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Leveraging water utility customer reporting for resilient operations and management

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ABSTRACT

Water utilities collect information from various sources to gain continuous insights into the state of drinking water systems. Among the available data types, service problems that customers report are critical sources of information—especially during emergencies—which allow utilities to gage the impact of system operations on the resulting level of service. While some utilities increasingly collect and analyze customer reporting data to track key performance indicators (e.g., total complaints, response times), this information remains largely underutilized in research and practice. Further, little is known about spatial variations in the quantity or types of problems reported, which can indicate disparities in level of service and customer engagement. Here, we identify and compare spatial patterns in customer reporting against technical system performance and evaluate how trends change during emergency events (e.g., natural disasters). Our analysis demonstrates tightly coupled sociotechnical interdependencies between end user populations and drinking water systems. For instance, results reveal the prevalence of service problems in certain areas and show that several sociodemographic characteristics were statistically different in areas with higher or lower reporting levels. Finally, we offer recommendations for incorporating customer data into operational decision making and outreach efforts.

1. Introduction

Water utilities are tasked with managing complex infrastructure systems to supply safe, reliable drinking water to communities. Drinking water systems (DWS) are sociotechnical systems, meaning they are comprised of social and technical components which must be considered together to achieve effective and efficient system performance (Fischer & Amekudzi, 2011; Zechman Berglund, 2015). Social aspects of DWS include the end users (e.g., customers, communities) who consume and depend on reliable drinking water. Technical aspects consist of the physical components making up the system (e.g., pipes, storage facilities, treatment plants). These social and technical components are inherently interconnected; for instance, end user water consumption (i.e., demands) profoundly impacts system-wide water availability. Utilities also rely on end users to report service problems, such as pipe failures, low pressure, or leaks, in order to direct utility resources and make repairs. These sociotechnical interfaces are especially important during emergencies such as natural disasters, when utility monitoring systems and water production capabilities may be compromised, resources are strained, and the public's assistance, e.g., through conserving water or reporting problems, may be required to help maintain system functionality and adequate water availability.

Reporting problems directly to a utility is one of the primary tools end users have to improve their level of service, especially when experiencing failures that result in water outages or poor water quality. These reports ultimately impact DWS operations and technical performance by influencing how utilities deploy resources, prioritize geographical areas, and schedule infrastructure repairs and upgrades. If problems are reported unevenly across different customer groups or portions of a DWS, disparate outcomes can occur in the level of service experienced by end users. For example, if customers in certain areas underreport problems, the utility may assume there are no issues; on the contrary, if customers in some areas frequently report problems, the utility may be more likely to deploy resources in a timelier manner. As such, spatial variations in customer reporting can have implications for system performance and the equitable provision of service.

Importantly, potential insights into these issues—e.g., spatially imbalanced customer reporting, isolated service disruptions—are lost if

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customer data is not analyzed in the context of technical system performance and the unique served populations. For instance, areas with higher or lower levels of customer reporting may have distinct differences in the sociodemographic makeup of the end user populations being served. Despite these potential differences, many utilities tend to treat end user populations as homogeneous entities when making communication and operational decisions (Boyle, Eskaf, Tiger & Hughes, 2011), even though "one-size-fits-all" approaches to characterizing and interfacing with the public are known to be less effective (e.g., Kreuter, Strecher & Glassman, 1999; Noar, Harrington & Aldrich, 2009). Failing to recognize that utilities serve many "publics," i.e., nuanced sub-populations of end users, and not just a singular customer base can thus hinder utility operations and communication practices (Boyle et al., 2011).

In this paper, we demonstrate these *tightly coupled sociotechnical interdependencies* in the context of DWS technical performance, as expressed through customer reports logged by a utility, water availability, and pipe failures, and *explore how these relationships change during normal and emergency operating conditions* (NOC and EOC, respectively). We show that considering technical and social aspects in tandem can ultimately lead to more resilient DWS, increasing utilities' ability to prepare for, recover from, and more successfully adapt to adverse events (National Research Council, 2012).

1.1. Previous work and study contributions

An increasing awareness of the importance of sociotechnical interdependencies in DWS has motivated researchers, policy makers, and utility mangers to focus on incorporating community-sourced data to ensure adequate, equitable service and better engage communities. Figure S1 in the Supplemental Information (SI) maps out the different aspects explored in related studies and the contributions of our work in this context. For instance, sociotechnical interdependencies in DWS have been explored in the context of public trust of water utilities (e.g., Grupper, Sorice, Stern & Schreiber, 2021; Pierce, Gonzalez, Roquemore & Ferdman, 2019; Weisner, Root, Harris, Mitsova & Liu, 2020; Yang, Butcher, Edwards & Faust, 2023), accountability in emergency scenarios (e.g., Alshboul, 2022), customer engagement (e.g., American Water Works Association, 2022a; Hahn, Metcalfe & Rundhammer, 2020), and management frameworks based on level of service experienced by end users (e.g., Ananda & Pawsey, 2019; Serag, Abu-Samra & Zayed, 2020). Researchers have also explored sociotechnical interdependencies between water systems and end users through various integrated modeling approaches which simulate the impact of consumption behavior and social interaction on water system performance (e.g., Baki, Rozos & Makropoulos, 2018; Berglund, Skarbek & Kanta, 2023; Koutiva & Makropoulos, 2016; Vidal Lamolla et al., 2022). However, these integrated modeling studies largely focus on end user demands and do not explore the significance of customer reporting patterns.

A limited but growing emphasis in research and industry practice has been placed on incorporating customer feedback into technical DWS operations. For instance, utilities use customer reporting data to evaluate key performance indicators in operations and customer service capacities by calculating metrics related to complaints, pipe failures, and supply/demand ratios, among others (American Water Works Association, 2023). Similarly, given customers' roles as "frontline signalers," reports about water quality, taste, and odor can be used by operators to identify problems, inform specific water quality improvements, and serve as opportunities to build trust with the community through timely and adequate responses (Adams et al., 2023; Dietrich, Phetxumphou & Gallagher, 2014; Gallagher & Dietrich, 2014; Tao, Huang, Xin & Liu, 2012; Whelton, Dietrich, Gallagher & Roberson, 2007). Researchers have also modeled how customer complaint data can be used with information about the water distribution system, buildings, and land characteristics to predict the location of customer-side leaks (Shin, Son & Cha, 2022). However, in terms of how customer reporting data is actually collected and used by utilities, substantial discrepancies exist based on organization size and resources: managing customer reporting data is a priority for medium and large utilities, but many small utilities fail to even store this data (DiCarlo et al., 2023). Further, only about half of larger utilities report using such data to track system-wide trends (e.g., water quality problems, widespread pipe failure events), highlighting the current underutilization of reporting information and potential opportunities for expanded use (DiCarlo et al., 2023). While utilities work to respond promptly to customer concerns, not all utilities view broader data analysis of customer reporting as a critical or effective tool for improving operations and management, and researchers have highlighted the need to develop and test analytical approaches for translating such data into actionable insights and uses (Whelton et al., 2007).

On the social side, an understanding has emerged more broadly across infrastructure systems, including DWS, that not all communities interact with natural or built environments equally, especially during emergencies. Specifically relevant to this work, these inequities have been explored and documented in the context of water access, affordability, and climate change (e.g., Brown, Spearing, Roy, Kaminsky & Faust, 2022; Osman & Faust, 2021; Rachunok & Fletcher, 2023). Further, when faced with disruptions (e.g., infrastructure failures, climate change) it is well established that more vulnerable groups typically bear disproportionate impacts and are less able to recover (e.g., Kasperson & Kasperson, 2000; Kim et al., 2023; T. Liu & Fan, 2023; Thomas, Phillips, Lovekamp & Fothergill, 2013; Wei & Mukherjee, 2023). For instance, Winter Storm Uri, which struck the southern U.S. in 2021, exacerbated preexisting inequities across multiple sectors—including energy, housing, transportation, and water—and disparities were found in the duration of power and water outages and storm-related boil water notices (e.g., Castellanos et al., 2023; Coleman et al., 2023; Grineski et al., 2023; Tomko, Nittrouer, Sanchez-Vila & Sawyer, 2023). Such studies have been vital in exposing inequities in the impacts of disasters and infrastructure failures (e.g., outage durations, property damage, health impacts), but often ignore the interface between end users and their utility provider, or how this relationship can change during an emergency.

This study lies at the intersection of work focused on increasing public trust between communities and utilities, using customer reporting data to improve operations and management (and therefore system performance), and enhancing equity as it relates to how communities experience infrastructure disruptions during disasters (see Figure S1 in the SI). At present, community-sourced data and the customer-utility interface remain largely understudied, and numerous opportunities exist for utilities to meaningfully leverage customer reporting data. A key underexplored area surrounds the implications of spatial variations in customer reporting, including the types of problems reported and customer demographics. Further, even less is known about how about how customer reporting may change during a disaster event, when communities and infrastructure systems are acutely strained. Exploring these existing gaps is critical because patterns in customer reporting can reveal disparities and enable better decision making around resource allocation, intervention strategies, and communication practices. In this work, we address the following objectives: (1) identify spatial trends in customer reporting during NOC and EOC; (2) characterize DWS technical performance, as measured by water availability and pipe failures, in areas with higher and lower levels of customer reporting; and (3) explore differences in sociodemographic characteristics between areas with higher and lower levels of customer reporting to reveal the presence of multiple "publics" served by this DWS. Our contributions are twofold: first, our analysis can be seamlessly applied to commonly collected reporting data at other utilities; and second, our results reveal new insights for utility operators and managers regarding the prevalence of service problems in certain areas and the sociodemographic makeup of end user populations.

2. Methods

Here, we analyze five years of customer reporting data (2018–2022) from a large city in the southern U.S. to reveal the presence of spatial patterns and identify areas with high and low levels of customer reporting—i.e., hotspots and coldspots, respectively—using spatial autocorrelation analysis. We then examine the sociotechnical characteristics of these clustered areas, first assessing technical performance before characterizing the sociodemographic makeup of the end user populations in areas with higher and lower levels of customer reporting during NOC and EOC.

2.1. Research context and data

The phenomena of interest in this study are: (1) trends in customer reporting, i.e., when do customers contact a utility, where are they located, and what problems do they report; (2) the correlation between customer reporting and technical system performance; (3) differences in the sociodemographic makeup of end user populations, as related to reporting trends; and (4) changes in reporting trends during EOC compared to NOC. To explore these themes, three types of datasets were used (listed in Table 1 and further described in subsequent sections): (1) customer reporting data, i.e., when and where reports are made, and what is reported, delineated by the problem type category; (2) technical system characteristics, i.e., components of the physical infrastructure system related to pipes and water availability; and (3) sociodemographic characteristics, i.e., various factors describing end user populations.

The study area is a large city in the southern U.S. which is served by a municipal water and wastewater utility. The utility serves a population of roughly 1 million residents with approximately 250,000 individual service connections, supplying a daily demand of 530,000 m^3 per day (~140 million gallons per day) via roughly 6300 km (~4000 miles) of pipes. This particular city is an especially suitable study area due to the utility's advanced data collection and management practices, large geographic size with varied hydraulic conditions (e.g., elevation, pipe materials, age, customer types), diverse population, and the recent occurrence of a natural disaster allowing us the opportunity to study these phenomena. Given the importance of customer reporting during emergency scenarios, in this study we compare spatial trends during NOC and EOC. EOC is represented here by Winter Storm Uri, which struck the southern U.S. and Great Plains regions—including this study area—in February 2021. Winter Storm Uri is an appropriate example of EOC given the historical severity of the event and the widespread devastation it caused, which was significantly greater than impacts typically seen from other extreme weather events or seasonal fluctuations in the region (Glazer et al., 2021; National Weather Service, 2022; Tiedmann et al., 2023). For instance, in Texas alone over 10 million people lost power (Pollock, 2021), approximately half of residents lost access to running water (Watson et al., 2021), and 40% of community water systems declared boil water notices (TCEQ, 2022). For the purposes of comparing NOC and EOC, these periods are defined temporally as follows: NOC = 2018–2022, excluding February 14–28, 2021, when the utility was under normal operating conditions; EOC = February 14–28, 2021, the time period including Winter Storm Uri and the immediate recovery. For all analyses, the datasets shown in Table 1 were stratified according to these NOC and EOC definitions.

Table 1
Datasets used, including units/format, date ranges, and sources. The customer reporting data are delineated by problem type category. Sociodemographic datasets were sourced from the American Community Survey (ACS) and Center for Disease Control (CDC).

Dataset (units/format)	Date(s)	Source
1. Customer Reports (point data including date, time, location, problem type):	2018–2022	Utility
Customer-side infrastructure	2018–2022	Utility
Utility-side infrastructure	2018–2022	Utility
Water quality and availability	2018–2022	Utility
2. Technical Characteristics:		
Pipe network (GIS shapefile including pipe material)	2022	Utility
Pipe repairs (count including date and time of repair)	2018–2022	Utility
Reservoir storage (volume)	February 2021	Utility
3. Sociodemographic Characteristics:		
Households with children under the age of 6 (count, households)	2020	ACS
Median household income ($)	2020	ACS
Population (count, people)	2020	ACS
Population of Hispanic origin (count, people)	2020	ACS
Percentage of population over the age of 65 (%)	2020	ACS
Percentage of renter-occupied households (%)	2020	ACS
Population speaking language other than English at home (count, people)	2020	ACS
Social Vulnerability Index (SVI, percentile ranking 0–1)	2020	CDC

2.2. Description and classification of customer service request data

The customer service request dataset was provided by the utility and included the date and time that each service request was created, the address of the customer making the report, and the problem code assigned to the request. Service requests originate from reports or complaints made by customers to the utility. When a customer contacts the utility to report a problem, the issue is recorded, a service request is created, and a problem code is assigned to the request by the utility representative logging the report. Problem codes are selected from a predefined list maintained by the utility. The utility then investigates and, when appropriate, generates a work order to address the problem (e.g., by repairing a pipe failure). Other times, e.g., if the problem is on customer property or resolved through others means, the request is closed without action taken.

To analyze service requests according to the impacted sector of the DWS, we broadly classified the dataset based on the reported problem types. Table S1 in the SI lists all problem codes and descriptions associated with the service request data. The three broad categories applied to the problem types are: *customer-side infrastructure*—relating to meters, pipes, and other infrastructure on the customer's side of the meter; *utility-side infrastructure*—relating to pipes, hydrants, and other infrastructure that is owned by the utility or municipality; and *water quality and availability*—relating to lack of water, low pressure, or compromised water quality. The data were geolocated using the customer address to allow for geospatial analyses in ArcGIS Pro (ESRI, 2023).

2.3. Identifying global and local spatial patterns in customer reporting

The first step in our analysis is to determine if levels of customer reporting are randomly distributed across the service area or clustered in certain areas, which is accomplished via global and local spatial autocorrelation analysis (Anselin, 1995; Moran, 1950). We first calculated Global Moran's I to reveal whether the data display spatial patterns system-wide before applying Local Moran's I to identify specific cluster locations (i.e., hotspots and coldspots) (Abokifa & Sela, 2019; Zhang, Luo, Xu & Ledwith, 2008). Computing Global Moran's I indicates whether the customer reporting data are predominantly randomly dispersed or spatially clustered, which can then warrant further investigation of local cluster locations if evidence of clustering is found globally (Abokifa & Sela, 2019).

Local indicators of spatial association were used to identify clusters by calculating the Local Moran's I index for each spatial unit (Anselin, 1995). The outcome of the Local Moran's I analysis is a classification of each spatial unit based on similarities or differences with its neighbors. First, for each spatial unit Local Moran's I indicates if unit i is spatially autocorrelated with neighboring unit j, where $I_i > 0$ indicates similarity to neighbors, thus forming a cluster, and $I_i < 0$ indicates dispersion or dissimilarity, thus not forming a cluster. Then, these spatial units are examined to determine if the number of service requests is above or below the expected (mean) number of requests across the entire area (all units). In this context, hotspots are clusters of neighboring spatial units that have similarly high values of customer service requests ("high-high" clusters), while coldspots are clusters with similarly low values of customer service requests ("low-low" clusters). If an individual spatial unit is dissimilar from neighbors that are similar to each other, e.g., a low value surrounded by average or high values, that unit is categorized as an outlier. Spatial units that do not have statistically significant similarities or differences with their neighbors at a 95% confidence level are categorized as "not significant" (Anselin, 1995). Identifying areas with similarly high values (hotspots) and low values (coldspots) of customer service requests is critical because these areas can be characterized and compared to determine if there are significant differences between them. See Sections S2.2-S2.4 in the SI for the detailed Global and Local Moran's I procedure.

2.4. Technical characteristics of hotspots and coldspots

To evaluate technical system performance in clustered areas and compare with customer reporting, we examined several technical characteristics of the DWS. When characterizing the identified clusters and assessing potential differences between them, we focus specifically on the NOC hotspots and coldspots and the new hotspots and coldspots that emerged during EOC, i.e., areas that were not significant during NOC but were identified as such during EOC. By focusing on these "new" or emergent clusters, we aim to specifically assess how customer reporting patterns change during emergencies when compared to NOC.

First, the reported problem types from the service request dataset were grouped for the NOC clusters, new EOC clusters, and the full dataset to enable comparisons with technical system performance. These groupings were also used to assess whether reported problem types vary between NOC and EOC hotspots and coldspots. Technical characteristics consisted of information about the physical water infrastructure system (Table 1) and were selected because they indicate DWS technical performance, as measured by pipe failures and water availability. The technical datasets—pipe network and materials, water availability measurements (i.e., system reservoir storage), and pipe failure records—were overlaid spatially with the NOC and EOC clusters. Water availability measurements, which were provided for the EOC time period, were compared between EOC hotspots and coldspots to determine if there was a correlation between water availability and increased customer reporting during the emergency event. Pipe materials were compared between NOC clusters, new EOC clusters, and the full system to identify potential trends in pipe material composition between clusters.

To determine if pipe failures on the utility-side of the DWS correspond with customer service requests, as well as evaluate if customer reporting accurately reflects documented pipe failures, pipe failure records were analyzed for the same time period as the service requests (2018–2022). To compare spatial patterns in customer reporting and pipe failures, the Global and Local Moran's I clustering analyses were repeated for the pipe failure dataset, with the variable of interest being the pipe failure rate (number of failures per linear meter of pipe per spatial unit). Lastly, an analysis spatiotemporally matching the customer service request dataset to the pipe failure dataset was performed to assess how well customer reporting captures documented pipe failures. See Section S2.5 in the SI for the complete procedure for the pipe failure analysis.

2.5. Sociodemographic characteristics of hotspots and coldspots

Next, we assess the sociodemographic makeup of the end user populations in the identified clustered areas, specifically comparing and contrasting the NOC and EOC hotspots and coldspots, to reveal the presence of multiple "publics" served by this DWS. Sociodemographic characteristics (Table 1) were chosen based on a review of literature (e.g., Nayak et al., 2018; OECD et al., 2008; Spielman et al., 2020) and consultation with subject matter experts to represent a relevant range of indicators that characterize the served population and provide actionable takeaways for utilities. Seven datasets from the 2020 American Community Survey (ACS) (United States Census Bureau, 2020) were used to represent total population, income and economic status (median household income, renter occupied households), age (households with children under six, population over 65), and language (population speaking a language other than English at home, population of Hispanic origin) (Table 1). In addition, Social Vulnerability Index (SVI)—a composite measurement based on 16 social factors at the census tract level developed by the Center for Disease Control (CDC)—was included to represent overall social vulnerability (CDC, 2022). For all sociodemographic datasets, geocoded census tract level data were used due to the availability of more indicators at this scale and to maintain consistency with SVI data, which is not available at finer resolutions. To explore trends in sociodemographic characteristics, we then compared between NOC hotspots and coldspots and examined whether these trends changed during EOC. See Section S2.6 in the SI for the sociodemographic analysis procedure.

3. Results

3.1. Overview of customer reporting

To contextualize the spatial analyses presented in subsequent sections, here we provide a brief summary of the primary dataset used in this study, customer service requests. Fig. 1 shows the total number of customer service requests received within each 1km^2 cell across the service area from 2018 to 2022. The number of service requests per km^2 ranged from 0 to 372 over the five-year period, with an average of 60.8 and standard deviation of 68.6. An initial visual review of the dataset suggests that customer reporting may not be randomly distributed across the system, but further analyses are needed to confirm statistically whether spatial patterns actually exist.

3.2. Global imbalances in customer reporting

Global spatial autocorrelation results show that the customer service

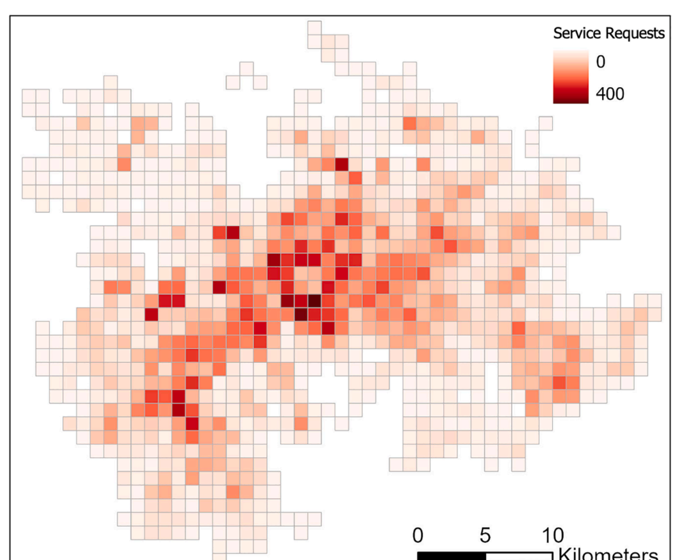

Fig. 1. Total customer service requests, of all problem types, made per 1km^2 cell in the service area from 2018 to 2022. Service requests were assigned to cells based on the address location of the customer making the report.

request data display a global spatial pattern, i.e., are globally clustered, indicating that customers do not report problems evenly or randomly across the service area. Instead, there are spatial imbalances, and some areas account for higher or lower numbers of requests. Table 2 shows spatial autocorrelation results for the entire service request dataset, NOC service requests, and EOC service requests. For all datasets, the Global Moran's I was > 0.5 with a positive z-score and p-value < 0.001, indicating that the null hypothesis—that underlying spatial processes are random—can be rejected, and the data are spatially clustered (Liu, Bi, Wang, Li & Guo, 2013). Computing Global Moran's I as a first step in the analysis establishes that the data are spatially structured system-wide, which justifies exploring spatial trends on a local level to identify more refined patterns.

3.3. Local imbalances in customer reporting

The local spatial autocorrelation analysis of customer reporting in NOC and EOC revealed spatial imbalances in both datasets and showed that several new clusters emerged during EOC which were not present during NOC. Fig. 2 shows service request hotspots, coldspots, and outliers identified using Local Moran's I during NOC (Fig. 2A) and EOC (Fig. 2B). During NOC (Fig. 2A), a large hotspot of service requests exists in the center of the system which extends to the southwest portion of the service area. Coldspots are primarily present around the edges of the service area, with the largest coldspot in the northwest of the DWS. These patterns are generally to be expected, given the distribution of population and pipe densities across the system (see Figure S2 in the SI), and show that the hotspots largely occurred in areas with more people and water infrastructure.

Comparing the NOC (Fig. 2A) and EOC (Fig. 2B) clustering, the location and size of hotspots and coldspots shifted in several areas, indicating that customer reporting changed during this extreme event. Fig. 2C shows the changes between NOC and EOC, with red and blue areas indicating *emergent clusters*, i.e., cells that were *not* part of a cluster during NOC but became hotspots or coldspots, respectively, during EOC. As expected, a large hotspot still exists in the center of the system during EOC (Fig. 2B). However, during EOC this cluster extends further to the south/southwest, and the hotspot in the southeast more than doubled in size. Overall, increases in hotspots combined with decreases in coldspots in the southern part of the system indicate significant increases in customer reporting in these areas during the extreme event. Conversely, increases in coldspots in the northern portion of the system indicate relatively fewer customer requests coming from these areas. Having established that reporting patterns changed during EOC, we now look to explore these shifts further.

3.4. Technical performance in hotspots and coldspots

Beginning with the technical characteristics that describe the DWS, our results show that spatial variations in customer reporting correspond with differences in technical performance, as measured by water availability and pipe failures.

Changes in the types of problems reported by customers: Fig. 3A shows the types of problems reported by customers, comparing the full service request dataset (2018–2022) against NOC hotspots and coldspots, and new EOC hotspots and coldspots (see Table S2 in the SI for the total number of service requests per dataset). Notably, the full dataset, NOC

Table 2
Spatial autocorrelation analysis results for customer service requests showing that spatial patterns exist in all datasets.

Service Request Dataset	Global Moran's I	z-score
All Service Requests	0.60	39.5
Normal Operating Conditions (NOC)	0.60	39.2
Emergency Operating Conditions (EOC)	0.51	33.4

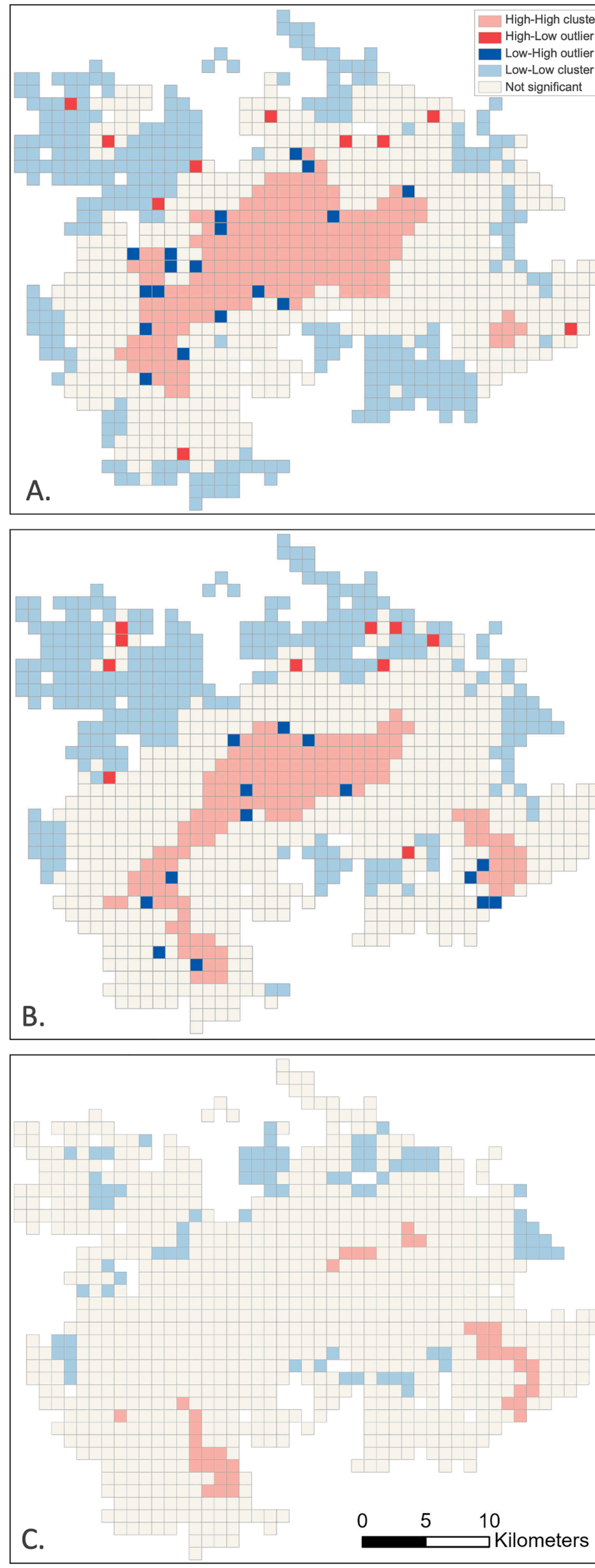

Fig. 2. Clustering results based on Local Moran's I for service requests from: (A) 2018–2022 (NOC) and (B) Winter Storm Uri (EOC). High-high clusters indicate "hotspots" of customer reporting while low-low clusters indicate "coldspots." (C) shows new hotspots and coldspots that emerged during EOC.

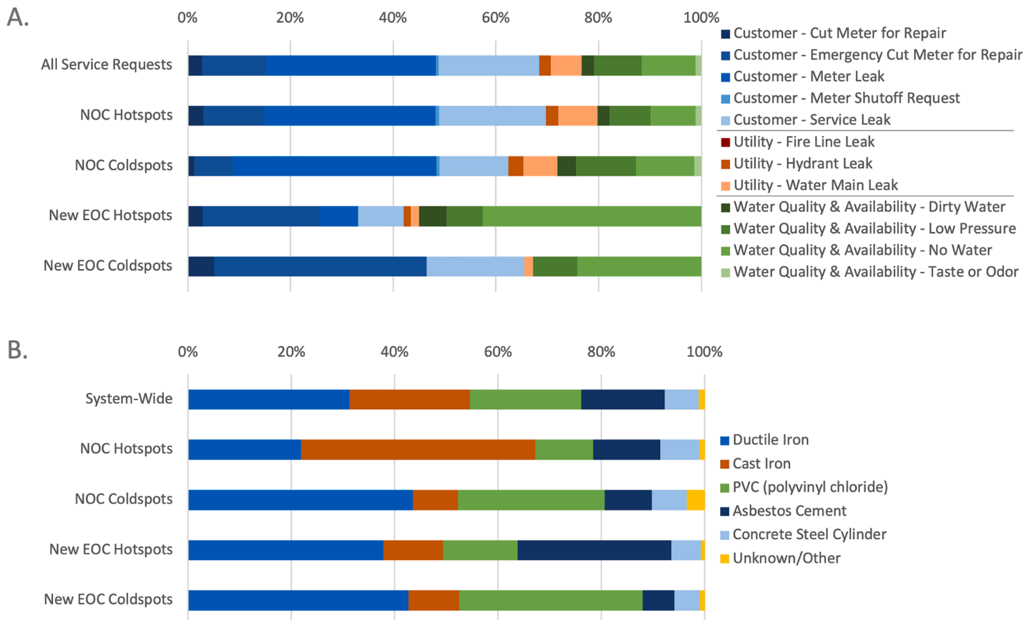

Fig. 3. Technical characteristics describing the full water infrastructure system, hotspots and coldspots based on clustering of service requests during NOC, and new hotspots and coldspots that emerged during EOC. (A) shows service requests by problem type, with blue shades representing customer-side infrastructure problems, orange shades utility-side infrastructure problems, and green shades problems related to water quality and availability. (B) shows pipe materials in the utility distribution system.

hotspots, NOC coldspots, and new EOC coldspots display a similar breakdown by problem category, with ~70% of requests coded as customer-side, ~10% utility-side, and ~20% water quality and availability, on average. However, the new EOC hotspots display a distinct pattern, with over 50% of reports relating to water quality and availability problems (mainly no water for this particular event) and smaller portions of customer-side (~45%) and utility-side (~5%) related reports, indicating that reporting in new hotspots was driven largely by water outages during EOC. In EOC coldspots, the largest percentage of reports were emergency "cut meter for repair" requests, which likely indicate customers had urgent premise plumbing problems, such as frozen or burst pipes, and were unable to shut off their water themselves. This large percentage of emergency meter shutoff requests, followed by no water reports, shows that the new coldspots still saw storm-related impacts, but not nearly as many reports came in from these areas.

Changes in pipe material composition: Turning to the piped water network that delivers water to end users, we examined pipe material across the DWS. Fig. 3B shows the breakdown of pipe material across the entire system and clustered areas, based on the linear meters of pipe of each material in each cell (see Table S2 in the SI for the total lengths of pipe in each dataset). In comparing pipe materials, the most notable difference is that the NOC hotspots contain a significantly greater proportion of cast iron pipes than the other clusters and the system as a whole. These results are somewhat expected, as the main NOC hotspot is located in the core of the system, which is known to be older, denser (Figure S3), and contains a greater proportion of cast iron lines; the utility discontinued the use of cast iron several decades ago. Regarding the new EOC hotspots, these areas contain a smaller portion of cast iron lines than the entire system and the NOC hotspots, instead having a greater proportion of ductile iron lines. Conversely, the pipe material breakdown in the new EOC coldspots closely resembled the NOC coldspots. Overall, the pipe material composition reflects the fact that pipe material (specifically the presence of more cast iron pipes) was not a driver of increased customer reporting during EOC, despite being correlated with NOC hotspots.

Customer reports versus *available water:* To confirm some of the problem types customers reported in the new EOC hotspots and coldspots, we examined technical system performance in terms of water availability. During the storm, many water storage facilities were depleted, leading to widespread low pressure and water outages throughout the DWS. Figure S4 in the SI shows the total available water system-wide during this period, reflecting the severe impact the storm had on utility operations and serviceability. Fig. 4 shows the average storage, as a percentage of total capacity (y-axis), in the areas serving the new EOC hotspot (red) and coldspot (blue) clusters as a function of size, i.e., the number of cells (1km^2) in each cluster (x-axis). While approximate, average reservoir storage provides an estimate of the relative amount of water that was available in each area, thus serving as a useful indicator of the level of service experienced by end users. Unsurprisingly, all of the new hotspot cells were located in areas of relatively low

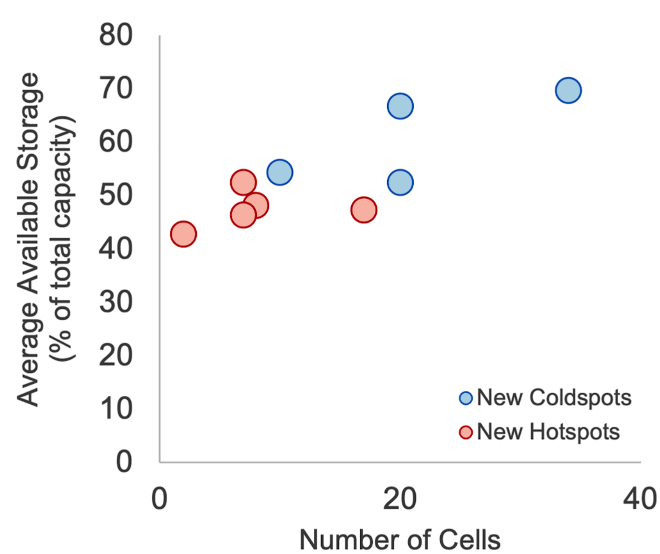

Fig. 4. Average available storage during EOC in the new hotspot and coldspot areas. The y-axis shows the average available water (based on reservoir storage measurements) during EOC in each cluster; the x-axis represents the number of 1 km^2 hotspot (red) and coldspot (blue) cells in these areas.

water storage (~40–55% full), while most of the new coldspots were in areas that had higher storage levels (~50–75% full). The water availability measurements confirm the pattern seen in the reported problem types (Fig. 3A), in which EOC hotspots mostly reported no water problems while EOC coldspots mostly requested emergency meter shutoffs

Spatial agreement between customer reports and pipe failures: Pipe failures were examined to provide additional insight into technical performance of the DWS. To determine if pipe failures in the utility side of the system correspond with greater numbers of customer service requests, we first investigated whether failure trends in NOC and EOC align spatially. The Global Moran's I was computed for pipe failure rates (failures per linear km of pipe), with $I = 0.29$ and $z = 19.0$, showing that spatial patterns in failures exist globally, though to a lesser extent than the service requests. The Local Moran's I clustering analysis was then repeated for failure rates during NOC, with failures that occurred during EOC overlaid on top (Fig. 5A). Notably, the EOC failures generally aligned spatially with NOC pipe failure hotspots. Further, when considered with Fig. 3B, these results align with previous work which demonstrated that areas with more cast iron pipes tend to experience higher failure rates (e.g., Abokifa & Sela, 2019; Rifaai, Abokifa & Sela, 2022).

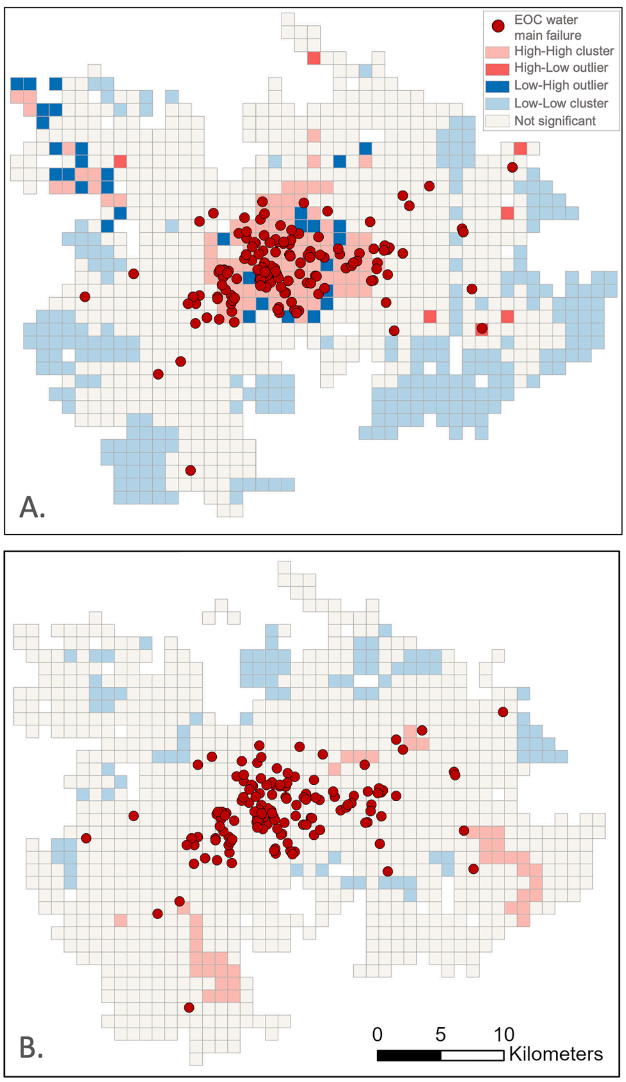

Fig. 5. Spatial analysis of pipe failures. (A) Local Moran's I clustering results based on pipe failure rates from NOC, overlaid with failures that occurred during EOC (red dots). (B) New customer reporting hotspots and coldspots that emerged during EOC overlaid with EOC pipe failures (red dots).

Unsurprisingly, the pipe failures that occurred during EOC happened in areas that were already problem areas for high pipe failure rates (i.e., NOC hotspots), and this preexisting vulnerability was exacerbated during the event. Figure S5 in the SI shows the number of pipe failures per week over the study period, with a substantial increase in failures in February 2021 due to the storm. However, the EOC pipe failures do not correspond spatially to increases in customer reporting during the storm. Fig. 5B shows the pipe failures that occurred during EOC (red dots) overlaying the new EOC customer reporting hotspots and coldspots (also shown in Fig. 2C). While a small number of EOC pipe failures are close to the new hotspots, no pipe failures fell within these new clusters, and it is visually apparent that pipe failures did not align with the new reporting clusters. This misalignment is supported by the pipe material results (Fig. 3B), which show that most new EOC hotspots were in areas primarily composed of newer, non-cast iron materials that are typically less prone to failures (Rifaai et al., 2022). In sum, the pipe failure analysis confirms that the new EOC reporting hotspots did not correspond spatially to pipe failures, but rather to issues of water availability caused by low storage in the water system, in addition to customer-side problems.

Customer reports versus *utility-side failures:* Pipe failures were further examined to determine how consistently customers report utility-side failures to the utility, and whether these tendencies change in an emergency. The number of accurately reported utility-side failures can serve as an indication of how reliable customers are as "sensors" for issues in the distribution system, which is especially important given how heavily utilities rely on end users for this information. Table 3 shows that many repairs made to utility-side pipe failures corresponded to at least one customer service request during NOC and EOC. "All Problem Codes" includes all customer service request problem types, accounting for problems potentially misreported or misinterpreted (e.g., the customer reports a break on their side that was actually a utility-side pipe failure, or vis-versa). "Utility-side problem codes" includes only service requests coded as utility-side issues (fire line leak, hydrant leak, and pipe leak).

The analysis revealed that during NOC, 72% of all utility-side repairs (1439 of 1985 total from 2018 to 2022) could be connected to at least one customer service request, and 51% of these repairs were matched to at least one customer request that specifically indicated a utility-side problem. During EOC, these percentages increased significantly, with 91% of utility-side repairs (131 of 144 total from February 14–28, 2021) matched to at least one service request, while 75% were matched to at least one request coded as a utility-side problem. This suggests that customers report utility-side problems thoroughly but may not be

Table 3
DWS pipe repairs matched to service requests during NOC and EOC. Matching was based on a service request being made within 300 m of the pipe failure in the two weeks prior to it being repaired.

	Number of repairs matched to at least 1 service request	Percent of repairs matched to at least 1 service request
NOC (1985 total repairs)		
All problem codes	1439	72%
Utility-side problem codes	1015	51%
EOC (144 total repairs)		
All problem codes	131	91%
Utility-side problem codes	108	75%

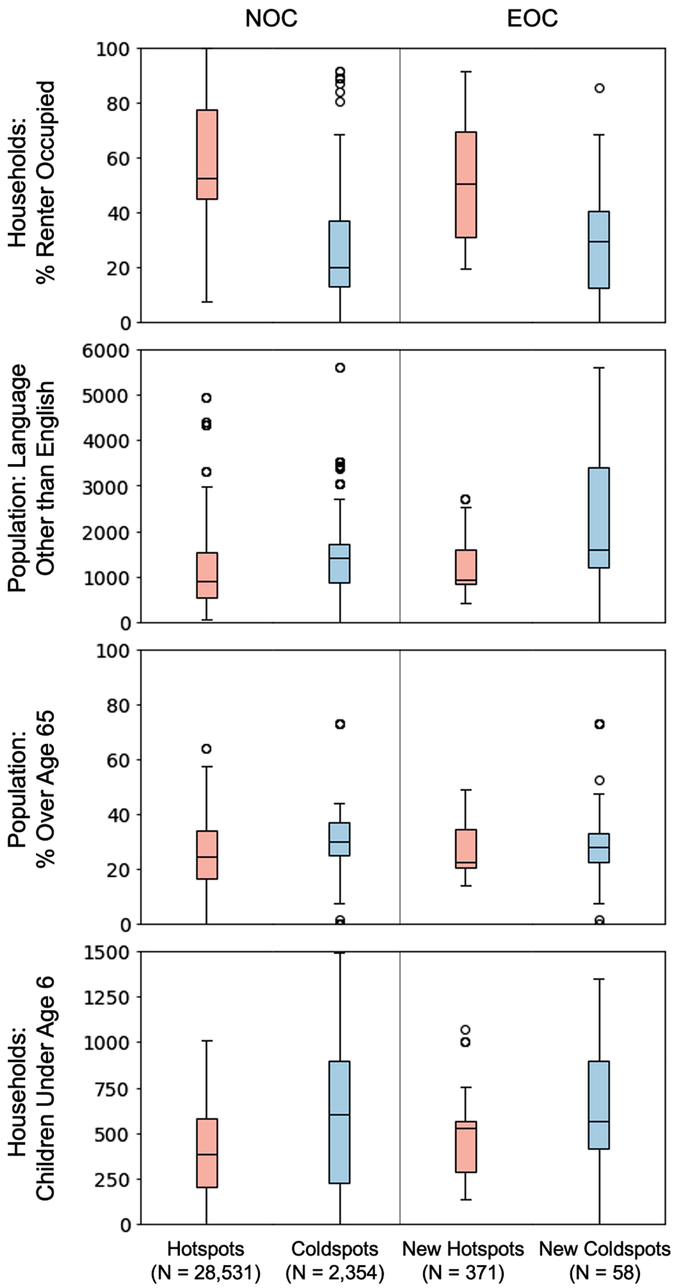

Fig. 6. Boxplots comparing key sociodemographic characteristics in hotspots and coldspots based on clustering of service requests during NOC (left) and new hotspots and coldspots that emerged during EOC (right).

sensitive to the type of problem (i.e., who owns the impacted infrastructure). However, during EOC customers not only report more failures, but also report failures more accurately (75% of utility-side problems were reported during EOC versus 51% during NOC). Histograms in Figure S6 in the SI show the distribution of the number of service requests matched to each repair. Individual pipe repairs were matched to more service requests during EOC, as illustrated by the longer tails on the right side of the histograms. These distributions show that multiple customers reported the same problem, indicating that during emergencies customers become more effective signalers but may also tend to overreport issues.

3.5. *Sociodemographic associations in hotspots and coldspots*

Sociodemographic characteristics were considered across NOC hotspots and coldspots and the new hotspots and coldspots that emerged during EOC, revealing differences between the populations in these areas. That is, in the context of customer reporting, there is not one singular, homogeneous end user population being served by this DWS. Fig. 6 shows boxplots for four of these characteristics (see Figure S7 in the SI for the remaining boxplot results). The plots indicate visually that differences between hotspots and coldspots are present. For instance, hotspots during NOC and EOC have a higher number of renter-occupied households relative to coldspots, while coldspots have more households with children under the age of 6. Beyond these preliminary observations, to inform utility management and policy it is important to determine if perceived differences between these groups are statistically significant. To do so, we test whether the values of each characteristic are significantly different in hotspot versus coldspot areas in NOC and EOC. Table 4 summarizes *t*-test results for each characteristic between NOC hotspots and coldspots (left) and new EOC hotspots and coldspots (right).

Differences in median household income, population density, and the percentage of renter-occupied households were statistically highly significant during both NOC and EOC. For the two age-related characteristics, changes in the significance level indicate that households with young children or seniors contacted the utility less during NOC but were more willing to report issues during EOC. For the two characteristics pertaining to language and ethnicity—population of Hispanic origin and population speaking a language other than English at home—differences became more significant during the storm. These two groups (non-English dominant and Hispanic populations) already contacted the utility less during NOC, but the discrepancy between hotspots and coldspots increased further during EOC. Differences in SVI, the CDC's composite index measuring social vulnerability, were not significant during NOC or EOC, meaning there was no measurable difference in the SVI of areas that were hotspots versus coldspots in either scenario.

Table 4
Results for pairwise *t*-tests between hotspots and coldspots based on clustering of service requests during NOC (left) and the new hotspots and coldspots that emerged during EOC (right).

	NOC: hotspots vs coldspots		EOC: new hotspots vs coldspots	
Sociodemographic Characteristics	*t*-statistic	*p*-value	*t*-statistic	*p*-value
Households with children under the age of 6	−6.68	6.89×10^{-11}**	−2.89	0.004*
Median household income	−4.02	6.89×10^{-5}**	−4.74	5.78×10^{-6}**
Population density	12.1	1.42×10^{-25}**	7.59	7.78×10^{-10}**
Population of Hispanic origin	−3.00	0.003*	−4.91	3.02×10^{-6}**
Percentage of population over the age of 65	−4.57	6.82×10^{-6}**	1.50	0.14
Percentage of renter-occupied households	15.74	5.56×10^{-43}**	6.95	1.61×10^{-9}**
Population speaking language other than English at home	−2.75	0.006*	−4.89	3.04×10^{-6}**
Social Vulnerability Index (SVI)	1.71	0.09	−1.57	0.12

* *p*-value < 0.05.
** *p*-value < 0.001.

4. Discussion

Our analysis revealed differences in technical system performance between NOC and EOC which corresponded with customer reporting trends. Further, differences in the sociodemographic makeup of hotspots and coldspots were statistically significant for several characteristics during NOC, and these significance levels changed during EOC. Here, we discuss the implications of these results in this study area and for other water utilities more broadly.

4.1. What drives customer reporting?

Technical performance indicators revealed that water storage, which determines water availability, was the most probable driver of increases in customer reporting during EOC. That is, the storage facilities that serve these areas were depleted, likely due to increased demands, pipe failures in the core of the system, and widespread premise plumbing failures, leading to a loss of pressure in the distribution system and ultimately to water outages. The low storage levels in the new EOC hotspots (Fig. 4), combined with the greater share of no water reports (Fig. 3A) support this finding. The large share of emergency requests to cut meters for repair suggest a large number of customer-side problems (e.g., leaking meters, premise plumbing breaks); widespread customer-side failures were observed throughout the region during this event and contributed significantly to the loss of reservoir storage (Austin Water, 2021; Texas Section of the American Society of Civil Engineers, 2022; Tiedmann et al., 2023). The low percentage of utility-side reports in new EOC hotspots (Fig. 3A), in combination with the fact that no pipe failures occurred in new EOC hotspots (Fig. 5B), show that customer reporting is generally not driven by utility-side issues during this type of emergency.

From an operational standpoint, these results can be used by utility mangers to spatially identify which portions of the system tend to experience certain issues during NOC versus EOC. For instance, during NOC, customer reporting hotspots overlapped with areas that also experienced higher rates of pipe failures in the older, denser core of the system, indicating that focusing on upgrading aging infrastructure in these areas (e.g., cast iron pipes) will likely improve system performance. During EOC, while pipe failures were a significant problem (as shown by the large increase in failures shown in Figure S5 in the SI), the prevalence of no water reports in new hotspots farther from the core of the system indicates that these areas were more vulnerable in terms of water availability and connectivity to the distribution network, i.e., it was more difficult for water to reach these areas during the emergency. These insights can help utilities when making planning and operational decisions around pumping and reservoir filling schedules, replacing aging pipes, and planning new transmission and storage capacity. For instance, with the knowledge that some areas are more vulnerable to water availability issues during emergencies, operators may take additional measures to route more water to these areas during EOC through increased pumping from other portions of the system. Important to note, while these specific operational takeaways may be unique to this system, a similar analysis pairing service requests with commonly available technical characteristics such as pipe material, failures, and storage levels could be replicated in other study areas to yield new insights about those systems. Where available, incorporating additional datasets such as pressure and usage measurements would likely enhance the resulting recommendations for improved operations.

4.2. There is more than just one "public"

Our analysis found sociodemographic differences between hotspots and coldspots which changed during NOC and EOC, showing that the public is not a homogeneous entity when it comes to interacting with DWS, and utilities should consider these spatial trends when making operational decisions and communicating with end users.

Three of the sociodemographic characteristics examined—population density, renter population, and income—were all highly significant during both NOC and EOC. As expected, hotspots of customer reporting had higher population densities because there are more people to contact the utility, as confirmed by the *t*-test and boxplot results (Table 4 and Figure S7). We might expect coldspots to have larger renter populations and lower median income, because renters are frequently not direct utility customers and may be unclear as to whether the utility or landlord is responsible for a given issue (Pierce et al., 2019). Further, previous research has generally found that higher income was positively associated with increased numbers of complaints in other contexts, such contamination or pollution incidents (e.g., Dong, Ishikawa, Liu & Hamori, 2011; Weersink & Raymond, 2007). However, the opposite was revealed here, with hotspots having significantly more renters and lower median income during both NOC and EOC (Figs. 4 and S7). The population distribution in this specific city (see Figure S3) may partially explain this result: higher density housing (e.g., apartments) tends to be renter-occupied and located more in the core of the city, and renters, on average, tend to have lower income than homeowners (Raymond, Green & Kaminski, 2022).

Notably, the new EOC coldspots had slightly higher population densities and larger renter populations compared to the NOC coldspots (Table 4, Figure S7). This may indicate less willingness to contact the utility in denser, renter-occupied areas during this specific emergency when compared to NOC. Because many of the issues experienced by renters were on the customer side (e.g., burst pipes, property damage; Oxner & Garnham, 2021), renters may have been more likely to contact landlords rather than the utility in their efforts to obtain quick assistance. In general, utilities should be cognizant of customer reporting trends in areas with larger renter populations and multifamily residences because individual failures, whether on the utility or customer side, impact more people. It has been well-documented that during this particular disaster residents of multifamily housing experienced disproportionate impacts of prolonged water outages and premise plumbing failures, which were exacerbated by inadequate communication with utilities and landlords (Castellanos et al., 2023; Oxner & Garnham, 2021; Tiedmann et al., 2023).

Several sociodemographic characteristics changed in significance level, highlighting shifts in customer reporting during EOC. Hotspots had significantly fewer households with young children (under 6) and seniors (over 65) compared with coldspots during NOC, but these differences became less significant or disappeared during EOC. Households with young children or seniors may have been more willing to contact the utility during EOC, perhaps because they had a heightened awareness of the severity of the emergency and increased concern for health and safety. Such tendencies have been confirmed in previous research, which has shown that having children in a household corresponds with a greater concern for water quality and health issues (Dosman, Adamowicz & Hrudey, 2001; Yang & Faust, 2019). Concerns especially over providing unsafe water for drinking or in infant formula were likely prevalent in households with young children during Winter Storm Uri, when widespread water outages and boil water notices occurred. Similarly, households with vulnerable senior populations may have been facing urgent safety issues due to broken pipes, medical conditions, and lack or water, e.g., for drinking, sanitation, or use in medical devices. Widespread reporting in the aftermath of the storm confirmed that elderly residents disproportionately suffered due to lack of power and water, broken pipes, and need for critical medical support (Aldhous, Lee & Hirji, 2021; Austin Water, 2021; Soergel, 2021; West, 2021).

Given the vulnerability of these age groups, it is important for utilities to conduct emergency-specific outreach to improve preparedness for potential future disasters and ensure residents have necessary supplies (e.g., emergency kits, bottled water, medical devices). With lower reporting levels observed during NOC, utilities should work to improve routine engagement with these groups by encouraging residents to report problems even in non-emergency times, for instance through smartphone applications, utility websites, and customer service phone-lines. Increasing participation during NOC builds relationships and awareness so that communities are ultimately better prepared for future emergencies.

The language-related characteristics—language spoken at home and population of Hispanic origin—also saw changes in significance between NOC and EOC. These variables were included in this study because multilingual communication, specifically Spanish, has been a known challenge for utilities in this region, especially during crises. Indeed, our results suggest discrepancies in these categories, with coldspots having larger populations of individuals speaking a language other than English at home and individuals of Hispanic origin compared to hotspots. The expansion of these differences during EOC (both *t*-statistics went from significant to *highly* significant) indicates that additional communication is needed, in multiple languages, to improve engagement and emergency preparedness among these groups. During Winter Storm Uri specifically, utilities throughout the region largely excluded non-English speakers from outreach and communication efforts (Castellanos et al., 2023). The importance of efficient, multilingual communication during crises is well established, but officials' ability to deliver such information successfully is frequently hindered when they only focus on preparing and translating messages once in the response phase of a disaster—i.e., in the midst of the crisis (O'Brien & Federici, 2019). Instead, translation and multilingual communication should be considered part of disaster prevention and preparedness, to be incorporated into routine NOC activities (O'Brien & Federici, 2019). An additional aspect of multilingual communication which is often overlooked by utilities is the presence of language brokers, i.e., children or adolescents who act as translators for adult family members in non-English speaking households (Kam & Lazarevic, 2014; Murillo & Kam, 2021). As such, utility messaging—e.g., emergency preparedness tips, conservation requests, and instructions for how to reach the utility to report a problem—is typically not prepared with the target audience of adolescent translators in mind. Given that our results suggest a widening reporting gap among Hispanic and non-English dominant populations during EOC, it is recommended that utilities prioritize developing multilingual communication during NOC, prepare more age-inclusive messaging to accommodate potential language brokers, and work to forge relationships with cultural or community groups to establish trust and increase awareness about the ways in which residents can contact a utility during an emergency.

It is noteworthy that no significant differences in SVI were found between hotspots and coldspots in NOC or EOC, despite the differences found in the other seven characteristics. This result may indicate that there were no significant differences in the overall vulnerability of populations that fell into hotspots or coldspots. A more likely explanation, given the differences seen in the other indicators, is that SVI is too broad of an index for this particular research context and obscures the more nuanced distinctions uncovered by examining more specific characteristics that are relevant for the individual study area. While beyond the scope of this work, others have weighed the merits of using SVI and put forth protocols for compiling alternate specialized composite indicators (e.g., OECD et al., 2008; Spielman et al., 2020), suggesting that another type of index could reveal more distinct patterns. Overall, this exploration of sociodemographic characteristics demonstrates the importance of selecting a range of indicators that are relevant to the study area and context.

4.3. Is customer-reported data reliable?

In examining trends in customer reporting, one of our objectives was to evaluate how well these reports align with known failures in a DWS. While utilities manage and apply customer reporting data to widely varying degrees, most rely on customers—at least in part—to notify them when problems occur (DiCarlo et al., 2022). Though our spatiotemporal analysis of customer service requests and pipe failures was approximate, the results yielded useful insights about reporting during NOC and EOC.

As expected, considering all types of problem codes led to more repairs being matched to service requests (Table 3), showing that multiple customer service requests in a given area could potentially signal a utility-side failure and warrant investigation, even if the problem code indicates differently. Customers accurately reported about half of all pipe failures during NOC, but became significantly more thorough during EOC, as seen by the increase in pipe repairs matched to service requests and the number of duplicate requests per repair (Table 3 and Figure S6). This shift is likely due to increased infrastructure awareness during the emergency, as well as communication from the utility encouraging customers to report problems during the event. Utilities should therefore direct resources to increase customer reporting of utility-side issues during NOC, when the public may be less inclined to report water infrastructure failures observed in the DWS. For instance, during NOC individuals may assume someone else has already reported the problem, or that the utility is already aware. Customers generally report pipe failures reliably, but utilities have opportunities to improve effectiveness by making communication methods more accessible, and increasing engagement during NOC will likely also improve customers' willingness to report problems when the next emergency occurs.

4.4. Data challenges and opportunities

As in all studies examining real-world systems, there are limitations to the datasets applied here but also opportunities for expanding analyses of sociotechnical aspects of DWS and customer-utility relationships. It must be noted that no study can account for all interfering factors which may impact a behavior or phenomena of interest. In our case, in comparing NOC and EOC across a five-year study period, other events and changes such as population dynamics, new policies, and demographic shifts likely occurred which may have impacted spatial patterns in customer reporting. Though beyond the scope of this work, future efforts would likely yield valuable insights by examining the impact of specific demographic shifts or policy events on customer reporting. Further, many utilities—including the one studied here—have multiple modalities that customers use to contact their provider to report problems, and not all communications from customers ultimately generate service requests or repairs. For instance, many utilities have phone lines, smartphone applications, online forms, email, and social media pages, all of which may be utilized by customers. It should also be noted that when customer reports are made, some level of processing is completed to generate a service request or other actionable task. In our context, this processing occurs when a utility representative assigns a problem code to the request (chosen from a pre-defined list of codes), and there is potential for bias to be introduced in this stage, especially when distinguishing between utility- or customer-side issues based on a customer's description of the problem. Utilities should therefore consider routinely refining these codes and processes, especially as new reporting modalities become available (e.g., smartphone applications, web forms). Despite this, and the fact that the dataset used here does not include all communication channels or account for communications that did not result in service requests (e.g., social media comments), our analysis draws useful insights about trends in reporting given the large sample size (>60,000 datapoints between 2018 and 2022) and ability to make comparisons between NOC and EOC.

Many factors potentially contribute to whether an individual customer may or may not contact their utility to report a problem during NOC or EOC, and our analysis does not attempt to predict or provide a comprehensive list of all possible contributing causes. While our sociodemographic analysis suggests that trends in reporting are statistically associated with characteristics of the population—particularly around age and language—additional qualitative data are needed at finer resolutions to gain more refined insights into how end users interact with utilities, how utility communication is received, and how this relationship changes in an emergency. For instance, conducting surveys or interviews that allow for open-ended responses among people who experienced Winter Storm Uri and documenting sociodemographic information and end user experience may further confirm these trends or perhaps reveal new statistical associations. Further analysis might continue exploring how customers experience service disruptions or how they choose to report customer- versus utility-side problems. Our results provide a more complete picture of both the technical and social aspects of DWS during NOC and EOC and establish a basis for future work to further explore social system interactions with utilities.

4.5. Leveraging customer reporting for resilient operations, management, and communication

While the core goal of providing safe, reliable drinking water has not changed in recent decades, water utilities have entered a “new era” where priorities must extend beyond technical system performance to also include community-informed management and equitable service. Our analysis shows how other utilities can use customer reporting and other commonly available data (Table 1) to identify spatial trends and determine if there are distinct sociotechnical characteristics within areas that have higher or lower levels of reporting. Though these patterns will be unique to every study area, our results yielded recommendations with broader applicability, synthesized below.

(1) *Collect and manage customer reporting data:* Collecting and maintaining customer reporting data is a necessary first step to ultimately using this information to investigate trends and system-wide problems and proactively improve DWS operations. Incorporating analyses of spatial patterns in reporting, technical performance, and sociodemographic trends can help utilities improve key performance indicators in operations and customer service and better serve communities. While data management remains a persistent challenge in the water sector (e.g., DiCarlo et al., 2023; Kadiyala & Macintosh, 2018), curating data effectively ultimately provides vast opportunities for rigorous analysis of customer reporting. Future work should incorporate data from additional communication modalities, especially as social media and new technologies (e.g., advanced metering infrastructure (AMI) and smartphone applications) become increasingly important for utility management. Further investigations should also consider how compromised data might inhibit utilities’ operations and management.

(2) *Know your public(s)*: Our analysis shows that utilities do not serve a singular, homogeneous public, but rather diverse and nuanced populations, and interactions with these populations can change during EOC. When utilities view their end user population as a single entity, they lose critical leverage points where interventions can be made to improve not only level of service but also customer trust and satisfaction (American Water Works Association, 2022b). Knowing the makeup of the served population can enable utilities to target messaging to population groups, or even tailor to individuals, practices that have been well-established in other sectors such as health care (Kreuter et al., 1999; Noar et al., 2009; Schmid, Rivers, Latimer & Salovey, 2008; Stephens, Rimal & Flora, 2004). For instance, our results highlight the need for more public communication conducted during NOC that focuses on both general education and emergency preparedness to build community and DWS resilience to future extreme events. Our results also suggest different approaches may be needed to reach households with children, older adults, and non-English dominant populations. Targeted approaches can be valuable tools for utilities to improve community trust and engagement but must be data driven and informed by analysis.

(3) *Implement new technologies, with appropriate education:* To encourage and streamline customer reporting, major cities throughout the U.S. have launched smartphone applications for reporting of non-emergency issues (i.e., 3–1–1) such potholes, street light outages, and water-related problems (e.g., City of Chicago, 2023; City of Houston, 2023; City of San Antonio, 2023). Similarly, the deployment of AMI currently underway in many utilities across the U.S. provides numerous opportunities for improving communication and public awareness of water infrastructure systems, but also comes with challenges (American Water Works Association, 2022a; Downs, 2020; Solis & Bashar, 2022; US EPA, 2022). These new technologies potentially make reporting faster and easier by removing the need to place a phone call or wait on hold, but users must have access to smartphones, know that the application exists, and have it downloaded. These prerequisites highlight the need for utilities to conduct education during NOC to ensure end user buy-in and equitable outcomes, e.g., via schools and community groups; further, utilities must maintain multiple communication pathways that are accessible to end users with different technical abilities and needs.

(4) *Prepare for unique technical disruptions during emergencies:* Our results showed that technical performance in hotspots and coldspots of customer reporting varied between EOC and NOC, indicating different utility interventions are needed in different parts of the system in these contexts. While we expect the types of problems experienced during an emergency to be unique, confirming this assumption is still useful because it helps utilities identify pain points and better prepare for various emergency scenarios. Further, showing how types of problems vary spatially can help utilities better deploy resources to the areas most prone to certain issues (e.g., pipe failures, water outages) to improve performance and service.

(5) *Foster academic-utility partnerships:* This research was enabled through a partnership with a forward-thinking utility who was willing and able to provide complete and accurate data and explain the nuances of the datasets, distribution system, and utility operations to the research team. As utilities continue to collect increasing amounts of data, especially with the growing implementation of sensing technology (e.g., AMI), there is a critical opportunity for collaboration to co-design replicable and rigorous analysis procedures. Such partnerships offer indispensable benefits to both parties and can support data-driven systems planning and resilience.

Conclusions

This study explored spatial variations in sociotechnical characteristics of a large DWS and evaluated the alignment of customer reporting with technical system performance, showing that spatial patterns in reporting not only exist on both a global and local scale but also change between NOC and EOC. Our analysis suggests that customer reporting can be leveraged to inform more resilient operations and management, for instance by revealing areas where certain service problems, e.g., low water availability and pipe failures, are more prevalent. Results also revealed several statistically different sociodemographic characteristics in areas of higher and lower reporting levels, implying the importance of recognizing the diverse make up of end user populations to reach customers more effectively and improve engagement during both NOC and EOC.

Importantly, our analysis relied on datasets that are increasingly collected by water utilities, though often underused, and highlights the value of performing spatial analyses of customer reporting data to gain insights about technical performance and end user populations. Our approach can thus be applied to other water utilities collecting similar types of data to reveal their system-specific trends in sociotechnical characteristics and performance that can inform operations and management. In this growing area of focus, future work should incorporate additional qualitative data collected from communities as well other customer reporting modalities such as social media, web correspondence, and smartphone applications. As community engagement, equity, and customer feedback continue to grow in importance for utilities and their operations, incorporating community-sourced data into routine assessments can help providers better engage end users and direct technical solutions to improve long-term resilience.

CRediT authorship contribution statement

Helena R. Tiedmann: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Lina Sela:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Keri K. Stephens:** Writing – review & editing, Funding acquisition. **Kasey M. Faust:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.105087.

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