Effects of the COVID-19 Pandemic on Water Utility Operations and Vulnerability

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ABSTRACT

The COVID-19 pandemic affected the operation of water utilities across the world. In the context of utilities, new protocols were needed to ensure that employees can work safely, and that water service is not interrupted. This study reports on how the operations of 27 water utilities worldwide were affected by the COVID-19 pandemic. Interviews were conducted between June-October 2020; respondents represent utilities that varied in population size, location, and customer composition (*e.g.*, residential, industrial, commercial, institutional, and university customers). Survey questions focused on the effects of the pandemic on water system operation, demand, revenues, system vulnerabilities, and the use and development of Emergency Response Plans (ERPs). Responses indicate that significant changes in water system operations were implemented to ensure that water utility employees could continue working while maintaining safe social distancing or alternatively working from home. Twenty-three of 27 utilities reported small changes in demand volumes and patterns, which can lead to some changes in water infrastructure operations and water quality. Utilities experienced a range of impacts on finances, where most utilities discussed small decreases in revenues, with a few reporting

more drastic impacts. The pandemic revealed new system vulnerabilities, including supply chain management, capacity of staff to perform certain functions remotely, and finances. Some utilities applied existing guidance developed through ERPs with slight modifications, other utilities developed new ERPs to specifically address unique conditions induced by the pandemic, and a few utilities did not use or reference their existing ERPs to change operations. Many utilities suggested that lessons learned would be used in future ERPs, such as personnel training on pandemic risk management or annual mock exercises for preparing employees to better respond to emergencies.

INTRODUCTION

The coronavirus disease 2019 (COVID-19) pandemic affected communities across the globe and required measures, including social distancing, mandatory lockdowns, and shelter-in-place orders, to reduce transmission of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). These measures changed the way people visit and interact at work, school, institutions, and places of business, and the impacts of these changes were felt by businesses, industries, and governmental services. Like other businesses and industries, water utilities adjusted to the need for employees to work from home or carry out assigned tasks while social distancing and found challenges in workforce management, loss of revenue, and providing personal protective equipment (PPE) (AWWA 2020; Berglund et al. 2021). Water utilities were uniquely impacted by social distancing, working from home, and lockdowns, as these changes in daily patterns led to new water use patterns. Changing demand patterns that led to delayed morning peaks and lower institutional and commercial demands were reported by several studies (Balacco et al. 2020; Kalbusch et al. 2020; Ludtke et al. 2021). Unprecedented hydraulic characteristics in water distribution networks can create a need for operational adjustments, such as in the timing of pump and tank operations. New hydraulic patterns can also lead to changes in the circulation of water, allowing growth of bacteria due to longer residence time (*i.e.*, water age). For example, a few utilities reported increased water quality issues during the pandemic (Spearing et al. 2020). Water utilities were also uniquely impacted by the COVID-19 pandemic because water infrastructure is a critical infrastructure and is required to continue to operate regardless of crises. Water utilities are typically equipped with Emergency Response Plans (ERPs), which provide protocols to respond to urgent conditions during emergencies and hazards. The

COVID-19 pandemic created unique circumstances beyond other emergencies, and legacy ERPs were not crafted to provide relevant guidance to address emerging challenges during a pandemic. New ERP guidelines are needed to include the proper use of PPE, cleaning and disinfecting public areas, and monitoring water quality for pathogens (Gude and Muire 2021). Changes in supply chains may reveal new vulnerabilities that affect chemicals needed for treatment; infrastructure components, materials, and tools needed for maintenance or repair; and PPE, leading to sudden changes in the way utilities need to operate. ERPs should be updated to include preparedness activities and response actions that can be applied in pandemics.

Several studies have been conducted to learn how utilities were affected by and responded to the COVID-19 pandemic. Spearing et al. (2020) conducted surveys of 28 utilities to understand broadly how social distancing practices affected water utilities. They found that impacts fell within a set of themes, including planning and management, the technical system, finances, community-related, and regulatory requirements and testing. Impacts were noted by respondents in all these areas, and the study concluded an importance to integrate planning for pandemics into existing long-term planning activities. Demand dynamics provide new insight about the performance of infrastructure under other population changes, and disaster management can integrate pandemic planning into research around multi-modal hazards. Other utility surveys were conducted with research questions focusing on specific utilities and impacts. Bostic et al. (2021) summarized 13 state and national studies that had been conducted by agencies across the U.S., with a focus on the financial burden of the COVID-19 pandemic on water utilities. They synthesized these surveys to emphasize that small community water systems (serving fewer than 10,000 people) are vulnerable to customer debt and declining revenue, as small systems are less likely to have cash reserves, and customers may be struggling to pay their water bills (Bostic et al. 2021). Eleven U.S. utilities were studied based on water consumption and utility revenues, and most utilities saw an overall increase in water consumption and an increase in utility revenues (Smull et al. 2021). Bracciano (2021) interviewed water conservation managers of five large water utilities and found out that the primary challenge for water conservation programs was equipping staff with the technology needed to successfully work remotely or from home.

The research described in this manuscript was designed to apply a sub-set of the research constructs developed by Spearing et al. (2020) to explore impacts on planning and management, the technical system, and finances. Interview questions were selected to develop understanding and insight about the experience of water utilities during the pandemic, with a focus on operational changes, new vulnerabilities that emerged during the pandemic, and how ERPs were used and amended to address new vulnerabilities. This research tested these constructs at utilities across the globe.

To answer these questions, interviews of 27 utilities were conducted to assess (i) changes in operations, (ii) demand changes, (iii) revenue changes, (iv) new vulnerabilities and challenges, and (v) the use of ERPs to address changing conditions. The discussion following the analysis of these interviews provides new insight about these five topics. Many respondents indicated that significant changes in water system operations were implemented to ensure that water utility employees could continue working while maintaining safe social distancing or alternatively working from home. Small changes in demand volumes or patterns lead to some changes in water infrastructure operations, such as decreasing chemical dosing for lower volumes of produced water. Utilities experienced a range of impacts on finances, where most utilities discussed small decrease in revenues, and a few utilities reported more drastic impacts. The pandemic revealed new system vulnerabilities, including supply chain management, capacity of staff to perform certain functions remotely, and finances. The applicability of existing ERPs is also explored and reported. Some utilities applied existing guidance developed through ERPs with slight modifications, other utilities developed new protocols to specifically address unique conditions induced by the pandemic, and a few utilities did not use or reference their existing ERPs to change operations. Overall, the analysis of interview results reveals the capacity of water utilities to respond and adapt to emergency conditions and provides guidance for improving the resilience of infrastructure to a changing environment.

The manuscript is organized as follows. The next section describes the set of respondents and five overarching interview questions. The following sections focus individually on each interview question, with subsections in related background and literature, analysis of survey responses, and recommendations and implications for utilities around that topic. The paper concludes with Discussion and Conclusions sections to demonstrate take-home messages for water utilities.

MATERIALS AND METHODS

Interview Sample

Researchers interviewed utilities from across the globe during the period of June-October 2020. The purpose of these interviews was to explore, rather than quantify, the impacts of the COVID-19 pandemic on utilities and utility operations, and questions were developed by the group of researchers to allow free responses around emerging issues during the pandemic (Table 1). Further description of the topics explored by each question are provided in subsequent sections of this manuscript. Utilities were selected based on prior existing working relationships with participating researchers and through internet searches. An initial set of utilities were contacted by researchers, and 27 participated in the interview. Each utility was interviewed by one or two researchers. Each respondent was asked questions about utility operations during the COVID-19 pandemic (Table 1). Utility characteristics were determined through inspecting utility websites and asking questions during interviews. Most utilities answered all questions orally during a phone call or in person, while some utilities also provided answers in written text that was submitted over email. Researchers asked follow-up questions at the time of the interview or through email around some answers that were provided to further probe and explore issues that were brought up by respondents. A total of 27 water utilities were interviewed, of which 19 were very large water systems (≥ 100,000) and eight were large water systems (≥ 10,000 and ≤ 100,000), based on the U.S. Environmental Protection Agency (EPA) categories (U.S. EPA 2019) (Fig. 1). Eighteen utilities are located in the U.S., five respondents are located in Canada, two in Europe, one in South America, and one in Oceania (Fig. 2a and b). Most water utilities serve a mix of customers, including residential, industrial, and commercial, and for most of these utilities, more than half of the customer base is classified as residential. For most of the responding utilities (82%), surface water is the predominant or sole water source.

WATER SYSTEM OPERATIONS

Background

The COVID-19 pandemic created major challenges for many water utilities. Utilities balanced the growing need to provide adequate water and sanitation services as hygiene is critical to combat pandemics and new personnel constraints created by remote work, social-distancing, and reductions in workforce. There was an urgent need for water utilities to adapt to new and rapidly changing situations and modify messages communicated to customers (International Water Association 2020), in an era when utilities must navigate consumer distrust, manage a presence on social media, and respond to misinformation (American Water Works Association 2019). A few studies described management challenges and changes to water system operations for utilities. Cotterill et al. (2020) reported on the UK utility operational perspective through a sector-wide survey that explored impact, preparedness and resilience in the UK. Of primary importance were the capabilities to facilitate remote work necessary to continue to meet increased water demands, and these results highlight the importance of communication and collaboration. Antwi et al. (2021) described a suite of policy interventions and mechanisms implemented by European governments and found that only 11 (40.7%) of the countries implemented at least one policy intervention that considered the water sector. Those interventions typically included short-term measures that involved either full cost absorption or suspension of water bills. Renukappa et al. (2021) explore the influence of the COVID-19 pandemic on the water industry. Their study describes organizational practices that had been adapted from business-as-usual, based on interviews of six water utilities. While the pandemic caused slower utility workflows, it accelerated digital transformations and the adoption of online and connected technologies.

Analysis of Responses

Survey responses revealed that utilities continued working to meet the regulatory requirements of safe and clean water by adjusting protocols for how employees interact with other employees and customers. Responses that are summarized in Table S1 show that 18 out of 27 utilities mentioned management challenges. Large utilities ($10{,}000 < \text{population} < 100{,}000$) serving residential customers have shown higher concerns with the safety of personnel. They reported the highest number of measures implemented. Utilities serving less than 1,000,000 with mixed demand customers (commercial, industrial, residential) reported a significant number of measures involving the organization of staff to minimize the risk of exposure while ensuring the utility could continue to deliver services. In some cases, utilities reduced their workforce. In other cases, they introduced health and safety policies such as daily temperature screens, including self-reporting, social distancing, and masks. Utilities required COVID testing if staff reported symptoms or close contact with someone who had COVID. One of the major initiatives needed by utilities was to adjust operational protocols to reduce transmission in the case that employees were exposed to COVID. Dividers were installed between workstations, and non-operational employees worked remotely. Employees who managed operations changed schedules to reduce contact with other work crews and were separated into teams that did not interact to reduce chances of the disease breaking out at the utility.

Utilities also adjusted protocols for customer service. Contact with customers through digital channels, such as online bill payment, was reinforced or encouraged. Utilities allowed customer visits only through appointment or closed in-person (face-to-face) customer service. Customer service actions requiring home entry were deferred or cancelled. In-person public meetings were cancelled, while one utility adjusted community meetings and outreach to ensure public trust. Customer management issues led 9 out of 27 utilities to increase their efforts to overcome possible undesired effects. This response was more significant for utilities serving a population > 1,000,000 with a varied portfolio of customers, and these utilities focused more on the effects of customer contacts.

Utilities faced other operational impacts related to strategic and production management. Utilities reported that they were able to complete planned construction on time, but some utilities postponed the implementation of new projects and spent resources to review contingency plans. Operations were impacted by reduction of efficiency in supply chains, and utilities dealt with uncertainty in water sales and revenue. As consumption patterns changed, utilities addressed concerns in operations and water quality impacts. Utilities also managed early retirements and union contracts to understand how policies, such as the Family Medical Leave Act in the U.S., affected employee placement. Very large utilities serving residential customers with a mixed portfolio of customers described more strategic and production management issues.

The small sample size limits the development of definitive conclusions, though some common themes emerge. Wholesale utilities did not report difficulties in managing system operation during the pandemic period. For utilities that did not face major challenges associated with the pandemic, preparedness measures that were implemented before the onset of the pandemic helped to safeguard operations. In general, large utilities were equipped to weather the changes introduced by the pandemic, while smaller utilities were more affected. For example, seven out of 27 utilities, serving a population ≤ 1,000,000 and across different types of demand portfolios, reported that they addressed challenges associated with the COVID-19 pandemic without suffering any major impacts, maintaining a good level of supply and sanitation without degradation in the quality of processes. Utilities that serve a population < 500,000, irrespective of the customer portfolio, were most affected by the COVID-19 pandemic. This analysis found that operational issues were not dependent on the types of supply sources (groundwater, surface or purchased water) or changes in demands.

Implications and Recommendations

The COVID-19 crisis brought to light the importance of sustaining water system operations. Water access plays a vital role in public health, especially during a pandemic, for hygiene and cleaning surfaces. Measures were taken by utilities to ensure staff could work safely and continue to be available to deliver services without degradation in the quality of processes. Utilities were pushed to the adoption of digital technologies, and adjusting operational protocols was crucial in maintaining supply and sanitation.

COVID-19 also impacted strategic and production management. The implementation of new projects was put on hold, contingency plans were adjusted, difficulties in supply chain reliability were experienced, and the effects of demand change patterns and the uncertainty of water sales and revenues created additional concerns.

Lessons learned from the COVID-19 pandemic reiterate that the management of protracted crises depends on the strength of Emergency Response Plans and the flexibility of utilities to accommodate new information in a structured way. Proactive management of stocks of consumables and knowledge about supply chains can be improved to address possible disruptions in future similar situations.

Moving forward, a greater focus is expected to be placed on preparedness actions, including aspects related to the reorganization of the workforce and to the adoption of Information and Communications Technologies (ICT) for developing new forms of communication. ICT technologies should also be used to monitor water systems and collect data to improve rules for operation that can adapt to the emergence of new demand patterns. Further, financial reserves are needed to avoid revenues disruption that were noted during the pandemic.

WATER DEMANDS

Background and Literature Review

Several research studies as of the date of this publication explore and describe how water demands changed during the COVID-19 pandemic. Spearing et al. (2020) surveyed water utilities in the US. They reported that 43% of utilities surveyed observed an increase in residential water demand, 46% observed a decrease in commercial water demand, and 21% observed a reduction in industrial water demand. Similar observations were reported showing increased residential water demand in New York (+28%), Texas (+12%), California (+11.5%), and Minnesota (+25%) in the U.S. AWWA (2020) reported a 12% water demand reduction at Pittsburgh Water and Sewer Authority, because college students left campus and commercial facilities were closed. AWWA also noted that leisure and hospitality, as well as transportation industries were expected to go through significant water demand reductions, while more moderate reductions were expected in sectors such as retail, wholesale trading, manufacturing, and construction. Cooley et al. (2020) reported changes in total water demand during the pandemic for 41 locations in the US. They noted that the net effect of the COVID-19 pandemic on total demand varies from utility to utility and largely depends on the ratio of residential to non-residential uses. Larger metropolitan systems, such as Boston, Massachusetts, and Austin, Texas, have experienced modest increases or minor reductions. Eastman et al. (2020) examined the impacts of COVID-19 on eight water utilities in the US (California, Arizona, Georgia, Colorado, North Carolina, and Texas). Some utilities' residential consumption increased by up to 44% compared to the averages of previous years, while no utility reported a significant demand increase compared to historical averages. They noted that in each case utilities reported that variations in demand were affected by various factors such as climate, local, state, and federal-level COVID-19 policies and regulations. The spring and summer of 2020 were hot and dry for many regions in the west, south, southwest US, which confounds the picture and complicates separating signal from noise in demand estimation due to COVID-19.

Additional studies focused on local changes in specific cities and buildings of interest. A study in Portsmouth, England, reported that residential demand increased by 15% during a lockdown, while non-residential demand declined by 17%. Similarly, residential demand increased by 10%, while non-residential demand fell by 32% in San Francisco, California. In general, they found that more significant reductions in water use were reported by the more commercialized communities during the lockdown period.

Balacco et al. (2020) studied water use data before and during the lockdown period at five Southern Italy locations. Specifically, they calculated the minimum daily volume before lockdown and compared that to the percentage of days above the minimum value during the lockdown period. With lockdown, especially when the industrial sector was fully affected, large community towns saw significant increases in the number of days where minimum demands were higher than pre-COVID values. They also observed unusual peak demand patterns during the lockdown period. While typical morning peak hours were about 8 AM, during lockdown this peak shifted two hours later. They attributed this phenomenon to a delay in people's daily routine, as individuals started activities later in the day when working from home. A similar trend was observed in Germany, where peak hour delays of about two hours were reported (Watner et al. 2020). Kalbusch et al. (2020) examined water demand studies in Southern Brazil during the COVID-19 pandemic. They presented comparative graphs showing that the demand was lower during lockdown compared to pre-lockdown in commercial, industrial, and public sectors, while residential use increased during the lockdown. Demands in the city of Wroclaw, Poland, increased for residential users and decreased for commercial and educational users (Kazak et al. 2021). Pesantez et al. (2021) analyzed water demand for a residential medium-sized utility in California. They found results similar to others, with peaks that were lower and shifted to a later time during weekdays. Similarly, in Cornwall, UK, and Rovigo, Italy, total water usage increased at residential accounts, with decreases and delays in peak demands (Menneer et al. 2021; Alvisi et al. 2021). A study of water demands found that while residential and non-residential demands changed, overall, the total volume of water consumption did not change significantly (Bakchan et al. 2022). They also found that within 4-5 weeks after a lockdown, demands returned to pre-pandemic levels. Spearing et al. (2021) analyzed how water and electricity consumption changed at five buildings of varying types at the University of Texas at Austin during the pandemic by identifying characteristic weekly demand profiles and exploring how these changes were related to regulatory and social systems.

Analysis of Responses

In the responses reported here, most of the residential demand increased, and only a few utilities showed no change or a small decrease in residential demand. Some utilities reported flattening of daily water demand patterns and shifting of morning peak hours (*i.e.*, later hours). There were minimal overall demand and demand pattern changes. Most of the utilities reported no significant changes in their operations or peak demand. In some cases, where demand fluctuations occurred, they coincided with climatic fluctuations. It was, therefore, impossible to tell whether demand increases were partially driven by warm and dry weather or, conversely, demand decreases driven by cool/wet weather. It appears that in many cases, increases in residential demand were largely offset by a corresponding decrease in commercial demand. Utilities with Advanced Metering Infrastructure (AMI) capacities allowed a more detailed quantification of demand changes. Specific observations (see Table S1 in Supplemental Material) include:

- Variable demand decreases (up to 44%) in commercial (retail, entertainment, tourism, etc.).
- Variable levels of demand increase (up to 18%) in residential areas, where the magnitude of the observed increases depends on the nature of the community or utility.
- Significant demand reduction in university towns due to remote or e-learning.
- In some cases, peak demand shifted somewhat to a later morning hour, probably due to changes in population routines resulting from working from home.
- Wholesalers of water reported moderate or no demand changes, probably due to a large and diverse customer portfolio.
- One utility reported a sharp reduction in non-revenue water, probably due to a drop in 3rd party interferences (i.e., few construction sites & excavations).
- Some utilities reported that demand fluctuated due to the severity of the locally imposed lockdown (demand picked up as severity was reduced).
- Some industrial customers, including food and beverage manufacturing, saw demand increase, possibly due to status as essential businesses and seasonal production fluctuations.

Of the 27 utilities interviewed, only four utilities reported no or negligible changes in total demand. Four utilities reported an overall increase, and 10 reported an overall decrease. Nine utilities reported increases in residential demands; 12 reported decrease in non-residential demands; and two reported increases in non-residential demands, such as those demands related to refuge areas and industries that produce food and beverages (Table S1). Analysis of responses does not reveal patterns in the impact of the utility size and location on changes in demand patterns; however, there is an apparent effect due to the type of demands on demand fluctuations. For example, bedroom communities, which tend to be smaller and have a more significant segment of residential customers, experienced a typical increase in demand upon COVID-related lockdowns and work-from-home patterns. Towns with a significant post-secondary education institution saw a sharp decrease in demand. Cities with a substantial tourism/hospitality industry saw a sharp reduction in demand in the commercial areas. Wholesalers and larger municipal centers, providing water to a diverse customer portfolio reported overall minor changes in demand, probably because retail decreases largely offset small residential increases. It was also challenging to decouple the impact of weather fluctuations from the effects of COVID with such a small sample. More research and modeling are needed to draw meaningful conclusions.

Implications and Recommendations

It has been noted that some of the utilities with AMI could have in-depth demand characterization for each sector, which can help develop management strategies in the long term. However, there are knowledge gaps in defining the specific factors that drive changes in water demand patterns due to the convergence of COVID, weather, drought, and conservation. While utilities reported some significant changes in demands, the changes did not create hydraulic conditions that were signficantly outside the bounds of typical operations. Other research implemented a digital twin to examine the effects of changing demands on hydraulics and found that changes to water flows, pressure, water age, and energy consumption were not significant (Pesantez et al. 2021), and these findings are corroborated by the interview responses in the research presented here. Utilities need a robust data collection infrastructure and coupled models to predict future service levels over broader scales, providing greater insight into the socio-economic and infrastructure performances. Typical demand loads continue to shift with changes in societal norms, such as water conservation, adoption of water efficient technologies, xeriscaping, and now, working remotely. Historical demand patterns can be updated to better reflect behaviors, and new research can explore the significance of demand changes on the design and operation of infrastructure. Data collection, analysis, and modeling efforts can support water utilities through improved emergency planning, response, and recovery; better risk assessments linked to improved estimations of the likelihood of failure and consequence of failure; and more robust, streamlined, and accurate processes to create, calibrate, validate, and maintain in-house modeling and analytics capacities (Keck and Lee, 2021). These improvements will ultimately lead to broader application and higher confidence in utility system-level plans and programs.

Although campaigns, implementation, and outcomes of water conservation programs have been successful, these programs unintentionally raise the 'water age/ residence time' in water distribution systems and building water systems. It is well known that this can present emerging human health concerns and public safety issues as opportunistic premise plumbing pathogens (OPPPs) can thrive under low flow/high water age conditions (Keane 2020; Proctor et al.2020; Rhoads et al., 2016, 2017, 2020). These OPPPs are estimated to cost the US $1 billion worth of economic activity annually (Falkinham et al., 2015). This problem has been aggravated further by the COVID-19 lockdowns, which resulted in significant water age increases due to almost zero water consumption in commercial buildings. Public officials, building water managers, water utilities, and other stakeholders should pay extra attention to water quality issues and strategic flushing strategies when recommissioning non-residential buildings.

UTILITY REVENUES

Background and Literature Review

Researchers have examined the financial impacts of the COVID-19 pandemic on water utilities. Spearing et al. (2020) found through their survey that 43% of utilities experienced decreased revenue, 7% of utilities saw revenue increase, and 18% experienced no discernable change (the remaining 32% did not explicitly mention an impact to revenues). In another study, Cotterill et al. (2020) found decreased revenue in United Kingdom utilities due to decreased commercial demand during this pandemic. Aligning with these studies, analyses from the Rural Community Assistantship Partnership (2020) found that 43% of rural water systems surveyed were negatively financially impacted by the pandemic. Additionally, the American Water Works Association (2020) quantified the U.S. drinking water sector's expected loss of $13.9 million over the duration of this protracted crisis. These impacts were due to decreased revenue, increased spending, and increased delinquent accounts, among other reasons. Aside from some research (Gude and Muire 2021), each of these studies focuses on a single country (e.g., U.S., Spearing et al. 2020; UK, Cotterill et al. 2020), creating uncertainty as to how revenue changed globally that is explored here.

Other work has explored factors that may impact utility revenues during the COVID-19 pandemic, such as protecting low-income residents from disconnection (Warner et al. 2020). For instance, Warner et al. (2020) determined which states implemented mandatory water moratoriums and characteristics of the states that imposed such policies (e.g., states with economic regulation of private water utilities). In addition, utilities delayed upcoming and planned rate increases during the pandemic to support customers, which has reduced projected revenues and future investments in new infrastructure projects (Retzlaff 2020; Spearing et al. 2020).

Analysis of Responses

The ongoing COVID-19 pandemic has impacted the finances of utilities differently, as might be expected; our dataset reflects this large variation in revenue impacts to utilities. The responses were categorized in terms of revenue outcome/response/observation (Table 2). The categories are: 1) Explicit reduction; 2) Implicit Reduction (lower demand, delinquencies, postponed rate increases); 3) No loss of revenue; 4) Unknown Impact on Revenue; and 5) Explicit Increase in Revenue. Approximately half of the utilities reported explicit or implicit reduction.

Utilities from our dataset most frequently mentioned decreases of ~5% in revenues or less, with a few mentioning more drastic impacts of upwards of 15%. Interestingly and important to note, the impact on revenues varied throughout the duration of the pandemic. Many utilities were impacted more drastically at the beginning of the pandemic in Spring 2020 when initial stay at home orders were put in place and were more stringent. With this sharp decrease in revenues, many utilities braced themselves for more financial impacts than actually occurred later in the pandemic, shifting capital plans and making changes to operations. However, as phased openings occurred, much of the water demands returned to levels which the utilities expected for 2020.

Utilities' varying characteristics in terms of customer portfolios and geographic locations (*e.g.*, weather patterns) ultimately led to different levels of financial resilience. For example, urban utilities with a large customer base were seemingly more likely to absorb financial shocks, adapting operations and capital planning to reflect the new reality—whether short or long term. On the other hand, small or rural utilities may not have the financial capacity to absorb increases in delinquent accounts or drastic changes in revenue streams. Important to note, there are a myriad of factors impacting finances. For example, two utilities - one in the U.S. and one in Canada - explicitly discussed that due to extremely hot weather, water demands, and corresponding water revenues increased drastically from the expected, even when compared with pre-pandemic levels. The set of utilities that responded to this survey did not include those in the 'small' category, or less than 10,000 customers. Further research can explore how the relationship between demand portfolios, geographic locations, and financial resilience differs for small and large utilities.

In general, most (but not all) utilities did see a decrease in revenues. One of the most cited reasons for this include increases in delinquent accounts and late payments due to increased financial burdens on customers. One southeastern U.S. utility stated that past due accounts had increased from $3.5 million to $7 million U.S. dollars. In response, utilities implemented water moratoriums (*i.e.*, policies ensuring that customers do not lose water services due to non- payment (Warner et al. 2020). Notably, these policies were often spurred by regulations at the state level in US utilities (US Senate Committee on the Environment and Public Works, 2020). Although many moratorium policies are paired with payment plans, some utilities in our sample mentioned loan forgiveness programs. Other utilities mentioned aid to commercial customers; for instance, one utility allocated 5 million U.S. dollars for retailers that missed their payments. Although these policies play an important role in ensuring public health and safety (i.e., ensuring people are able to maintain proper hygiene to curb the spread of COVID-19), there can be negative financial impacts on utilities (*e.g.*, a loss in revenue). Further, five respondents noted that planned rate increases were postponed or cancelled, leading to unexpected revenue loss.

The makeup of customer portfolios affects the loss of revenue for water utilities. One commonly mentioned reason for revenue drop was attributed to decrease in water sales to commercial customers. Commercial sales may be more profitable than residential sales due to volume-based price tiers. College campuses that were essentially closed from March 2020 through the end of 2020, as expected, saw a sharp decrease in water use and corresponding drop in revenues for utilities serving these areas. Two utilities mentioned that they had experienced increases in demand from residential customers, likely due to stay at home orders. Irrespective of the customer portfolio, many utilities did cite an overall decrease in revenues due to lower demands. Moving forward, when looking at rate tiers for different customers, utilities will have to reassess their expected revenues. It is commonly thought that there will be a new norm post the pandemic that many companies will allow much of their workforce to work remotely, leading companies to give up much of their commercial space in anticipation. As such, the water demand portfolio across customers is likely to permanently change, altering expected revenues in the future.

Implications and Recommendations

Revenue decreases had cascading impacts on utility operations. For instance, respondents mentioned delays to capital projects or reduction in project scopes. Although most utilities attributed this to decreased revenue or increased operating expenses (often due to workflow adaptations to ensure social distancing), some respondents mentioned that a lack of response from contractors led to project delays. This decrease in water infrastructure investment may exacerbate existing issues and lead to decreased resiliency in the future, due to delayed maintenance leading to breaks or delayed development of needed additional capacity.

Water moratorium policies, which were widespread during the COVID-19 pandemic, can lead to negative financial impacts on water utilities. This should be considered in moratorium legislation. For instance, moratorium policies may be paired with loan funds, for which water utilities can apply to receive aid during the pandemic. This would ensure that water utilities are able to continue investing in infrastructure despite the financial constraints present due to the pandemic. Notably, we did not collect this data to find out which cities or countries had mechanisms to receive alternative forms of financing outside of revenues from customers, a gap that should be explored in the future to possibly serve as a model for pandemics or similar circumstances in the future. After the pandemic is over and utilities resume normal operations, it is likely there will be pressure by utilities to conduct rate adjustments in order to compensate revenue losses and achieve or adjust financial health.

At the time of this writing, the pandemic is still ongoing, and the financial implications that are discussed in this manuscript provide a snapshot of the early impacts experienced during the first few months of this protracted crisis. The true financial impact will not be revealed until well after the crisis is over.

SYSTEM VULNERABILITIES

Background and Literature Review

Systems vulnerabilities mainly relate to the mechanical functioning of the network under natural or man-made extreme events and to the management of water utilities. Physical disruptions, contamination events, or operational malfunctions affect the vulnerability of a system and eventually can interrupt the normal distribution of potable water at adequate pressures (Berardi et al. 2014). Management refers to the organizational side of water utilities and its employees, vendors, and customers. For instance, a shortage of chemical products may affect the treatment of drinking water and lead to service interruptions.

Under normal operating conditions, water utilities typically evaluate system vulnerability based on robustness to physical disruptions and mitigating service disruptions (Diao et al. 2016). For example, disasters such as earthquakes are assessed based on their damage to physical infrastructure, including pipes, pumping stations, and reservoir controls. However, few studies have explored personnel management and supply chain as a vulnerability issue of water utilities. During COVID-19, utilities experienced new vulnerabilities in managing people, supplies, and technology to maintain uninterrupted service. Personnel had to be split into groups with an experienced trained person acting as the group head to avoid personnel shortage in case of an outbreak. Some utilities experienced delays on the shipping of disinfectants and hygiene products such as chemicals and alcohol, and their stocks were running short at the time this survey was conducted. Finally, reduced availability or lack of PPE also affected the normal activities of workers as face coverings were scarce at the beginning of the pandemic.

Analysis of Responses

Virtually all responses mentioned vulnerabilities that the crisis revealed. The availability of staff and supply chain management were mentioned most, followed by reliance on teamwork, the inability to perform certain functions remotely, and finances. IT services and strategic planning were also mentioned by a few utilities. The most prominent vulnerability was the limited availability of staff, particularly highly trained and certified staff performing critical operational tasks such as treatment plant operators. Losing one or more operators for a few weeks may prevent the utility from providing a safe and reliable service to the communities they serve.

Some responses mentioned tight staffing programs with few reserves, with normal backstops, such as the ability to temporarily second staff from other utilities, not being available since they would be in a similar bind. The second most prominent vulnerability that was raised is related to supply chain management. Most of the responses mentioned problems with the supply of materials and equipment, including PPE, treatment chemicals, parts such as valves and hydrants, and even common items such as toilet paper, bleach, and disinfection wipes. This led to delays in maintenance work and even service suspensions. After the first month of lockdown, shipping dates with products that included PPE improved.

Many responses mentioned challenges related to the need for utility staff to work in teams, for instance, treatment plant operators and field workers. Social distancing was not always possible and a single infection in a team may mean that the whole team has to step down for a period of quarantine. Team dynamics were affected by different challenges faced by those who could work remotely and those who could not. One response mentioned critical comments from the public when coming across teams working without maintaining social distancing. Some utilities mentioned that more and better telemetry and automated control systems would have allowed them to further reduce on-site and group work.

Utilities with limited IT services realized the importance of having IT and communication infrastructure and equipment. Communication between operators and engineers allowed a team dynamic that was not developed before the pandemic. Using IT services, operators knew what assignments needed to be performed without meeting in person with their supervisors. Similarly, managers and supervisors could check the compliance of the work without being in person but using cellphones and electronic reports. An interesting observation was that measures taken to physically and virtually separate automated control systems from external systems to improve cybersecurity made it impossible for workers to connect to the system from home.

Implications and Recommendations

Water utilities can invest in better business continuity planning to address vulnerabilities exposed by the pandemic. The COVID-19 pandemic revealed that resiliency is not based on asset management and physical infrastructure alone, but depends on the resilience of personnel and staffing. Guidelines can be developed to provide protocols for managing personnel in pandemic conditions that will enhance utility resilience, using the following suggestions:

- Teams and management personnel split into units with no contact among teams and cleaning of work areas between shifts
- More internal staff trained to be able to handle critical tasks
- Retired and part-time staff stay involved after they leave
- In extreme cases, staff can be housed in isolated quarters to ensure continued operation and maintenance of critical infrastructure

In addition, significant investments in mobile and IT technology are essential to improve resilience. Utilities should modernize communications, reporting, documentation to be more amenable to remote working. Greater stockpiles are needed to provide a reserve of critical infrastructure components, PPE, chemicals, and other materials. During the COVID-19 pandemic, there was uncertainty in supply chains for a number of items, with unexpected shortages emerging due to heightened demands during shelter-in-place orders and supply reduction when some facilities temporarily shut down. Water treatment facilities can develop flexibility in their protocols to use different products or methods to reduce vulnerability to supply chain disruptions. For example, Ferrous Chloride can be substituted with Ferric Chloride if ferrous chloride were unavailable. Finally, respondents reported the need for leadership from management teams in taking health and safety threats seriously and taking actions to mitigate risk.

EMERGENCY RESPONSE PLANS

Background and Literature Review

The American Water Infrastructure Act (AWIA) of 2018 requires that water systems serving more than 3,300 people have an updated emergency response plan (ERP) to incorporate risk assessment findings (EPA 2019). The COVID-19 pandemic revealed new risks and vulnerabilities to be considered in developing and updating ERPs. This new insight can be used to enhance system resiliency and ensure preparedness, quick response, and rapid recovery for essential operations, management, and maintenance of a water utility (Curnin and Heumüller 2016; Curnin, 2018; Sowby 2020; Gude and Muire 2021).

According to the U. S. Environmental Protection Agency (EPA 2019), an ERP must outline and include the plans, procedures, strategies, and resources in the event of any natural or man-made disasters to implement emergency roles and responsibilities, recall personnel on vacation, activate incident command system structure, and notify associated external agencies (EPA 2019). To develop or update an ERP, it is important to gather pertinent information, such as personnel, utility components, storage, and safety about the water system first, before following the key steps, which include conducting a risk and resilience assessment; identifying regulatory requirements; identifying and integrating other local emergency plans; coordinating with local response partners and emergency planning committees; and planning for resources such as personnel, supplies, equipment, and facilities.

The COVID-19 pandemic led researchers and utility managers to assess ERPs. Gude and Muire (2021) discussed the potential impacts of COVID-19 outbreaks on water and wastewater utilities resilient operations and suggested different practices, beyond existing ones, for enhancing and amending ERPs. They suggested the inclusion of proper use of PPE, cleaning and disinfecting public areas, carefully monitoring water quality for pathogens, continuously improving ERPs to avoid unexpected events, and collaborating with academic researchers and peers to normalize research findings from different institutes.

Switzer et al. (2020) integrated professional experience and responses from interviews with water utilities managers to evaluate the challenges that utilities are facing in COVID-19 outbreaks. They focus on the strategies and plans to maintain system operation while keeping employees safe, and identified the importance of collaboration among utilities through, for example, shared resources, including staff and equipment, and coordinated responses by an association of utilities. Cotterill et al. (2020) conducted a survey to understand the impact, preparedness, and resilience of water utilities due to COVID-19. The questionnaires were designed to evaluate the measures of adaption and coping, mitigation, and learning. They found that although IT and care service created some difficulties in coping with changes for some individuals, the system wide adaptation was quick, and 84% of employees worked from home and continued in their usual roles. The significance of good communication, collaboration, and preparation for a potential prolonged crisis were identified as important in their study. After reviewing several existing U.S. policies on emergency preparedness, Sowby (2020) also highlighted the need for comprehensive planning in response to COVID-19 outbreaks.

Analysis of Responses

Interviewees were asked how they used ERPs during the pandemic and whether their ERP plan should be updated and modified based on their experience during the pandemic. Twenty-two practitioners responded to this question. Total responses to this question can be broadly classified into three categories, (C1) use of an existing ERP with slight modifications, (C2) development of a new ERP to specifically address COVID-19 or pandemic situation, and (C3) normal operations. The percentage of total response under each of these three categories include 41% for C1, 50% for C2, and 9% for C3. While utilities in the C1 category did not develop any new protocols, utilities in the C2 category developed protocols specifically to address the COVID-19 situation. These percentages are consistent with other studies (Spearing et al. 2021). Some of these protocols included actions related to PPE, scheduling, forming COVID-19 response teams with backup, redundant operation centers, development of virtual environments for remote operations. The utilities under the C2 category developed their protocols with an objective to minimize exposure and hence risk by utilizing technology as much as possible. Many of the utilities suggested including the lessons learned from the COVID-19 pandemic into their ERPs, personnel training on COVID-19 risk management, and annual mock exercises for preparing employees to better respond to the emergency.

We observed that the years of the responder's experience, system location, customer type and the water source showed no obvious relationship with the ERP. However, all four utilities that use groundwater as the primary water source have existing ERP, while two utilities out of 18 that rely on surface water implicitly indicated that there was no ERP in place before the pandemic. Some utilities reported that they were in the process of updating their ERPs at the time of the pandemic, based on the U.S. EPA’s ERP certification deadlines (USEPA 2021).

The size of the population that these utilities served seems to result in some differences regarding their responses about updating their ERP. While all the responses indicate that they intend to or are in the process of updating their ERP during or after the pandemic, responses tended to be more specific for utilities serving more than one million customers and utilities serving less than 100K customers. This result might imply that those larger (more than 1 million customers) and smaller (less than 100K customers) utilities had already discussed this matter internally before the interview due to different reasons. Larger utilities might have additional capacity to do so, and smaller utilities might be more constrained in maintaining normal operations. Some common examples of larger utilities' specific responses to their ERP update include: (i) set up trailers onsite as an isolated and protected place for key staff to live near the facilities, (ii) set up redundant operations for both staff scheduling and control centers and (iii) introduce new restricted access rules for some key spots of their facilities. As an example of an ERP update, one utility reported that they had weekly phone calls with other utilities and the local Environmental Protection Agency office to exchange and share information. One respondent reported that their director has a daily update newsletter shared with the organization to keep employees and customers connected and updated. Compared to larger utilities, two common examples of smaller utilities specific responses to their ERP update are (i) supply of PPE is a critical issue and (ii) staff training regarding pandemic response should be mandatory. This demonstrates ways in which the pandemic imposes significant impacts on smaller water supply systems, because they have limited budgets and resources to set up isolated housing units and redundant routines to maintain their normal operation. As a result, their responses focus on following the pandemic guidelines to ensure the safety of individuals, such as providing PPE and training staff, rather than creating new processes that satisfy the pandemic guidelines in addition to managing their system effectively. These observations are consistent with other studies (Spearing et al., 2020).

Implications and Recommendations

Emergency management includes a range of activities, including risk assessment, mitigation, emergency preparedness, response, and recovery (Lindell et al. 2017). In the context of the COVID-19 pandemic, preparedness activities would focus on identifying and acquiring the facilities and equipment that are needed for responding to outbreaks. Moyer (2005) suggested conducting tabletop exercises to develop emergency scenarios and prepare staff and emergency response plans. The outcome of such exercises gives specific instructions to manage similar emergencies with higher confidence and agility. Preparedness activities can be used to inform and update a utility's ERP. Based on vulnerabilities identified in this research, it is recommended that utilities update ERPs to ensure redundancy in stocked items, such as chemicals for disinfectant and PPE. Other preparedness activities can focus on developing new protocols and policies to improve access to water services and financial assistance for low-income populations during periods of lockdowns or social distancing.

Response activities should also be included in an ERP, and the insight developed here through activities that water utilities took during COVID-19 pandemic can be used to develop guidance for response activities. The Center for Disease Control and Prevention (CDC, 2021) classifies pandemics and provide general guidelines to prevent and respond to different types of pandemics. Response activities include emergency assessment, hazard operations, population protection, and incident management (Lindell et al. 2017). Utilities should be able to assess the threats and challenges introduced through a pandemic and identify guidance, checklists, and potential restrictions that should be considered for continued operation of water delivery. For example, at the beginning of the COVID-19 outbreak, it was unclear if the virus could be transmitted through drinking water and drinking water treatment and infrastructure, and identifying steps to detect and mitigate pathogens in the water system is part of both emergency assessment and hazard operations. Population protection is another emergency response activity that prevents the further spread of a virus among the community and staff. Through practicing population protection activities, utilities may learn practices to isolate personnel who contract a virus, keep other employees safe, minimize the impact of the outbreak on daily operations, and inform customers if a virus is transmissible through water networks. Finally, incident management provides guidelines for short-term and long-term water facilities management and underscores procedures to work with other agencies for mitigating consequences of the pandemic.

Recovery is another critical component of emergency management and ERPs. As utilities transition back to business-as-usual, new insight about recovery will begin to emerge. This research was conducted during the summer of 2020, during the COVID-10 pandemic, and did not explore questions around recovery. Based on responses provided here, impacts on the technical system were minimal, and it is expected that recovery activities would focus on managing revenue shortfalls to resume investment in necessary infrastructure improvement projects.

In this research, we found that most utilities reported vulnerabilities in personnel, revenue sensitivity, technology, and supply chain disruption, and few reported concerns about threats to the physical infrastructure itself. These findings demonstrate that the pandemic created vulnerabilities that differ from vulnerabilities associated with other emergencies, such as earthquakes, contamination events, pipe breaks, and cyber attacks. Attention is needed to update ERPs to prepare utilities to respond to vulnerabilities that develop during pandemics. ERPs can include strategies that help utilities respond to pandemics by staggering personnel in shifts that maximize social distancing, adopting information technology (IT) to facilitate working remotely, and continuing service for households that cannot afford to pay water bills. For example, one respondent reported that the utility was rewriting their ERP to continuously stock a 3-month supply of PPE, a 3-month supply of disinfection supplies, and common items such as vinegar. Further research has developed modeling frameworks to study how the onset of multi-modal disasters, such as water supply outages (Pesantez et al. 2021) and contamination events (Kadinski and Ostfeld 2021) that occur during a pandemic, can cause unexpected outcomes. ERPs can be updated to provide guidance for responding to emergencies, as appropriate response actions may differ during a pandemic.

DISCUSSION

Almost all utilities (20 of 23 responding utilities) reported major challenges associated with managing the workforce, including creating new shifts for staff to allow social distancing and reducing opportunities for transmission of the disease among employees and customers. Similar to other studies (Cotterill et al. 2020; Renukappa et al. 2021), this research found that the pandemic accelerated the adoption of IT within the water industry, and the ability to work remotely through IT was vital to continue operations. Six of 23 responding utilities described efforts to improve IT capabilities or the ability of personnel to work from home.

The impact of the pandemic on utility finances has been explored by others (e.g., Spearing et al. 2021; Bostic et al. 2021; Antwi et al. 2021), finding that though impacts ranged for different utilities, in general, this was a major challenge, especially for smaller utilities. This research finds that 50% of utilities interviewed report reductions in revenues finances. Many utilities reported that they were able to absorb moratoriums and delayed bills. Some utilities, however, were not able to increase rates as planned, and rate increases may not be implemented for an extended period, leading to further revenue shortfalls and delays in needed system upgrades. While this research focused on large utilities, other research has explored the effect of size on the impacts of the pandemic on water utilities. Other research has documented severe impacts on small utilities (Bostic et al. 2021), with recommendations for building resilient systems and communities, such as reassessing block rate structures, which could pose affordability problems for some households (especially, low-income households) if people continue working from home and consuming more water there (Karanovitz et al. 2021). The findings of this research are limited to medium and large utilities; further analysis can identify how vulnerabilities and appropriate response actions differ based on utility size.

While acute management challenges arose around issues associated with personnel, infrastructure management was also a concern as changes in demands led to some infrastructure impacts. Of the 27 utilities interviewed, 23 utilities reported notable changes in water demands, with consistent reports of increased residential demands and decreased non-residential demands. In this study, one utility reported the need to change chlorine dosing in response to reduced demands, and another utility reported changes to water quality. This follows research reported by Spearing et al. (2021), in which six of 28 utilities that were interviewed reported changes or challenges around water quality due to changes in demands. In this research, a few utilities reported reduction in non-revenue water, due to a reduction in breaks caused at construction sites (3rd party intervention) and less traffic on roadways (the latter hypothetical cause is uncertain as very few water main failures are in fact associated with traffic load). Several utilities reported that new construction projects were delayed, which may create capacity issues in the future. Though not reported by the utilities in this survey, some pandemic conditions, such as reduced roadway traffic, may lead to acceleration of construction projects, and some participating utilities reported that planned construction was completed on time. These outcomes of this research demonstrate the multiple ways that infrastructure performance was affected due to changes in behaviors and water demands, and this insight can be used to inform the development of protocols that address management of changing water quality and hydraulics in the network.

This research found that most utilities report vulnerabilities in the availability of staff, supply chain management, reliance on teamwork, inability to perform certain functions remotely, finances, IT services, and strategic planning. Based on these findings, this research develops suggestions around managing personnel as listed above to improve resilience, such as splitting teams into units and developing redundancy in trained personnel to manage operations. For many utilities, protocols for managing personnel, creating alternative ways to work while social distancing, and facilitating working remotely were not included as part of their existing ERPs. In fact, 91% of utilities needed to update or modify their existing ERPs to address conditions created by the pandemic. Recommendations for reducing vulnerabilities can be used to update ERPs that would include planning shifts for utilities to allow social distancing and mitigate the risk of transmission of disease.

The COVID-19 pandemic has created, in addition to tremendous public health crisis, a cultural phenomenon that has shifted historically accepted norms around work, employment, and supply chains. Changes in the way that society works and consumes goods can ultimately lead to changes in water demands. Emerging research has explored how water demands changed during both the onset of the pandemic and the relaxation of social distancing practices (Pesantez et al. 2021; Menneer et al. 2021; Bakchan et al. 2022). As the impacts of societal changes on water infrastructure evolve, a more adaptive design process for water infrastructure can improve water delivery and service in response to shifting consumer behaviors and expectations. New research can explore infrastructure that is built to respond flexibly to unpredictable changes in demands.

CONCLUSIONS

This research conducted interviews with 27 water utilities to test for and explore impacts of the COVID-19 pandemic in five areas, including operations, demands, revenue, vulnerabilities, and ERPs. Responses indicated that utilities were affected by the COVID-19 pandemic in each of these dimensions. Overall, personnel issues drove needs for operational changes, contributed to system vulnerabilities, and drove needs to improve existing ERPs. New measures around isolating crews to allow social distancing and technologies and protocols for working remotely arose as significant issues for which utilities were not prepared. The experiences of the utilities that were interviewed in this research contribute to emerging literature around lessons learned for improving the resilience of water systems and utilities during pandemics and other emergencies. Utilities were impacted by changes in demands, which affected water quality and infrastructure operations, and revenue reductions, which created vulnerabilities and delays in new construction. These findings demonstrate the importance of the accelerated adoption of IT capabilities and of the preparedness of utilities for operational scenarios that hinder the ability of the workforce to complete tasks in their usual ways. Through exploring areas of vulnerability that arose during the pandemic, utilities can use the insight gained through this research to develop system resiliency for managing disasters and emergencies.

DATA AVAILABILITY

Some data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. Data that are restricted include recorded interviews of respondents and notes taken by interviewers. Available data are provided in this manuscript, found in Table S1 in the Supplemental Material. Table S1 provides the characteristics of each utility and a summary of the respondent's response to each of the five interview questions.

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Table 1. Interview Questions

Questions
How has COVID-19 affected your water system operation?
How has water demand changed?
How has COVID-19 affected utility revenues?
What system vulnerabilities has the crisis revealed?
How should Emergency Response Plans be updated based on your experience during the pandemic?

Table 2. Categories of outcome, response, observations.

Category	Outcome/Response/Observation	Count (Location of Utilities)	Percent
1	Explicit Reduction in Revenue	6 (5 U.S., 1 outside North America)	22.2%
2	Implicit Reduction in Revenue (lower demand, delinquencies, postponed rate increases)	8 (7 U.S., 1 outside North America)	29.6%
3	Reported “no loss of revenue”	3 (2 U.S., 1 Canada)	11.1%
4	Unknown Impact on Revenue	5 (4 U.S., 1 outside North America)	18.5%
5	Explicit Increase in Revenue	5 (1 U.S., 4 Canada)	18.5%
	TOTAL	27	100%

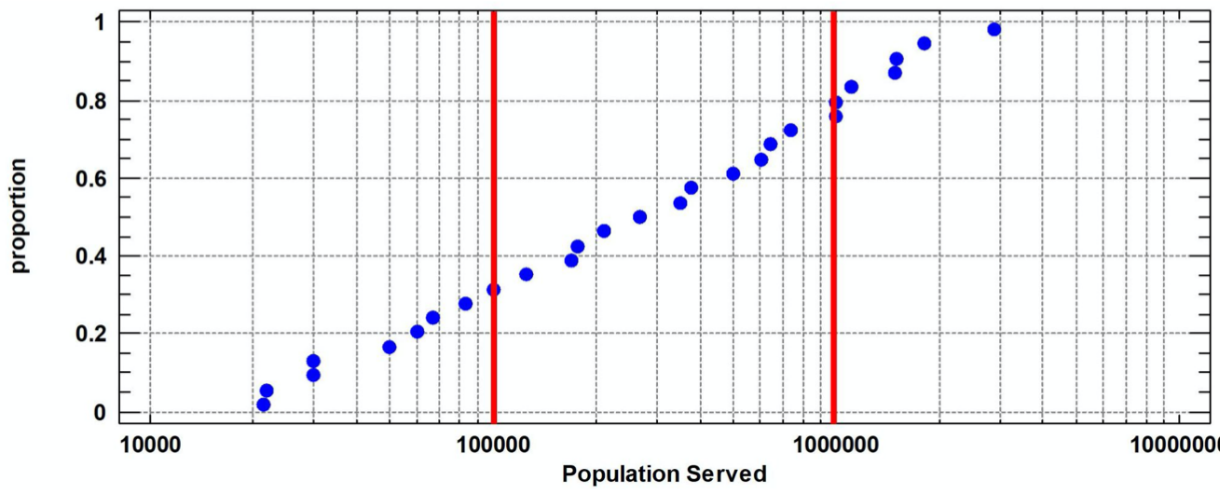

Figure 1. Quantile plot of population served

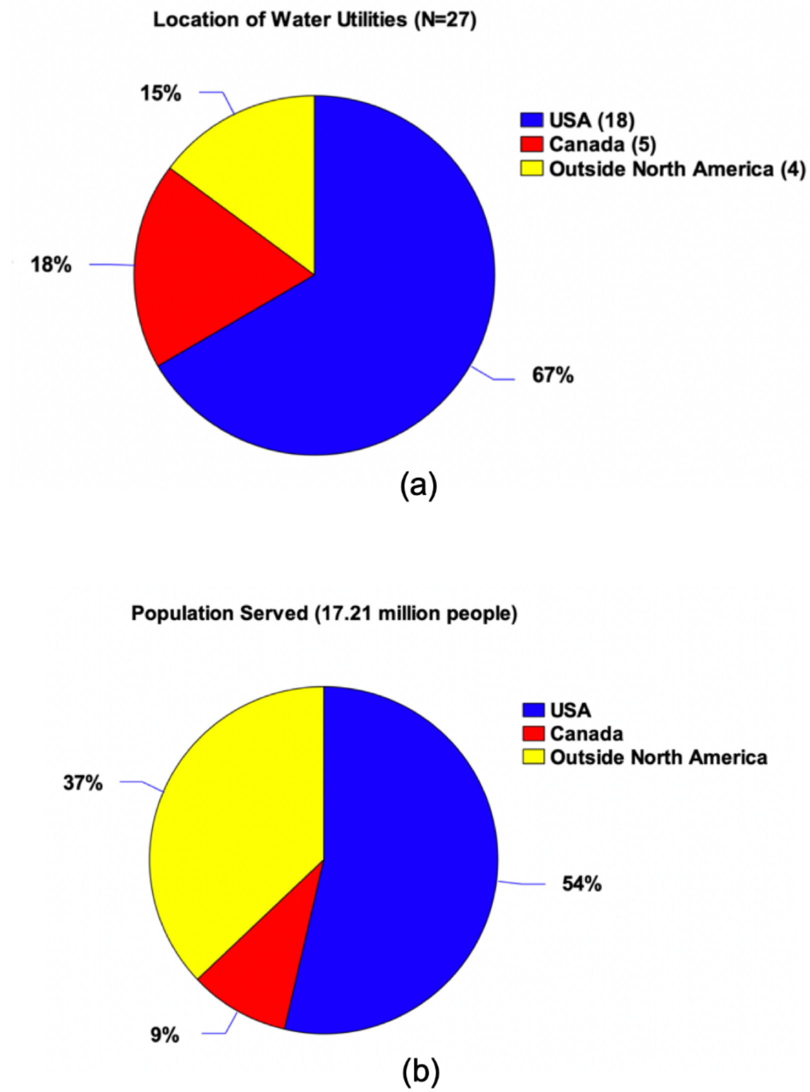

Figure 2. Distribution of a) number of utilities and b) total population served by location (USA, Canada and Outside North America).