, age, income, and familial education levels (all survey questions are available in Section 3 in S1 Text). We defined "first-generation" status as any participant whose parents had not completed college (of note, all participants had received at least some college training themselves). First-generation status tends to be positively correlated with families who are also low income [33, 34]. To control for the differences across these variables' scales, we z-transformed each variable before analysis. More information is provided in Section 3 in S1 Text.

To explore how Participant Ethnicity, Income, and First-Generation Status related to their experiences with Water Access, we conducted first (1) an analysis of covariance (ANCOVA) on a binary variable indicating whether participants were issued a boil water advisory, derived from the linked geospatial data; and second (2) a multivariate analysis of covariance (MANCOVA) on the thirteen survey items; we also controlled for two variables across both analyses from the geospatial study: the fraction of rural households (System-Level Rural Housing) as a measure of urban development in the participant's area and the total number of households (System-Level Total Housing) as a measure of the scale of the public water system that served the participant.

3. Results

3.1. Analysis of public water systems

Most boil water advisories were issued on February 17, approximately one day after freezing weather descended on the state of Texas (Fig 1A). Advisories were lifted anywhere from 1 to 36 days later, though below-freezing weather only lasted a maximum of 12 days (Fig 1B). The mean length of an advisory was 7.96 days (d), with an standard deviation of 3.57 d. Meanwhile, the mean length of below-freezing weather was 3.83 d, and the standard deviation was 3.26 d (Fig 1B). Some of the coldest weather occurred in the northwestern regions of Texas farther from the coast (Fig 1D), and consequently at higher latitude and longitude (for example, $r = 0.64$, $p < 0.01$ for latitude and frozen days in Fig 2). In contrast, the duration of advisories was scattered and showed no clear spatial trends with latitude or longitude (Fig 1C). As further evidence, global Moran's I (a measure of spatial autocorrelation calculated here with a binary, nearest-neighbors weighting system) was 0.977 and 0.988 for minimum recorded temperature and number of freezing days, respectively, indicating smoothly varying weather conditions. Moran's I was only 0.139 for the length of the advisory, indicating a more random distribution.

Indeed, the length of the boil water advisory was weakly (linearly) correlated with all the individual weather and sociodemographic factors analyzed, according to the values of bivariate Pearson correlation coefficients (Fig 2). Public water systems that served a smaller number of homes had a weak tendency to issue longer advisories ($r = -0.25$, $p < 0.01$). Those public water systems that served a higher proportion of families who owned their homes outright also had a weak tendency to issue longer advisories ($r = 0.19$, $p < 0.01$). It is important to note that at the scale of public water systems, greater rates of homeownership were consistent with lower median income ($r = -0.44$, $p < 0.01$) and more rural service areas ($r = 0.24$, $p < 0.01$), meaning

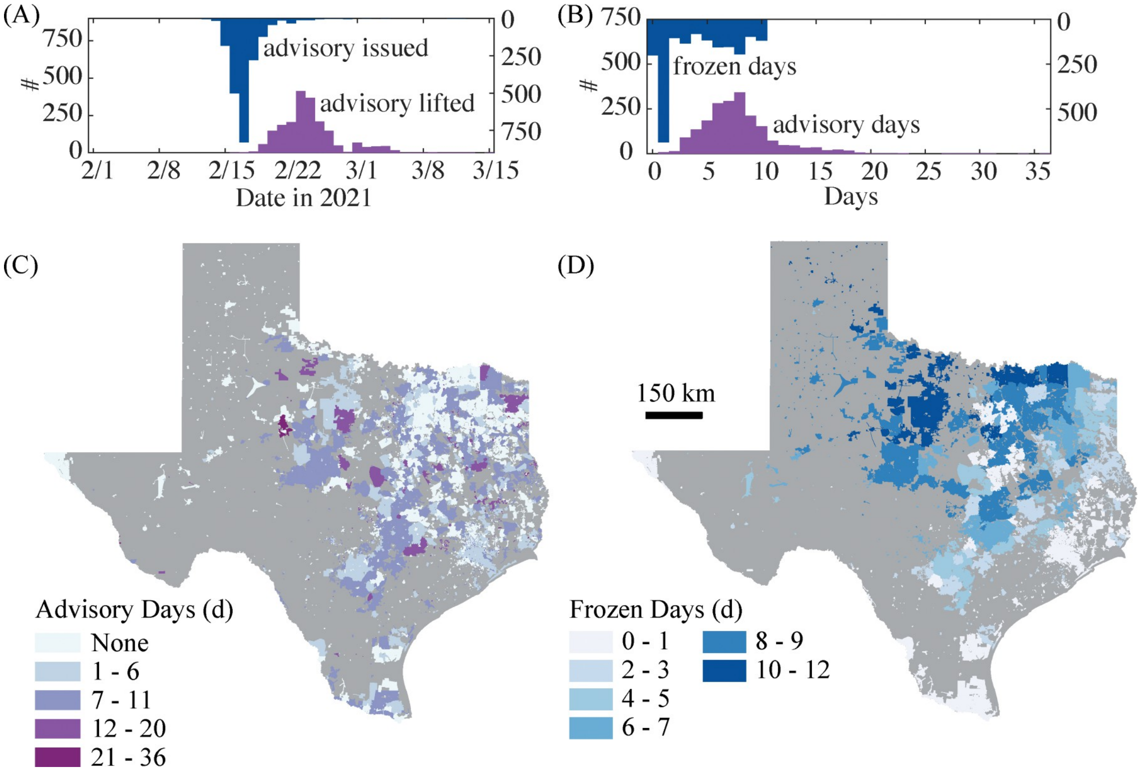

Fig 1. Patterns in the length of boil water advisories differ from patterns in cold weather. (A) Histograms showing when advisories were issued and lifted (total number of samples, N = 2,038). (B) Histograms showing length of advisories and length of time the maximum daily temperature was below freezing in February. (C) Map of boil water advisories duration. (D) Map of freezing weather duration (number of days in February when the maximum daily temperature was below freezing). Map base layer and technical documentation available from U.S. Census 2010 TIGER/Line shapefiles for Texas.

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that homeownership rates are not an indicator of wealth when aggregated by public water system and compared across urban and rural areas. In fact, public water systems with greater median income tended to have a greater fraction of mortgaged homes ($r = 0.76$, $p < .01$) and be more urban ($r = 0.24$, $p < .01$).

Within public water systems, the fraction of White families and Black or African American families was strongly negatively correlated ($r = -0.86$, $p < 0.01$), and a weak negative correlation was also evident between White families and families of Hispanic or Latino ethnicity ($r = -0.38$, $p < 0.01$). This outcome is not forced by having compositional variables that sum to one, as race and ethnicity are independent and overlapping categories in the census data. Also, families could identify with additional races that include American Indian or Alaska Native, Asian, and Native Hawaiian or Other Pacific Islander. The public water systems that served greater proportions of White families tended to be more rural (less urban, $r = -0.50$, $p < 0.01$), whereas the public water systems that served greater proportions of Black or African American families and Hispanic or Latino families were mostly urban ($r = 0.32$ and $r = 0.33$, respectively, with $p < 0.01$ in both cases).

The bivariate correlations in Fig 2 do not provide a comprehensive vision of the dataset. For this reason, we developed a multivariate interpretation by means of PCA. We found that approximately half (48%) of the geographic, meteorological, and demographic variability among public water systems was explained by only the first two principal components (Fig 3B).

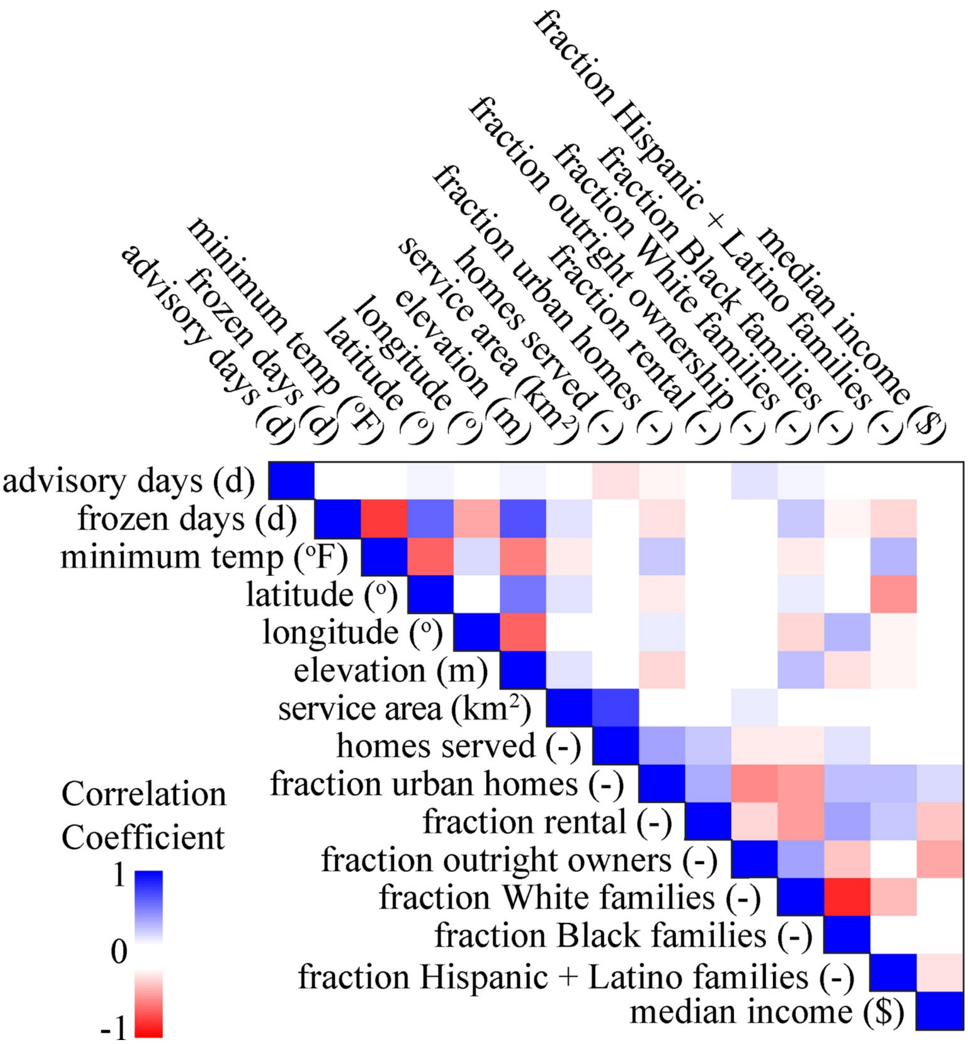

Fig 2. Correlation matrix for public water systems that issued an advisory in response to Winter Storm Uri.

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PCA resulted in geographic and weather-related variables being projected onto the first and third quadrants in the plot of components 1 and 2 (Fig 3B). For example, public water systems at greater latitude that experienced more freezing days in February of 2021 project toward the first quadrant. Meanwhile, variables that describe the scale and demographics of the service area projected more or less orthogonally. For example, public water systems that served greater number of homes and were located in more urban areas are projected toward the second quadrant. These public water systems were also associated with a greater proportion of rented homes and lower proportion of White families. The four public water systems that served the greatest number of customers (all >1 million, as reported to TCEQ by the providers) clustered in the second quadrant and all experienced advisories of intermediate length (within mean plus one standard deviation). These include the City of Houston, San Antonio Water System, City of Fort Worth, and City of Austin Water & Wastewater (Fig 3B). In contrast, the public water systems associated with some of the longest advisories tended to cluster in the fourth quadrant. Specifically, 14 of the 15 systems with the longest advisories (all 20 days or more) were similar in terms of their small populations and service areas and their tendency to serve

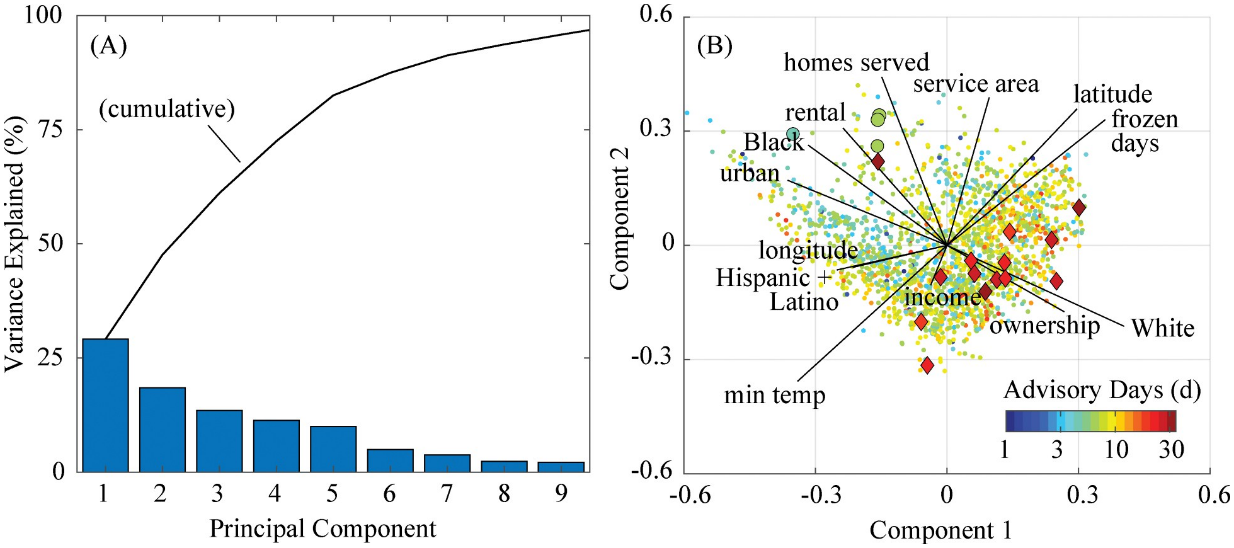

Fig 3. Principal component analysis of public water systems. A) Percent of variance among public water systems explained as a function of the number of components. B) Projection of public water system data on a graph of principal components 1 and 2. Each point represents a public water system that issued a boil water advisory, colored according to length of the advisory. Large diamonds indicate the 15 public water systems with the longest boil water advisories. Large circles show the 4 public water systems that serve the largest populations. Vectors show the projection of the geographic, meteorological, and demographic variables involved in the analysis.

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more rural, homeowning families (Table A in S1 Text). The one system that did not cluster with the 14 others was a small, rural system that served a large proportion (51%) of Black or African American families (Table A in S1 Text). Interestingly, public water systems with very short boil water advisories (1–2 days) did not cluster strongly according to the first two principal components (Fig 3A).

In summary (Table 1), the geospatial analysis suggests that no one factor resoundingly explains recovery times for public water systems, but large, urban systems consistently issued advisories of intermediate length affecting large, diverse communities. The longest recovery times were experienced by small, rural systems of variable community demographics (Table 1).

3.2. Individual experiences and awareness

Eighteen percent (N = 48) of the 266 participants who were on public water systems stated that they were under a boil water advisory during the storm. Meanwhile, 37% (N = 98) were not sure if they were under a boil water advisory, and 45% (N = 120) stated they were not under a boil water advisory. Interestingly, 53% (N = 29 people) who said they were under a boil water advisory actually were not, based on their locations at the time of the storm; 10% (N = 11) of those who were not sure actually were; and 5% (N = 6) of those who said they were not under a boil water advisory actually were. This finding highlights gaps in the way advisories were communicated to the public (Fig C and Table B in S1 Text). These gaps did not appear to vary strongly across racial and ethnic groups (Fig C in S1 Text).

A majority of participants (69%; N = 183) reported that they did not lose access to water where they were living, while 31% (N = 76) did lose access to some degree. Specifically, 16% (N = 43) lost access to running water altogether (no water flowed when they turned on their tap); 12% (N = 33) experienced some change in water pressure. A majority (91%; N = 243) stated that they did not notice any visible changes in the color, taste, or smell of their water.

Table 1. Summary of key findings from geospatial analysis, the survey tool, and their relationships.

	System-Level Geospatial Analysis	*Individual-Level Survey*
Sample	**2,038 community public drinking water systems**	**266 individuals**
How extensive were boil water advisories, and what was the impact to surveyed individuals?	44% of the 4,572 community public water systems with mapped service areas in Texas issued boil water advisories. The mean length of an advisory was 7.96 days (d), and the standard deviation was 3.57 d.	Boil water advisories were issued to 14% of participants based on their locations (for comparison, 18% said they were issued an advisory in the survey); 31% experienced loss of water pressure, 9% noticed changes in color, taste, or smell of their water, 18% experienced burst pipes, and 16% experienced water damage.
What communities were affected?	There was no one clear demographic variable that explained the length of boil water advisories, but longer advisories tended to be issued by smaller public water systems (serving fewer homes).	ANCOVA results: Although White, non-Hispanic individuals were under confirmed boil water advisories significantly more often than Black/Hispanic/Biracial individuals, the difference was driven by the proportion of first-generation college participants across ethnic categories who were more likely to be under boil water advisories.
	The 4 public water systems that served the greatest populations (all >1 million, as reported to TCEQ by the providers) experienced advisories of intermediate length (within 1 standard deviation of the mean). These urban systems served relatively greater proportions of home renters and were more racially and ethnically diverse.	MANCOVA results: White, non-Hispanic individuals also identified that they were under confirmed boil water advisories significantly more often that Black/Hispanic/Biracial individuals, but these differences (~5%) must be considered in light of communication gaps between water utilities and the public.
	The 15 pubic water systems with the longest advisories (> 20 days) were similar in terms of their small populations and service areas. Most served more rural, White, homeowning families, but 3 of the 15 worst served an above-average proportion of non-White or Hispanic and Latino families.	
How well were boil water advisories communicated?	There was broad public confusion: 37% of the sample was not sure if they were placed under a boil water advisory; 53% of people who said they were issued a boil water advisory (18%) actually were not, based on their locations during the storm; 5% of those who said they were not issued a boil water advisory (45%) actually were, based on their locations.	
What are some of the limitations of the tool?	Not all public water systems may have reported boil water advisories to the TCEQ; Age of census data; Uncertainties of calculating system demographics from aerially weighted census data.	Snowball sampling approach, which favored college students and specific regions; Small numbers; Uncertainties in participants' geographic locations; Delayed survey dissemination.

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Further, most participants did not experience burst pipes in their homes (82%; N = 217) or water damage (84%; N = 224) (Fig D in S1 Text). The detailed omnibus and univariate test statistics, F-statistics, and effect sizes are reported in Tables C and D of S1 Text, so we summarize only high-level findings below.

First, using the ANCOVA, we observed main effects of race and ethnicity ($p = .01$) and first-generation status ($p = .04$) on boil water advisories that were issued to participants (as determined from combining public water system and participant datasets). Although White individuals ($M_W = 0.21$, $SE_W = 0.04$) were under confirmed boil water advisories significantly more often than Black/Hispanic/Biracial ($M_{BLB} = 0.16$, $SE_{BLB} = 0.05$) participants, these effects were driven by the experiences of White first-generation participants ($M_{FG} = 0.25$, $SE_{FG} = 0.05$). Participants who identified as White first-generation were significantly more likely to be under boil water advisories than non-first-generation participants ($M_{NFG} = 0.14$, $SE_{NFG} = 0.03$) (Table C of S1 Text). Income effects were less clear, but first-generation status may be a better indicator of socioeconomic status than income in this survey, given that many participants were college students whose income responses may have been shaped by multidimensional factors.

Second, using the MANCOVA, we observed that race and ethnicity had a significant main effect on boil water advisories that were experienced by participants (as determined from participant responses alone), such that White, non-Hispanic participants were significantly more likely ($p = .03$) to report being under a boil water advisory ($M_W = 2.12$, $SE_W = 0.11$) than

Black/Hispanic/Biracial participants ($M_{BLB} = 2.35$, $SE_{BLB} = 0.14$) (Table C of S1 Text). The difference was approximately 5%. Both the ANCOVA and MANCOVA analyses hold across public water system characteristics (the number of households that the participants' water systems served, and the fraction of rural households, which we control for in both analyses).

In summary (Table 1), we find that (1) across race and ethnicities, 42% to 49% of participants were incorrect regarding their actual boil water advisory status, which points to a gaping opportunity to improve public health communications during extreme weather events and emergencies. Additionally, (2) when we examined the influence of various socioeconomic factors on these experiences, we found that although White, non-Hispanic participants were more likely to report being under boil water advisories than Black, Hispanic and Latino, and Biracial participants, these results were driven by the experiences of first-generation participants within the White-identifying group (ANCOVA results). Finally, our (3) MANCOVA results replicate the race and ethnicity effect we observed, and again point to communication gaps between drinking water utilities and the public across racial and ethnic groups (Table 1).

4. Discussion

Considering all results in a holistic way (Table 1), we found that large, urban public water systems and small, rural ones had different recovery response times to Winter Storm Uri. Furthermore, first-generation participants, who may come from more socioeconomically disadvantaged backgrounds, were more likely to be issued boil water advisories across race, ethnicity, and rural or urban communities. Advisories were not communicated effectively, which disadvantaged all racial and ethnic groups. Below, we consider factors behind these trends and implications for water security and future disaster recovery.

4.1. Response times across big, urban and small, rural systems

Winter Storm Uri impacted water access for large urban and small rural communities differently, revealing two scales of vulnerability in public water services. A small number of large water providers serve a majority of the Texas population and issued boil water advisories that left mostly urban residents without reliable drinking water for 5–7 days. Meanwhile, a very small number of mostly rural public water systems issued boil water advisories that lasted weeks and had acute effects on small portions of the Texas population. Of the 15 public water systems with the longest boil water advisories, 11 served exclusively rural communities (fraction of rural households = 1). All but one served fewer than 1,000 residents ($M = 415$ and $SD = 398$). The cross-sectional survey showed similar effects: the total number of households served and the fraction of those households being rural in a participant's public water system had a significant impact on whether that participant was issued a boil water advisory (Table C of S1 Text).

The scale or size of public water systems can influence resilience to severe weather in different ways. Large (typically urban) providers have more available resources for responding to power loss and infrastructure damage during extreme weather, but large treatment plants also require more power to operate and expertise to troubleshoot or maintain under extreme scenarios [13, 35]. Large systems also have longer distribution networks or more places where pipes can burst, requiring more time and resources to identify and repair damage. As a result, the largest systems are highly vulnerable to extreme weather events. Importantly, this small number of large public systems impact the greatest share of the population, not only in Texas but all across the United States. Just 8% of the approximately 52,000 community water systems in the United States serve 82% of the population [36]. Therefore, investments in upgrades to large public water systems can yield big returns–particularly for urban communities.

In comparison, smaller systems range widely in their resilience to extreme weather events because of uncertainties in the human and financial resources available to them [35]. In the current study, smaller systems (serving less than 1,000 individuals) displayed a wide range in the lengths of their boil water advisories (range of 1–36 days), consistent with Glazer et al. [11], who showed that smaller public systems tended to take longer to recover. Of the 15 systems with the longest recovery times, many were already struggling to meet federal drinking water standards during typical weather conditions (they had multiple violations to the standards before and after Winter Storm Uri). Most (12) of these 15 systems used groundwater as their water source, which often requires little treatment prior to distribution [37], making it likely that these public water systems had little to no infrastructure to oversee, but also few staff to address emergencies, leaving their customers water insecure in the face of extreme weather. In general terms, many rural communities have limited access to resources to make repairs during a winter storm [13]. Some of the rural systems with the longest advisories in this study also served residents in unconventional housing such as mobile homes, consistent with other studies that have noted unreliable water access in mobile home communities [11, 38].

In total, Winter Storm Uri revealed weaknesses in both water policy and management across urban and rural areas. The U.S. Federal Energy Regulatory Commission (FERC) and industry stakeholders had previously identified critical infrastructure to winterize in order to mitigate the effects of future winter storm events, but the recommendations were generally not implemented [11]. Policy reform and funding are thus imperative to incentivize weatherization and emergency preparedness. Under Texas Senate Bill 3, which passed in response to Winter Storm Uri, public water utilities were required to have an alternate power source for emergencies and to establish Emergency Preparedness Plans. In a follow-up survey of large water utilities conducted one year after the storm, most had either established backup power systems or were taking steps to do so [13]. However, 90% of these relatively well-resourced utilities still cited economics as a limit to further action. With the influence of climate change and urbanization, many large public water systems therefore remain vulnerable to extreme weather, which creates water insecurities for growing populations [39].

4.2. Water service inequalities

Given the large number of public water systems that issued boil water advisories (Fig 3), it is perhaps unsurprising that impacts were felt across racial and ethnic groups in both our system-level and individual analyses (Table 1), though public water systems are organized around communities that have been shaped by legacies of discrimination (including redlining and gentrification). Glazer et al. [11] also observed no clear relationship between duration of boil water notices and a social vulnerability index at the county level. We note, however, several limitations in our finer-scale analysis that introduced additional uncertainties (Table 1). For example, calculating an aerially weighted average set of demographics for a public water system assumes that housing density within the service area is uniform. Differences may also be masked by reducing demographic and income statistics to average values for entire communities (for example, two public water systems might have very similar average incomes but very different income distributions).

It is important to note that other studies have revealed clear racial and ethnic disparities in water supply and outage factors during Winter Storm Uri. Lee et al. [22] showed that more 311 calls related to burst pipes were placed by low-income and minority groups, and a survey by Grineski et al. [21] showed that Black participants experienced longer water outages. Burst pipes and loss of water pressure are not necessarily distributed evenly throughout individual public water systems, unlike boil water advisories, allowing for more disparate impacts to neighborhoods based on race, ethnicity, and income demographics. Power outages were not equitably distributed across racial and ethnic identities either [20]. Although power outages had knock-on effects on water providers, they were only one of many factors that led providers to issue advisories [6, 40].

The importance of the first-generation status in our cross-sectional survey data may point to underlying socioeconomic disparities in how boil water advisories were issued. We specifically found that first-generation, White participants were more often under boil water advisories than non-first-generation, White participants. Our method of recruiting participants using snowball sampling via our own networks (e.g., research and conference contacts) and a human subjects research participant pool of college-aged students within a large, public university in Texas likely influenced the types of individuals within each income bracket and masked income effects. First-generation status may therefore be the best measure of socioeconomic status in our survey. Future research could explore income and education effects across even a wider community sample.

Lastly, this study underscores other issues with disparity in public water services across racial and ethnic groups, particularly a tendency for small, rural systems in Texas tend to serve predominantly White communities (Fig 2), consistent with studies from elsewhere in the U.S. [19, 41]. For example, a study from North Carolina showed that only 15% of small public water systems served an above-average proportion of non-White or Hispanic and Latino families (>26.96%) [42]. Yet, in our study, 4 out of the 15 (25%) small systems with the longest advisories served an above-average proportion of non-White families; three served mostly Hispanic and Latino families, and one served mostly Black or African American families. Our ANCOVA analysis (Table C of S1 Text), similarly shows that the longest recovery times in rural public water systems in Texas were not consistently concentrated in predominantly White communities.

To dismantle inequalities in public water system services and improve resilience for all communities, there should be more investment in vulnerable geographic areas, including low-income non-White communities [20], and steps should be taken to de-centralize and diversify water supply systems. Additionally, identifying urban and rural communities that are underserved by public water systems, and extending those services is important for ensuring equitable water access [42].

4.3. Public awareness gaps

This study revealed wholesale communication gaps between water utilities and surveyed participants. Tiedmann et al. [13] Castellanos et al. [43] also highlighted gaps and inconsistencies in the way utilities communicated with the public. In a post-storm survey of large public water utilities, roughly 80% cited communication issues with the public as an important complicating factor during the storm; yet, one year later, few of these utilities had taken steps to improve communications [13]. A number of strategies have been suggested to improve communications, particularly to younger ages and minoritized groups. For example, public utilities could leverage social media more frequently in their communications [13] and translate messages to languages other than English [43]. Communication gaps can be exacerbated for communities that rely less on traditional forms of media communication or where there are more non-Native English speakers [44]. The large communication gap documented in this study has important public health consequences and reinforces the need for diverse and tailored communication strategies to reach diverse customer populations.

5. Conclusions

The factors that affected public water supplies in Winter Storm Uri were complex, but the severity of temperatures was not clearly correlated to the length of the advisory. Instead, the size or scale of the public water system and its urban or rural location were most important. Smaller systems faced some of the longest boil water advisories lasting for multiple weeks, while a large portion of the Texas population living in urban areas served by large public water systems was placed under advisories lasting less than a week. Additionally, cross-sectional survey data suggest that first-generation, White individuals were more likely to be issued a boil water advisory than non-first-generation, White individuals. These findings highlight differences in the resilience of public water services to communities of varying size, urban or rural location, and socioeconomic status that affect water security for Texas residents. In the wake of Winter Storm Uri, a clear need exists to help public water service providers prepare for more extreme weather events in a changing climate. Survey data also revealed massive communication gaps between public water service providers and customers, indicating a need for new communication strategies.

Supporting information

S1 Text. Additional information on public water system demographics, survey methods, and results.
(PDF)

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