Small Drinking Water Utilities' Resilience: The Case of the COVID-19 Pandemic

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SYNOPSIS

This study examined the experiences of small and medium drinking water utilities during the COVID-19 pandemic to develop conclusions on small utility resilience during emergencies.

ABSTRACT

Extreme events can significantly disrupt the operation and maintenance (O&M) of drinking water utilities (DWUs), compromising community access to water in critical times. However, we posit that utility size can influence DWUs' resilience, as large DWUs may have a greater capacity to handle extreme and sudden changes characteristic of emergencies. Here, we explore the resilience of small DWUs by understanding how a global crisis (i.e., the COVID-19 pandemic) affected small DWUs and how these impacts statistically differ from those of large DWUs using statistical inferencing. We used two datasets that reflect the perspectives of 28 large and 26 small DWUs from 14 states. We found that small DWUs experienced issues involving supply chain, finances, and personnel management that pre-existing issues may have magnified. Additionally, small and large DWUs experienced statistically significant differences in personnel management, revenue change, increase in delinquent accounts, and emergency response plan activation. For example, large DWUs experienced more revenue loss than small DWUs due to economies of scale and larger changes from status-quo operations. This study reveals areas of concern (and opportunities) regarding the resiliency of small DWUs in the face of emergencies that can allow policymakers to assist small DWUs.

1. INTRODUCTION

Emergencies (e.g., humanitarian crises, extreme weather events) significantly disrupt and influence how water infrastructure systems operate and serve the public.[1–4] For example, large-scale disruptions like the COVID-19 pandemic lockdowns forced drinking water utilities (DWUs) to continue providing the public with clean water necessary to maintain proper hygiene and sanitation while incorporating social distancing policies (SDPs) into their operation and management and placing moratoriums (e.g., temporary halt on water utility shut-offs due to non-payment).[5–8] Beyond introducing new stresses, emergencies can reveal potential imbalances in infrastructure resilience depending on socially determined factors that impact operations, such as the number of customers and ownership, for instance.[2,9] Here, we refer to resiliency as "the resistive and adaptive capacities that support infrastructure functionality in times of crisis or stress."[10]

The existing disparities between water utilities of varying sizes spurred the allocation of additional funding for the less-resourced water utilities (i.e., under 10,000 customers) through the Safe Drinking Water Act.[11] Despite avenues that provide other resources and assistance to very small, small, and medium DWUs (i.e., less than 501, between 501 and 3,300, and between 3,301 and 10,000, respectively)[12] these utilities often face unique challenges that are difficult to mitigate with funding alone. For example, according to the 2020 State of the Water Industry report by AWWA, small water utilities were uniquely confronted with reduced customer bases and an absence of funding for technical system upgrades and certified operators in predominantly rural communities.[13] As 97% of all public drinking water utilities in the United States have customer sizes less than 10,000, understanding how small drinking water utilities operate in extreme events can be instrumental in assessing resiliency.[46] Thus, we posit that a drinking water utility's customer size has important implications for the technical system's performance and resiliency.

Multiple studies have documented the unique challenges that small water utilities experience, frequently citing financial restrictions.[14–19] Other studies have examined how a water utility's technical, financial, and managerial (TFM) capacity can influence water quality and potential mitigation strategies, especially during extreme events.[20–23]

The COVID-19 pandemic presents an opportunity to explore the relationship between customer size and resiliency as it is a unique large-scale disaster that impacted DWUs globally, regardless of their customer size.[24] For example, some small DWUs face more detrimental consequences on their revenue due to minimized financial reserves and relatively smaller customer bases.[25,26] On the contrary, very large DWUs (i.e., customer size of over 100,000) may have more extensive financial reserves due to their location or customer size and can fund new capital projects more easily than smaller DWUs (i.e., economies of scale).[26]

In the context of COVID-19, researchers described how customer size may have influenced financial challenges experienced by water utilities during the lockdowns and moratoriums. For example, researchers at the Pacific Institute and the Rural Community Assistance Partnership published a report that extrapolated data from national and state-level surveys to describe the revenue losses, deferred maintenance, and customer debt associated with small drinking water utilities.[26] Generally, this report is among the few studies centered on small water utilities.[27,28]

Presently, the literature comparing the operations and maintenance (O&M) of smaller and larger DWUs in emergencies is limited. [29,30] Additionally, few studies have examined the impacts of the COVID-19 pandemic on small and medium water utilities in the United States. This absence in the literature prevents us from comprehensively understanding how large-scale disruptions impact the resiliency and adaptability of critical water infrastructure.[24] Thus, we leverage two sets of semi-structured interviews of small and large water utilities to provide insight into the resiliency of U.S. DWUs through the scope of the COVID-19 pandemic. Our goal is 1) to evaluate the COVID-19 pandemic's impact on small and medium water utilities and 2) to understand the difference between the impacts on small and large DWUs to develop conclusions on small DWU resilience. In our study, we categorize small water utilities as having a customer size of 10,000 and less (i.e., very small, small, and medium water utilities according to the EPA)[12] and large water utilities as having a customer size of more than 10,000 (i.e., large and very large water utilities according to the EPA).[12] Through this exploration of water utility O&M during the COVID-19 pandemic, we present an opportunity to solve various sociotechnical problems affecting water utilities during crises.

MATERIALS AND METHODS

We conducted and analyzed semi-structured interviews with practitioners at 26 small DWUs in the United States using a hybrid content analysis approach (deductive analysis with additional inductive coding).[31] To compare the experiences of small and large DWUs during the COVID-19 pandemic, we performed chi-squared tests using data collected from the 26 small DWUs and interview data previously collected by the research team of 28 large DWUs. More information about the interviews with large water utilities referenced in this study can be found in Spearing et al. or the archived interview data.[6,32]

2.1. *DATA SOURCES AND COLLECTIONS*

Before data collection, the team received institutional review board approval at the University of Texas at Austin and the University of Washington. The small drinking water utility dataset consists of interviews with 23 practitioners from 26 DWUs across five states, with three interviewees each representing two DWUs. Additional information involving the interviewees can be found in Table 1. We selected interviewees through stratified sampling as we used existing databases of small state DWUs to contact via email or phone.[33] Interviews were conducted using video conferencing or phone calls, recorded, transcribed, and then reviewed for quality. Interviews were conducted from May 18th, 2021 to August 12th, 2021. The procedures used in this analysis complemented the methods used in the study of semi-structured interviews with stakeholders from 28 large DWUs,[6] of which supplemented the statistical analyses. The final dataset of large and small DWUs includes interviews with 76 practitioners from 54 DWUs in 14 states. A table showing information about the entire dataset is included in Supporting Information (S.I.).

Table 1: Interviewee and Small DWU Information

State	Interviewees	Roles of Interviewees	EPA Size Classification (Number of Customers)
Alaska	1	Owner	< 500
Alaska	1	HOA Treasurer	< 500
Alaska	1	HOA President	< 500
Alaska	1	Owner	< 500
Alaska	1	Lead Operator	500 - 3,300
Alaska	1	Manager	500 - 3,300
Alaska	1	Assistant Manager and Utility Engineer	3,301 - 10,000
California	1	General Manager	500 - 3,300
Colorado	1	General Manager	< 500
Colorado	1	Manager and Operator	< 500
Colorado	1	Operator	< 500
Colorado	1	Board Member	< 500
Colorado	1	Operator	< 500
Colorado	1	Operator	< 500
Colorado	1	Operator	500 - 3,300
Colorado	1	Public Works Director	500 - 3,300
Colorado	1	Manager and Operator	500 - 3,300
Colorado	1	Office Manager	500 - 3,300
Colorado	1	General Manager	3,301 - 10,000
Colorado	1	Public Works Director	3,301 - 10,000
Colorado	1	District Manager	3,301 - 10,000
Colorado	1	Public Works Director	3,301 - 10,000
Colorado	1	Water and Wastewater Director	3,301 - 10,000
Colorado	1	Utility Director	3,301 - 10,000
Connecticut	1	President	< 500
Oregon	1	Superintendent	3,301 - 10,000

The interview questions were designed to facilitate thoughtful conversations about water utilities' changes, challenges, and responses during the COVID-19 lockdowns. Interviewees were initially asked about their status-quo operations before we explored specific questions involving water utility operations during the pandemic (e.g., workforce management, water quality). Questions for large and small water utilities followed the same structure and themes. Interviewees who represented smaller utilities were also asked additional questions to understand their perception of the difference between water utility performance during the pandemic based on customer size. An example of the interview questions can be found in S.I.

2.2. *QUALITATIVE ANALYSIS*

Interview transcripts were analyzed using a hybrid, inductive-deductive qualitative coding technique with the NVivo software.[31,34] First, we took a deductive approach letting our research questions drive parent codes (see Supplemental Table 3 in S.I. for coding dictionary and examples). Next, we used an inductive, data-driven approach, allowing specific themes to emerge as child codes. Such a qualitative approach is documented in Spearing et al.[31] Two researchers completed the qualitative coding analysis and an intercoder reliability test based on eight excerpts. The resulting kappa value of 0.80 is considered strong for qualitative research.[35]

2.3. *STATISTICAL ANALYSIS*

Following the qualitative analysis, we performed tests to understand the statistical differences between the self-reported impacts of the COVID-19 pandemic on small and large DWUs using both datasets. We categorized the themes that arose in the interviews into three of the five resilience dimensions used commonly in resiliency literature: financial, social, and infrastructure (Figure 1).[10] Using the resulting categories, we completed nine chi-squared tests to determine the associations between large and small water utilities and various resiliency metrics. These categories were chosen due to their relevancy to infrastructure systems and the absolute nature of interviewee responses (e.g., yes, no, no change, or unknown). We used chi-squared tests for this analysis since all of the cells in the 2x2 tables have expected frequencies greater than five.[36] One category was combined to complete the statistical test (i.e., we incorporated staffing issues and shift changes into personnel management). The results of the statistical tests were used to compare interviewees' perspectives on utility size and system resilience.

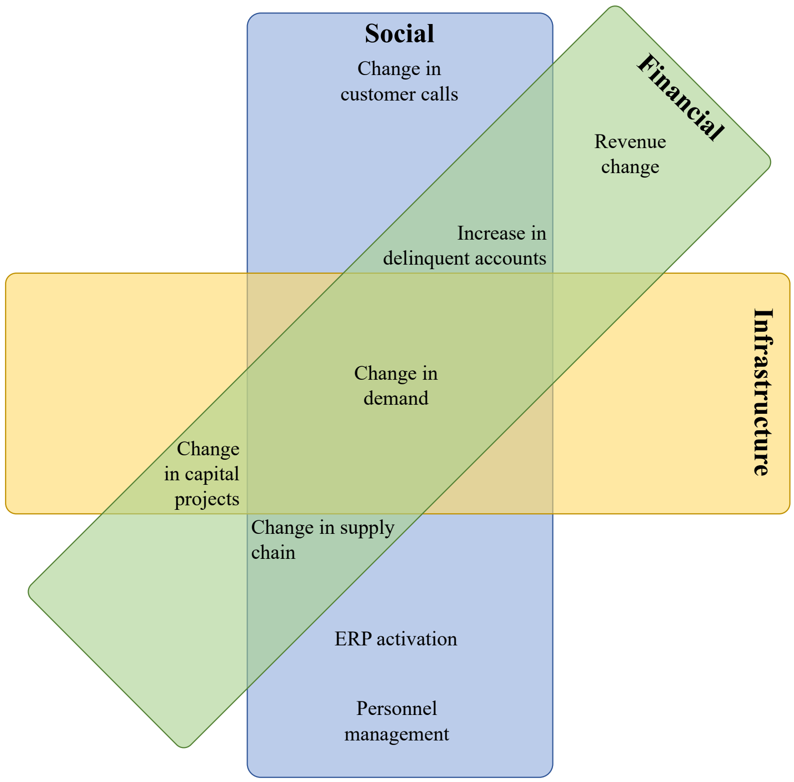

Figure 1: Conceptualization of factors from resilience categories analyzed statistically. Factor placement is based solely on its effect or impact on the resilience category and are uniformly weighted. Here, change in supply chain includes separate distinctions for operational materials and for PPE.

2.4. *LIMITATIONS*

One of the main limitations of this work is the sample size, as this study only represents a small fraction of drinking water utilities in the U.S. Similarly, this work does not differentiate further between the types of small utilities (e.g., small utilities with large financial capacities). Despite this, we believe that the 54 utilities included in this study provide valuable trends in how the COVID-19 pandemic has influenced different-sized drinking water utilities, allowing us to explore how this may translate to other emergencies. Although alternative data collection approaches (e.g., surveys) may have resulted in a larger sample size, interviews allow for a deeper understanding of DWU operations. Furthermore, the interviewed practitioners had explicitly expressed interest in participating in this study. In acquiring the participants for the small water utility dataset using email databases, we had an acceptance rate of less than 5% in some states. Thus, this study may be reporting the experiences of water utilities willing and able to share their COVID-19 impacts, whether positive or negative. We followed a strict qualitative protocol when completing the analysis to ensure that we reduced bias.[37] Lastly, we used self-reported data to understand the implications of utility size on drinking water utility resilience. Although this self-disclosed information reduces the general objectivity of the data, it provides helpful insights into what can impact water infrastructure during crises. Future work can supplement the perspectives captured in this study with a more extensive survey of COVID-19 impacts on DWUs across the United States.

2. RESULTS AND DISCUSSION

3.1. CHALLENGES, CHANGES, AND RESPONSES EXPERIENCED BY SMALL UTILITIES

The complete list of challenges, changes, and responses experienced by small DWUs in our study is described in Table 2. The relative frequency reported refers to the percentage of all interview responses coded as a challenge, change, or response. A table highlighting the experiences of both large and small utilities in terms of the selected excerpts is reported in S.I.[6]

Table 2: Selection of frequency table of small drinking water utility challenges, changes, and responses because of the COVID-19 pandemic

Code	Small Water Systems	
	Number of DWS	*Count of Responses (Relative Frequency)*
Excerpts about Utilities' Changes, Challenges, and Responses	***26***	***626 (100.0%)***
Planning and Management	***26***	***317 (50.6%)***
Change in capital projects (e.g., delayed, increased during shutdown)	*12*	19 (2.9%)
Institutional collaboration (e.g., conferences canceled, working with government/unions)	18	38 (6.1%)

Planning	*25*	*31 (5.0%)*
Activated/used emergency response plan or created/improved a pandemic plan	9	9 (1.4%)
Other (pandemic) planning (e.g., front-end planning, for a possible recession)	6	6 (1.0%)
Supply chain	26	86 (13.7%)
Difficulty procuring or worry about routine supplies (e.g., chemicals, valves)	16	16 (3.7%)
Difficulty procuring personal protective equipment (PPE) or sanitation materials	12	12 (1.9%)
Late-stage supply chain issues	15	18 (2.9%)
Workforce Related	24	116 (18.5%)
General shift changes or furloughs for all staff	11	20 (3.2%)
New workplace policies (*e.g.,* social distancing, cleaning, leave policies, vehicle rules)	15	29 (4.6%)
Concerns of staffing (e.g., family leave, retiring early, lack of staff)	14	20 (3.2%)
Technology usage for virtual work	12	15 (2.4%)
Finances	***25***	***61 (9.7%)***
Billing (e.g., customer payments, rates, revenue)	25	61 (9.7%)
Increase in delinquencies or enrollment in customer assistance programs	12	14 (2.2%)
Revenue Change	20	22 (3.5%)
Decrease in revenue	8	9 (1.4%)
Increase in revenue	2	2 (0.3%)
Spending or financial capacity	6	7 (1.1%)
Increase in expenditures (due to social distancing policies or expected budget cuts)	6	7 (1.1%)
Technical System	***26***	***145 (23.1%)***
Demand and water use	*25*	40 (6.3%)
Overall system demand	25	40 (6.3%)
Decrease in overall demand	0	0 (0.0%)
Increase in overall demand	12	13 (2.1%)
Non-critical maintenance deferred, slowed, or stopped at one point	2	2 (0.3%)
Water quality	*23*	58 (9.3%)
Disinfectant residuals	22	22 (3.5%)
Higher than normal residuals	0	0 (0.0%)
Lower than normal residuals	1	1 (0.2%)
Community-related	***26***	***79 (12.6%)***
Change in customer service operations (e.g., reduced hours, in-person service suspended)	11	12 (1.9%)
Adapted outreach strategies (e.g., building flushing protocols, safety information, virtual)	18	31 (5.0%)

Customer calls or complaints	*22*	29 (4.6%)
Decrease in customer calls (e.g., because there are no shut-offs)	1	1 (0.2%)
Increase in customer complaints/concerns (e.g., aesthetics, worry about water safety)	6	8 (1.3%)

3.1.1. PLANNING AND MANAGEMENT

All 26 small drinking water utilities included in this study discussed impacts and changes related to planning and management. Nearly half (12) of the small DWUs experienced slowdowns or cancellations on either ongoing or planned capital projects. Due to employee shortages (e.g., employees getting sick with COVID), some water utilities needed to delay projects and focus on critical maintenance, given their pre-existing minimal staff. A representative of one water utility described how the COVID-19 lockdowns and associated work-from-home (WFH) policies slowed the process of receiving a Clean Water State Revolving Fund (CWSRF) grant from the state, impacting their ability to make capital improvements. Still, because state employees were working from home, their slower communication lines caused the contract approval to take an "exceptional amount of time that should have not been happening." Although this concept has not been explored at the utility level, studies have shown that lower levels of internal communication during COVID-19 have led to lower productivity despite potential increases in total hours worked.[38,39] The pandemic and other emergencies that affect workforce management and can lower productivity levels (e.g., a recession) could pose additional complications for small drinking water utilities, given their reduced staffing.

Other water utilities cited supply chain issues as a cause of capital project delays. Slowdowns on necessary construction materials and mechanical parts impacted project schedules, but many water utilities described being able to resume their planned projects. Furthermore, 16 water utilities (62% of the sample) experienced delays with equipment and material needed to support regular operations. Some interviewees reported canceled orders for materials, which delayed planned capital projects. While some DWUs experienced these slowdowns within the first few months of the pandemic, 15 water utilities (58% of the sample) faced “late-stage” supply chain challenges in 2021. One interviewee detailed:

> “[Someone at a neighboring water company] was calling all of his neighbors trying to find [a pump]. And a backorder on that pump was for four weeks. They couldn’t backwash their filters for four weeks because [they] couldn’t get it anywhere in the United States… I think it’s probably even worse in a rural area than a bigger Metropolitan place because we’re probably a little further down the totem pole of priority.”

Such challenges were not unique to small DWU—the later stage supply chain slowdowns in 2021 resulting from worker shortages had widespread impacts.[40] However, for smaller water utilities with fewer resources than their larger counterparts, the increased wait times for critical materials rendered some utilities incapable of completing specific maintenance. The issue of delayed material shipments was additionally coupled with increased pricing on essential chemicals and equipment. For water utilities in more remote locations (e.g., small communities in Alaska), price gauging and high shipping costs have made acquiring materials “very challenging.” Similar emergencies that disrupt the supply chain (e.g., natural disasters) could enable the same issues, depending on the small water utility location.

However, some DWUs benefitted from their remote nature. Although 46% of the water utilities experienced challenges in retrieving sanitation materials and PPE, 35% of water utilities did not have any supply chain issues. The DWUs that did not initially face significant challenges tended to be smaller (e.g., customer size of less than 3,300) and more remote. As described by interviewees, the isolated nature of remote water utilities motivates employees and volunteers to procure items for their reserves during status-quo operations. Similarly, three DWUs (i.e., two very small DWUs and one small DWU by EPA standards) do not use disinfectant in their treatment, influencing their supply chain needs. The lack of supply chain issues translated to minimal change to workforce management and operation, which six water utilities in our study encountered. One respondent, who served as the sole operator for two water utilities, described this:

> "Because they're such small systems, it's kind of a stop and check on the [system] every couple of days. There's no human interaction to speak of… I could see the concern, though, as the sole operator, should I have contracted COVID and was not able to operate the plant? But we didn't change anything or make any formal plans."

In the case of the COVID-19 pandemic and similar emergencies that mainly impact personnel management, a smaller staff may have allowed for increased resilience against workforce challenges that impacted larger DWUs. On the other hand, 14 water utilities in our study (54% of the sample) experienced staffing concerns. One interviewee described, "dealing with the normal problems with [a] reduced crew was a challenge in itself." This sentiment corroborates AWWA's 2021 State of the Water Industry survey of small and medium water utilities, where 30% of the 553 respondents described being impacted by absenteeism.[41] Approximately 42% of the interviewed water utilities in our study (11 utilities) underwent shift changes to accommodate their staff better and ensure sanitation. For example, one water utility distributes water to the community via a public watering point, and the representative described the need to work "seven days a week…. Keeping the sanitation of [the water point] intact so we're not a local source of contamination for COVID-19 pandemic." The additional actions to ensure safety during the pandemic may have contributed to additional stress for small DWUs already experiencing difficulties with O&M.

To help manage the impacts of the COVID-19 pandemic, many water utilities across the United States enacted emergency response plans (ERPs). However, only water utilities with a customer size greater than 3,300 (i.e., medium-sized DWUs, according to the EPA) must have an ERP verified by the EPA following the establishment of America's Water Infrastructure Act (AWIA).[42,43] Five of the eight water utilities that fit this size requirement referred to their ERPs. Three smaller utilities also enacted or referred to their emergency planning documents. Many of these utilities had an ERP "that wasn't quite COVID-tailored" but was adapted to fit the situation. Approximately 65% of water utilities (17) did not refer to ERPs. Despite many utilities in our sample having ERPs, the majority saw minimal changes to their operations and did not see a need to enact emergency actions. This discrepancy suggests the unique resilience of small water utilities during emergencies like the COVID-19 pandemic that impact personnel and the supply chain.

3.1.2. FINANCES

Based on the stakeholders' accounts, the financial capacities of water utilities in this study were impacted by two categories: additional expenditures and delinquent accounts due to moratoriums. Six utilities (23% of the sample) reported additional expenses to enhance technology, purchase extra supplies, or account for additional labor costs as employees put more hours into operations and other tasks. One respondent described that a large amount of money was spent on "updating [their] council chambers with video cameras and screens and just new equipment from basically the ground up." While the COVID-19 pandemic and associated lockdowns disrupted status-quo operations and procedures, it allowed many DWUs to advance their digital capacities. However, for some small DWUs in the more rural parts of the country, the abrupt change to digitalization may have negatively impacted revenue. Outside of emergency contexts, digitalization in rural communities faces numerous socio-cultural, technical, economic, and regulatory-institutional barriers.[44] Thus, adopting digitalization prompted by the COVID-19 pandemic or other emergencies that require advanced technical adoptions may not have the same impacts on water utilities of different sizes and resources.

On the other hand, government-enacted moratoriums on utility shut-offs led to an increase in late and non-payments in 12 water utilities (46% of the sample). In response, seven water utilities (27% of the sample) described increasing communication and payment options to assist customers with paying their bills. The small water utilities involved in this study often found that the smaller community size contributed to more effective communication on overdue payments:

> "Because we're such a small community, we've tried to go the extra mile to assist the people that are having difficulties and try to talk to them... let them know that we know there are certain agencies that will assist them [with] keeping their utilities off. I think we had a few that were late… maybe four months delinquent, but we would generally get them to come around and we've been very successful at it."

Overall, the effect of additional expenditures and delinquent accounts on revenue was variable. Two DWUs (approximately 8% of the sample) saw an increase in revenue due to the "20% to 30% increase on the day-to-day flows." Other DWUs (8; 31% of the sample) reported a revenue decrease due to the COVID-19 pandemic. Although none of the water utilities reported significant reductions in revenue that could compromise water utility operations, this was a concern for many small water utilities across the country due to their pre-existing financial limitations. Notably, 38% of the sample (12 utilities) experienced no or limited impact on their revenue. The described effects on revenue provide additional insights into preliminary work done to examine the overall financial implications of the pandemic on DWUs in the country. For example, although the AWWA predicted a collective $13.9 billion loss in revenue for DWUs, few of the utilities polled to form the prediction were small utilities.[45] The DWUs in our study that reported minimal effects on their finances additionally experienced minimal changes in their planning, management, and overall operations. This lack of impact suggests potential areas of resiliency for small DWUs in emergency contexts, with possible dependence on socially determined characteristics (e.g., status quo economic capacity or the number of personnel.)

3.1.3. TECHNICAL SYSTEM

During the pandemic, water usage changed across the United States due to government-ordered lockdowns and people's changing behavior. Twelve water utilities reported increased water usage, partly due to the public working from home. However, the DWUs' responses demonstrate that there may be a correlation between water demand change and the community served. For example, one interviewee believed that the increase in water usage was caused by "an influx of people buying real estate and moving… because they could now work from home." On the other hand, one of the 13 water utilities that experienced no significant water demand change described its position as a "very agriculturally based community" as one of the main reasons for unimpacted water demand. As described in Spearing et al.,[6] a DWU's customer type may influence overall demand change; water utilities that serve primarily residential communities with limited commercial zoning, for example, may not experience as noticeable water demand changes as water utilities that serve communities with large industrial and commercial businesses.

Generally, the COVID-19 pandemic did not impact small DWUs' water quality. Only one water utility increased the testing of their water mains to monitor consumption more effectively. For another water utility, the increased water usage brought about "better quality in their distribution system" because of decreased water age. Although 14 water utilities described not having any changes to flushing schedules, three water utilities described either changing flushing protocols or deferring the flushing of the distribution system due to minimized staff availability. While this did not cause any known water quality issues for the water utilities involved in this study, this example demonstrates the potential risk that small water utilities may face regarding reduced staff and compromised water quality in emergencies that predominantly affect the water source or the technical system.

3.1.4. [44]COMMUNITY-RELATED

To minimize the spread of the virus, 12 water utilities (46% of the sample) did not allow the public the enter their offices (e.g., for bill payment, customer service). Four water utilities explicitly mentioned using offsite bill drop-off locations to assist community members. At one water utility, more individuals made "phone and credit card payments instead of bringing in a check or cash… like they normally would have done." Despite regional differences, social networks between community members in small towns are often reinforced by in-person interactions that the COVID-19 pandemic halted.[46] The closures of non-essential businesses shifted how the public interacted with DWUs and altered a critical component of maintaining the closeness and social capital within small communities.[47]

As a response to this shift from in-person interactions, interviewee respondents especially highlighted the efforts made to adapt outreach and communication efforts during the pandemic (18 water utilities; 69% of the sample.) For example, 50% of DWU sought electronic ways to inform customers about water utility operations, bill payments, and general information related to COVID-19 and the water supply. Communication depended on the community; one respondent mentioned communicating with the public via physical signage and announcements via the local radio station, while several others mentioned updating the water utility or the city's website. One interviewee described the benefit of using technology to connect with the population:

> "We have a mixed neighborhood of different demographics. And there are some folks who probably don't use a computer very much or a cell phone. And so, they've opted to receive phone calls… I get more phone calls initially with 'You, sent me a text message. What was that about?' You know, they got an alert. So now it actually increased communication because somebody would follow up."

Generally, the water utilities that reported increased customer calls (6 DWUs, 23% of the sample) could maintain pre-existing connections. For instance, one water utility mentioned that for longtime customers that would drop off bill payments and chat in person, employees would continue those connections through phone calling in addition to reassuring customers about "the status of their water utility." Alternatively, one water utility experienced fewer customer calls as water service was no longer shut off due to the moratoriums. The COVID-19 pandemic, like many other emergencies, demonstrated the importance of maintaining communication networks. For small and often rural communities that often rely on more in-person communication, the pandemic demonstrated the DWUs' ability to adapt in more extreme contexts.

3.2. DIFFERENCES BETWEEN SMALL AND LARGE UTILITY EXPERIENCES

Figure 2 shows small DWUs' perspectives on the differences between pandemic impacts on small and large water utilities. Table 3 reports the results of the chi-squared tests that explored how resilience differed between small and large drinking water utilities as reported by utility stakeholders. Based on the data, we see statistically significant differences between large and small DWUs for change in revenue, increase in delinquent accounts, personnel management, and activation of ERP in the population of water utilities. An additional visualization of the percentage of large and small utilities that reported changes within the nine resilience dimensions can be found in S.I.

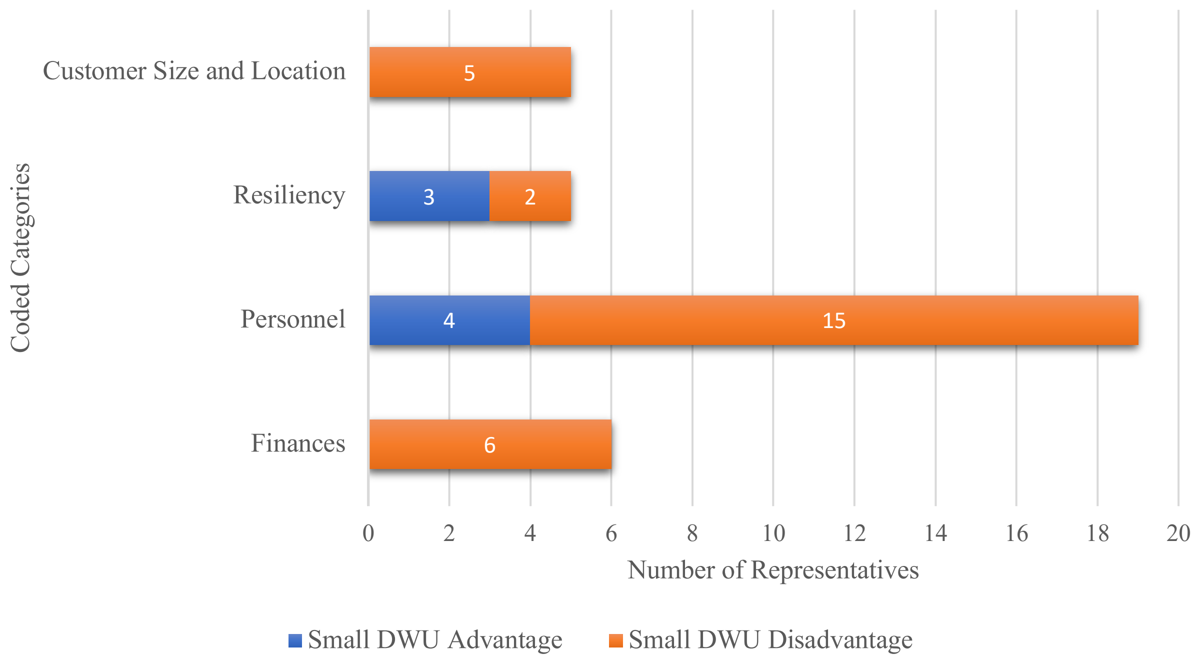

Figure 2: Small DWU representatives' perspectives on small DWU advantages and disadvantages compared to large DWUs during the COVID-19 pandemic

Table 3: Results of the chi-squared tests

Resilience Dimension(s)	**Drinking Water Utility Impact**	**Drinking Water Utility Size (Less than 10,000 customers or more than 10,000 customers)**
Social	Change in customer calls	0.38
Social	**Personnel management**	**0.02***
Social	**Activation of ERP**	**0.03***
Financial, Social	**Increase in delinquent accounts**	**0.05***
Financial, Social	Change in the supply chain for operational materials	0.31
Financial, Social	Change in the supply chain for PPE and sanitation materials	0.10
Financial	**Change in revenue**	**0.03***
Financial, Infrastructure	Change in capital projects	0.79
Financial, Infrastructure, Social	Change in demand	0.39

Note: * $p<0.05$

There was a statistically significant difference between the changes in personnel management (e.g., staffing issues and shift changes) of small and large DWUs during the COVID-

19 pandemic. 82% of large DWUs experienced changes in personnel management compared to 74% of small DWUs. To adequately service their communities, the size of a DWU workforce tends to be proportional to the size of its serviced community (e.g., large water utilities have more operators). Thus, large water utilities with many employees may have more significant concerns with managing the workforce to minimize COVID-19 exposure. Generally, small DWUs experienced similar circumstances differently, especially the DWUs that may only have one operator managing the technical system. However, when asked to compare the experiences of small and large water utilities during the COVID-19 pandemic, 15 representatives of small DWU (65% of all interviewees) described the number of personnel as a disadvantage for small water utilities during the pandemic. The interviewees often cited the risk associated with relying on a smaller staff, especially in communities where the staff are volunteers:

> "I think larger water utilities have the infrastructure and the staff in place to handle situations like [the COVID-19 pandemic] a lot better… We have 95 homes in our system. And we have an entirely volunteer board for our HOA… We're not paid, and we're not full-time employees, so we're doing this in our spare time… And so, I don't think that the attention is paid to some of these smaller water utilities. I mean, I know systems where there are only eight homes in the whole system. And so, if there were an impact, it could potentially shut down those eight homes from having water entirely."

Due to minimized staff, the threat of being unable to perform needed maintenance during an emergency can be high for many small DWUs as they don't have "lots of employees that can back each other up." However, four respondents mentioned that being a small DWU may have been advantageous during the pandemic. One interviewee hypothesized that "smaller water utilities had less challenges from the standpoint of logistics because there are fewer people involved and fewer contact points." This sentiment was often shared by representatives of DWUs that had minimal impacts due to the pandemic. The streamlined processes found in small utilities corroborate the concept that small organizations can adapt more quickly than large utilities.[48] In general, limited staff may be beneficial for personnel management but can put a DWU at a higher risk in the case of emergencies that influence an employee's ability to work (e.g., natural disaster, pandemic).

There was also a statistically significant difference between large and small water utilities that activated their ERP in the population based on our sample (67% of large and 36% of small DWUs). Many large DWUs had to drastically change their operations due to the size and complexities of their organizations. Additionally, AWIA required water utilities that serve a population of 100,000 or greater to submit emergency response plans by September 2020 for certification from the EPA.[42] Thus, large DWUs tended to enact their ERPs to support the changes, particularly during the lockdowns in 2020. On the other hand, smaller utilities that may not have deviated from their status-quo operations did not see the need to reference their ERPs. Two interviewees highlighted the lack of planning as a limitation and described the need for more effective plans for future emergencies. However, five interviewees suggested that small water utilities are less likely to face impacts from the COVID-19 pandemic due to their size, remoteness, and existing operations. For example, one DWU representative mentioned that his water utility's experience "trying to adapt to the situation on a daily basis" results in becoming "more resilient in the end." While the idea that small utilities are less likely to face severe impacts supports the lack of ERP activation, the EPA does not require DWUs with a customer size of less than 3,300 to have an ERP. Similarly, medium-sized water utilities (i.e., utilities that serve a population between 3,301 and 10,000) were not required to submit emergency response plans until June 2021, which could explain the difference in ERP adoption.[42] Although the majority of the utilities in our sample had an ERP, the result of our chi-squared test that supports a statistical difference between the ERP activation of small and large drinking water utilities may be influenced by our potentially unique sample.

The customer base for large and small DWUs potentially contributes to the statistical difference in revenue change in the population based on our sample (79% of large DWUs and 47% of small DWUs experienced a change in revenue). The COVID-19 lockdowns temporarily and permanently closed many commercial and industrial customers, which had more significant implications for large DWUs more likely to serve those users. The shutdowns of those businesses thus impacted the water sales that large DWUs would typically make. On the other hand, many small DWUs primarily service residential communities with limited commercial customers, causing their revenue to be smaller than in urban areas. DWUs' revenue change is additionally influenced by a change in delinquent accounts, which was found to be statistically different between DWUs of various sizes in the population based on our sample (81% of large and 52% of small DWUs). Based on size alone, large DWUs serve a bigger population, likely increasing the number of delinquent accounts. Additionally, many small water utilities faced minimal negative changes to status quo operations and community engagement, which could reflect a limited increase of delinquent accounts compared to large DWUs. Small DWUs may not have seen a stark increase in delinquent accounts as they likely could communicate and effectively reach the customers in their smaller communities to discuss bill payments and updates with the utility. The comparison between the two demonstrates the benefit of the social capital found within smaller and more rural communities that may aid in communicating changes during extreme events.[47,48]

Although there were statistically significant differences between large and small DWUs for revenue and delinquent account change in the population, six interviewees (25% of the sample) described finances as a disadvantage for smaller water utilities. One respondent highlighted that water utilities with a larger customer base may benefit from more significant economies of scale as they have more robust savings and inventory, and small utilities may have "nothing to depend on." A representative of a different utility shared how the risk increases as the customer size decreases when saying, "[Smaller utilities] just don't have enough people to spread the costs… to try to pay for everything. And it's really tough on the small ones; I'm going to say anything less than 150 taps; it's pretty tough, especially below 100." Seemingly, the financial capacity of water utilities depends on the socioeconomics of the community a DWU serves. However, there may be fewer protections, especially for small DWUs that could be magnified in emergencies (e.g., recessions) that significantly influence the financial capacities of DWUs.

3. STUDY IMPLICATIONS

Our study reveals specific challenges and changes experienced by small DWUs during the COVID-19 pandemic and what that may suggest for resiliency in other emergencies. We found that DWUs of different sizes had different experiences during the pandemic. For example, several small water utilities cited that personnel management issues were less apparent due to having a small staff, demonstrating areas of resilience for small utilities during emergencies that mainly impact planning and management. However, utilities that noted the disadvantages of having a small staff acknowledged that it increases the vulnerability of a water utility as additional responsibilities may need to be assumed by the small workforce, as in other emergencies. This vulnerability is especially true for emergencies that impact technical system operation and maintenance, as small utilities with a single shared operator would need to maintain water service while rectifying issues. As workforce shortages are a current issue for small DWUs, further support should be given to strengthening the workforce in these smaller communities. This strengthening may be in the form of government subsidies that can be passed down to the DWUs to aid in hiring or through enhanced partnerships between small drinking water utilities in the same region supported by local organizations. For instance, the EPA currently supports and guides a variety of partnerships (e.g., Water/Wastewater Agency Response Networks (WARNs), informal cooperation) at the state level.[49] With additional support, these partnerships may better facilitate mutual aid agreements for public and private small utilities during emergencies without needing to go through state-specific processes.

The formation of such networks has aided small DWUs during the pandemic. One DWU representative mentioned reaching out to a local community water utility to interchange "manpower to cover for sick days." With nine DWUs in our study benefitting from collaboration with other utilities, additional financial support should be given to the EPA and groups like the Rural Community Assistance Partnership and National Rural Water Association to facilitate the creation of DWU partnerships. The supplemental government funding can also be used to develop solutions for the more remote communities that could benefit from partnerships but lack the proximity to do so adequately to bolster utility resilience during status-quo and emergency operations.

Furthermore, the pandemic exemplified how emergencies often magnify the financial difficulties that small DWUs experience daily. Although not all small DWUs in our study experienced revenue decreases, the repercussions of those could be especially impactful because small utilities typically operate with small financial reserves. Future studies should examine the implications of enforcing the Bipartisan Infrastructure Law to increase the financial robustness and resilience of small water utilities. The bill aims to "target resources to disadvantaged communities" (e.g., small and rural water utilities), assist in service line replacement, and "renew the water workforce," which could strengthen the financial reserves and overall O&M of particularly challenged water utilities.[50] We recommend that funding considers a water utility's customer size, customer base, and location, which can be aided through enhanced connections and communication between water utilities of similar characteristics. Using the COVID-19 pandemic as a case study on widespread emergencies, this work reveals similar challenges that small DWUs may experience in other emergency scenarios at regional levels. More support would particularly be needed for small utilities in the case of future extreme events that can influence resilience.

Supporting Information: Additional tables and figure that detail interviewee demographics, sample interview questions, the coding dictionary, and frequencies for statistical analyses (PDF)

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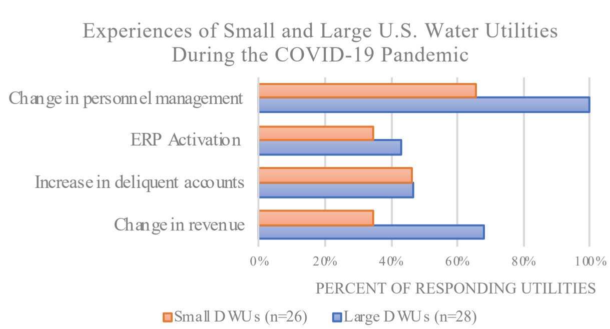
ToC GRAPHIC



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