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Tracking the Post-Disaster Evolution of Water Infrastructure Resilience: A Study of the 2021 Texas Winter Storm

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Abstract

In February 2021, severe winter weather in Texas caused widespread electrical blackouts, water outages, and boil water notices. Water systems faced extensive challenges due to cascading failures across multiple interdependent infrastructure systems. Water utilities have since made considerable progress in improving resilience to extreme events, but ongoing challenges remain. Through a qualitative analysis of semi-structured interviews with 20 large water utilities in Texas, this study tracks the evolution of water infrastructure resilience across three phases: the storm and immediate aftermath, the subsequent one-year period, and the "new normal" in the post-disaster environment. We consider five dimensions of resilience—economic, environmental, governance, infrastructure, and social—to identify where solutions have been implemented and where barriers remain. This study contributes to efforts throughout the United States to build more robust water systems by capturing lessons learned from Winter Storm Uri and providing recommendations to improve hazard preparedness, resilience, and public health.

Keywords: water resources, infrastructure, resilience, extreme events, interdependencies

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1. Introduction

In February 2021, a series of winter storm systems impacted much of North America, causing severe damage particularly in the southern United States (U.S.). Texas experienced snow, sleet, and freezing rain with sub-freezing temperatures from February 10-20, 2021 (National Weather Service, 2022)—an event commonly referred to as Winter Storm Uri (after the most severe storm system to occur during that 10-day period). Winter Storm Uri caused extensive energy system failures which left approximately 10 million Texans without power for multiple days (Pollock, 2021); severely impacted communication, healthcare, and water infrastructure (Busby et al., 2021); and resulted in as many as 700 deaths (Aldhous et al., 2021; City of Austin, 2021). Water systems—the focus of this study—faced extensive challenges due to cascading failures across interdependent infrastructure systems. For instance, prolonged freezing temperatures caused widespread equipment and pipe failures in water systems and at points of use (i.e., plumbing). As water utilities worked to repair frozen infrastructure and increase production to meet rising demands, energy system failures caused power outages which left critical water facilities incapacitated. Many utilities experienced water outages or were unable to maintain distribution system pressures above regulatory minimums (20 PSI during an emergency; Texas Commission on Environmental Quality (TCEQ), 2021) and declared boil water notices. Approximately 49% of Texans lost access to running water for more than two days on average (Watson et al., 2021), and 40% of community public water systems issued boil water notices (TCEQ, 2022).

While Texas saw some of the most significant impacts, capturing lessons learned from Winter Storm Uri has far-reaching implications as much of the U.S. faces increasingly extreme weather events, often in unprecedented contexts. Infrastructure systems are designed to operate and serve communities under specific conditions. When operating conditions change, for instance due to abnormally severe weather, infrastructure systems might not be designed or weatherized to withstand such extremes, resulting in failures. These climate stressors are compounded by other known challenges facing the water sector, such as workforce shortages and the pressing need to replace aging infrastructure (American Water Works Association, 2020). Winter Storm Uri and other recent U.S. water crises (e.g., Flint, Michigan, (Masten et al., 2016); Jackson, Mississippi, (Hawkins, 2022)) have increased awareness among policymakers and the broader public of the urgent challenges facing America's water systems. Recent national legislation (e.g., *America's Water Infrastructure Act of 2018,* 2018; *Infrastructure Investment and Jobs Act*, 2021) has prompted increased efforts to improve water infrastructure resilience. At the state level, in response to Winter Storm Uri the Texas legislature passed *Texas Senate Bill 3* (SB3, 2021), which primarily targeted the energy sector but contained some provisions aimed at improving water system resilience (see the Supplemental Materials for the full text of SB3). It is imperative to gauge the effectiveness of such policies, which can be done by understanding how water utilities have responded to major crises. Since Winter Storm Uri, water utilities in Texas have made considerable investments to make systems more robust, but barriers remain. Here, we present a qualitative analysis of semi-structured interviews with 20 large water utilities to track the evolution of water infrastructure resilience one year after the storm and offer recommendations for applying lessons learned in Texas and beyond.

1.1 Previous Studies

Infrastructure resilience to extreme events has increasingly captured the attention of researchers, policy makers, and utility managers alike. Researchers have previously defined water system resilience and resilience criteria (e.g., Ebrahimi et al., 2022; Matthews, 2016; Shin et al., 2018), categorized related challenges (Pamidimukkala et al., 2021), and proposed frameworks for measuring and improving resilience (e.g., Balaei et al., 2020; Knodt et al., 2022; Saikia et al., 2022). Previous work has also examined water infrastructure resilience in the context of numerous other disasters and multiple concurrent crises (e.g., Castaño-Rosa et al., 2022; Matthews, 2016; Moglen et al., 2023; Opdyke et al., 2017b; Shrestha et al., 2020; Stødle et al., 2021). In their review of infrastructure hazard resilience research, Opdyke et al. (2017a) establish that across diverse disciplines, "scholars have converged on a core understanding that resilience consists of resistive and adaptive capacities in economic, environmental, governance, infrastructure, and social systems." Similarly, researchers have established that infrastructure systems, including water supply and distribution systems, can be considered as sociotechnical systems due to their continuous relationship with human and natural environments which have the ability to profoundly impact infrastructure performance (Fischer & Amekudzi, 2011; Zechman Berglund, 2015).

In the aftermath of Winter Storm Uri, researchers have identified infrastructure failures that occurred in energy and water systems, in addition to their causes and impacts on communities (e.g., Busby et al., 2021; Cardinal et al., 2022; Doss-Gollin et al., 2021; Glazer et al., 2021; Kemabonta, 2021; Reed et al., 2022). Glazer et. al. (2021) focused particularly on the impacts of cascading failures on water systems, while Reed et al. (2022) illustrated the interconnectedness of impacted sectors through the lens of Multisector Dynamics. On the industry side, municipalities, utilities, and industry groups published after-action reports detailing pre-existing weaknesses, points of failure, and recommendations for improvements (e.g., Austin Water, 2021; Texas Section of the American Society of Civil Engineers (ASCE), 2022; The City of San Antonio, 2021). For instance, the Texas ASCE's comprehensive report detailed energy system failures and compounding impacts in each infrastructure sector. Survey results from water utilities detailed how specific failures impacted utility operations, actions taken before and during the storm, and assessments of how water utilities performed (Texas ASCE, 2022).

Existing work examining Winter Storm Uri, and other disasters more generally, focuses primarily on the disaster event and immediate aftermath without longitudinally tracking recovery and improvements made over time, thus making it difficult to identify remaining vulnerabilities. Such studies and surveys on disaster events like Winter Storm Uri largely concentrate on answering the important question of "What happened?" to build understanding of how failures occurred and measure system performance during the event. However, without revisiting long-term progress made over time, it is impossible to gauge if lessons learned have been converted into actionable improvements or if new challenges have emerged. To address this gap, we assess water infrastructure improvements made one-year post-disaster to identify where changes have been implemented and pinpoint remaining barriers. In doing so, we are able to offer concrete recommendations based on the evolution of water infrastructure resilience in the post-disaster period.

1.2 Research Framework

Previous work on infrastructure resilience provides a foundation for this study to track how water system resilience has evolved since Winter Storm Uri. Here, we employ the five dimensions of resilience summarized by Opdyke et al. (2017a) as the basis of our analysis. Figure 1 shows the definitions of these five dimensions—economic, environmental, governance, infrastructure, and social—that contribute to overall resilience. We employ the National Research Council's definition that resilience is "the ability to plan for, absorb, recover from, or more successfully adapt to actual or potential adverse effects" (National Research Council, 2012). Resilience curves—a common tool used to communicate system performance before, during, and after a disruption—

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provide a useful temporal framework for qualitatively understanding recovery in this context (Poulin & Kane, 2021). As shown in Figure 2, we use a conceptual resilience curve to define three periods of interest: Phase 1, the winter storm event and immediate recovery; Phase 2, the one-year period following the storm; and Phase 3, the "new normal" in the post-disaster environment (i.e., the new status quo that systems reach following the disaster and full recovery). Within Phase 1, in each resilience dimension we categorize resilience gaps (i.e., system vulnerabilities that compromised performance) and resilience sources (i.e., system strengths or mitigating factors that prevented worse outcomes). In Phase 2, we identify the subsequent changes and improvements utilities have made in each resilience dimension in the one-year since the storm. Finally, in Phase 3, we look to the future and pinpoint remaining challenges utilities are facing as they work to continue improving system resilience. By considering the five dimensions of resilience across these three phases, we are able identify areas where solutions have been implemented and where challenges remain.

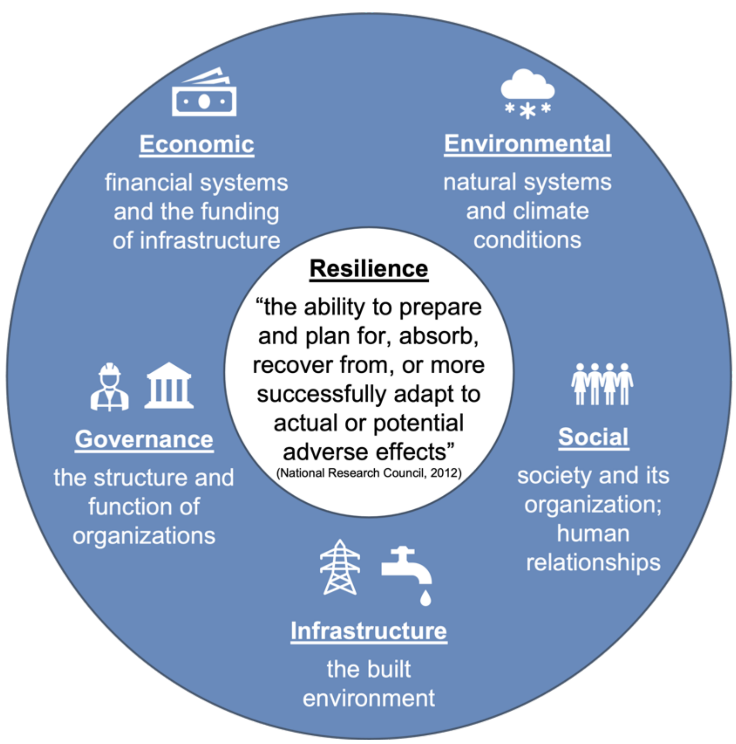

Figure 1: The five dimensions of resilience.

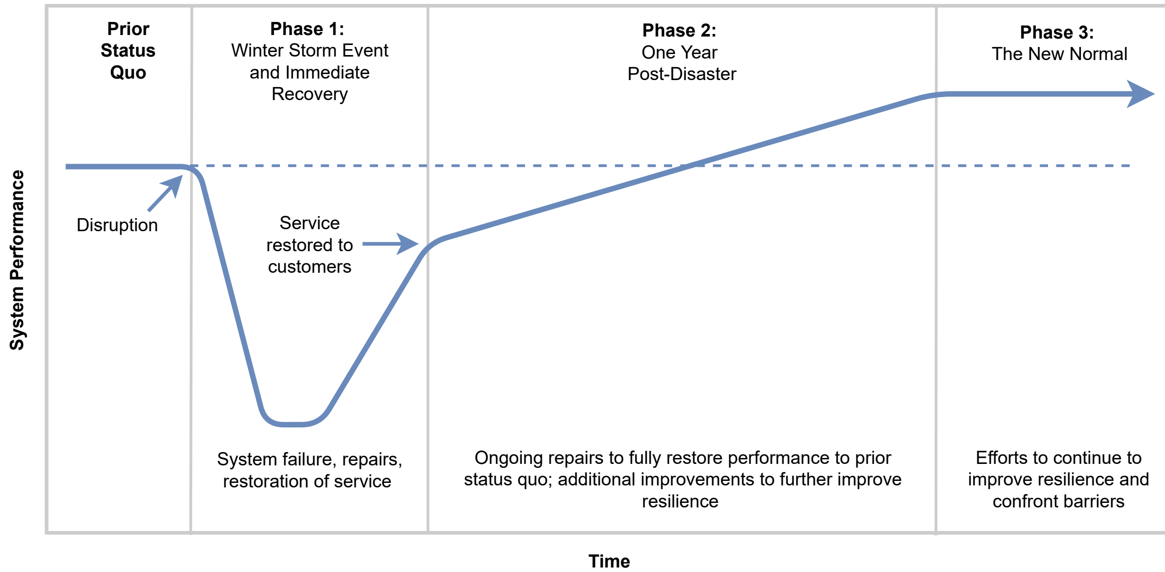

Figure 2: Conceptual resilience curve defining the three phases of interest for tracking the evolution of water infrastructure resilience.

2. Methods and Materials

2.1 Data Collection

The dataset for this study consists of 22 semi-structured interviews with 28 participants representing 20 water utilities in Texas. Some, but not all, of the participating utilities offered both water and wastewater services and saw limited impacts to wastewater infrastructure systems. However, drinking water infrastructure generally saw more widespread disruption statewide that greatly impacted communities. As such, this study focuses on drinking water infrastructure, while acknowledging that some wastewater systems were also impacted. The data collection period spanned from January 21, 2022 to April 5, 2022. With interviews taking place approximately one year after Winter Storm Uri occurred, participants were able to reflect on the progress made and remaining challenges to making their systems more resilient.

Data collection efforts via semi-structure interviews targeted large, urban water utilities. Initial interviewee contacts were obtained via public utility websites, and all outreach was conducted via email. Interviewees were asked at the end of each interview for contact suggestions, allowing us to broaden our outreach efforts via snowball sampling (National Science Foundation, 2022). In general, we targeted utility professionals at the director, assistant director, or upper-management level who oversaw operations and management, water treatment, or communications and could provide both a high level of detail and utility-wide understanding of the storm's impacts. Interviews followed Internal Review Board protocols and were approximately one hour in length, conducted via online video conferencing, recorded with permission, transcribed, and checked for accuracy. Data collection continued until theoretical saturation was reached. Theoretical saturation was defined as the point at which little to no new information was gained from each subsequent interview and all concepts were well defined (Corbin & Strauss, 2008; De Vries et al., 2008). Specifically, in this study theoretical saturation was reached when no new resilience gaps, resilience sources, changes, or remaining challenges (i.e., inductive codes) were identified from multiple consecutive interviews (see Section 2.2 Qualitative Analysis for a description of deductive and inductive codes).The dataset includes input from professionals at 20 unique utilities, in addition to one water professional representing a state-wide organization that assists utilities during emergencies. Table S1 in the Supplemental Materials provides further details about interviewees, including utility size based on the U.S. Environmental Protection Agency (U.S. EPA) criteria. The U.S. EPA defines utility size based on population served, with "large" utilities serving 10,001 – 100,000 people, and "very large" utilities serving over 100,000 people. (U.S. EPA, 2022). In total, representatives from 38% of "very large" public water systems in Texas (16 of 42) participated in the study in addition to two "large" public water systems and two regional water providers that each serve more than 1 million residents.

The interview protocol for this study was developed by two researchers and tested and validated by four additional researchers who are subject matter experts in infrastructure systems and interviewing techniques. Participants were asked to describe the following: impacts of Winter Storm Uri on their water infrastructure systems; any resulting service disruptions; processes for restoring service; communication with the public during the event; and changes made to physical infrastructure, planning, and other protocols since the event. Questions included, for example, "What service disruptions, if any, did your utility experience during Winter Storm Uri" and "Have you updated, or do you plan to update, your emergency response plan (ERP) in response to this event? If so, how?" (See the Supplemental Materials for the Interview Protocol).

2.2 Qualitative Analysis

Qualitative analyses can be used to better understand complex infrastructure problems, allowing researchers to explore emergent relationships, interdependencies between sociotechnical systems, and weaknesses or opportunities to improve resilience (e.g., Kaminsky, 2015; Opdyke et al., 2017b; Spearing & Faust, 2020). We employed a hybrid deductive-inductive analysis approach in which a framework based on existing literature was applied to form the top-level coding structure (deductive codes), while sub-codes (inductive codes) specific to the dataset and research question were allowed to emerge from the analysis (Saldaña, 2013; Spearing et al., 2022). This approach is especially appropriate in this context because resilience is a well-defined and established concept in the literature. However, Winter Storm Uri was a unique and unprecedented event, with widespread impacts to a large population. As such, incorporating established frameworks (resilience curves and the five dimensions of resilience) with the flexibility of context-specific emergent codes builds on the existing literature and produces results that are more accessible and actionable for utility managers and policymakers.

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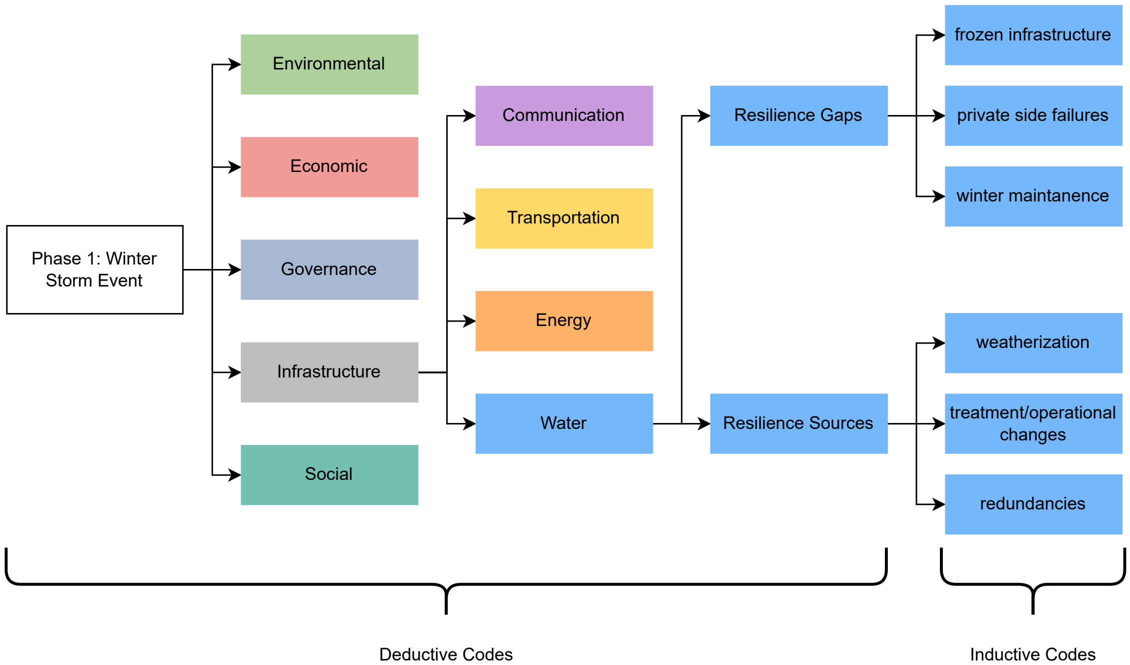

Figure 3. A portion of the hybrid deductive-inductive hierarchical coding structure. The deductive coding framework is shown (left) in addition to a subset of water infrastructure resilience gaps and sources from Phase 1: Winter Storm Event that were identified in the qualitative coding analysis (right).

Figure 3 shows an example of the hybrid deductive-inductive hierarchical coding structure implemented in this study. Here, the deductive codes consist of the five resilience dimensions and three event phases drawn from existing literature in addition to the categories of interest in this study: resilience gaps and resilience sources (Phase 1), changes made (Phase 2), and remaining challenges (Phase 3). Under the infrastructure dimension, additional deductive codes were also applied for the four infrastructure systems discussed in interviews (communications, energy, transportation, and water). Emergent inductive codes are the specific ideas within these established categories that were mentioned by interview participants. Excerpts—defined here study as the response to a question or a completed idea (Spearing et al., 2022)—were coded based on the specific idea(s) discussed and then categorized within the deductive coding framework. Simultaneous coding was used, meaning that each excerpt could be assigned more than one code (Saldana, 2013). The Coding Dictionary, with definitions and examples of all deductive and inductive codes, can be found in the Supplemental Materials. The interview coding was completed by two researchers and validated through an intercoder reliability check using kappa coefficient (k = 0.72, considered satisfactory for qualitative research) (De Vries et al., 2008; Mezzich et al., 1981).

2.3 Limitations

In targeting larger water utilities in Texas, our study reflects the experiences of relatively urban and well-resourced utilities, and our conclusions are therefore more generalizable to these types of organizations. Notably, many smaller utilities are resource-constrained and likely experienced (and are still facing) unique challenges related to Winter Storm Uri. In fact, multiple interviewees in this study noted their concern for such utilities, highlighting that, while outside the scope of this study, additional work is needed in this area. Other limitations inherent to qualitative analysis reflect the difficulty of completely eliminating biases and extrapolating ideas expressed by a small sample to a larger population. The potential for both interviewer bias and social desirability bias (i.e., response bias by the participant to answer questions according to the expectations of society or the interviewer) to influence data collection must be acknowledged (Kidder et al., 1986; Nederhof, 1985). One way we reduced this bias is by having multiple researchers involved in the analysis. Despite these limitations, we are still able to draw conclusions about the state of water infrastructure in Texas and offer recommendations for the future by following a consistent interview protocol vetted by subject matter experts and conducting interviews until theoretical saturation was reached. Further, it must be noted the frequency of a given code does not always indicate its relative importance; for this reason, we also focus on the relationships between infrastructure systems and resilience dimensions to highlight key themes related to water infrastructure resilience in this context.

3. Results and Discussion

3.1 Winter Storm Uri and Immediate Recovery

Resilience gaps and sources, subsequent improvements, and remaining barriers were identified across five resilience dimensions. Figure 4 summarizes high-level coding results based on the frequency data in Table S3, with symbol sizes representing the number of utilities to identify codes (A) and the total code frequency (B) within each phase and resilience dimension. While utilities mentioned strengths and vulnerabilities across almost all dimensions in Phase 1 (Figure 4-A), the most references to resilience sources and gaps fell in the governance and infrastructure areas, respectively (Figure 4-B). Figure 5 shows the specific codes for resilience gaps and sources identified within each dimension, indicating the percentage of utilities to mention each code.

Many resilience gaps and failures resulted from a complex chain of events across multiple resilience dimensions and infrastructure systems. Figure 6 maps these interdependencies and cascading impacts, as informed by our coding results. For instance, public communication issues such as utilities' failure to send regular updates, disjointed messaging, and lack of customer service staff resulted in rapidly spreading misinformation (Figure 6, arrow A), with 50% of utilities identifying misinformation as a problem (Figure 5). In particular, false rumors that water service was to be intentionally turned off led customers to store water (Figure 6-B), leading to increased water demands (Figure 6-C) at a time when utilities were already struggling to manage water loses from uncontrolled breaks and leaks (Figure 6-D, E). As a result, 85% reported significant increases in water demands (Figure 5). The significance of these social interactions and behaviors on system performance highlights infrastructure systems' sociotechnical nature and the criticality of considering societal context when responding to crises.

Power outages at treatment or pumping facilities were experienced by 85% of utilities interviewed (Figure 5) and substantially impacted the ability to produce safe drinking water (Figure 6-F). While many had some degree of backup power, few were able to fully operate their systems while cut off from the electric grid. Utilities with backup power experienced a variety of generator issues such as low diesel fuel supplies, fuel gelling in cold temperatures, and general failures. Power outages led to loss of building heat and frozen infrastructure, necessitating substantial repairs before facilities could be restarted. Ultimately, 55% of utilities interviewed declared boil water notices and 45% experienced water outages (Figure 5). The regional providers interviewed did not issue boil water notices or experience outages, but many of their utility customers did. In addition to the human health implications of these service disruptions, utilities noted the danger of losing fire protection (Figure 6-G), with three participants acknowledging that, tragically, fires occurred during the event in areas with little to no water pressure available to fight them. Utilities cited system redundancies (e.g., looping, diverse water supplies), technology (e.g., Advanced Metering Infrastructure (AMI), remote monitoring systems), prior weatherization efforts, and the ability to make quick and creative operational changes (e.g., temporarily using alternative chemicals in water treatment processes, strategically operating valves and pumps) as factors that strengthened response efforts (Figure 5).

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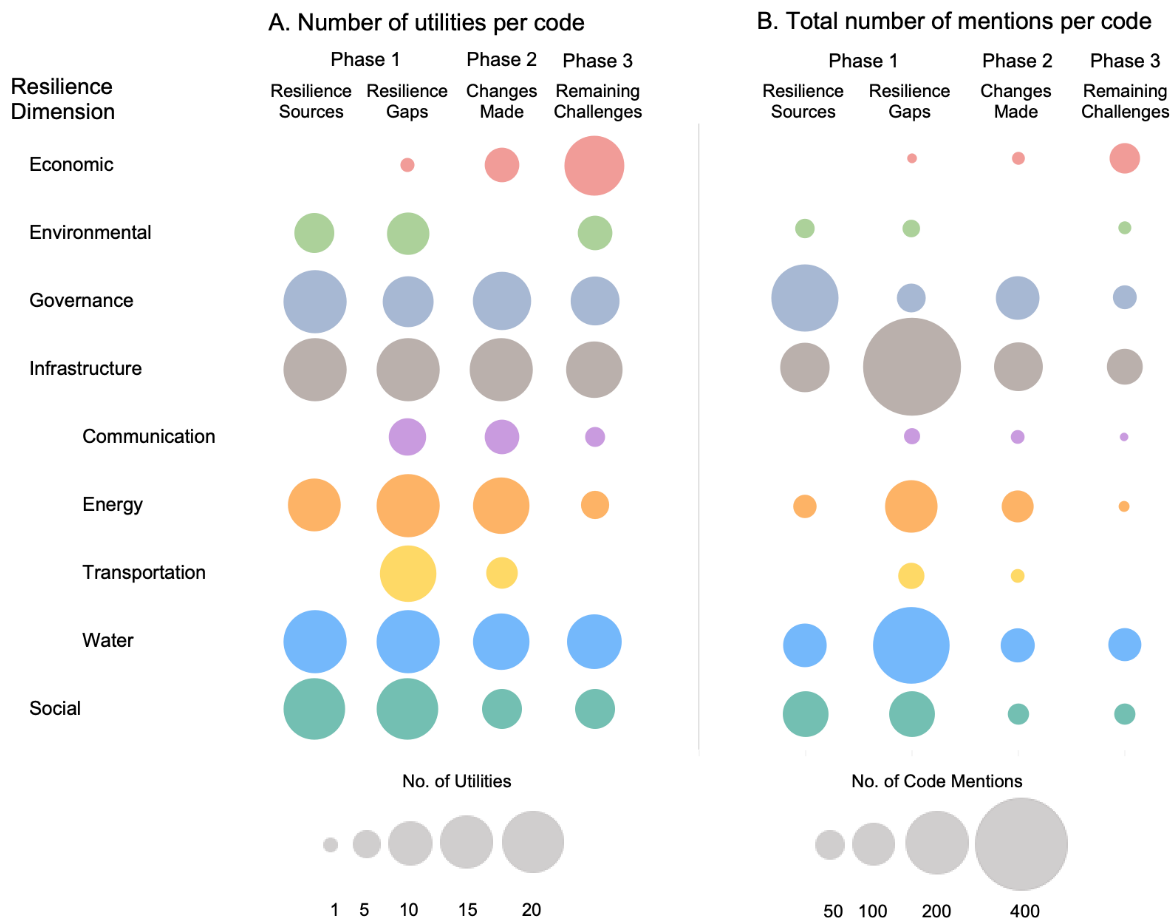

Figure 4: Qualitative coding results showing resilience sources, resilience gaps, changes made, and remaining challenges, categorized by resilience dimension. Symbol sizes represent the total number of utilities that identified codes in each category (A) and the total frequency of code mentions made in each category (B). (See the Frequency Table and Coding Dictionary in the Supplemental Materials for full qualitative coding results and code definitions with examples, respectively; coding results represent 18 municipal utilities and 2 regional providers).

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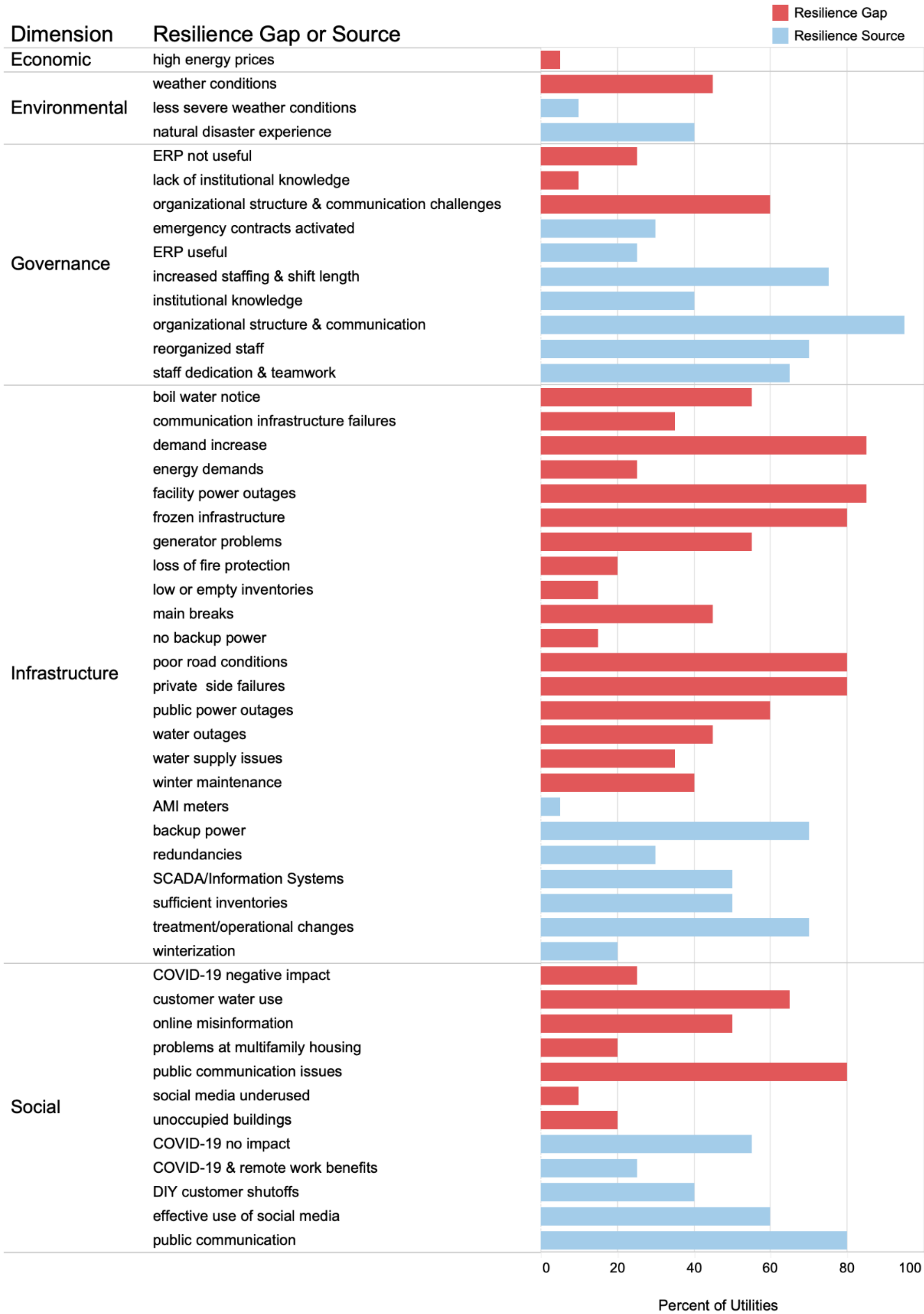

Figure 5: Results for Phase 1—Winter Storm Uri and immediate aftermath—indicating the percentage of utilities that identified each resilience gap and source.

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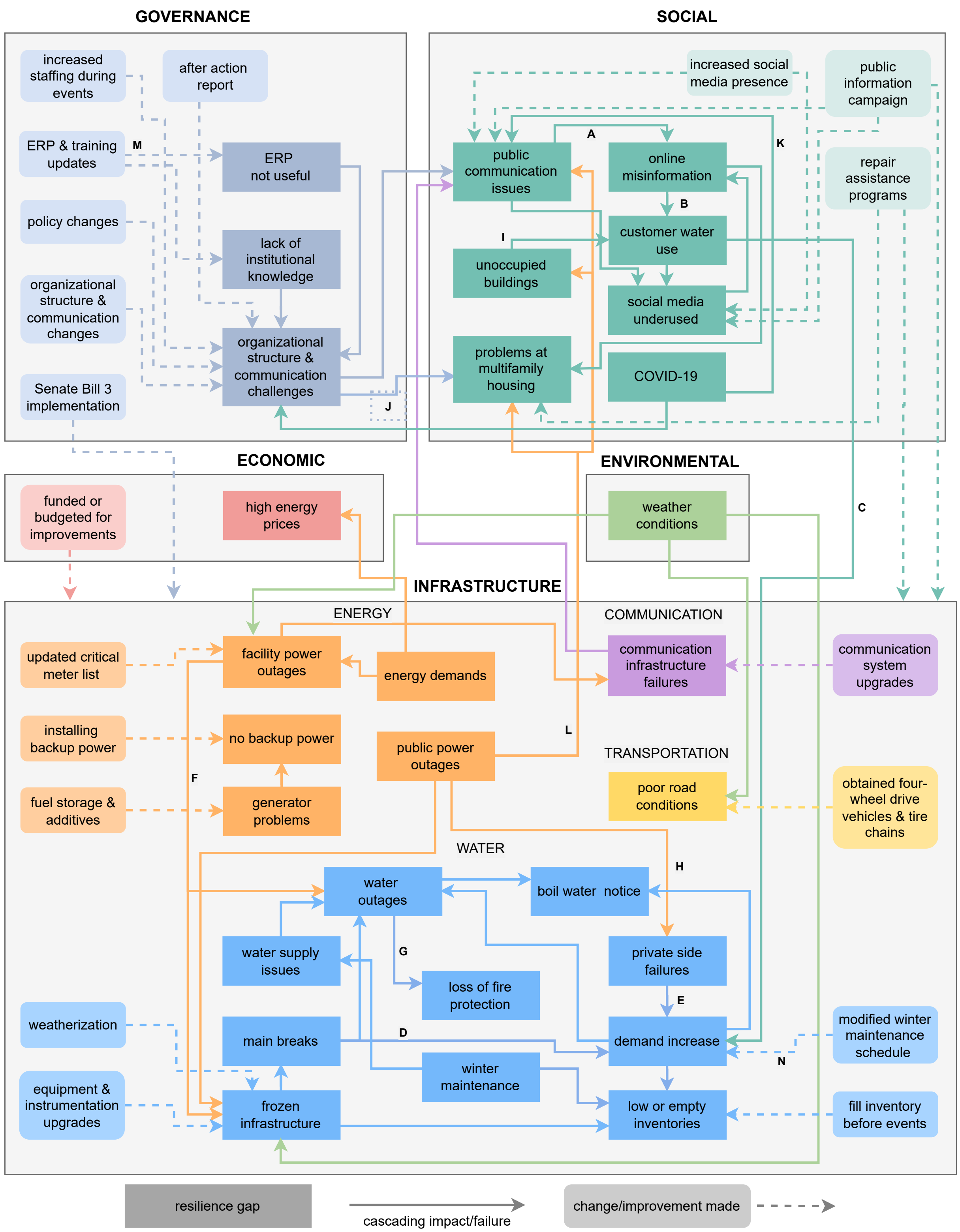

Figure 6: Resilience gaps (dark rectangles) and cascading failures experienced by utilities during Winter Storm Uri. Changes and improvements made in the one-year period following the storm are shown as light rounded rectangles. Solid lines indicate a cascading impact or failure from one resilience gap to another in the direction of the arrow. Dashed lines point to the resilience gap(s) targeted by each improvement made post-storm in the subsequent year. Lettering highlights/identifies relationships that are discussed in further detail in the text.

An immense need emerged to assist customers experiencing plumbing breaks during the storm. Plumbing lines in Texas are often not well-insulated due to typical weather patterns, so cold temperatures and loss of electricity (over 60% of Texans experienced power outages; Watson et al., 2021) caused burst pipes and leaks (Figure 6-H). In addition to causing property damage (over 30% of Texans suffered water damage to their homes; Watson et al., 2021), uncontrolled water loss via plumbing failures contributed to skyrocketing water demands which utilities struggled to meet (Figure 6-E). Because many residents left their homes to seek warmth and shelter, leaks often went undiscovered for days (Figure 6-I). Recognizing the tight coupling of communication practices with community behavior and infrastructure performance, utilities attempted to quickly educate the public on how to shut off water at the meter and disseminated social media posts with "do it yourself" (DIY) shutoff instructions. With overwhelming numbers of urgent shutoff requests and limited available staff resources, utilities realized (though too late in many cases) the importance of enlisting the public's help in getting water leaks under control and providing customers with the necessary instruction. Most utilities also reorganized staff during the event (Figure 5), primarily to respond to this influx of shutoff requests. For instance, utilities equipped administrative staff, firefighters, and waste collectors with meter keys and deployed them to neighborhoods to search for leaks and shut off customer meters. Multifamily residences proved uniquely challenging due to communication problems with property owners and delayed repairs (Figure 6-J), leading some utilities to deploy tanker trucks to hard-hit areas. Some apartment complexes were without water for weeks even after service was restored (Fisher, 2021; Oxner & Garnham, 2021).

Governance actions strengthened utilities' response capabilities (Figure 5). Utilities increased staffing and shift lengths, reorganized staff, and activated emergency contracts for repair

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assistance. While 60% of utilities noted organizational structure and institutional communication challenges, 95% cited strengths. Vulnerabilities included bureaucracy, difficulty communicating with partners (one participant described communication with their electric provider as “slim and none”), inexperienced staff, and ineffective Emergency Operating Center (EOC) staging. Strengths included having longstanding, strong relationships established with partners and communicating effectively internally and with wholesale and critical customers (e.g., hospitals, military bases). Institutional knowledge among experienced staff, strong dedication, and teamwork were cited as key factors in mitigating impacts and restoring systems quickly. As one participant stated, “I was impressed with the dedication of everybody to get the system back up. We had many people here overnight for days trying to keep the system running.”

While the storm occurred during the COVID-19 pandemic, 55% of utilities stated the pandemic did not impact their response because they were already accustomed to operating under COVID-19 conditions (Figure 5). In fact, 25% cited pandemic-related benefits because staff were comfortable communicating remotely via video calls and chat, which proved useful when roads were impassable. Some utilities mentioned negative pandemic impacts, mostly due to customer service staff working from home during the event. After losing power at home, staff were no longer able to receive calls, making it difficult for customers to report breaks and request information (Figure 6-K).

In addition to overwhelmed phone lines, utilities acknowledged other public communication problems such as ineffective social media use, difficulty conveying complex infrastructure problems to a general audience, and conflicting guidance. For instance, customers were advised to drip faucets to prevent frozen pipes then urgently asked to conserve water due to rising demands. Power outages further disrupted utilities’ ability to reach residents as many were without television, radio, or the ability to charge cell phones (Figure 6-L). Utilities cited more successful aspects of their communication efforts, such as working closely with their Public Information Office to issue regular updates and using social media effectively (one participant explained, “we’re very much a Facebook town…so [that] is really how we communicated during that time”). Some utilities quickly created interactive online maps for residents to look up their service provider, pressure zone (for boil water notice status), and outages—tools that were heavily utilized by the public during the emergency.

3.2 One Year Later: Changes Made

All utilities interviewed made improvements in the one-year following Winter Storm Uri. Figure 7 shows the coding frequency results for the changes utilities implemented, categorized by resilience dimension. The infrastructure and governance areas accounted for the greatest number of changes (Figure 7) as well as the highest frequency of code mentions (Figure 4-B). In the governance dimension, SB3 (which was passed in response to the storm) received significant attention from utilities. The bill mandated establishing alternative power to support emergency operations and submitting plans as an Emergency Preparedness Plan (EPP) to the state by March 1, 2022 (*Texas Senate Bill 3*, 2021). As such, most utilities were preparing or submitting their EPPs when interviewed. 70% described ongoing or completed measures to comply with SB3 (coded as “SB3 implementation”), with 65% working to obtain backup power for facilities (Figure 7).

One year after the storm, 75 % of utilities had updated their ERPs (Figure 7). This action was a direct response to utilities’ realization during and after Winter Storm Uri that their ERPs were not useful or relevant for the specific disruptions they faced (Figure 6-M). A small number were exploring policy changes around conservation mandates, which are typically triggered by

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drought conditions and did not account for water shortages due to other events. Other interventions included allocating funding for improvements, commissioning after-action reports, and increasing staffing during events (Figure 7). To target organizational and institutional communication challenges, utilities reduced bureaucracy around emergency contracts, revised EOC protocols, and strengthened relationships with key partners (e.g., other departments, hospitals, electric providers). As one participant stated, "I wasn't familiar with [our hospital organization]. Now we know those people very well." Despite indicating they had significant strengths and relatively few vulnerabilities in the governance area during the storm, utilities made many references to post-storm governance improvements (Figure 4-B). While this trend reflects the EPP process and SB3's significance, it likely also indicates that governance issues were easier for utilities to quickly address internally in the one-year post-storm period compared with vulnerabilities in other dimensions.

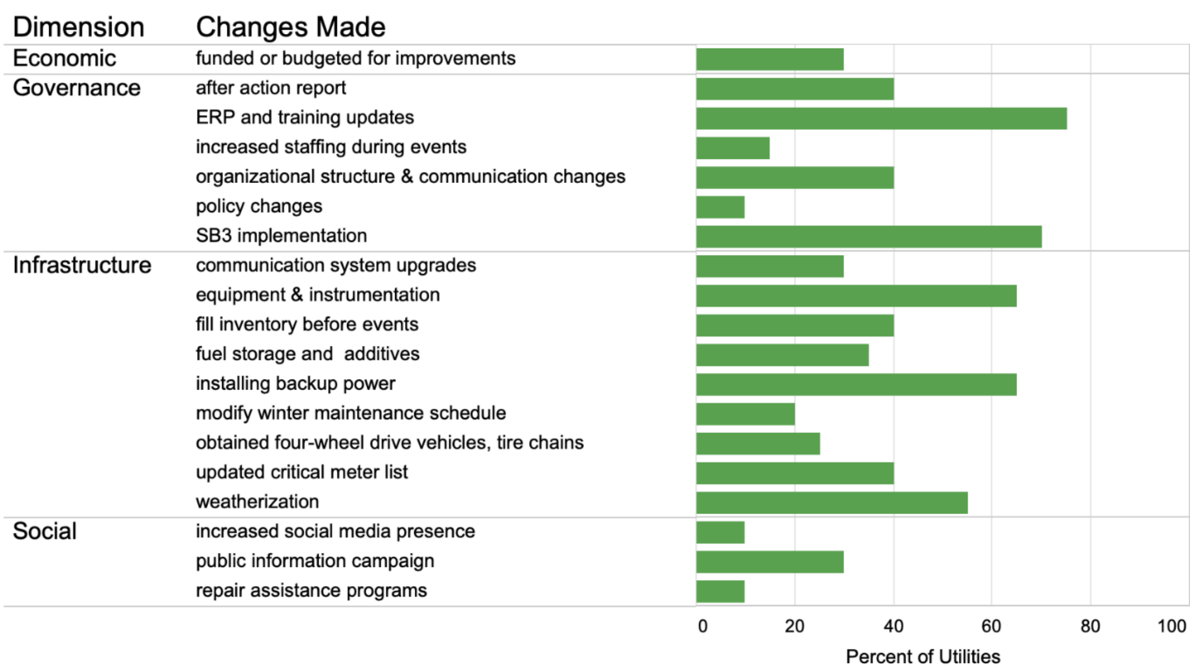

Figure 7: Results for Phase 2—one year after the event—showing changes and improvements implemented by utilities.

Concerning infrastructure, utilities focused on backup power and weatherizing equipment and facilities; they also invested in cold-tolerant instrumentation, anti-gelling fuel additives, tire chains, and four-wheel drive vehicles (Figure 7). From a resource management perspective, utilities revised protocols to fill chemical inventories and reservoirs before weather events and increased diesel fuel storage capacity for generators. 40% reported having facilities out of service for maintenance when Winter Storm Uri struck, leaving systems vulnerable (Figure 5; utilities typically perform maintenance during winter months when demands are lowest). As such, some utilities revised maintenance schedules to be better prepared to quickly increase winter production if needed (Figure 6-N). Utilities referenced energy-related infrastructure improvements almost as much as water (Figure 4-B), revealing the tight coupling between these two systems and reflecting the strong emphasis from SB3 on backup power capabilities.

Regarding changes made in the social dimension, some utilities stated they conducted more public outreach and education (Figure 7) on topics such as preparing for extreme weather, protecting plumbing from cold weather, and performing water shutoffs. The online interactive mapping efforts implemented during the storm were so successful and well-received, some utilities have continued them permanently. However, while almost all utilities acknowledged challenges in the social dimension during the storm (especially related to public communication), overall far fewer cited improvements made (Figure 4B), highlighting the need for further attention in this area.

3.3. Remaining Challenges in "The New Normal"

Despite considerable improvements, utilities identified ongoing vulnerabilities and barriers to further increasing resilience. Figure 8 shows the coding frequency results for the remaining challenges identified by participants in each resilience dimension. While barely mentioned as an

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issue during the storm, 90% of utilities cited economic factors as problems going forward (see Figure 4A and Table S3, 18/20 utilities discussed economic challenges in Phase 3). The prevalence of economic challenges as utilities look to the future highlights the difficulties around proactively continuing to improve resilience after the immediate recovery period passed. 35% of utilities expressed concerns for funding improvement projects (Figure 8). Some funding concerns were mentioned together with SB3 limitations and implementation challenges. For example, utilities expressed concern over the cost of installing new generators as mandated by SB3. For others, these challenges were related to broader issues in the public water sector around raising rates and securing funding to upgrade aging infrastructure. Describing improvement plans, one participant stated, "I am at the mercy of the city manager and the council," illustrating the relationship between funding concerns and ongoing barriers in the governance arena involving decision making, organizational structure, and politics. Others noted ongoing issues attracting and retaining staff and offering competitive wages, reflecting industry-wide workforce challenges (American Water Works Association, 2020). Supply chain issues, involving both standard supplies and large items (e.g., generators), were cited as key difficulties going forward (Figure 8). "The supply chain is eating our lunch right now," stated one participant, while another noted, "Everybody wants a portable generator in Texas now, so we anticipate that we're looking at probably 24 months before the generator even shows up."

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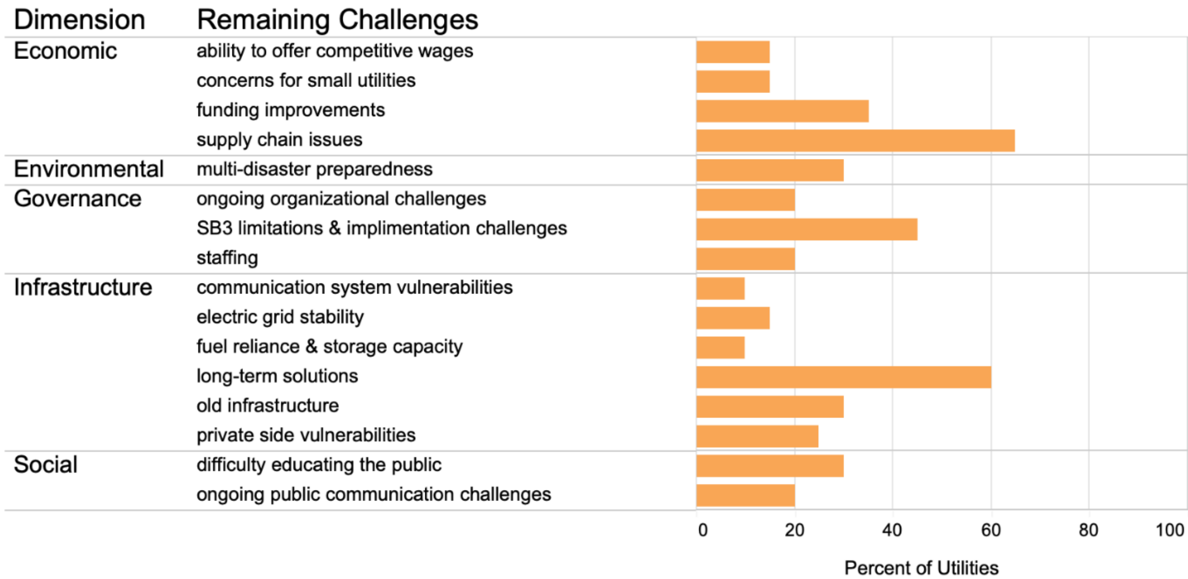

Figure 8: Results for Phase 3—"the new normal"—showing remaining challenges and barriers to improving resilience.

45% of utilities noted aspects of SB3 implementation that continue to pose challenges (Figure 8). The bill primarily targeted the energy sector, and water-related provisions focused mainly on backup power installation and requiring utilities to update and confirm critical meters with electric utilities. However, several participants noted their facilities were marked critical prior to Winter Storm Uri, but power was nonetheless cut. Further, no state law was subsequently passed granting water utilities critical load status (Glazer et al., 2021). For some utilities, their central failure point was not power loss at facilities but rather frozen infrastructure, main breaks, and private-side failures. Generally, many participants expressed the opinion that while installing backup power was important for increasing resilience, it was a high-cost endeavor that would not singularly prevent future failures without other interventions. For instance, one utility had functioning backup power during the storm but still experienced service interruptions because of enormous water loss via private-side failures. They stated, “If we had [another event], many of us would be in the same boat if we had all the private plumbing failures that we did [last year],” reflecting ongoing concerns over electric grid and plumbing vulnerabilities. The participant went

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on to note that building code changes could improve plumbing and building resilience, but such interventions had not happened.

Infrastructure accounted for the most mentions of remaining challenges (Figure 4-B). The most-referenced infrastructure challenge was the long-term nature of publicly funded water infrastructure improvement projects (Figure 8). For instance, one utility with a large amount of old cast iron waterlines experienced extensive main breaks during the storm (the distribution system "almost seemed like it was leaking like a sieve"). As the participant acknowledged, replacing all such waterlines overnight is not financially or logistically feasible. Utilities mentioned other ongoing improvement projects such as AMI, new water treatment plants, permanent generators, and water supply diversification. These critical projects will undoubtably improve resilience in the long-term but will take years (or decades) to complete, leaving systems more vulnerable in the meantime.

While few references were made to ongoing barriers in the social dimension (Figure 4-B), these challenges are likely more significant than the data imply. Many participants were not fully versed in their utility's public communications activities as these efforts are often led by other departments. Further, our study does not include perspectives from customers on the receiving end of utilities' communication. Anecdotal evidence and after-action reporting have acknowledged that utilities' communication with the public during the storm was largely inadequate (e.g., Austin Water, 2021; The City of San Antonio, 2021). As such, building resilience in the wider community will remain challenging if utilities struggle to communicate effectively during emergencies and fail to educate the public on the importance of water infrastructure. The interdependencies revealed between social and infrastructure systems during the storm—and the role that poor communication played in exacerbating failures—point to critical opportunities to strengthen infrastructure systems by better engaging communities and expanding beyond technical and governance interventions.

4. Conclusions and Recommendations

Our findings show that utilities have made substantial progress in improving resilience since Winter Storm Uri, especially in the governance and infrastructure arenas. Utilities have taken steps to comply with SB3's requirements, update ERPs, reduce organizational barriers, and improve relationships with partners. Utilities have begun installing backup power at facilities and substantially upgraded and weatherized their systems to better protect them from future extreme cold events.

However, interventions have not always targeted areas where the greatest vulnerabilities exist. Challenges persist in the economic, infrastructure, and social dimensions (Figure 4). The emphasis on governance interventions, despite relative preexisting strengths in this area, likely reflects SB3's significance in utilities' resilience planning and the speed and ease with which internal administrative changes can be accomplished relative to other improvements. Conversely, remaining infrastructure challenges (e.g., aging infrastructure, private-side vulnerabilities, electric grid stability), require long-term investments and complex coordination across infrastructure systems and resilience dimensions. The economic barriers that emerged in Phase 3 point to infrastructure improvements' high costs, lack of funding support, and ongoing supply chain disruptions from the COVID-19 pandemic (American Water Works Association, 2021).

Table 1: Recommendations for utilities and policymakers to address ongoing barriers to improving water infrastructure resilience

Resilience Dimension	Recommendations
Economic	• Expand state and federal funding mechanisms to support installation of backup power and other resilience measures • Grant preferential market treatment to water utilities to combat supply chain issues
Environmental	• Practice multi-disaster preparedness with consideration for changing climate and unprecedented weather events
Governance	• Perform yearly emergency response plan (ERP) reviews and updates • Conduct extreme event trainings (e.g., tabletop exercises for blackout scenarios, natural disasters) • Foster and maintain relationships with key partners during non-emergency times • Expand state and federal support for utilities in navigating policy requirements (e.g., SB3), grant applications, and other governance processes • Implement building code revisions and incentive programs for weatherizing or retrofitting homes to increase plumbing resilience • Establish clear protocols around staging of Emergency Operation Centers (EOC) and Joint Information Centers (JIC) in emergencies
Infrastructure	• Weatherize equipment and instrumentation • Perform seasonal checks of equipment, weatherization efforts • Regularly service and test generators • Modify winter maintenance schedule of critical facilities to minimize time offline • Explore alternative backup power options beyond diesel- and gas-powered generators • Maintain adequate inventory of meal rations, cots, blankets, warm clothing, and other supplies for extended emergency operations • Distribute weatherization and shutoff supplies to residents (e.g., hose bib covers, meter keys) • Accelerate AMI deployment • Address ongoing electric grid stability concerns
Social	• Expand use of relevant social media platforms • Conduct public communication in multiple languages as appropriate for customer base • Conduct public outreach and education on infrastructure functions, emergency preparedness, and protecting plumbing • Establish or improve automated emergency alert systems • Establish communication initiatives to reach historically under-resourced communities; Improve community trust through consistent, easy to understand communication during non-emergency times • Publish and maintain online interactive maps for customers to view service provider, pressure zone, and outage information

Given these barriers, Table 1 presents recommendations for policymakers and utility managers. It is critical to prepare for a wide range of future extreme and unprecedented weather events through tabletop exercises, regular ERP reviews and updates, and emergency scenario simulations. Likewise, increasing state and federal funding and administrative support is essential for utilities to implement large-scale resiliency improvement projects. Plumbing infrastructure remains vulnerable to another extended electrical blackout and cold weather event, constituting a significant threat to public water systems. Building code revisions and weatherization/retrofitting incentives may help harden homes against future climate threats, thus protecting the public water system; however, there is a lack of governance support for such efforts. Large gaps persist in public communication and engagement, and our work shows that utilities must continue investing in outreach efforts, building a strong social media presence, and developing better performing emergency alert and communication systems. As much of the U.S. responds to and prepares for more extreme weather events, the case of Texas following Winter Storm Uri offers valuable lessons for improving the resilience of water infrastructure systems across the country.

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Data Availability:

The interview protocol, coding dictionary, and complete coding frequency results are available in the Supplemental Materials.

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