Community and Crisis: A Multiscale Analysis of Drinking Water Infrastructure Resilience in the Face of Slow-Onset Disasters

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Abstract

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Disasters can disrupt drinking water infrastructure by negatively impacting its planning, managerial, and operational components. Furthermore, detrimental impacts may vary along with the resilience of drinking water infrastructure across the United States, posing additional risks to communities pre-existing infrastructure issues due to historical and sociodemographic considerations. This dissertation examined how different slow-onset disasters impacted drinking water infrastructure and what implications this posed on the marginalized communities served by the infrastructure. This dissertation explores this interaction at various magnitudes. First, I used the qualitative analysis of semi-structured interviews to determine the impacts of the COVID-19 pandemic on small water utilities and how these impacts differed from large water utilities across the country. Second, I examined the successful and failed project attributes of drinking water projects and systems in rural Alaskan communities using interviews with a variety of stakeholders involved with drinking water in the state. Lastly, I used geospatial and statistical techniques to explore associations between historic redlining distinctions and contemporary drinking water infrastructure at a city-level. Each exploration demonstrated that the relationship between slow-onset disasters, drinking water infrastructure, and marginalized communities provides indications to understanding the history of various inequities while determining areas of improvement for resilient systems. This dissertation contributes to the literature by providing additional avenues for including systems thinking, resiliency, and disaster approaches in drinking water infrastructure research. Additionally, it supplies practical suggestions for enhancing drinking water infrastructure in the pursuit of infrastructure justice.

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Beginning a Ph.D. during the lockdown months of the COVID-19 pandemic was undoubtedly a challenge. As difficult as it was, I was able to power through with the help of (1) incredible faculty and staff in the Civil and Environmental Engineering department at UW, (2) my peers in the Construction, Energy, and Sustainable Infrastructure program, and (3) the friends I've made through the Black Graduate Student Association, A Vision for Engineering Literacy and Advocacy, and Women Engineers Rise, and various cohort programs (i.e., MIT Summer Research Program, Trailblazers in Engineering, Rising Stars in CEE). I am grateful to have found homes where I could learn and receive encouragement from brilliant individuals.

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It really does take a village.

CHAPTER ONE: INTRODUCTION

According to the American Water Works Association (AWWA), 99% of individuals in the United States depend on drinking water infrastructure for their daily needs (VanDerslice 2011). The phrase "drinking water infrastructure" broadly refers to the systems that promote water supply, treatment, and storage, such as physical distribution systems, water treatment facilities, and reservoirs. The infrastructure type also encompasses how water supply would be managed or accessed through public or private water systems (e.g., municipal water utilities) or private wells (Janardhanan 2021; United States Government Accountability Office 2017).

Despite strong reliance, the United States' drinking water infrastructure has repetitively received poor ratings from the American Society of Civil Engineers (ASCE) quadrennial report card at a country and state level. This water infrastructure score reflects an average of infrastructure service, quality, and capacity across the 50 states. It provides inferences of drinking water infrastructure's resilience during both status-quo operations and operations during an emergency or disaster (Martin 2021). Disasters strain drinking water infrastructure's planning, management, operations, and maintenance (PMOM) components and magnify existing infrastructure-related inequities (Howell and Elliott 2018). While drinking water infrastructure ratings may generally vary between states and at different levels of management, infrastructure disparities can be seen on a more localized scale, especially when observing within the contexts of race and income (Katner et al. 2018; Truelove 2019; Wakhungu et al. 2021). The concept of "infrastructure justice" reflects the idea that marginalized communities may experience disparate critical infrastructure quality compared to communities with more resources. In this work, marginalized communities refer to populations that are disadvantaged economically, politically, and socially due to denied access to specific services and positions (Gaillard and Cadag 2009; Scott 2014).

Presently, the literature that examines infrastructure during disaster primarily focuses on rapid-onset disasters (e.g., earthquakes, wildfires), where hazards arise suddenly, instead of slow-onset disasters (e.g., public health crises, drought), where hazards are less immediately destructive and occur gradually (Chumky et al. 2022; Staupe-Delgado 2019; Staupe-Delgado and Rubin 2022). In the wake of recent slow-onset disasters such as the COVID-19 pandemic that altered the operations of drinking water infrastructure in novel ways, filling this gap in the literature provides an opportunity to better prepare for the unique challenges slow-onset disasters often present compared to rapid-onset crises (Zaidi 2018). This dissertation examines how slow-onset disasters impact the PMOM of drinking water infrastructure at different levels of governance and what implication this interaction has on infrastructure justice.

1.1. DISSERTATION SUMMARY

This dissertation examines three research questions within each chapter. First, qualitative content and quantitative statistical analyses were completed to investigate the COVID-19 pandemic's impacts on small and rural water utilities, which are historically under-resourced, and to compare them to the effects on large water utilities across the United States (Chapter 2). In the following chapter, qualitative content analysis was equipped to determine the natural, built, and social factors that influence the success and failures of drinking water projects and systems in historically marginalized rural Alaskan communities within the context of climate change and water insecurity (Chapter 3). Lastly, geospatial and statistical techniques were used to examine the associations between historically racist zoning policies (i.e., redlining) and contemporary drinking water infrastructure service at the city level (Chapter 4). The overarching theme in all chapters demonstrates a dynamic interaction between a slow-onset disaster (i.e., the COVID-19 pandemic, climate change and water insecurity, and racism and deteriorating infrastructure) and PMOM components of drinking water infrastructure that has critical implications for marginalized populations. To explore this interaction further, I apply a systems-thinking and mixed methods approach that is detailed in further chapters. Figure 1.1 summarizes the research described in this dissertation.

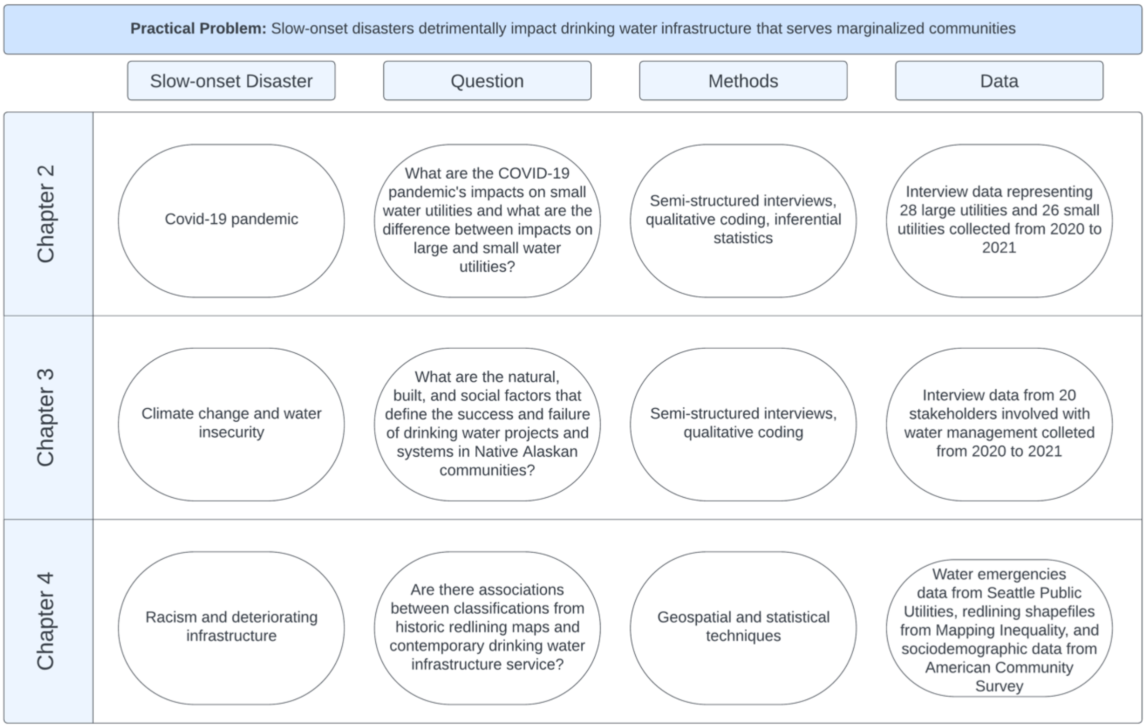

Figure 1.1: Research design

1.2. RESEARCH CONTEXT

The work described in this dissertation represents an assemblage of different research areas, including disaster research, resilience, and systems thinking. The synergy between the three research areas allows for a deeper understanding of drinking water infrastructure during emergencies and positions this research to better assess interactions between infrastructure and the community.

First, this research is conducted in the context of disasters. Disasters, or emergencies, disrupt a community, society, or system functioning, resulting in losses or impacts (United Nations Office of Disaster Risk Reduction 2024). Although all disasters can be considered slow onset when considering the historical conditions of vulnerability, it is still helpful to distinguish between slow and rapid-onset disasters due to the differing manifestation times that influence impact and disaster response (Lewis 1988). Furthermore, the designation of slow-onset disasters allows for the theoretical considerations of other crises (e.g., public health crises, infrastructure deterioration) that may not have traditionally been labeled as disasters but still disrupt the functions of society by impacting existing systems, such as drinking water infrastructure access (Fritz 1961, Quarantelli 1991).

Within this theoretical understanding of disasters, I additionally posit that slow-onset disasters' impact on drinking water infrastructure and, ultimately, on marginalized communities can be assessed using a systems thinking approach. Systems theory is based on the principle that there is an interconnectedness of components that are embedded within a whole (Montouri 2011). This theory gives way to more specific organizational theories, such as sociotechnical systems theory, which focuses on the interaction between social and technical (or built) dimensions of society (Ottens et al. 2006). This sociotechnical framing not only adheres to the interaction between drinking water infrastructure and marginalized communities but also reflects slow-onset disasters' impact on drinking water infrastructure: planning and management (i.e., social) and physical system (i.e., built), which is bolstered by operations and maintenance. Thus, within the context of slow-onset disasters, there is a dynamic interaction between drinking water infrastructure and marginalized communities that is in part due to the connectivity between social and built systems.

In the promotion of solutions for resilient infrastructure, my dissertation additionally examines the dynamic interactions between slow-onset disasters, drinking water infrastructure, and marginalized communities by examining drinking water infrastructure within resilience dimensions (i.e., economic, environmental, governance, infrastructure, and social) (Cutter et al. 2010; Opdyke et al. 2017). In my work, I often refer to infrastructure, natural, and social dimensions, where the governance and economic dimensions are embedded within social dimensions. Here, the infrastructure resilience dimension refers to the built environment (i.e., built system factors) rather than specifically water infrastructure systems. Figure 1.2 demonstrates the systems perspective used in this work. This assessment is similarly completed at differing magnitudes: at the national level (Chapter 2), the state level (Chapter 3), and the city level (Chapter 4). While the same general problem looking at the relationship between drinking water infrastructure, marginalized communities, and slow-onset disasters will be explored, the differing magnitudes reflect the different approaches of assessment that can be used. Additionally, the different scales demonstrate the contrasting solutions that may be developed to ensure equity in drinking water infrastructure (i.e., the smaller the scale, the more specific and actionable a solution might be for the infrastructure system or community).

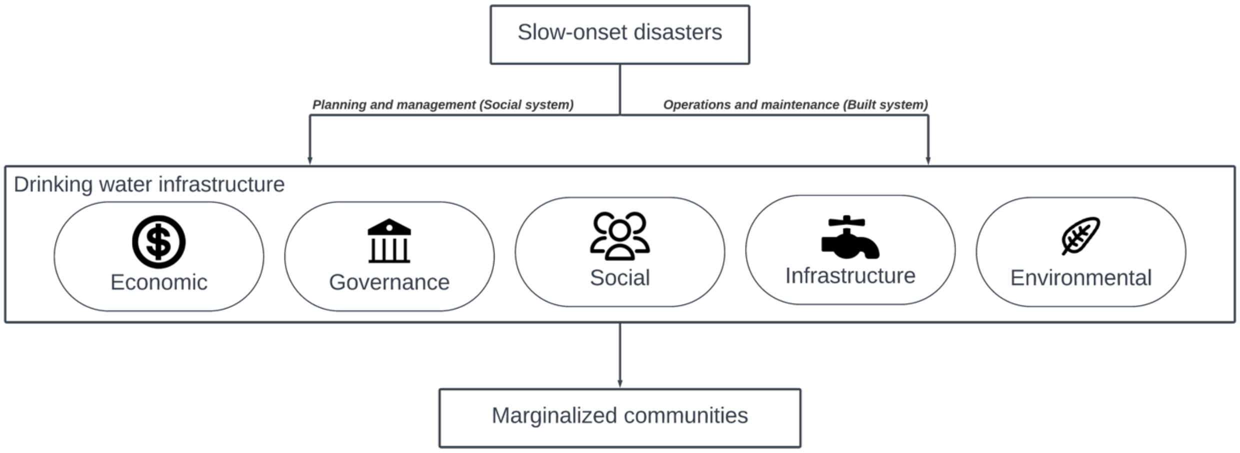

Figure 1.2: Systems perspective of relationship between slow-onset disasters, drinking water infrastructure, and marginalized communities

1.3. RESEARCH METHOD

Due to the nature of this work, I applied qualitative and quantitative research approaches to answer the research question: *how do slow-onset disasters impact drinking water infrastructure, and what do these impacts imply for marginalized communities?* This section briefly describes the two types of data collection and three analyses conducted to complete this analysis.

1.3.1. DATA COLLECTION: INTERVIEWS

In Chapters 2 and 3 of this dissertation, interview data was remotely collected from individuals representing water utilities across the United States and stakeholders involved at some level of drinking water infrastructure planning in Alaska, respectively. Both sets of interviews used a semi-structured format, allowing for the use of open-ended questions that could facilitate additional discussions (Kallio et al. 2016). With the interviewee's knowledge, each interview was recorded for documentation. The interview guides for each study are described in Appendix A and B. Incorporating qualitative methods within an engineering context accounts for the added complexity of social system interactions (Szajnfarber and Gralla 2017). As the work in this dissertation applies a sociotechnical systems view to drinking water infrastructure during disaster contexts, interview data permits the nuanced considerations of stakeholders involved with drinking water infrastructure that would be otherwise unmeasurable through quantitative means.

1.3.2. DATA COLLECTION: OPEN DATA

Chapter 4 will enable open data from various sources, including the American Community Survey (ACS), Seattle Public Utilities' infrastructure data, and Mapping Inequality, a geospatial tool produced by researchers at the University of Richmond. In my work, open data reflects a wave of digitalization that enables the examination of infrastructure systems with increasingly robust and publicly accessible data (Xu et al. 2018). The use of open data further demonstrates the potential of infrastructure research to examine various problems given continued and expanded data availability. Furthermore, the use of open data in equity related research demonstrates the potential of data sources that are accessible to the greater public, especially those impacted by slow-onset disasters.

1.3.3. DATA ANALYSIS: QUALITATIVE CODING AND ANALYSIS

In alignment with the interview data collection method, Chapters 2 and 3 utilize qualitative coding techniques to analyze the interview data. In both chapters, the qualitative coding software NVivo was used. Additionally, I iteratively use a deductive and inductive approach for categorizing themes with the interview transcripts, in which parent codes are developed from either research questions or theory, and child codes are created from what themes emerge from the interviews (Spearing et al. 2022a).

1.3.4. DATA ANALYSIS: GEOSPATIAL TECHNIQUES

In Chapter 4, I spatially organized the open data to examine the relationship between historical redlining distinctions and contemporary drinking water infrastructure service using ArcGIS Pro. Here, a combination of census tract and redlining grade shapefiles were used as geographic indicators to connect ACS and water infrastructure data. The ArcGIS software was primarily used to visualize the distribution of critical variables, including drinking water infrastructure service metrics and racial demographics.

1.3.5. DATA ANALYSIS: INFERENTIAL STATISTICS

Inferential statistics are equipped in both Chapters 2 and 4 to examine the impacts of slow-onset disasters on drinking water infrastructure. In Chapter 2, chi-squared tests are used to explore the difference in impacts between small drinking water utilities and large drinking water utilities during the COVID-19 pandemic. Chapter 4 enlists regression analyses to determine the associations between redlining distinctions and drinking water infrastructure service. Due to the nature of the variables defining infrastructure service in this study, both regression analyses with negative binomial and Gamma distributions were used. Especially in conjunction with qualitative research, using quantitative data analyses like statistics may corroborate results from qualitative research and depict a more complete story of an examined issue.

1.4. DISSERTATION FORMAT

This dissertation is organized using a publication approach, where each chapter represents an independent study that has or will be submitted to academic journals. Chapters 2 and 3 have already been published in Environmental, Science, and Technology: Water (ES&T Water). Following this dissertation, the study described in Chapter 4 will be further expanded before being submitted as a journal publication. This dissertation also includes supplementary information within the appendices, where Appendix A, B, and C correspond with the supplemental information for the research described in Chapters 2, 3, and 4, respectively. For reference, a copy of my curriculum vitae is in Appendix D

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CHAPTER TWO: SMALL DRINKING WATER UTILITIES' RESILIENCE: THE CASE OF THE COVID-19 PANDEMIC

Nathalie Thelemaque[1], Lauryn A. Spearing[2,3], Kasey M. Faust[3], Jessica Kaminsky[1]

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 understand3ing 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.

KEYWORDS: infrastructure management, small water utility resilience, drinking water, emergencies, COVID-19 pandemic

2.1. INTRODUCTION

Emergencies (e.g., humanitarian crises, extreme weather events) significantly disrupt and influence how water infrastructure systems operate and serve the public (Allen et al. 2019; Glazer

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et al. 2021; Gude and Muire 2021; Hailegeorgis and Alfredsen 2017). 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) (Bakchan et al. 2022; Bichai et al. 2022; Spearing et al. 2021; Zechman Berglund et al. 2021). 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 (Glazer et al. 2021; Hoffman et al. 2020). Here, we refer to resiliency as "the resistive and adaptive capacities that support infrastructure functionality in times of crisis or stress (Opdyke et al. 2017)."

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 (US Environmental Protection Agency 2004). 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) these utilities often face unique challenges that are difficult to mitigate with funding alone(US Environmental Protection Agency 2021b). 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 (American Water Works Association 2020). 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. 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 (Blanchard and Eberle 2013; Haider et al. 2014; Maier and Carpenter 2015; Maras 2009; McFarlane and Harris 2018; Scheili et al. 2016a). 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 (Hamouda et al. 2018; Mo et al. 2018; Roberts and Inniss 2014; Scheili et al. 2016b).

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 (Sowby and Lunstad 2021). For example, some small DWUs face more detrimental consequences on their revenue due to minimized financial reserves and relatively smaller customer bases (Bostic et al. 2021; Cooley et al. 2020). 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) (Bostic et al. 2021).

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 (Bostic et al. 2021). Generally, this report is among the few studies centered on small water utilities (Giné-Garriga et al. 2021; Switzer et al. 2020).

Presently, the literature comparing the operations and maintenance (O&M) of smaller and larger DWUs in emergencies is limited (Peda et al. 2013; Pinto et al. 2017). 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 (Sowby and Lunstad 2021). 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) 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) (US Environmental Protection Agency 2021b). 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.

2.2. 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) (Spearing et al. 2022a). 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 (Spearing et al. 2021, 2022b).

2.2.1. 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 2.1. We selected interviewees through stratified sampling as we used existing databases of small state DWUs to contact via email or phone (Etikan 2017). 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, of which supplemented the statistical analyses (Spearing et al. 2021). 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 Appendix B.

Table 2.1: 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 Appendix A.

2.2.2. QUALITATIVE ANALYSIS

Interview transcripts were analyzed using a hybrid, inductive-deductive qualitative coding technique with the NVivo software (Feng and Behar-Horenstein 2019; Spearing et al. 2022a). 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 (Spearing et al. 2022a). 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 (McHugh 2012).

2.2.3. STATSTICAL 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 2.1) (Opdyke et al. 2017). 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 (Cochran 1952). 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.

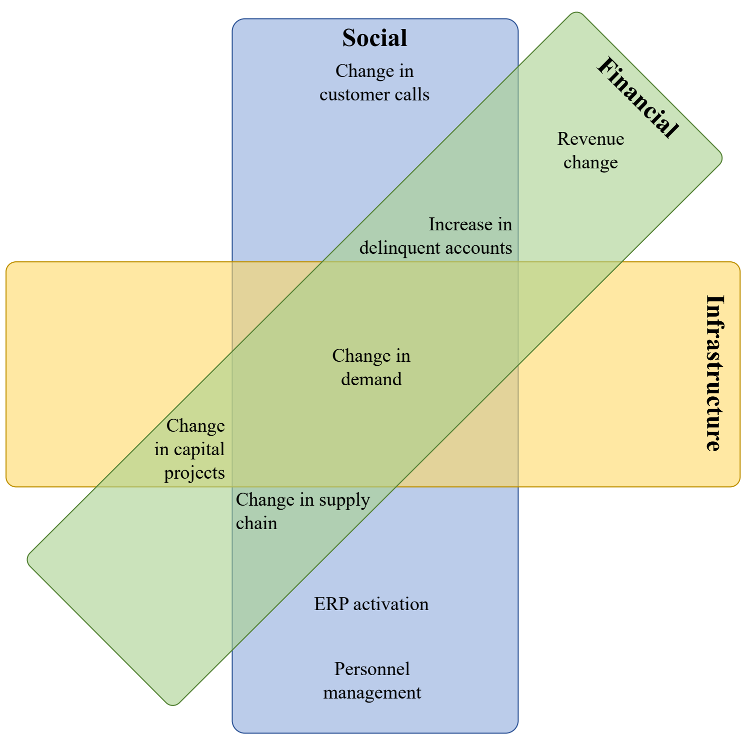

Figure 2.1: Conceptualization of factors from resilience dimensions

2.2.4. 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.(Saldaña 2016) 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.

2.3. RESULTS AND DISCUSSION

2.3.1. 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 2.2. 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 Appendix A.

Table 2.2: Frequency Table of Small Utility Responses

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%)

2.3.1.1. 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 (Farooq and Sultana 2021; Gibbs et al. 2021). 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 (Gamio and Goodman 2021). 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 (American Water Works Association 2021). 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). 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.

2.3.1.2. 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 (Ferrari et al. 2022). 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 (AWWA and AMWA 2020). 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.)

2.3.1.3. 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., 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 (Spearing et al. 2021).

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.

2.3.1.4. 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 (Wuthnow 2013). 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 (Debertin 1997).

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.

2.3.2. DIFFERENCES BETWEEN SMALL AND LARGE UTILITY EXPERIENCES

Figure 2.2 shows small DWUs' perspectives on the differences between pandemic impacts on small and large water utilities. Table 2.3 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 Appendix A.

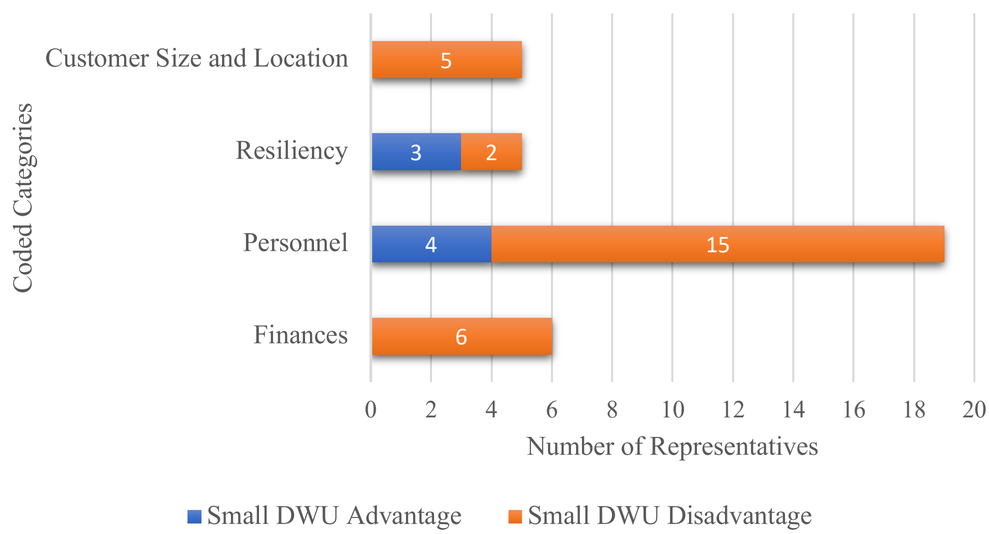

Figure 2.2: Advantages and disadvantages for small and large water utilities

Table 2.3: 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 (Dean et al. 1998). 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 (US Environmental Protection Agency 2022b). 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 (US Environmental Protection Agency 2022b). 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 (Dean et al. 1998; Debertin 1997).

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.

2.4. 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 (US Environmental Protection Agency 2021a). 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 (US Environmental Protection Agency 2022a). 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.

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CHAPTER THREE: IDENTIFYING THE BUILT, NATURAL, AND SOCIAL FACTORS OF SUCCESSFUL AND FAILED RURAL ALASKAN WATER PROJECTS: PERSPECTIVES FROM STATE AND REGIONAL PROFESSIONALS

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Drinking water projects in rural Alaskan communities face a myriad of issues, often due to environmental challenges and financial constraints. These issues threaten community members' access to clean drinking water. Here, we report the built, natural, and social system factors that contribute to the failures and successes of water projects, based on 20 semi-structured interviews with engineers, program managers, service providers, and researchers whose work involves some element of water infrastructure in rural Alaska. Using a hybrid deductive and inductive approach to qualitative coding analysis, we aimed to uncover common themes in the perspectives of the individuals who maintain and operate drinking water projects to advance understanding of rural water access. Interviewee responses indicate the importance of the interactions between built system factors (e.g., operations and maintenance), social (e.g., community engagement), and natural system factors (e.g., water quality) in determining the success of drinking water projects. Generally, the respondents agreed that design efforts that are rooted in the built and social systems (e.g., sociomaterial approaches) and that consider rural Alaskan communities' climate, geography, and cultures allow for the effective implementation of sustainable drinking water projects.

KEYWORDS: Drinking water, rural water systems, water management, Alaska water

3.1. INTRODUCTION

Household water insecurity is a critical problem affecting many remote Alaskan communities despite perceptions of water abundance in the state (Eichelberger 2014; Sohns et al. 2021; US Arctic Research Commission 2015). Household water insecurity is defined as inadequate

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access to stable and affordable clean water in sufficient quality and quantity to maintain health and support livelihoods (Cook and Bakker 2012). Many scholars have documented water insecurity in Alaska by focusing on inadequate access to water (Eichelberger 2019; Mattos et al. 2021a).

Although many rural communities have access to a safe drinking water source, they are often impacted by various natural, built, and social system factors that affect the continued implementation of drinking water projects (Cozzetto et al. 2013; Marino et al. 2009). For this analysis, we use the 2020 NSF definition of the natural system factors as "atmospheric, biological, cryospheric, ecological, geological, hydrospheric and marine processes," the built system factors as "human-built physical infrastructure, telecommunications, cyberinfrastructure, and data systems and their interactions," and the social system factors as "human behavior and social organizations such as the economy, politics, and environment (National Science Foundation 2020)." This definition generalizes the five dimensions of resilience (i.e., the "resistive and adaptive capacities" that may support the functionality of systems) that are commonly considered in resilience literature (i.e., built, economic, government, natural, social), where the social system factors encompass economic and governance system factors (Opdyke et al. 2017). Furthermore, this generalization is helpful within an engineering context where economic and government dimensions may not be referenced independently. An example of the built system influencing the social system is a lack of piped water systems that underserved and unserved rural communities may have based on their water system (e.g., closed haul water system, washeteria) impacting personal hygiene (Hickel et al. 2018; Lucas et al. 2021). Additionally, structural inequalities based on the legacy of American colonialism and domination have affected the governance and economies (i.e., social system factors) that currently support critical infrastructure (i.e., built system factor) (Thornburg and Roberts 2012). Historical processes such as settler colonialism have implications on both the physical loss of natural resources (i.e., natural system factor) and the drivers behind water stewardship (i.e., social system factor; e.g., viewing drinking water as a commodity without recognizing its social, cultural, and spiritual value) (Craft 2016; Wilson et al. 2019). The establishment of permanent Alaska Native settlements led to ongoing colonial processes of viewing water as something in need of human manipulation to purify and distribute drinking water (Berardi 1999; Eichelberger 2014). As such, water insecurity is a product of current and historical natural, built, and social system factors.

Several studies have observed the issue of household water insecurity in rural Alaska. Multiple studies focused on the relationship between water, sanitation, and hygiene (WASH) and drinking water projects and community health using analyses at the household and community level (Gessner 2008; Mattos et al. 2021b; a). For example, in the study completed by Mattos et al., researchers determined the technical and social factors that contributed to the success of household Portable Alternative Sanitation Systems (PASS) using collected qualitative data. The analysis determined that successful implementation of PASS and mid-tech WASH infrastructure is complex and may need to consider different built (e.g., technical sufficiency) and social system factors (e.g., user satisfaction) depending on the vulnerability of a specific household (Mattos et al. 2021b).

Other works have used frameworks to analyze community drinking water in rural Alaska comprehensively. For example, Williams et al. used the Arctic Water Resources Vulnerability Index to understand how a community's adaptive capacity varies based on different ecologies and socio-economic systems (2019). Their study found that different communities on the same type of topography maintain a similar ability to adapt biophysically and socially to changing environmental conditions. In recent work, Sohn et al. used casual loop diagrams to understand how stakeholders determined critical factors that impact household water vulnerability, resulting in five thematic models: economic, environmental, infrastructure, health, and social (2021). The involved researchers explored economic and environmental sub-models, citing climate change and maintenance funding as notable challenges for rural Alaskan communities. Other studies closely examined how existing water projects are improved to combat environmental threats. For example, a study by McOliver et al. described four Alaska Native case studies to review how stakeholders have addressed pressing ecological issues with community-centered research (2015).

Although studies have continued to address household water insecurity issues in rural Alaska, there have been calls to examine WASH-related matters from a systems perspective (Valcourt et al. 2020). In response to this call, this paper creates a conceptual model of the factors, interactions, and feedback that shape access to safe, reliable, and acceptable drinking water in rural Alaska. We aim to contribute to the existing literature by reporting the perspectives of state and regional professionals involved in or familiar with the implementation, management, and oversight of rural water projects across rural Alaska. To do so, we analyzed semi-structured interviews with stakeholders across the state, including individuals who work with off-road communities in the southwest, southcentral, and southeast Alaskan regions to identify the natural, built, and social factors that define the success and failure of drinking water projects and systems in rural Alaska.

3.2. MATERIALS AND METHODS

This research drew from 20 interviews with individuals working within tribal, federal and state agencies, private companies and firms, non-profit organizations, and academic institutions across Alaska to design, manage, and operate community drinking water projects. Our interviewees' experiences include a broad and representative range of rural Alaska drinking water systems built in recent decades, including federal and state-funded and volunteer projects. Here, we define a drinking water project as the process behind establishing access to drinking water, resulting in a final product: a drinking water system. Our hybrid approach to qualitative analysis (i.e., deductive content analysis with subsequent inductive coding) determined vital attributes and trends associated with successful and failed drinking water projects, discussions of water treatment and elements, and social equity and inclusion considerations within the context of rural Alaska (Spearing et al. 2022a). We seek to communicate these organizational stakeholders' viewpoints rather than solely providing our own ideas to co-create knowledge regarding drinking water project implementation.

3.2.1. DATA SOURCES AND COLLECTION

The interviewees were selected based on their experience with drinking water projects in the rural Alaskan context through a combination of convenience and snowball sampling. Interviewee selections were not dependent on demographic information nor an interviewee's specific role with Alaskan water projects (e.g., we did not choose to interview only engineers). Initial interviewee selections leveraged the research team's existing professional network, and subsequent interviews were sought following the interviewee's contact recommendations. The project proposal and sample interview questions were generated and approved by the Institutional Review Board at the University of Washington and the Alaska Area Institutional Review Board and reviewed by the Alaska Tribal Health Consortium Research Review Committee. Researchers distributed email invitations to potential interviewees requesting their participation, and interviews were completed through a combination of video conferencing (i.e., Zoom) and phone calls from October 2020 to April 2021. Each interview was approximately 60 minutes long, recorded with consent, and digitally transcribed before performing qualitative coding.

The resulting interviews captured the professional knowledge of 20 employees representing 11 organizations within the design, development, operation, maintenance, water conservation, regulatory oversight, public health, and academic communities. Individuals' experience ranged from 10 to 42 years of involvement in rural Alaska communities' water resources and supply systems (i.e., applicable experience). The majority of the respondents did not reside in rural Alaskan communities. However, we believe that the chosen participants provide unique perspectives considering their breadth of knowledge and experience in drinking water project implementation, management, and research. Additional information, including interviewee demographics, is included in Appendix B.

Questions included in the interview were initially designed to generate thoughtful discussion about drinking water resources in rural Alaska and additional probing about groundwater; however, respondents generally spoke about all water sources. Interviewees were first asked to define the success and failure of rural Alaska drinking water supply based on their experiences. Further questions built upon unique factors in Alaskan water projects, including impacts of climate change, geographic conditions, and equity and inclusion considerations for communities. Using a semi-structured interview approach, we could include additional questions based on the respondents' responses (Kallio et al. 2016). The complete interview protocol can be viewed in Appendix B.

3.2.2. QUALITATIVE ANALYSIS

Data analysis for this study involved qualitative coding of interview transcripts using the data analysis software MAXQDA. The qualitative coding process outlined and categorized segments of interest for each interview transcript and assimilated these coded segments with similar findings, ideas, and themes across the breadth of interviews. The analysis took an iterative approach to coding, revisiting interview transcripts, and recoding segments as new categories emerged (i.e., inductive qualitative analysis) (Spearing et al. 2022a; Thomas 2006). While the research team used a list of questions to facilitate interviews, we did not use a predetermined list of coded categories to allow themes to emerge in the codes (Spearing et al. 2022a).

The excerpts were categorized into four categories: (1) successful project attributes, (2) failed project attributes, (3) factors that matter to drinking water projects, and (4) advice and propositions. These parent codes were then analyzed and further segmented into the natural, built, and social system factors defined by NSF (i.e., deductive qualitative analysis) (Azungah 2018;

National Science Foundation 2020; Spearing et al. 2022a). Each system factor (i.e., project attribute) includes child codes that describe a specific factor (e.g., water quality, regulatory compliance). System factors were coded as a successful or failed project attribute based on respondents' explicit definitions, while "factors that matter to drinking water projects" encompassed topics that arose during separate questioning. A single researcher completed the coding, and a different researcher assisted with the intercoder reliability check based on one excerpt (5% of the total). The coding was validated by a kappa value of 0.93, which is considered satisfactory in qualitative research (De Vries et al. 2008).

3.3. RESULTS AND DISCUSSION

The following tables report the themes identified through qualitative analysis for successful and failed project attributes (Table 3.1) and advice and propositions (Table 3.2), categorized by built, natural, and social systems. The tables illustrate the relative frequencies (i.e., the proportion of responses in a category) for each parent code, including the number of coded excerpts. Additional information (e.g., coding dictionary, hierarchy chart for the factors that matter to drinking water projects) is described in Appendix B.

Table 3.1: Frequency Table for Successful and Failed Project Attributes

	Successful Project Attributes		*Failed Project Attributes*	
Qualitative Code	*Number of Interviewees*	*Number of Responses (Relative Frequency)*	*Number of Interviewees*	*Number of Responses (Relative Frequency)*
Project Attributes	20	115 (100.0%)	20	188 (100.0%)
Social System	19	66 (57.4%)	20	140 (74.5%)
Experienced and trained personnel	8	12 (10.4%)	16	40 (21.3%)
Regulatory compliance	5	7 (6.1%)	0	0 (0.0%)
Finances	7	11 (9.6%)	18	51 (27.1%)
Community affordability	6	7 (6.1%)	13	32 (17.0%)
Economic stimulus to the community	4	4 (3.5%)	0	0 (0.0%)
Financial management	0	0 (0.0%)	6	7 (3.7%)
Wages for employees	0	0 (0.0%)	8	12 (6.4%)
Community engagement	15	33 (28.7%)	17	49 (26.1%)
Community buy-in	15	24 (20.9%)	11	14 (7.4%)
Water resource education	6	9 (7.8%	0	0 (0.0%)
Cultural complexities	0	0 (0.0%)	15	34 (18.1%)
Community expectations	0	0 (0.0%)	1	1 (0.5%)
Built System	13	25 (21.7%)	10	16 (8.5%)
Operation, maintenance, and resilience	10	20 (17.4%)	10	16 (8.5%)
Water treatment scheme	3	5 (4.3%)	0	0 (0.0%)

Natural System	11	24 (20.9%)	12	32 (17.0%)
Water quality	5	7 (6.1%)	4	6 (3.2%)
Water resources (e.g., availability)	11	17 (14.8%)	5	5 (2.7%)
Climate and terrain	0	0 (0.0%)	5	9 (4.8%)
Geographic remoteness	0	0 (0.0%)	6	12 (6.4%)

Table 3.2: Frequency Table for Advice and Propositions

Qualitative Code	*Number of Interviewees*	*Number of Responses (Relative Frequency)*
Advice and Propositions	20	89 (100.0%)
Propositions	18	54 (60.7%)
Social System	15	30 (33.7%)
Financial	8	14 (15.7%)
Education and training	10	13 (14.6%)
Regulations and practice	1	2 (2.2%)
Personnel	1	1 (1.1%)
Built System	13	26 (29.2%)
Improved transportation	1	1 (1.1%)
Water system technologies	12	24 (27.0%)
Advice for Outside Organizations	19	35 (39.3%)
Social system	19	35 (39.3%)
Community engagement and understanding	12	20 (22.5%)
Finances	4	4 (4.5%)
Logistics in Alaska	9	11 (12.4%)

3.3.1. SUCCESSFUL PROJECT ATTRIBUTES

While respondents were tasked with determining definitions of success and failure based on their own experiences, they generally categorized successful drinking projects with well-maintained technical systems, access to natural resources, and adequate community engagement. The following sections summarize the discussion of social, built, and natural system factors contributing to successful projects.

3.3.1.1. SOCIAL SYSTEM

Nearly all respondents (19; 95% of the total) highlighted social system factors when discussing successful drinking water projects. Fifteen interviewees (75% of the total) identified community engagement; in particular, interviewees identified that early involvement of the local community could help convey the value of investing in properly regulated systems. The engagement described by interviewees may refer to community-led or non-community-led initiatives (e.g., programs hosted by researchers or engineers) that take a human-centered design approach to educating and informing decisions on drinking water project implementation (Alaska Department of Environmental Conservation Division of Water 2022; Sigman 2015). One respondent, a researcher with expertise in water treatment, expanded on this sentiment:

> "I think the communities that we've had the greatest success… are the ones where, before we ask anyone a single question, we spend four days in the community, not doing anything other than saying hello… If you think it's going to take two days to do the work, spend five times that amount of time out there… And if it's at all possible, leave something with the community so that they believe you helped on their needs… even if it's extraneous to your project."

According to six interviewees (30% of the total), communities' perceptions of whether to invest in water systems depend on water resource education. Bidirectional educational programs promote knowledge sharing and effective resource allocation for project planning and development, similar to the participatory rural appraisal approach used for rural development (Chambers 1994). Furthermore, it presents an opportunity to build trust between community members and water resource stakeholders that may be entering the community (Dobbin and Smith 2021). However, as described by interviewees, these programs can often be constrained by limitations to the available workforce and budget.

Eight respondents (40% of the total) discussed that experienced and trained personnel contribute to successful drinking water projects. While many respondents noted the benefit of having a certified operator, one respondent, a water operator, described the value of having an operator that cares about the water system. Having personnel that can maintain a drinking water system contributes to a water system that follows regulatory compliance, which 25% of respondents described explicitly as a successful project attribute. The five respondents, who all have academic, engineering, or government affiliations, mentioned the criticality of drinking water projects resulting in water systems that meet applicable standards, which may also reflect stances guided by their occupations. Other respondents (6; 35% of the total) mentioned finances as a successful attribute to drinking water projects, specifically focusing on affordability. Numerous respondents described the need to ensure that stakeholders plan water systems to be of reasonable cost to the community while still maintaining quality water. Governance structures and policies embedded in drinking water projects influence finances, personnel, regulations, and community engagement. Although not explicitly mentioned by the respondents when asked about successful project attributes, we theorize that the colonial impacts on drinking water systems may influence the success of project implementation.

3.3.1.2. BUILT SYSTEM

More than half of the respondents (13; 65% of the total) described built system factors when describing the success of drinking water projects, including well-maintained technical systems. Specifically, ten respondents described an aspect of the project's technical system's operations, maintenance, and resilience. For example, several interviewees mentioned the need to stockpile necessary materials, keep up to date with preventative maintenance, and adhere to a standard operation. One respondent, a researcher, described the benefits of uniformity in one remote area, "[the region has] 20 communities that all use the same parts… it's much easier to get [materials] when you're not the only one with something unique and in that place." Although there may be barriers to standardizing drinking water technical systems across a region, standardization could provide benefits for improving water system performance (i.e., built system factor) and water operator education and retention (i.e., social system factor), thus increasing the success of a drinking water project in the state (Choi et al. 2022). Interviewees noted the necessity of maintaining and creating simple water systems whose operations can quickly be passed down along multiple generations of operators or stakeholders, allowing for more resilient drinking water systems. For instance, one respondent, an engineer, described "a system that can last 20 years with bare-bones maintenance" as a characteristic of a resilient and successful drinking water system.

Interviewees described resiliency as the prolonged use of water systems supported by improved technical systems, more significant financial capability, and adherence to the intended design and operation. This definition of resiliency demonstrates the interaction between built and social system factors. Drinking water systems' operation, maintenance, and design (i.e., built system factors) that are unique to the climate and topography of rural Alaskan communities (i.e., natural system factors) may improve the resiliency and success of a drinking water project. For example, three interviewees (15%) mentioned that a system's water treatment scheme contributes to success. Although the water treatment level depends on natural system factors (e.g., turbidity, geogenic elements), a drinking water system's water treatment scheme could be manageable and affordable for a community while meeting treatment requirements (Mattos et al. 2021b).

3.3.1.3. NATURAL SYSTEM

Beyond the built system, drinking water projects in rural Alaska are highly dependent on water resources (i.e., natural system factors). Half of the respondents highlighted the importance of existing water resources in successful drinking water projects. As approximately 75% of all freshwater in the state is stored in glacial ice, access and proximity to water resources would ensure that rural communities have the foundation for sustainable and uninterrupted water service (Williams et al. 2019). For example, one interviewee, a programs manager, described the added benefit of having a water source that is close to a community as it reduces the need to pipe and heat the water (i.e., built system factors), which could affect operational costs (i.e., social system factor) and water quality (i.e., natural system factor). Five respondents (25% of the total) highlighted water quality as a successful drinking water project attribute. However, an interviewed engineering contractor described that "adequate yield… or usable quality yield is rarely the issue for" drinking water projects in the state, suggesting more significant concerns in other system factors.

3.3.2. FAILED PROJECT ATTRIBUTES

Interview respondents broadly described failed drinking water projects as initiatives that could not fulfill the mission of supplying quality water to communities due to designs that were inappropriate for rural Alaska's social and natural contexts, leading to unmaintained systems. The following sections summarize discussions involving social, built, and natural system factors that contribute to failed drinking water projects.

3.3.2.1. SOCIAL SYSTEM

Similar to the discussion of successful project attributes, most references (100% of respondents) of failed drinking water projects were social system factors. Notably, 18 respondents (90% of the total) described finances as a contributing factor to failure, with community affordability, financial management, and employee wages being discussed the most. One respondent with a background in engineering for rural water systems identified how financial capabilities impact the overall lifespan of rural water systems in a specific region:

> "Very few small water utilities here have any kind of capital, they don't have any [means] to borrow money or bond or any of these features, and generally the cost of improvements or even major repairs are far beyond anything that they're capable of doing on their own…

Over time, performance generally degrades substantially, and that usually means… a higher cost to the consumers."

Interviewees discussed that government subsidies, capital investment, and other programs in water supply projects would open doorways for improving local water infrastructure jobs, revenue, and opportunities with O&M support activities. While such initiatives have been implemented (e.g., programs through the Denali Commission and the Alaska Sewer and Water Challenge), many communities are still threatened by water insecurity and often lack the financial means to aid themselves (Alaska Department of Environmental Conservation Division of Water 2022; United States Government Accountability Office 2022).. For example, several interviewees described a point system used by the state government to determine what projects may receive financial support. However, communities would need to demonstrate "that they're going to protect that investment," leading to funding awards given to communities with a history of water project success rather than the communities that actively need the support. Such imbalances widen the gap between rural water systems and can intensify structural issues involving social equity and access as a result of colonialism (Hennessy and Bressler 2016).

Other interviewees noted how the minimized value of water system laborers and reduced community financial capability could negatively impact the number of hours and pay available for operators. Difficulties with workforce retention and personnel that may not be able to manage water quality and environmental concerns (i.e., natural system factors) can lead to an unmaintained water system (i.e., built system factor). A lack of certified operators is an issue for many small and rural communities across the United States (American Water Works Association 2020). Based on the interviewee responses, a combination of the remoteness of rural Alaskan communities and the lack of competitive pay in the water management sector further impedes the existence of long-lasting drinking water systems.

Although not explicitly described when asked about the failed attributes, we theorize that meeting regulations can pose challenges to the design of drinking water projects. One interviewee with experience in well-drilling detailed that the "one-size fits all" approach in policies for regulating surface water and groundwater wastes a considerable amount of funds that could go to O&M. The same interviewee described cases where groundwater may be connected to a spring that rises to the surface in a separate location. Although the same water may pass through the system, the interviewee perceives that additional treatment may be wasteful when describing, "the government deems it necessary to put sand filters, treatment, and everything else on it, even though the water surfacing is good." Not only would this scenario put a financial burden on water providers due to the additional treatment measures, but community members may prefer other water sources over the heavily treated water due to its additives. While several respondents highlighted the importance of these water standards in providing clean water to communities, they also recognized that general regulations might not consider the unique topography, water chemistry, and cultural considerations found in rural Alaska compared to the continental United States.

As described by 17 respondents (85% of the total), a lack of engagement with the community can lead to failure in a drinking water project with ample funding and access to water resources. Community engagement often depends on the consideration of local culture and conditions while implementing drinking water projects; 15 respondents (75% of the total) described cultural complexities as an attribute of failed water projects. One interviewee, a facilities manager, cited the "skepticism around chemical treatment practices" as a reason behind the preference for traditional water sources and thus leading to the failure of drinking water projects focused strictly on water treatment. The hydro-social cycle in many rural Alaskan communities follows their respective Indigenous traditions that value and interact with water resources differently from larger and more urban communities (Eichelberger 2018; Wilson et al. 2019). The interviews indicate that drinking water projects implemented without solid community buy-in could fail by not considering the cultural knowledge that develops from a community's cultural relationship with water.

3.3.2.2. BUILT SYSTEM

Compared to the discussion of successful project attributes, fewer interview respondents discussed built system factors as critical contributors to failed drinking water projects. While none mentioned the water treatment scheme, half of the respondents addressed potential shortcomings due to operation, maintenance, and resilience. One interviewee, a project manager, referenced the social system factors' influence on the built system, mentioning the difficulty of generating revenue to keep a water system in operation. As one facilities manager described, scenarios where it is difficult to generate revenue often lead to situations where "the operator and the community give it their best to keep the system running, and the system [would] usually stay running until something catastrophic happens" due to the lack of proper maintenance. Shortcomings within built system factors, further impacted by social and natural system factors, have led to troubling issues influencing communities' access to clean drinking water, as demonstrated by the American Society of Civil Engineers' "D" rating for drinking water infrastructure in Alaska. Like successful drinking water projects, the interactions between the different system factors can contribute to apparent failure.

3.3.2.3. NATURAL SYSTEM

Respondents (13; 65% of the total) described climate, terrain, and geographic remoteness, in addition to water quality and resources as attributes of failed drinking water projects. For example, one program manager explained the problem that "fill and draw" communities experience. These communities, which have insufficient groundwater sources, rely on surface water as their raw water source. Before the long winter, when their water sources freeze, these communities are forced to "make" and store sufficient water to last 6-8 months. This process involves drawing from a raw water source before treating and storing it to save in storage tanks for the colder months. The threat of household water insecurity is considerable, especially for certain communities that may run out of water before their water source thaws. Another respondent, a researcher, described the difficulty a remote community experienced due to alternating water availability and demand based on seasons. The community members often let the water run to combat frozen pipes in the winter, rapidly depleting the quantity of stored water. In previous winters, the community had used an alternate water source which the interviewee reported being "just full of silt."

Furthermore, the use of available water resources could be affected by water quality, given the amount of geogenic elements naturally found in groundwater, for example. While only four respondents (20% of the total) explicitly described water quality as a failed project attribute, nearly all mentioned a component of water quality when describing factors that matter to drinking water projects. One program manager discussed seeing an arsenic level as high as 7000 parts per billion in one well, much higher than the Environmental Protection Agency's (EPA) standard of 10 parts per billion (US Environmental Protection Agency 2020). This discovery caused issues for the specific community in drilling a new groundwater well nearby.

Other respondents described how geographic location differences could affect what type of element is more likely to cause complications for the water system. For example, iron poses more of an issue for Southwest Alaska than arsenic. Iron, a secondary contaminant that causes aesthetic and technical effects to the water and physical pipe system, respectively, does not receive the highest funding considerations as compared to arsenic, a primary contaminant that can cause health complications. However, the naturally occurring secondary contaminant can cause build-up in pipes and wells. Additionally, several respondents discussed other water quality factors that affect water systems, including non-geogenic elements and turbidity. One engineer detailed the variability in water quality due to weather in a water system where "the organic carbon varied from maybe two to three milligrams per liter to 10 to 12 milligrams per liter… [when it was sunny] you had one quality water and [when there was a storm] we had another quality water." These additional factors contribute to the overall challenge of enacting effective treatment processes for the natural system.

Five respondents (25% of the total) described climate and terrain as contributing to the failure of drinking water projects, especially highlighting ground conditions that can influence built system factors. Communities along the coast face challenges caused by the increasingly visible effects of climate change (e.g., widening rivers and eroding shorelines). Furthermore, technical systems (i.e., built system factor) that were put in place under previous considerations for climate and terrain may not be able to withstand impacts due to rising temperatures and other shifts in the environment. For example, one interviewee mentioned witnessing "a lot more pipe breakage" due to the thawing of the permafrost older water systems may have built on in communities above the Arctic Circle. Beyond infrastructure breakage, permafrost thaw can also lead to continued turbidity and erosion and reduced groundwater quality, especially in the 30% of Alaska that has continuous permafrost (American Society of Civil Engineers 2021). While there may be temporary solutions to infrastructure damage, this does not aid the rest of the distribution system, which could be subjected to differential movement.

Moreover, six respondents (30% of the total) mentioned the effect of communities' remoteness as a contributor to the failure of drinking water projects. As 86% of Alaskan communities are not connected to a road system, rural communities have the additional difficulty of receiving assistance to manage drinking water projects (Alaska Department of Commerce 2017). Scenarios like this exemplify the necessity of considering the interactions between the different system factors to solve impending threats to water security in the region.

3.3.3. ADVICE AND PROPOSITIONS

As described by interview respondents, there are factors that stakeholders involved with drinking water project implementation can focus on to ensure the success of drinking water projects in rural Alaska. While some system factors may be unchangeable at the project management scale (e.g., geographic remoteness of a community), considering the interactions between built and social system factors may help reduce household water insecurity in the state. Here, we discuss the implications of this analysis within existing literature and report respondents' actionable propositions for assistance to rural Alaskan water projects (Table 2). Broadly, the coded interview excerpts in this analysis agree with the findings of previous studies that uncover the limitations of water system success as geographic remoteness, water quality, and financial affordability (Eichelberger 2018; McOliver et al. 2015; Sohns et al. 2021). However, this work also reveals how the interactions between system factors can contribute to a drinking water project's level of success (Table 1). Such interactions can be seen within discussions of climate (i.e., natural system factor) and how that may influence the design of a technical system (i.e., built system factor) or how a lack of community engagement (i.e., social system factor) can lead to an unused and unmaintained water system (i.e., built system factor).

Based on the experiences described by interviewees, many of the discussed project attributes could directly influence or be influenced by built system factors. This same relationship is not seen between other system factors (e.g., climate and terrain may not directly affect wages for employees and vice versa), suggesting the critical role and influence that the built system has on the implementation of drinking water projects. As such, this realization can better inform the ideation of techniques and actions to improve the more readily adaptable system factors (i.e., built and social) to reduce household water insecurity by enabling approaches rooted in sociomateriality. Here, we refer to sociomateriality as a reference to the space in which "social and material agencies" overlap to produce technologies and organizations, respectively (Leonardi 2012). An example of using sociomateriality to guide solution generation would be community engagement that drives the decision-making behind technologies used in a drinking water system.

Of the respondents (18; 90% of the total) that described ongoing and future suggestions for aiding drinking water projects in rural Alaskan communities, more than half of the respondents (65% of the total) highlighted built system factors. As climate change impacts water availability and existing technical systems, stakeholders at different levels recognize the various developments necessary for the built system. For example, several respondents discussed the continued need to create and use technologies unique to rural Alaskan regions' natural and cultural environment (e.g., alternate and affordable filtration techniques and solar panels for energy during summer months). One respondent, an engineer, described a situation in which allowing a water system to operate unmanned “was one means of being able to [empower] the community to be able to control the system.”

However, while describing the benefits of technological innovation, a different engineer stated, "… you have one trip-up with automation, and [then] nobody can fix it… There's a fine line… between levels of automation [and] the levels of manual control that you want to provide for systems like that." Although digitalization and automation have increased in urban water systems, technological innovations in the rural Alaskan context should consider the community's needs and overall resiliency before being implemented (Yuan et al. 2019). Beyond technology needed for water infrastructure, an interviewed geophysicist speculated how improving transportation infrastructure to a condition similar to that in rural communities in Nordic countries would reduce the issues caused by geographic remoteness. In more remote areas of Alaska, the geographic remoteness lowers the reliability of a water supply due to location and heightened transportation costs (Wu et al. 2018). Although the investment needed for the described transportation infrastructure is unlikely due to financial restraints and habitat impacts, increased connectivity could assist in the transfer of resources between communities which has previously been found to help rural water systems in the United States during emergencies such as the COVID-19 pandemic (Switzer et al. 2020).

However, the interviewees additionally recognized the financial need (i.e., social system factor) required for an improved built system. Eight interviewees (40% of the total) identified the benefit of government subsidies, specifically for water costs and operator pay. As 90% of respondents described finances as an attribute of a failed water project source, "a revenue source to help fund the utilities" would be the most "desperately needed thing" for water systems, as described by program manager. Tribal nations across the United States experience funding limitations and may depend on federal grant programs to improve technical systems.(Jones et al. 2007) In addition to finances, 50% of the interviewees suggested other interventions for the social system through education and training programs. For example, one engineer described working with community members on the implementation of the water project:

> "… We'd send in one or two or maybe three very qualified people, depending on the type of work that we're doing. And then we hire the majority of the labor from the village and will train them… We… build local capacity to integrate sustainability into our systems, so people understand how they're built, they can fix it themselves."

These initiatives, which may be supported through ongoing government subsidies or organizational aid, would assist in improving community buy-in for drinking water projects and the operations and maintenance (O&M) needed to sustain water systems. For example, the Northwest Arctic Borough government subsidizes local water and sewer systems which help keep rates and O&M costs affordable (Alaska Native Tribal Health Consortium 2018). Similarly, some communities used CARES act funding to subsidize rates or pay residents' delinquent bills during the COVID-19 pandemic (Eichelberger et al. 2021).

Furthermore, 95% of interviewees provided insights for outside organizations (e.g., organizations from the continental United States or abroad or organizations unfamiliar with rural Alaska) that want to improve drinking water systems in rural Alaska. All suggestions were related to the social system; respondents recommended that organizations and government entities outside of Alaska be aware of the difference in cultures and the necessity for community engagement. One interviewee with experience in well drilling highlighted the need for patience and communication, especially when drilling to find a water source:

> "Too many times where [looking for water by drilling] went wrong where there were tons of money waste and results were minimal. And so, a lot of the time, if they just went out and asked [local] people about where they might go and [drill water], it might be a little bit better done."

Generally, interviewees agree that outside organizations must recognize the uniqueness of Alaska and the specific rural community and actively use a participatory rural appraisal to assist in developing any drinking water project. To improve built system factors, social system factors should be carefully considered to ensure that a community's autonomy is respected while adequate access to clean drinking water is provided. Overall, approaches to drinking water project implementation that understand the interactions between the system factors can help reduce household water insecurity in rural Alaska.

3.4. LIMITATIONS

Although this study represents a subset of a larger population, we consider these generalizations an applicable and valuable representation of technical stakeholder input for rural Alaska community drinking water projects and systems. By using a systematic coding approach, the research team ensured that the emerging information in the study could be adequately used to draw conclusions and determine potential interventions. Additionally, the line of questioning used in interviews included additional questioning on groundwater. Although this did not prevent respondents from generally speaking about surface and groundwater, the questions may have influenced the responses. Separately, variations may exist even between water supply projects in the same region as each project has unique facets in scope, site conditions, and community expectations. This study aims to draw out broad themes and factors that will assist future rural Alaska water resource development with varying characteristics. Furthermore, the frequency of coded segments and the number of respondents may not directly represent the significance of a factor or theme for water supply projects and systems. Consideration should be given that higher or lower frequencies may be attributed to the level of the interviewee's awareness of each factor or idea presented. The results indicate that some aspects are more pervasive or deeply rooted within the known sphere of rural water supply projects than others.

This paper reports the perspectives of individuals with occupations that involve rural water systems, most of whom do not reside in the communities where they work on projects. One major limitation of this paper is that only one interviewee (5% of the sample) identified with the Alaska Native/American Indian demographic in our survey, while the racial background comprises 15% of the total Alaskan population (US Census Bureau 2020). This limitation is mostly due to the demographic make-up of those involved in drinking water system projects and disruptions caused by the COVID-19 pandemic, including regional and community travel restrictions and stay-in-place mandates. Our results therefore reflect the perspectives of a different population: individuals involved with the implementation, structural management, and oversight of rural Alaskan drinking water projects but not the direct consumers of that water. As such, interviewees' discussions involving governance, a subset of social system factors, revolved mostly around regulations. We speculate that if our sample pool included more Alaskan Natives, there could have been more discussion of social system factors, especially related to cultural considerations, history, governance, and community autonomy.

We believe this preliminary study may begin to provide insights into critical areas of concern shared by interviewee respondents statewide related to water supply projects and potential mitigation strategies. Given the large influx of federal funding allocated to Alaska for water and sanitation projects, understanding concerns on these different levels of positionality (e.g., state-level managers, community-level managers, developers, researchers, and consumers) will be of vital importance.

3.5. CONCLUSION

The threat of household water insecurity looms over some rural communities in rural Alaska, especially with the influence of climate change. While temporary solutions may be implemented, stakeholders must continue to navigate existing difficulties with drinking water projects and systems regarding cultural complexities, water quality, and technical system maintenance. Here, we identified factors that characterized successful and failed water system projects in rural Alaska using the qualitative coding and analysis of 20 interview excerpts spanning a diverse set of individuals in occupations that interact with drinking water projects. By identifying the factors interviewees commonly mentioned as contributing to the success or failure of water system projects, we can begin to characterize the built, natural, and social factors that affect household water security in a rapidly changing climate. Although communities and involved water infrastructure stakeholders may not be able to alter some aspects of the natural system at the project management scale, social (i.e., finances, regulations, cultural sensitivities) and built (i.e., technical system, transportation) system attributes were identified as factors that could be enhanced to impact the success of a water system. This work identifies areas of concern and development for stakeholders involved at various levels of water management.

ACKNOWLEDGEMENTS

Although conducted remotely, we acknowledge the multitude of Indigenous peoples and territories of those interviewed for our study. As authors, our workplaces are on the ancestral homelands of the Coast Salish and Dena'ina peoples. We thank the 20 very busy interviewees who made time to share their perspectives with us on water systems in rural Alaska. Many of these individuals also dealt with community emergencies related to weather and the COVID-19 pandemic. We humbly thank them for their time.

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CHAPTER FOUR: FROM PAST TO PRESENT: EXAMINING THE IMPACT OF REDLINING ON DRINKING WATER INFRASTRUCTURE SERVICE QUALITY

Nathalie Thelemaque[6], Julian Marshall[6], Jessica A. Kaminsky[6]

Following decades of use, many miles of the distribution system of drinking water infrastructure in the United States are deteriorating and contributing to the decrease in the quality and condition of infrastructure service. The condition of critical infrastructure varies based on location, where historically marginalized communities often experience worse service quality in part due to the creation of unjust geographies. We examine associations between historic redlining distinctions, which used race to restrict investment in certain neighborhoods, and contemporary drinking water infrastructure. Using geospatial and statistical techniques, we investigated if areas with redlining "D" distinction currently experience worse infrastructure service quality, measured by the number of maintenance events and duration of maintenance events. The results of the analyses suggest that redlining D distinctions have the highest odds of experiencing a condition-based maintenance event and longer durations for condition-based maintenance. Furthermore, the study provides inferences on the influence of contemporary sociodemographics and the role of maintenance type when examining infrastructure performance. Overall, this work provides a proof-of-concept to connect historical decision-making and policy to contemporary infrastructure performance and a basis to identify areas of improvement for enhancing infrastructure justice.

KEYWORDS: drinking water infrastructure, infrastructure maintenance, redlining, infrastructure justice

4.1. INTRODUCTION

Over the past two decades, the American Society of Civil Engineers (ASCE) has given poor ratings to the critical infrastructure services in the United States. The C- rating on the country's drinking water infrastructure was assigned because of technical system age and the lack

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of consistent maintenance, which influence drinking water infrastructure's overall performance (Martin 2021). The average pipe age in the United States water distribution system is 45 years, with tens of thousands of miles of pipe needing to be replaced within the next few decades (US Environmental Protection Agency 2009). The condition of a water utility's distribution system depreciates as water infrastructure ages, resulting in higher rates of failure and reduced service quality (Grigg 2019). Here, we define drinking water infrastructure failure at the utility level as an instance where maintenance is required, ultimately impacting overall infrastructure performance (Clark et al. 1982). While infrastructure performance is multidimensional and should be assessed within user needs, water main breaks and emergency maintenance interrupting water access or quality significantly impact the effectiveness and reliability of infrastructure service (National Research Council 1996).

Furthermore, studies have suggested disparities in service quality, in which marginalized communities often experience worse infrastructure conditions. One reason for this is historical decision-making involving zoning (Bise et al. 2018; Henderson 2021; Hendricks and Van Zandt 2021; Silver 2021a). Political and social structuring of physical space in the United States perpetuated the creation of unjust geographies, where physical concentrations of marginalized races and classes were coupled with social exclusion and reduced access to adequate essential services (Soja 2010; Zuniga-Teran et al. 2021).

One example of a historical driver behind the geospatial variation in infrastructure service quality is the legacy of "redlining." Redlining refers to the physical distinctions made by the Homeowner's Loan Corporation (HOLC) beginning in the 1930s to decide which communities were considered hazardous investment areas. The HOLC considered race and ethnicity, income, and location to grade areas on a map (i.e., residential security maps or redlining maps) on a scale from A to D, where areas with the "A" grade were determined to have the lowest financial risk and "D" graded had the highest (Perzynski et al. 2023; Rothstein 2017). Due to the HOLC's usage of racial composition as an assessment metric, many neighborhoods restricted from investment had predominately Black populations, demonstrating racism's influence on policy and spatial injustice (Bailey et al. 2021; Soja 2010).

Although redlining is no longer legal in the United States, there is evidence that this history has impacted current infrastructure service quality. For example, the water crisis in Flint, Michigan was caused by changing the city's water source without adapting the corrosion control to prevent lead contamination (Butler et al. 2016; Ruckart et al. 2019). Soon after the shift, residents, primarily racial minorities, identified water discoloration, increased water main breaks, and skin inflammation, especially in children (Zahran et al. 2017). Although this water crisis occurred in the 21st century, many argue that it resulted from decades of disinvestment and spatial-structural racism, including Flint's redlining past (Butler et al. 2016; Hammer 2019; Highsmith 2016). Furthermore, Flint's predominately Black population highlights the connection between historical decision-making and contemporary water infrastructure service inequities, further perpetuating racial injustice. As racism has been considered a public health crisis, understanding structural racism's intentional and unintentional impact on infrastructure, human well-being, and water access is essential to informing equitable infrastructure planning and management (Mendez et al. 2021).

Infrastructure quality and history have been associated with racial demographics in the U.S. in the environmental justice literature (Mohai et al. 2009). For example, Bullard and Wright used case studies in different U.S. cities to demonstrate the inequitable protections against toxic contamination from nearby manufacturing plants. Their analysis suggested that the "residuals of Jim Crow segregation" continued to influence contemporary infrastructure and therefore community health (2012 p. 104). In another example, Silver uses an urban political ecology approach to examine the enabling of decaying infrastructure in inner-city areas by looking at water infrastructure in Camden, New Jersey (2021b). The research unveiled that financial capital and racism played a role in disinvesting critical infrastructure and demonstrated the need to integrate race in similar analyses that observe infrastructure inequities.

Much work examining infrastructure conditions and sociodemographic disparities centers on the transportation sector (Lowe 2016; Schweitzer and Valenzuela 2004). For instance, Bise et al. used geospatial techniques to identify the accessibility and quality of sidewalk networks available to different racial groups (2018). In the study, non-white neighborhoods were found to have the poorest sidewalk quality, demonstrating a contemporary impact of historical segregation. Another study leveraged publicly available census data with geospatial analysis and field observations to survey the disparity in neighborhood conditions (e.g., walkability and sidewalk quality, clean streets, vehicular crashes) (Neckerman et al. 2009). Poorer census tracts, which generally housed more disenfranchised racial communities, were significantly less walkable, affecting residents' physical activity levels and health. Additionally, some literature has focused on the disparities within drinking water infrastructure, generally from the water quality perspective (Balazs and Ray 2014; Doyle et al. 2018; Heaney et al. 2013; Levin et al. 2023; VanDerslice 2011). These studies broadly corroborate the idea that marginalized communities experience higher exposure to water contaminants due to proximity to toxic sites and aging infrastructure.

Recent research has leveraged redlining maps in analyses involving a variety of topics related to infrastructure, including but not limited to health inequities, present-day mortgage lending, urban heat island effect, walkability, and air pollution (Asher 2021; Bramble et al. 2023; Hoffman et al. 2020; Kowalski et al. 2023; Krieger et al. 2020; Lane et al. 2022; Locke et al. 2021; Lynch et al. 2021; Moxley and Fischer 2020; Nardone et al. 2020; Perzynski et al. 2023; Sterling et al. 2023). For example, studies by Asher and Lynch et al. overlaid historical redlining maps and census tracts to examine the relationship between redlining mortgage lending and community resilience estimates, respectively (2021). The article revealed the ongoing legacies of redlining as the neighborhoods that previously underwent the most financial restriction still face limitations today. Another study by Sterling et al. examined the relationship between modern-day plumbing access and historical redlining distinctions. The researchers found that nationally, areas with the "D" redlining distinction were more likely to have a higher rate of incomplete plumbing than areas that historically received "A" grades. Similarly, two recent articles examining the association between redlining and air pollution found that communities that were in the lowest redlining grade have the highest levels of pollution both at a national and city (i.e., Seattle) scale (Bramble et al. 2023; Lane et al. 2022). Bramble and colleagues further found that the lowest income group and Black populations were additionally more likely to experience the highest exposure to ultrafine particles, demonstrating an association between historical and contemporary disparities. However, the use of redlining maps is still relatively new and piecemeal. To our knowledge, studies of structural racism enacted through redlining and its relationship to drinking water infrastructure service are limited. This gap makes it difficult to understand the historical legacy of redlining and how it may perpetuate contemporary inequities in drinking water infrastructure service. Examining this relationship would enable targeted work towards resilient and equitable systems, as called for by recent national initiatives for infrastructure improvement and justice.

Considering redlining's influence on neighborhoods and populations' access to financial, environmental, and physical and soft infrastructural services, we hypothesize that areas with poorer drinking water infrastructure performance are associated with historic HOLC designations, where "D" designations have the highest likelihood of experiencing more maintenance events and longer durations to complete emergency maintenance. To test this hypothesis, we use open data made available by the city of Seattle, Washington and statistical techniques to examine the relationship between historical decision-making and policy and contemporary inequities in drinking water infrastructure service in Seattle. By examining the relationship between redlining and infrastructure service quality, we provide a proof of concept that links historical actions to the present-day to help inform future research, regulation, and improvements relating to emergency maintenance and infrastructure justice.

4.2. MATERIALS AND METHODS

We employed geospatial and statistical techniques to examine associations between historical redlining distinctions and contemporary water infrastructure service inequities at the utility level. Using open infrastructure, census, and redlining map data, we used linear regression models to analyze the relationship between historical (i.e., redlining) inequities and 1) the number of contemporary maintenance and 2) contemporary completed household-weighted emergency maintenance durations to understand location-based inequities.

4.2.1. DATA SOURCES AND COLLECTION

This research pulls from multiple data sources: (1) the Mapping Inequality database (Nelson et al. 2020), (2) the 2022 American Community Survey (ACS) Census Data (US Census Bureau 2022), and (3) water main emergency data provided by Seattle Public Utilities (SPU) from the City of Seattle Public Records.

The Mapping Inequality database is the geospatial collaboration from the University of Richmond's Digital Scholarship lab that documents the redlining maps with area descriptions of over 200 cities across the United States (Nelson et al. 2020). Seattle, Washington was chosen for this proof-of-concept research given its data availability (i.e., water main emergency and redlining data). The spatial data for the City of Seattle contained 60 polygons with the following HOLC designations from 1936: A for "best," B for "still desirable," C for "definitely declining," and D for "hazardous." As the aim of the analysis was to examine relationships between redlining and the persistence of social inequities, we removed the polygons (n = 4) that received their redlining grade solely due to geographic conditions (e.g., slide areas) and did not include areas that did not receive the A through D grades (i.e., business and industrial areas). Data downloaded from the

2022 ACS included racial demographics, poverty, and population density at the census tract level. They were joined to the 2022 TIGER/Line shapefile for Washington state in ArcGIS Pro 3.1. As the boundaries of the census tracts and the redlining distinctions were dissimilar, the two layers were joined in ArcGIS to create a total of 307 regions that each have a unique combination of census tract GEOID and HOLC ID (e.g., 53033009600, A10). The census data, such as the number of households within each census tract, was calculated to be proportional to the shape area of each of the 307 regions. The HOLC grades and racial demographic data for each of the regions included in the final analyses are depicted in Figure 4.1.

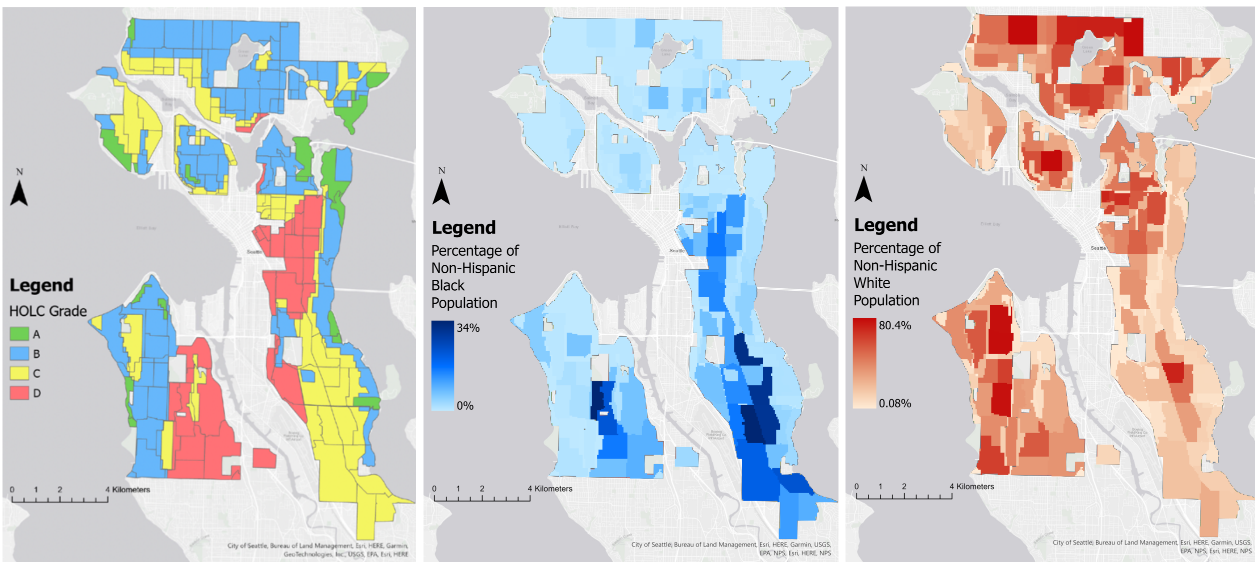

Figure 4.1: Maps of spatial distribution of HOLC grades (left) and select racial demographics: non-Hispanic Black population (middle) and non-Hispanic white population (right)

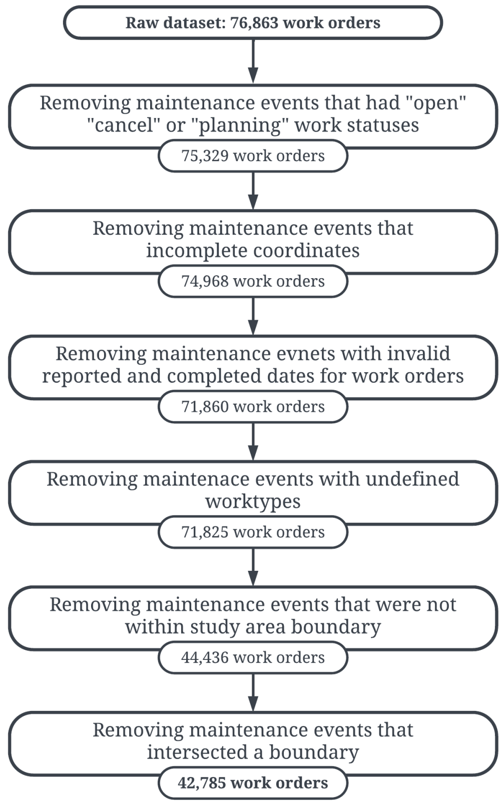

Figure 4.2: Process used for developing water maintenance dataset

The water main emergency dataset consists of 76,863 emergency maintenance events (i.e., work orders) reported by the public or SPU from 1998 to 2022. Each maintenance event included information on the type of maintenance completed (e.g., reactive, demand, predictive), geographic coordinates, and the date and time each maintenance event was reported, started, and completed. Maintenance duration was measured from when a work order was reported to when the work order was completed in a unit of hours. The process used to organize the data is described in Figure 4.2. We initially removed maintenance events with incomplete data (e.g., no coordinates, invalid durations, undefined work types) in Excel, resulting in 71,825 emergency maintenance events imported into ArcGIS Pro 3.1. After applying a 5-meter buffer around each maintenance event, we removed maintenance events that were not within the study area and that crossed a boundary to remove the possibility of double-counting and regions that did not contain maintenance events, resulting in 42,785 work orders and 274 regions. The descriptive statistics for the 274 regions are described in Table 4.1. Using the Spatial Join tool, we calculated the number of maintenance events within each region. We additionally calculated the mean maintenance duration for each region and weighted by the total households of each region within that census tract:

$$\frac{\sum(\text{number of households in region } a)\ x\ (\text{mean maintenance duration in region } a)}{\text{total number of households in study area}}$$

Applying the weights considers the number of households' impact on the calculated average of maintenance durations in each region.

There are many ways to measure performance, failure, and pipe condition related to drinking water utilities using techniques from various disciplines like asset management and machine learning (Li et al. 2014; Rasoulkhani et al. 2019; Rifaai et al. 2022). Borrowing metrics of performance used in various industries, such as the number of maintenance events (i.e., disruptions to service) and maintenance durations (i.e., lead times), provides an additional way to provide initial measurements of service quality that point out flaws in the system (Kaplan and Norton 1992; National Research Council 1996).

With the understanding that categorical work types would impact maintenance and durations, we completed statistical analyses on three separate datasets for all maintenance events (42,785 events in 274 regions), reactive maintenance (20,999 events in 268 regions), and condition-based maintenance (2,841 in 193 regions). SPU defines reactive maintenance as request-based maintenance that is usually more urgent and reacting to a call from the public (e.g., something broke in the field) and condition-based maintenance as a condition-monitoring type of maintenance driven by an internal inspection. In addition to examining overall maintenance, isolating reactive and condition-based maintenance allows for examining inequities in emergency response times and physical infrastructure conditions, respectively.

Table 4.1: Descriptive Statistics of Key Census and Water Maintenance Data

			HOLC Grade		
Characteristic	**A**	**B**	**C**	**D**	***Total***
Regions (% of total)	20 (7.3%)	109 (39.8%)	100 (36.5%)	45 (16.4%)	***274***
Drinking Water Maintenance Data					
Total Number of Maintenance Events (% of total)	2425 (5.7%)	19944 (46.6%)	12999 (30.4%)	7417 (17.3%)	***42785***

Condition-Based Maintenance (% of total)	66 (2.3%)	1366 (48.1%)	674 (23.7%)	735 (25.9%)	***2841***
Reactive Maintenance (% of total)	1313 (6.3%)	9577 (45.6%)	6397 (30.5%)	3712 (17.7%)	***20999***
Average Duration of Maintenance in Hours (St. Dev)	396.6 (586.6)	374.3 (646.3)	329.3 (303.9)	466.0 (401.7)	***374.6***
			Census Data		
Shape Area in km^2	7.51	48.92	36.65	22.9	**115.98**
Total Population (% of total)	10840 (2.8%)	176634 (44.9%)	125406 (31.9%)	80091 (20.4%)	**392971**
Non-Hispanic White Population (% of total)	8377 (3.5%)	123350 (51.6%)	68854 (28.8%)	38615 (16.1%)	**239197**
Non-Hispanic Black Population (% of total)	280 (1.0%)	5582 (19.1%)	12873 (44.0%)	10499 (35.9%)	**29234**
Non-Hispanic American Indian or Alaskan Native Population (% of total)	6 (0.05%)	441 (31.6%)	595 (42.7%)	352 (25.3%)	**1394**
Non-Hispanic Pacific Islander or Native Hawaiian Population (% of total)	1 (0.1%)	204 (19.7%)	456 (44.0%)	374 (36.1%)	**1036**
Non-Hispanic Asian Population (% of total)	936 (1.5%)	21597 (34.7%)	24473 (39.3%)	15270 (24.5%)	**62276**
Population Non-Hispanic Other Race (% of total)	66 (3.5%)	755 (40.3%)	711 (38.0%)	342 (18.3%)	**1874**
Population Non-Hispanic Two or More Races (% of total)	931 (2.4%)	17152 (44.8%)	11536 (30.1%)	8699 (22.7%)	**38318**
Hispanic or Latino Population (% of the total)	482 (1.6%)	12015 (40.4%)	9103 (30.6%)	8154 (27.4%)	**29754**

4.2.2 REGRESSION ANALYSES

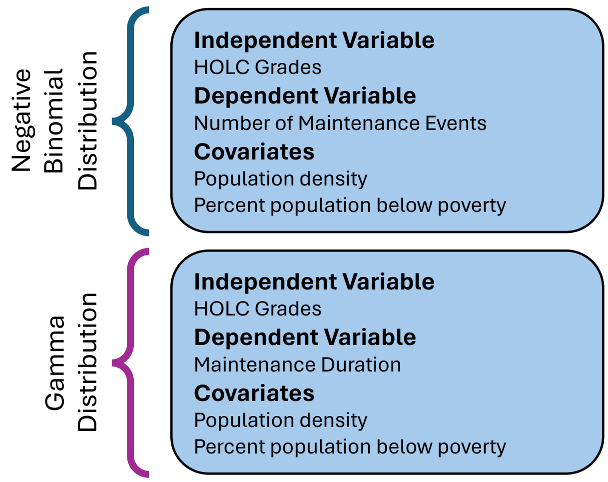

Figure 4.3: Visual representation of the statistical analyses

To examine the relationship between historical redlining distinctions and disparities with drinking water emergency maintenance, we completed two multivariate regression analyses described in Figure 4.3 in RStudio Version 2023.12.1+402 for each of the three datasets (i.e., all emergency maintenance, reactive maintenance, and condition-based maintenance events). The analyses that examined disparities related to the number of maintenance events and redlining distinctions used a negative binomial model with a log link function. The negative binominal dispersion is best suited for non-normal skewed discrete (e.g., count) data where the variance of the dependent variable is larger than the predicted mean, which works well with the nature of the dependent variable (Green 2021). Our second set of analyses that examined disparities related to the length of maintenance used a Gamma distributed model with a log link function, as the Gamma distribution is better suited for continuous data such as maintenance duration (Gustavsson et al. 2014). The HOLC grades serve as our explanatory variables, with population density and the percentage of the population below poverty included as covariates. As the chosen regression model outputs results as logarithmic odds, we report the exponentiated coefficient, where the presented value reflects the rate of change in the mean of the dependent variable compared to the intercept, considering the categorical nature of our independent variables (McCullagh and Nelder 2019).

We conducted two sensitivity tests to determine if 1) examining each region's median maintenance duration instead of the mean maintenance duration and 2) changing the buffer (e.g., 10 meters, 20 meters) around each maintenance event changes results odds for the number of maintenance events or the emergency maintenance durations related to HOLC grades. In the analysis, we present the results using the mean maintenance duration and 5-meter buffers, as they yield the most conservative results. There was no remarkable difference in the magnitudes nor significance levels of the exponentiated coefficients.

4.2.3 LIMITATIONS

There are several limitations to this study. For example, many variables not included in this analysis could impact the number of maintenance events and maintenance durations beyond the work type (e.g., dispatch locations, pipe age, traffic). Including these variables would allow for a more robust model that actively considers the physical components of drinking water infrastructure and should be considered for future analyses. Another limitation is that the HOLC redlining maps focused primarily on urbanized regions in the 1930s and 1940s. They do not include more rural areas, which have historically experienced disparities in infrastructure quality compared to urban areas (AWWA and AMWA 2020; Guo et al. 2024). As this research focuses only on areas that received HOLC grades, it only includes a subset of Seattle's current population and urban residential area. Lastly, the analysis was only done in Seattle. Although this analysis allows us to make inferences on the population, a more robust dataset would better account for the associations between historic redlining distinctions and contemporary drinking water infrastructure service across the country. Despite these limitations, we believe this research presents an opportunity to examine current infrastructure service quality within social demographics and historic redlining distinctions. Measuring infrastructure service quality is a nuanced and complex task that must often consider various water utility components and overall infrastructure capability. Like in environmental justice literature, this work does not aim to relate the causation of present-day infrastructure service to historical or contemporary racism but instead demonstrates notable associations that can drive equitable infrastructure investment. Future researchers and practitioners would be able to build on this work to examine infrastructure service quality at the utility level while rectifying potential disparities.

4.3. RESULTS

The results for the analyses connecting historic redlining distinctions and contemporary infrastructure performance metrics (i.e., the number of maintenance events and maintenance durations) are presented in Tables 4.2 and 4.3. Figure 4.4 depicts the spatial distribution of the number of maintenance events and the weighted maintenance durations for all maintenance types, reactive maintenance alone, and condition-based maintenance alone.

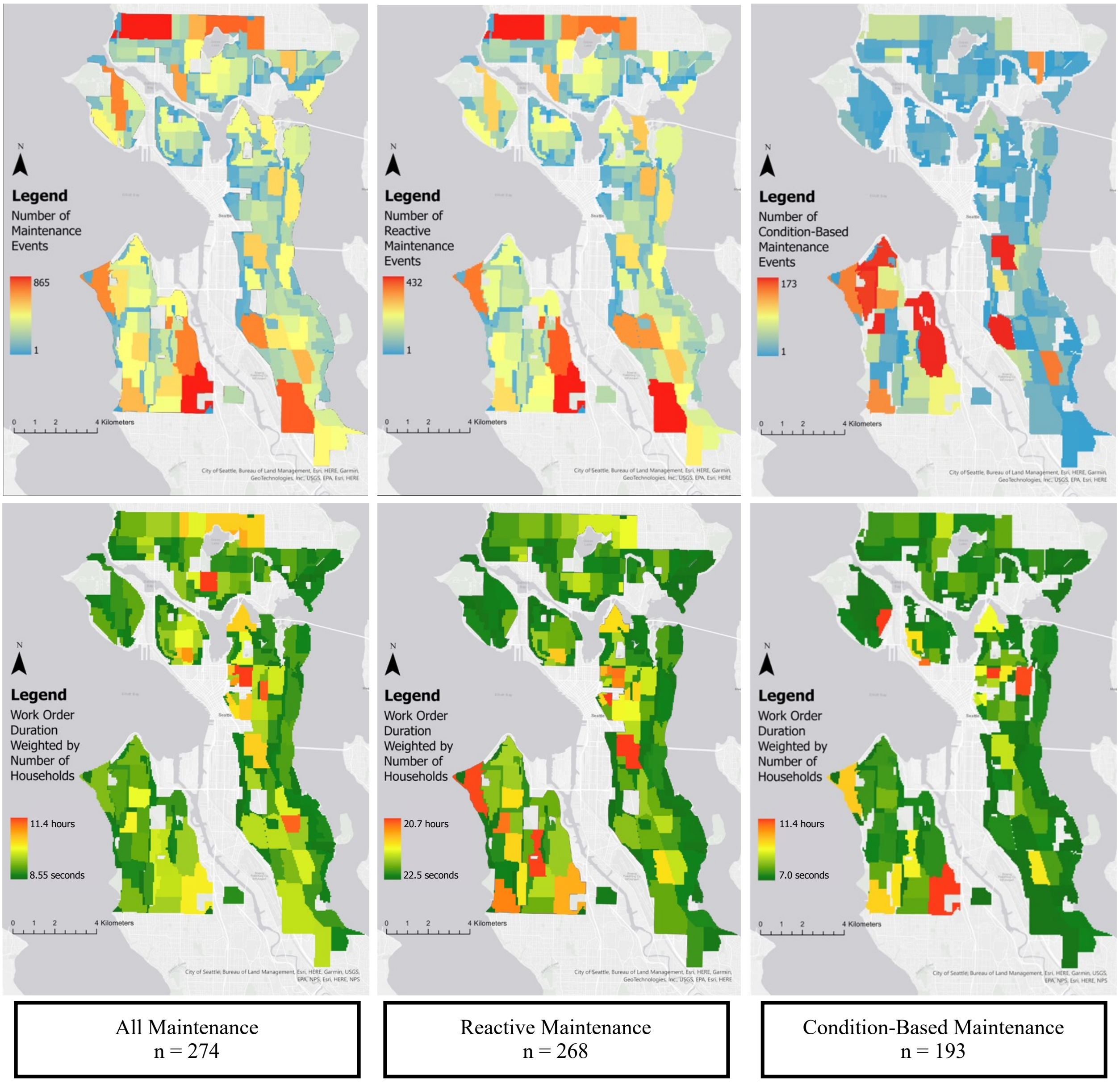

Figure 4.4: Maps depicting spatial distributions of number of maintenance events (top row) and duration of maintenance (bottom row) for all maintenance types, reactive maintenance, and condition-based maintenance, where n refers to the number of regions

Statistical significance is observed when examining the relationship between condition-based maintenance of water infrastructure and redlining distinction. The odds of experiencing a maintenance event increased by a rate of 3.776 for the B redlining distinction, 2.475 for the C redlining distinction, and 5.329 for the D redlining distinction, with the A redlining distinction as the reference. Additionally, the odds of experiencing longer maintenance durations are the highest for the D redlining distinction (18.79), followed by the C redlining distinction (5.799) and the B redlining distinction (1.067), with the A redlining distinction again as the reference.

The analyses examining the number of maintenance events tend not to have statistical significance on coefficients outside the intercept (i.e., A redlining distinction). The odds of having maintenance events were the highest for the B redlining distinction (a rate of 1.524 times greater than the A distinction), followed by the C redlining distinction (a rate of 1.056 greater than the A distinction), and the D redlining distinction (a rate of 1.012 greater than the A distinction). A different ranking was found when isolating for reactive maintenance, in which the odds of experiencing a maintenance emergency increased by a rate of 1.419 for the B redlining distinction, decreased by a rate of 0.992 for the C redlining distinction, and increased minimally by a rate of 1.001 for the D redlining distinction, compared to A redlining distinction.

In the case of all maintenance types, the odds of experiencing longer maintenance durations increase by a rate of 2.058 for the B redlining distinction, 1.236 for the C redlining distinction, and 2.296 for the D redlining distinction referenced to the A redlining distinction. Here, statistical significance is observed on all redlining distinctions except the C distinction. Reactive maintenance durations are predicted to increase the most for the B redlining distinction (2.354) and increase by a rate of 1.142 for the C redlining distinction and 1.578 for the D redlining distinction compared to the A redlining distinction. Here, statistical significance is only observed on the intercept and the B redlining distinction.

Table 4.2: General Linear Model Regression Results of Number of Maintenance Events Associated with Redlining Distinctions

Independent Variables	All Maintenance		Reactive Maintenance		Condition-Based Maintenance	
	Rate	CI (95%)	Rate	CI (95%)	Rate	CI (95%)
A Redlining Distinction (Intercept)	138.9***	89.32 – 232.4	76.93***	50.68 – 124.4	6.131***	3.255 – 12.98
B Redlining Distinction	1.524	0.8720 – 2.512	1.419	0.8423 – 2.273	3.760***	1.695 – 7.570
C Redlining Distinction	1.056	0.6023 – 1.752	9.992	0.5875 – 1.622	2.429**	1.082 – 4.968

D Redlining Distinction	1.012	0.5481 – 1.799	1.001	0.5624 – 1.727	4.895***	2.079 – 10.73
Observations	274		268		193	
Log Likelihood	-1,613.784		-1,393.190		-694.870	
Theta	0.862*** (0.066)		0.987*** (0.079)		0.787*** (0.076)	
Akaike Inf. Crit.	3,239.569		2,798.379		1,401.739	

Note: *p<0.1; **p<0.05; ***p<0.01

Table 4.3: General Linear Model Regression Results of Weighted Maintenance Durations Associated with Redlining Distinctions

Independent Variables	All Maintenance		Reactive Maintenance		Condition-Based Maintenance	
	Rate	CI (95%)	Rate	CI (95%)	Rate	CI (95%)
A Redlining Distinction (Intercept)	0.3602***	0.2047 – 0.7181	0.2698***	0.1363 – 0.6487	1.501	0.5202 – 7.54
B Redlining Distinction	2.058**	0.9796 – 3.917	2.354**	0.9138 – 5.225	1.067***	1.9800 – 36.05
C Redlining Distinction	1.236	0.5765 – 2.422	1.142	4.302 – 2.667	5.799**	1.004 – 22.64
D Redlining Distinction	2.296**	1.002 – 4.950	1.578	9.5591 – 1.134	18.79***	3.096 – 81.88
Observations	274		268		193	
Log Likelihood	-292.082		10.734		-475.347	
Akaike Inf. Crit.	596.164		-9.467		962.694	

Note: *p<0.1; **p<0.05; ***p<0.01

4.4. DISCUSSION

The results of this regression analysis demonstrate an association between historic redlining distinctions and contemporary water infrastructure maintenance. They describe the perpetuation of location-based inequities. Specifically, the analyses examining condition-based maintenance show that regions with D redlining distinctions have a higher likelihood of experiencing more maintenance events and longer maintenance durations, suggesting a difference in the infrastructure condition. Based on our results, we believe that future research is needed to explore (1) the influence of contemporary demographics and impacts on racial inequities and (2) the role that each examined maintenance work type serves in understanding the relationship between redlining distinctions and infrastructure service quality. Overall, this analysis establishes a foundation for future research that examines how the physical technical system, internal planning and management, and local contexts influence drinking water maintenance.

4.4.1. MAIN FINDING: POTENTIAL FOR WORSE INFRASTRUCTURE CONDITION IN REDLINED AREAS

The strongest support for our hypotheses was found when examining the relationship between historical and contemporary injustices in condition-based maintenance. Regions that previously received the D designation have the highest odds of experiencing condition-based maintenance and longer durations for condition-based maintenance. The condition of water distribution networks depends on numerous factors such as pipe age, diameter, length, and material (Barton et al. 2019; Folkman 2018; Ortega-Ballesteros et al. 2021). Cast iron pipes also tend to be the oldest materials used in distribution systems, with several miles of cast iron pipes placed in the 1930s and 1940s during the era of HOLC designations (Folkman 2018). As the legacy of redlining has demonstrated a history of disinvestment, the combination of old pipes and traditionally used pipe materials would impact the present-day condition of water infrastructure. In Seattle, pipe materials vary between cast iron and ductile iron placed at opposite ends of the 20th century (i.e., cast iron in the early 1900s and ductile iron in the late 1900s). Areas with the D distinction, such as the historically labeled “Negro area of Seattle,” have primarily cast-iron pipes, some of which were installed in 1890 (Nelson et al. 2020).

SPU considers condition-based maintenance to be a work type driven by internal inspections rather than public calls (e.g., response to main breaks in the distribution system). This suggests that utility staff have identified these regions as locations with infrastructure that needs improvement. These results show that previously redlined areas disproportionately need infrastructure investment. As historically marginalized populations tend to be still concentrated in the lower redlining grades, this is important infrastructure justice work. With the implementation of Justice40 and similar policies that target improving infrastructure justice (Hoague et al. 2023; Schott and Whyte 2023), it should be ensured that previously redlined areas around the nation are included in benchmarks when determining which areas should receive investment.

4.4.2. ADDITIONAL INFERENCES

4.4.2.1. POTENTIAL INFLUENCE OF CONTEMPORARY DEMOGRAPHICS

The establishment of HOLC redlining grades in the 1930s and 1940s not only influenced the state of soft and hard infrastructure but also shaped the spatial distribution of racial demographics in the United States (Asher 2021; Perzynski et al. 2023; Sterling et al. 2023). Although gentrification, urban flight, and other intra-urban migrations have impacted the racial makeup of urban centers, Black and other disenfranchised populations tend to be concentrated in historically redlined C or D regions (Aaronson et al. 2021; Freeman and Sunshine 1976). For example, approximately 80% of the Black population resides in the C or D redlining distinctions in Seattle, corroborating previous studies regarding the contemporary racial compositions of historical HOLC grades (Aaronson et al. 2021). However, these populations interact with public services the least due to the historic disengagement between government entities and marginalized populations (Brandt et al. 2015).

There is a history of racial inequity related to water infrastructure service in the United States, primarily associated with water affordability and access (Jaffee 2024; Montag 2019; Osman and Faust 2021). Considering this history and lack of communication, the larger percentage of marginalized communities in C and D redlining distinctions could contribute especially to the number of maintenance events in those redlining distinctions. The presence of historically marginalized races could impact maintenance durations, as demonstrated in the literature observing longer medical emergency response times for underserved and marginalized communities (Hsia et al. 2018; Mell et al. 2017).

Future research should continue to examine the relationship between redlining distinctions and present-day demographics to understand the influence of contemporary racial demographics. Furthermore, in understanding the impacts of location-based inequities as presented in this analysis, stakeholders at water utilities should actively consider the sociodemographic factors that could impact infrastructure service. For example, regularly issued customer climate surveys that are geographically identified by zip code and question customers about their perception of infrastructure service would present water utilities with the opportunity to begin assessing customer sentiments in comparison to measured location-based disparities.

4.4.2.2. ROLE OF MAINTENANCE TYPES IN LOCATION-BASED INEQUITIES

Drinking water infrastructure maintenance encompasses a variety of components, including but not limited to pipe installation, treatment, service lines, and plant equipment

(American Water Works Association 2023). SPU categorizes these different aspects of maintenance within seven work-type classifications: condition-based, reactive, demand, predictive, preventative maintenance, overhead activities, and projects. Different work types are expected to have different durations (e.g., a large-scale capital project to replace a water main line could take longer than a routine replacement), so analyses that isolate a specific type of maintenance may more accurately measure maintenance service quality. For example, while maintenance durations are likelier to be the greatest in the D redlining distinctions across all maintenance types, the B redlining distinction has higher odds of experiencing longer maintenance durations for reactive maintenance. Reactive maintenance refers to the maintenance that the public calls explicitly in and reports to the water utility. Thus, the larger population in B distinctions could explain the higher odds of reactive maintenance, as it is the most represented HOLC grade in Seattle.

Due to the various considerations that come with different types of maintenance, future research should incorporate variables related to the technical system (e.g., pipe material, dispatch locations) to predict better the relationship between redlining distinction and metrics of infrastructure service quality. For example, SPU and other utilities can continue to isolate a single type of maintenance for analyses but include considerations related to internal maintenance procedures to provide additional context to potential relationships between redlining and water infrastructure.

4.5. CONCLUSION

Water infrastructure performance is dependent on a variety of factors ranging from technical system components to internal planning and management and should be measured within the context of user needs and location. Variations in water infrastructure performance at the utility level can be understood by examining historical inequities as done in observations of other infrastructure systems. Using geospatial and statistical techniques, we studied the association between historical redlining distinctions and infrastructure service measured by the number of maintenance events and the duration of maintenance events. We found that redlining D distinctions have the highest likelihood of experiencing condition-based maintenance events and longer durations for condition-based maintenance. Contemporary racial demographics are strongly linked to historic demographic distributions (Aaronson et al. 2021). This means the inequitable impacts of historic racist policies are still being felt today. This research provides a proof-of-concept that can be replicated in other cities with similar datasets and for other critical infrastructure types to link historical redlining distinctions to metrics of contemporary infrastructure service.

CHAPTER FIVE: SUMMARY AND CONCLUSIONS

The aim of the three studies was to explore the resilience of drinking water infrastructure within the contexts of crises (i.e., slow-onset disasters) and communities (i.e., marginalized populations). Given the ongoing crisis of infrastructure deterioration, this work answers the question of what drinking water infrastructure issues arise during slow-onset disasters and what those implications might be for the most historically disenfranchised communities. Generally, the research presented here suggests that slow-onset disasters provide complex challenges to the planning, management, operations, and maintenance of drinking water infrastructure. However, with the use of resilience dimensions and sociotechnical system framing, different magnitudes of solutions arise that align with the varying scales (e.g., national-level, state-level, and city-level) explored in this research. When implemented, these solutions offer avenues for equitable infrastructure improvement to benefit the marginalized populations the explored drinking water infrastructure systems serve. Figure 5.1 summarizes the research questions and contributions from each chapter in the dissertation.

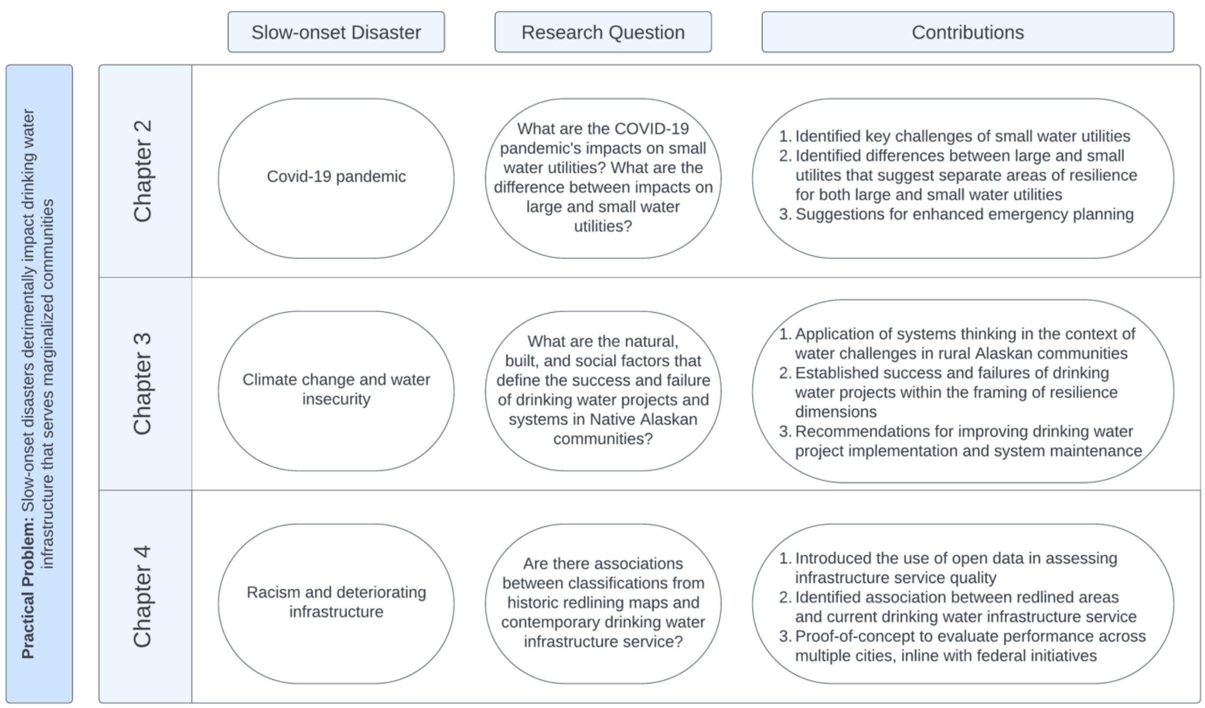

Figure 5.1: Dissertation summary

Beginning at the national level in Chapter 2, my collaborators and I used deductive and inductive qualitative coding approaches of semi-structured interviews with stakeholders at small and large water utilities across the United States to determine how the COVID-19 pandemic lockdowns influenced water utilities. The research revealed that small and large drinking water utilities experienced difficulty with supply chain, finances, and personnel management. However, existing conditions (e.g., a lack of personnel and lower financial reserves) magnified issues for small drinking water utilities, further adding strain to the small and often rural communities that small drinking water utilities serve. This observation was further supported by statistically significant differences in the experiences of small and large water utilities under the categories of personnel management, revenue change, and increase in delinquent accounts, speaking further to the different economies of scale that sustain the challenges faced by smaller communities.

Chapter 3 continues focusing on small and rural communities by transitioning to the state level. The study explored the successful and failed project attributes of implementing drinking water infrastructure in Alaskan Native communities across the state under the threat of climate change and water insecurity. Using a systems perspective adapted from the resilience dimensions (i.e., natural, built, and social) to analyze interviews with stakeholders involved with drinking water projects in the state, my collaborators and I revealed that projects are the most successful water systems emphasize community engagement and buy-in to ensure system longevity. On the other hand, a lack of maintenance, usually caused by poor financial capacity, would lead to drinking water projects that fail over time despite a robust and supported initial implementation. This work demonstrates the necessity of community inclusion throughout the project implementation process and the benefit of using sociotechnical approaches to solution-making that actively consider the capacity, culture, and geography within rural Alaskan Native communities.

The research in Chapter 4 narrows the scope to the city level to examine the associations between historic redlining distinctions, which used racial composition to deny investment in certain areas, and contemporary drinking water infrastructure service. Our analysis found that the redlining D distinction experienced the most condition-based maintenance events and the most prolonged condition-based maintenance events, suggesting worse drinking water infrastructure quality in these areas. Additionally, we revealed areas for future research that examine the influence of contemporary demographics and the role of maintenance types in location-based inequities.

5.1. CONTRIBUTIONS TO PRACTICE

The final findings from this research can be referenced and used in numerous ways, with each study providing different solutions within the various magnitudes of impact. The results from Chapter 2 indicate the need to strengthen government subsidies for water utility personnel recruitment and retention and support local organizations that promote mutual aid agreements for public and private utilities (U.S. Environmental Protection Agency 2021a). As disasters that unexpectedly impact water utilities increase in the future, putting financial support into organizations like the Rural Community Assistance Partnership and the National Rural Water Association can assist with developing more robust emergency response planning that responds to both rapid and slow-onset disasters. Additionally, stakeholders at small water utilities can incorporate the study's suggestions in their planning (e.g., building networks and partnerships with neighboring utilities). At the state-level scale, the results from Chapter 3 provide actionable considerations for aid organizations outside of rural Alaskan Native communities interested in implementing drinking water projects. Similar to the national scale recommendations, the results of this study additionally point to further support for subsidies for organizations like the Northwest Arctic Borough to ensure operation and maintenance costs are economical. Furthermore, entities looking to implement drinking water projects in rural Alaskan contexts should hold community buy-in as paramount. Lastly, the results in Chapter 4 will provide direct recommendations at the city level. The developed maps can be used to inform Seattle Public Utilities on areas of improvement for water utility service quality. Beyond the city of Seattle, the research provides a proof-of-concept linking redlining distinctions to infrastructure performance that can be replicated in different cities and for different types of infrastructure. Moreover, it can include various aspects of the technical system, planning, and management that maintain critical infrastructure systems.

Overall, the findings from the studies in the proposed dissertation align with the goals of the Bipartisan Infrastructure Law and the Justice40, which actively aims to bring resources to disadvantaged communities. As lawmakers in the United States seek to improve its infrastructure through this bill and additional policies, it is necessary to ensure that investment and improvement are done in an equitable manner that takes economies of scale, historical considerations, and racist policy into consideration. Additional steps must be taken to incorporate equity benchmarks in water infrastructure at the federal level and in localized contexts (Osman and Faust 2021). However, the research that continues to develop by examining the relationship between slow-onset disasters, critical infrastructure, and marginalized communities will be essential for identifying problems and solutions for equitable water infrastructure improvement.

5.2. THE PATH FORWARD

While each study in this dissertation presents results and solutions that can be applied in practice, this dissertation also uniquely presents areas for future research. The development of further research can unveil additional considerations for the planning, management, operations, and maintenance of drinking water infrastructure during disaster contexts. Furthermore, results of future analyses may continue to provide insights on how policy and legislation at all scales may be adapted to ensure infrastructure justice.

For example, the work presented in Chapter 2 focuses on the resilience of small drinking water utilities (i.e., drinking water utilities with a customer size of less than 10,000) and the difference in resilience compared to large drinking water utilities. However, as this study used stratified sampling to collect stakeholder data, there were no additional considerations in specifying the different types of small drinking water utilities. While small drinking water utilities generally face issues due to their economies of scale, the resilience of these utilities varies due to ownership. For example, whether an investor-owned company owns a privately-owned small drinking water utility may influence the utility's financial capacity (US Environmental Protection Agency 2011). Future research that longitudinally examines the disconnect between small and large water utilities during disasters should consider identifying characteristics of water utilities that may impact resilience. Building on the work established in this dissertation, a potential study can focus on small water utilities challenges with supply chain challenges related to the COVID-19 pandemic and examine the disparate impacts between the types of small water utilities. This work could demonstrate the challenges of a specific kind of small water utility to inform additional considerations for state and federal organizations that support these small water systems.

As previously described, the analysis of the successful and failed attributes of drinking water projects and systems using built, natural, and social system factors in Chapter 3 demonstrates systems thinking when approaching issues within the rural Alaskan context. Systems thinking, and specifically the application of sociotechnical systems thinking, broadens our ability to assess the interconnectedness of a problem to inform the development of solutions (Ottens et al. 2006). Exploratory research can expand upon the results presented in this dissertation by applying systems dynamic models. This work could have the capability to model the feedback loops and interconnectedness found with drinking water project implementation that additionally considers the built, natural, and social system factors described in this research. Considering the various applications of systems thinking in the literature related to water infrastructure (Ahmad and Prashar 2010; Park et al. 2014; Rehan et al. 2011), its continued application when assessing drinking water infrastructure in rural Alaskan contexts allows for an enhanced assessment of how the physical landscape, water utility's capacity, and consumer needs impact success and failure.

Perhaps one of the most novel and potentially timely avenues for future research originates from the work presented in Chapter 4. The chapter primarily focuses on the associations between redlining distinctions and contemporary infrastructure service quality and provides inferences for implications for current populations based on sociodemographics and locations. Rather than mainly focusing on historical injustices, future research could examine the potential of *contemporary injustices* by examining different sociodemographic factors associated with infrastructure service quality while controlling for redlining distinctions and aspects of the technical system. This work would broaden the realm of infrastructure justice by demonstrating the influence of location-based and social-based inequities related to infrastructure service that could be applied at a larger scale, given infrastructure data availability. I plan on continuing this exploration next as my collaborators and I gather more data to enhance our models.

5.3. WHAT NEXT?

This dissertation was developed with the idea of drinking water infrastructure operations during disasters and soon evolved into an assessment of drinking water infrastructure, slow-onset disasters, and marginalized communities at different scales. The studies present various ways that the PMOM of drinking water infrastructure can be impacted during emergencies and what considerations this would have for enhancing infrastructure justice. Overall, this dissertation applies frameworks from other schools of thought (i.e., sociotechnical systems thinking, resilience, and disaster research) to demonstrate a way to examine this interaction. In totality, the work suggests that there is not a one-size-fits-all solution for drinking water infrastructure during disasters. Still, there are a variety of resolutions that can be developed to help improve water infrastructure services and lessen existing inequities. Regardless of the method used, level of governance explored, or population examined, each study demonstrates the challenges that drinking water infrastructure faces. As the government and water utilities in the United States begin the arduous task of replacing drinking water infrastructure, I hope that the research presented in this dissertation may inspire relevant stakeholders to prioritize equity when enhancing water infrastructure planning, management, operations, or maintenance.

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APPENDIX A: Supporting Information for Chapter 2

Table A.1: Interviewee and Drinking Water Utility Information for all Small and Large Utilities Included in Study

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
Alabama	1	Water Resources Management Director	10,001-100,000
Arizona	1	Water Director	10,001-100,000
Arizona	1	General Manager	10,001-100,000
Arizona	1	Operations Manager	100,001 - 1 million
Arizona	1	Deputy Director	100,001 - 1 million
California	1	Operations and Maintenance Director	100,001 - 1 million
California	1	Operations Manager	>1 million
California	4*	Varying roles	100,001 - 1 million
California	1	Assistant General Manager of Operations/Engineering	100,001 - 1 million
California	1	General Manager	500 - 3,300
California	6*	Varying roles	>1 million
Colorado	2	Deputy Director of Public Works; Drinking Water Program Supervisor	100,001 - 1 million
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
Colorado	2	Project Manager; Senior Lead Operator	10,001-100,000
Connecticut	1	President	< 500
Connecticut	1	Supply Operations Manager	100,001 - 1 million
Kentucky	2	Vice President of Communications and Marketing; Manager of Distribution Water Quality	100,001 - 1 million
Massachusetts	1	Assistant Superintendent	10,001-100,000
Michigan	1	Water Quality Manager	100,001 - 1 million
Michigan	1	Deputy Director of Water & Wastewater	100,001 - 1 million
New Jersey	1	Superintendent	100,001 - 1 million
Oregon	1	Superintendent	3,301 - 10,000
Oregon	1	Water Quality Manager	>1 million
Oregon	2	Director of Water Quality & Treatment; Human Resources Manager	100,001 - 1 million
Texas	2	Assistant Director; Supervising Engineer	>1 million
Texas	1	Water Treatment and Compliance Manager	10,001-100,000
Texas	4*	Varying roles	>1 million
Texas	1	Building Manager	**University campus
Utah	1	Water Quality & Treatment Administrator	100,001 - 1 million
Washington	1	Senior Environmental Specialist	100,001 - 1 million
Washington	1	Senior Water Quality Engineer	>1 million
Washington	10*	Varying roles	100,001 - 1 million

*was a focus group conducted online; **interview was with practitioners at a university campus

Table A.2: Example of Interview Questions for Small Drinking Water Utilities

Interview Question	Resulting Parent Codes from Interviewee Responses
In your experience, how has COVID-19 impacted your water system?	General
Did your water utility activate an emergency response plan?	Planning and Management
If you use disinfectant in your water utility, did you have consistent residuals?	Technical System
Was there any stimulus dollar anticipation to support spending during the pandemic?	Finances
Did the utility experience an increase in customer calls?	Community-Related
Based on your experience, how do you think the COVID-19 pandemic impacted small and large drinking water utilities differently?	Comparison Between Small and Large Utilities

Table A.3: Coding Dictionary for Parent Codes

Code	Definition	Example of an Excerpt

Planning and Management	Discussions regarding planning and management, including supply chain and workforce management	"Well, when it all started, of course, we went into very cautionary status, manipulated scheduling, changed some workloads… to minimize contact within the staff itself."
Technical System	Discussions related to the technical system, including demand change, water quality, and operations and maintenance	"It was probably on the magnitude of a 20 or 30% increase on the day-to-day flows."
Finances	Discussions regarding finances, including revenue change and moratoriums	"There was a small number of folks that were not able to make payment, and there was a moratorium imposed on cutting off people's accounts."
Community-Related	Discussions related to the community, including outreach initiatives and customer service	"Yes, for both systems… are actually managed by homeowner associations. And they continued their meetings although they changed the format to do those virtually."
Comparison Between Small and Large Utilities	Discussions regarding the difference between smaller and larger water utility operations during the pandemic	"I am going to hypothesize that the smaller water utilities had less challenges from the standpoint of logistics because there are fewer people involved and fewer contact points or meetings."

Table A.4: Frequency Tables for Selected Large and Small Water Utility Challenges, Changes, and Responses

Code	Small Water Systems		Large Water Systems	
	Number of DWUs	*Count of Responses (Relative Frequency)*	*Number of DWUs*	*Count of Responses (Relative Frequency)*
Excerpts about Utilities' Changes, Challenges	***26***	***626 (100.0%)***	***28***	***880 (100.0%)***
Planning and Management	***26***	***317 (50.6%)***	***28***	***536 (60.9%)***
Change in capital projects (e.g., delayed, increased during shutdown)	*12*	19 (2.9%)	14	17 (1.9%)
Institutional collaboration (e.g., conferences canceled, working with government/unions)	18	38 (6.1%)	5	19 (2.2%)
Planning	*25*	*31 (5.0%)*	*23*	*47 (5.3%)*
Activated/used emergency response plan or created/improved a pandemic plan	9	9 (1.4%)	20	28 (3.2%)
Other (pandemic) planning (e.g., front-end planning, for a possible recession)	6	6 (1.0%)	14	19 (2.2%)
Supply chain	26	86 (13.7%)	28	100 (11.3%)
Difficulty procuring or worry about routine supplies (e.g., chemicals, valves)	16	16 (3.7%)	16	30 (3.6%)
Difficulty procuring personal protective equipment (PPE) or sanitation materials	12	12 (1.9%)	20	30 (3.6%)
Innovative actions to meet supply chain issues (e.g., in house manufacturing)	1	1 (0.2%)	6	8 (0.9%)
Late-stage supply chain issues	15	18 (2.9%)	0	0 (0.0%)
Workforce Related	24	116 (18.5%)	28	283 (32.2%)

General shift changes or furloughs for all staff	11	20 (3.2%)	7	8 (0.9%)
New workplace policies (*e.g.,* social distancing, cleaning, leave policies, vehicle rules)	15	29 (4.6%)	22	54 (6.1%)
Concerns of staffing (e.g., family leave, retiring early, lack of staff)	14	20 (3.2%)	7	12 (1.4%)
Technology usage for virtual work	12	15 (2.4%)	10	12 (1.4%)
Finances	**25**	**61 (9.7%)**	**24**	**102 (11.6%)**
Billing (e.g., customer payments, rates, revenue)	25	61 (9.7%)	22	76 (8.6%)
Increase in delinquencies or enrollment in customer assistance programs	12	14 (2.2%)	13	25 (2.8%)
Revenue Change	20	22 (3.5%)	14	21 (2.4%)
Decrease in revenue	8	9 (1.4%)	12	19 (2.2%)
Increase in revenue	2	2 (0.3%)	2	2 (0.2%)
Spending or financial capacity	6	7 (1.1%)	3	3 (0.3%)
Increase in expenditures (due to social distancing policies or expected budget cut)	6	7 (1.1%)	3	3 (0.3%)
Technical System	***26***	**145 (23.1%)**	***25***	**135 (15.3%)**
Demand and water use	*25*	40 (6.3%)	*24*	91 (10.3%)
Overall system demand	25	40 (6.3%)	13	22 (2.5%)
Decrease in overall demand	0	0 (0.0%)	10	15 (1.7%)
Increase in overall demand	12	13 (2.1%)	3	7 (0.7%)
Non-critical maintenance deferred, slowed, or stopped at one point	2	2 (0.3%)	*9*	14 (1.6%)
Water quality	*23*	58 (9.3%)	*6*	12 (1.4%)
Disinfectant residuals	22	22 (3.5%)	4	6 (0.7%)
Higher than normal residuals	0	0 (0.0%)	1	1 (0.1%)
Lower than normal residuals	1	1 (0.2%)	3	5 (0.6%)
Community-related	***26***	**79 (12.6%)**	***21***	**72 (8.1%)**
Change in customer service operations (e.g., reduced hours, in-person service suspended)	11	12 (1.9%)	7	9 (1.0%)
Adapted outreach strategies (e.g., building flushing protocols, safety information, virtual)	18	31 (5.0%)	19	38 (4.3%)
Customer calls or complaints	*22*	29 (4.6%)	*9*	14 (1.6%)
Decrease in customer calls (e.g., because no shutoffs)	1	1 (0.2%)	4	6 (0.7%)
Increase in customer complaints/concerns (e.g., aesthetics, worry about water safety)	6	8 (1.3%)	6	8 (0.9%)

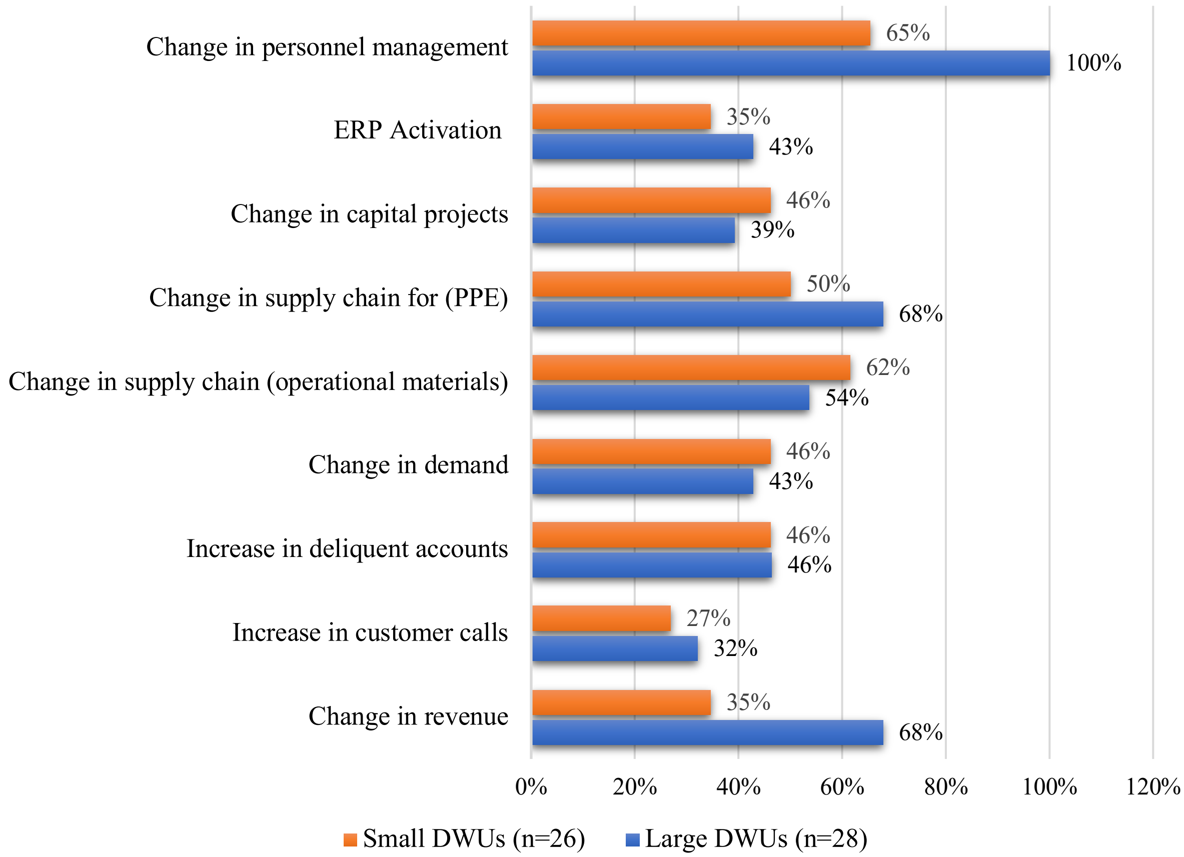

Figure A.1: Comparison between small and large utility experiences in selected categories

Table A.5: Observed and Expected Values for Chi-Squared Analyses

Customer Calls			
Utility	**Interviewee Response**	**Observed Frequency**	**Expected Frequency**
Large	Yes	9	7.62
Small		7	8.38
Large	No	11	12.38
Small		15	13.62
Change in Revenue			
Utility	**Interviewee Response**	**Observed Frequency**	**Expected Frequency**
Large	Yes	19	16.00
Small		9	12.67
Large	No	5	8.57
Small		10	6.79
Increase in Delinquent Accounts			
Utility	**Interviewee Response**	**Observed Frequency**	**Expected Frequency**
Large	Yes	13	9.52
Small		12	13.69

Large	No	3	5.33
Small		11	7.67

Change in Demand

Utility	Interviewee Response	Observed Frequency	Expected Frequency
Large	Yes	12	12.00
Small		12	14.29
Large	No	9	11.00
Small		13	13.10

Change in Supply Chain - Operation Materials

Utility	Interviewee Response	Observed Frequency	Expected Frequency
Large	Yes	15	15.50
Small		16	19.19
Large	No	6	8.00
Small		10	9.90

Change in Supply Chain - PPE

Utility	Interviewee Response	Observed Frequency	Expected Frequency
Large	Yes	19	16.76
Small		13	15.24
Large	No	3	5.24
Small		7	4.76

Change in Capital Projects

Utility	Interviewee Response	Observed Frequency	Expected Frequency
Large	Yes	11	10.40
Small		12	12.05
Large	No	8	8.14
Small		10	9.43

Activated ERP

Utility	Interviewee Response	Observed Frequency	Expected Frequency
Large	Yes	12	9.00
Small		9	12.50
Large	No	6	9.43
Small		16	13.10

Personnel Management

Utility	Interviewee Response	Observed Frequency	Expected Frequency
Large	Yes	28	36.43
Small		17	24.64
Large	No	6	9.71
Small		6	6.57

APPENDIX B: Supporting Information for Chapter 3

Table B.1: Occupation Information of Respondents

Number of Respondents	*Current Roles**	*Combined Years of Applicable Experience*
1	Geophysicist	25
2	Water pump service provider	92
2	Researcher in engineering, Alaskan rural water, or arctic research	21
7	Engineer/project manager/construction manager	176
8	Director/program manager for environmental health, drinking water, facilities, operator certification, and/or remote maintenance	136

* Retirees classified under last contributing role in Alaska rural water supply projects/systems.

Table B.2: Demographic Information of Respondents

Gender		
Category	*Number*	*Percentage*
Woman	2	10%
Man	11	55%
Preferred not to Respond	7	35%
Race		
Category	*Number*	*Percentage*
White (including Middle Eastern)	11	55%
Asian	1	5%
Alaska Native/American Indian	1	5%
Other	1	5%
Preferred not to Respond	6	30%

Table B.3: Complete Interview Protocol for Respondents

What Are We Asking About	**Why Are We Asking This**	**Question**
Consent		Detail confidentiality plans and remind respondents that we will not publish their names or organization names. With permission, we will audio record.

Role		Can you please tell me about your current role at your workplace? Please include your years of experience. Can you please tell me about your experience with drinking water in rural Alaska? How much of your experience has been with groundwater? (follow up: Have you dealt with groundwater contaminated with arsenic, iron or manganese?)
Water then groundwater*	Define Success & Failure for Water Projects	How would you define success for water supply projects in the rural AK context? (Please think of water supply broadly, including accessing a water source, treating water, delivering water to users, acceptance and use of treated water, life cycle of treatment materials, etc.) Similar question - how would you define failure for water supply projects in the rural AK context? What about groundwater projects? Is there anything different about the use of groundwater in this context? What are some reasons why groundwater is developed as a water source in rural Alaska? How do you think climate change has or will affect water supply projects in rural Alaska? (follow up: are any of these unique to groundwater?)
Water then groundwater*	Brainstorm & Explain	To start us off, could you brainstorm with me as many factors as possible that matter for drinking water supply in rural Alaska. Please tell me a little more about each of those factors. Revisiting your list is there anything on there that would be unique to or different for groundwater? …. And how might FACTOR be different for groundwater contaminated with arsenic, iron or manganese?
Groundwater specific*	Geographic & Discipline Context	What do folks used to working outside of the rural AK context not understand about groundwater supply in AK? What do folks outside of your discipline not understand about providing groundwater in this context? In your experience, what are some things, big or small, that may get ignored when people try to provide clean (drinking) water using groundwater in rural Alaska?
Groundwater specific*	Good/Bad Projects	Can you please tell me about any really successful groundwater supply projects you've seen or even heard of? From your point of view, why do you think they were so successful? What about any groundwater supply projects you've seen or heard of that went badly? From your point of view, why do you think they failed? In a perfect world, what would you make sure happened in every groundwater supply project?
Water then groundwater*	Equity	I'd like to ask you to think out loud about issues of equity and inclusion in rural AK water supply. From your perspective, how have you seen water projects impact equity or power dynamics in communities? Reversing the question - how might equity or power dynamics impact AK water supply projects? What about groundwater? Are there any equity & inclusion issues specific to the use of groundwater that we should know about?
Snowball		Who else should we be talking to? Can you help put me in touch with them to ask for an interview? What should we have asked you, but didn't?

*Although the presented line of questioning focuses on groundwater, interview respondents answered generally about all water sources

Table B.4: Coding Dictionary for Factors that Matter to Drinking Water Projects

System	System Factor	Definition	Example of Defining Factor
Built	Operations and maintenance	Related to general descriptions of technical system operations and maintenance	"We design systems that can survive even without maintenance."
	Technical system design	Related to general discussions on technical system designs and layout (e.g., water treatment scheme, system connections)	"That gets pretty challenging trying to design the onsite septic systems that will also handle the wastewater from water treatment from their homes."
Natural	Water quality	Related to general discussions on water quality in rural Alaska	"They have in that part of the country typically high iron and manganese in the groundwater."
	Climate change	Related to influences of climate change on drinking water projects	"Climate change is hitting us really bad and everything that we've built all of our infrastructure, like in western Alaska is built to be on permafrost."
Social	Social equity and access	Related to equity concerns related to drinking water project implementation	"If you don't have the power to get the financing for your community you know you're going to be powerless and not be able to build your infrastructure."
	WASH and safety	Related to water, sanitation, health, or safety	"You may be lucky we might get sick, or you may have not ended by getting sick from that water source, but there are other vulnerable populations that may not be so fortunate."
	Regulations	Related to general discussions on regulations	"And they needed to meet, EPA standards because everything that EPA funds has to meet the national drinking water."
	Finances	Related to general descriptions of finances	"It's super expensive to get a drill rig out there."
	Community engagement	Related to the community (e.g., community buy-in, cultural complexities)	"There's definitely regional knowledge of things like that so I think people would be willing to adapt.”

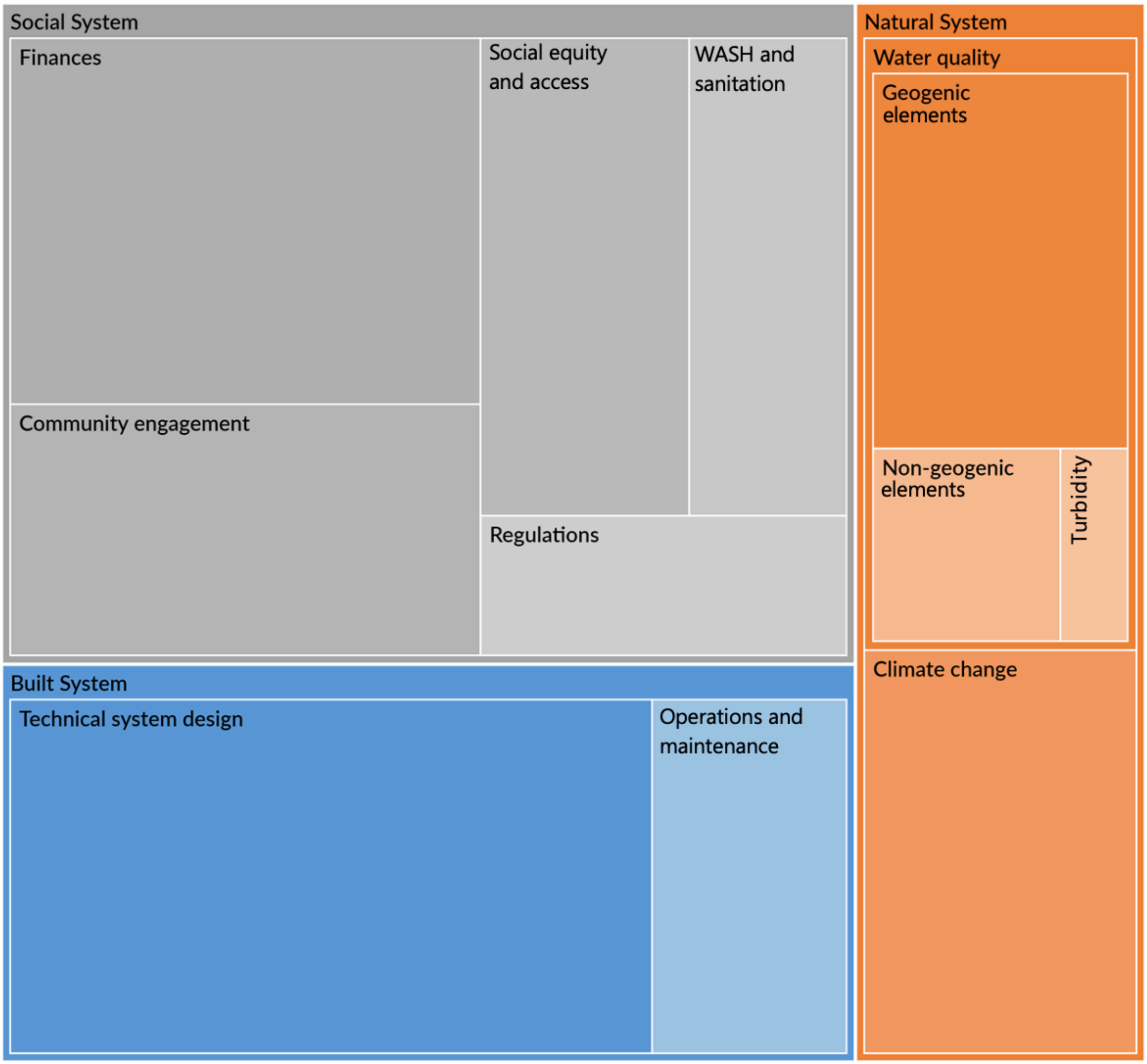

Figure B.1: Hierarchy chart of the factors that matter to drinking water projects. The intensity of color correlates to number of items coded to the factor. The size of the areas refers to the number of coding references (i.e., relative frequency).

APPENDIX C: Supporting Information for Chapter 4

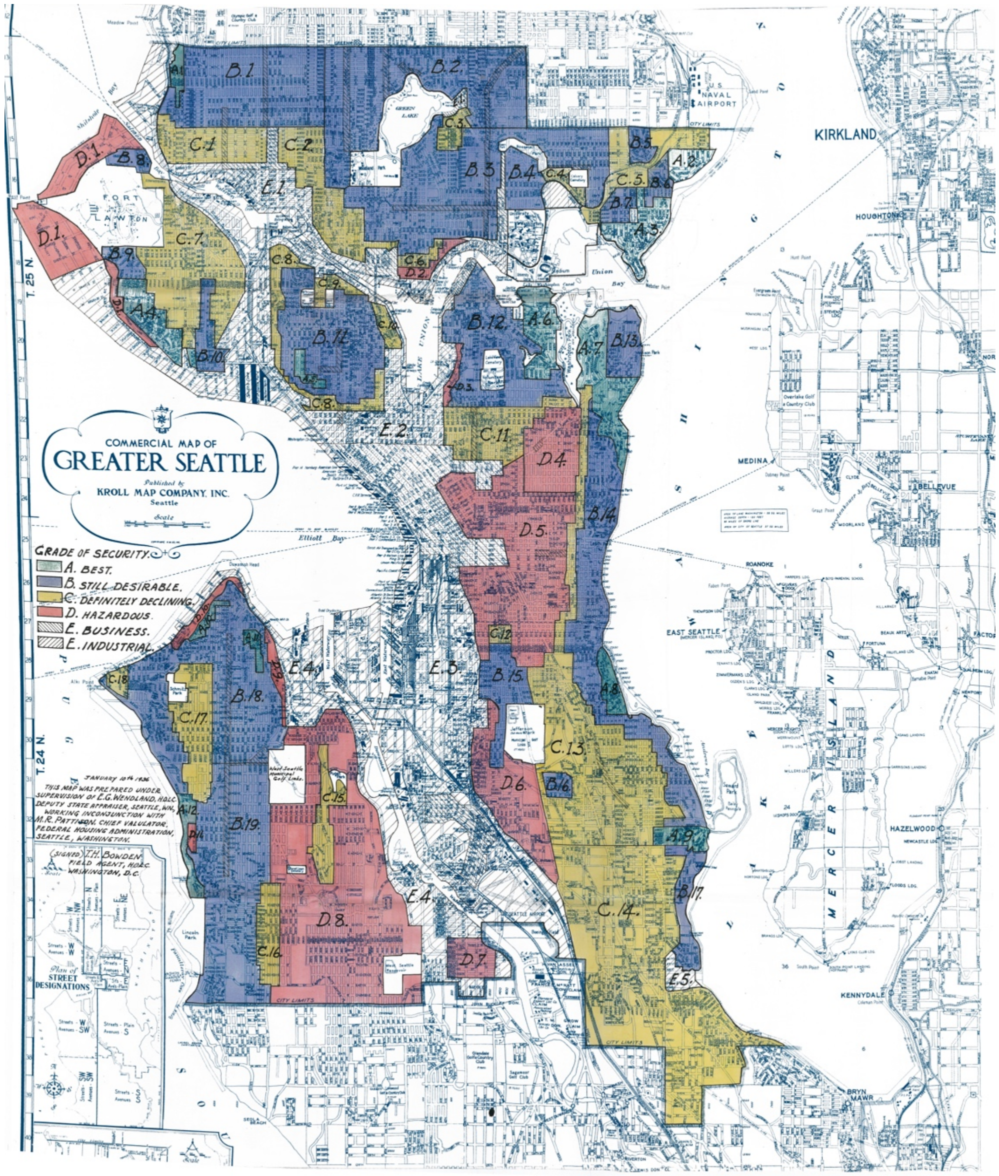

Figure C.1: Digitalized version of the 1936 redlining map of the Greater Seattle, Washington area (Nelson et al. 2020)

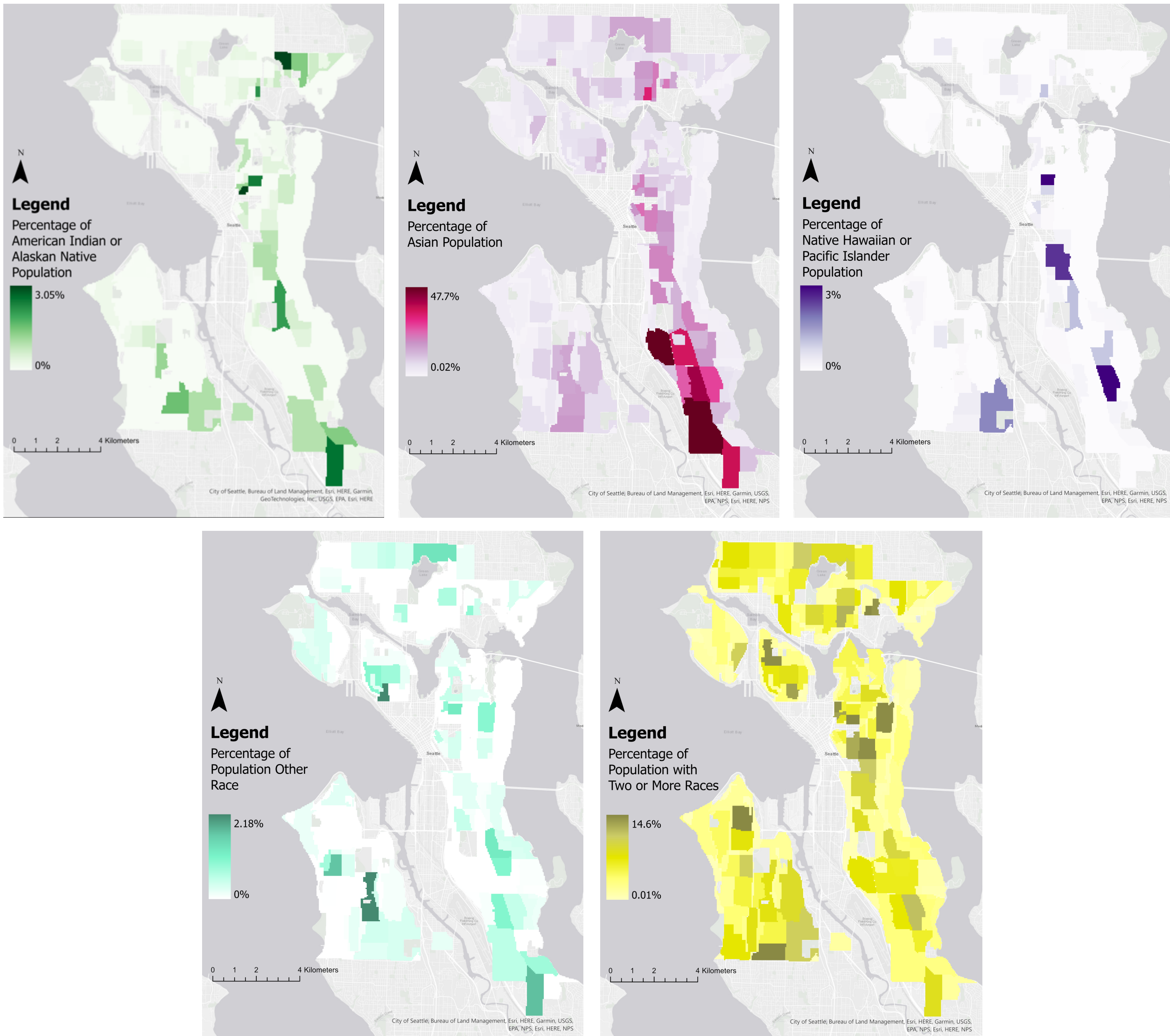

Figure C.2: Maps of spatial distribution of additional racial demographics: percent non-Hispanic American Indian or Alaskan Native population (top left), percent non-Hispanic Asian population (top middle), percent non-Hispanic Native Hawaiian or Pacific Islander, percent non-Hispanic other race (bottom left), and percent non-Hispanic two or more races (bottom right)

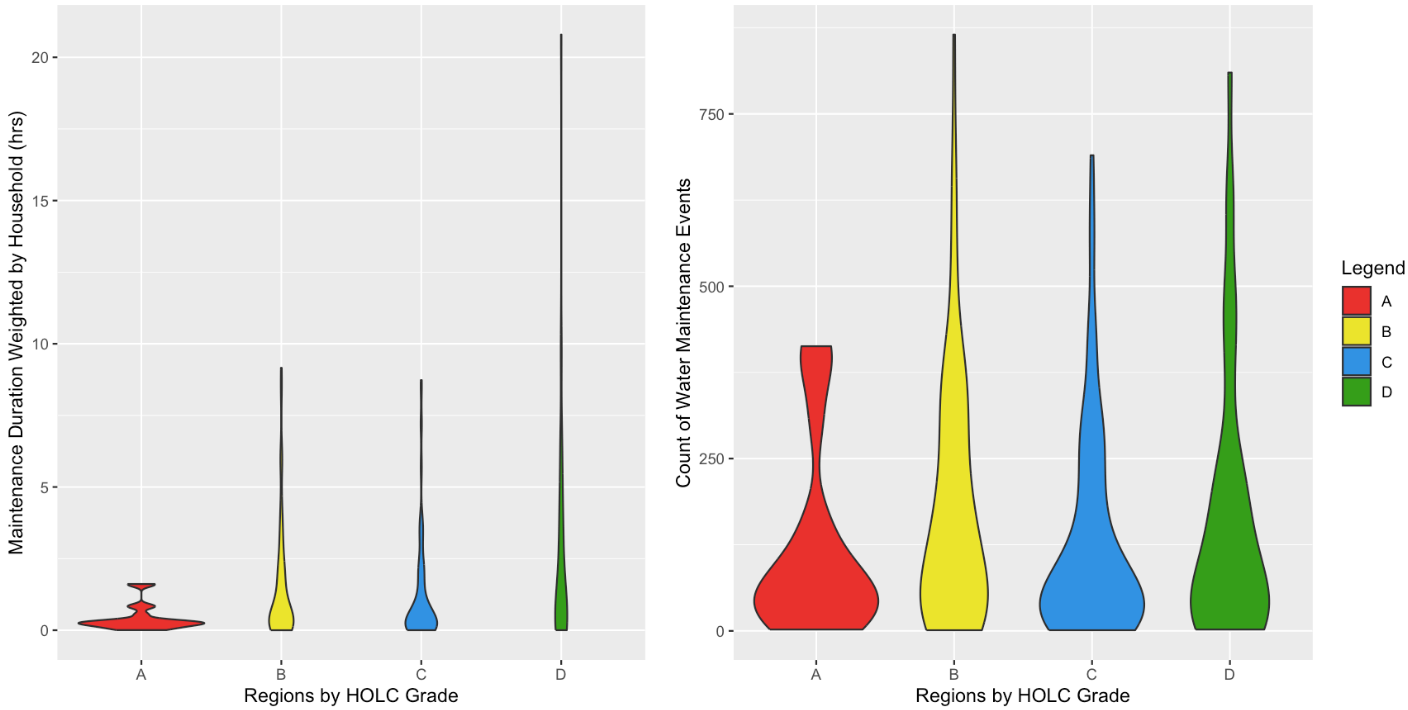

Figure C.3: Violin plots that display the distribution of the weighted maintenance durations (left) and number of maintenance events (right) for all maintenance types

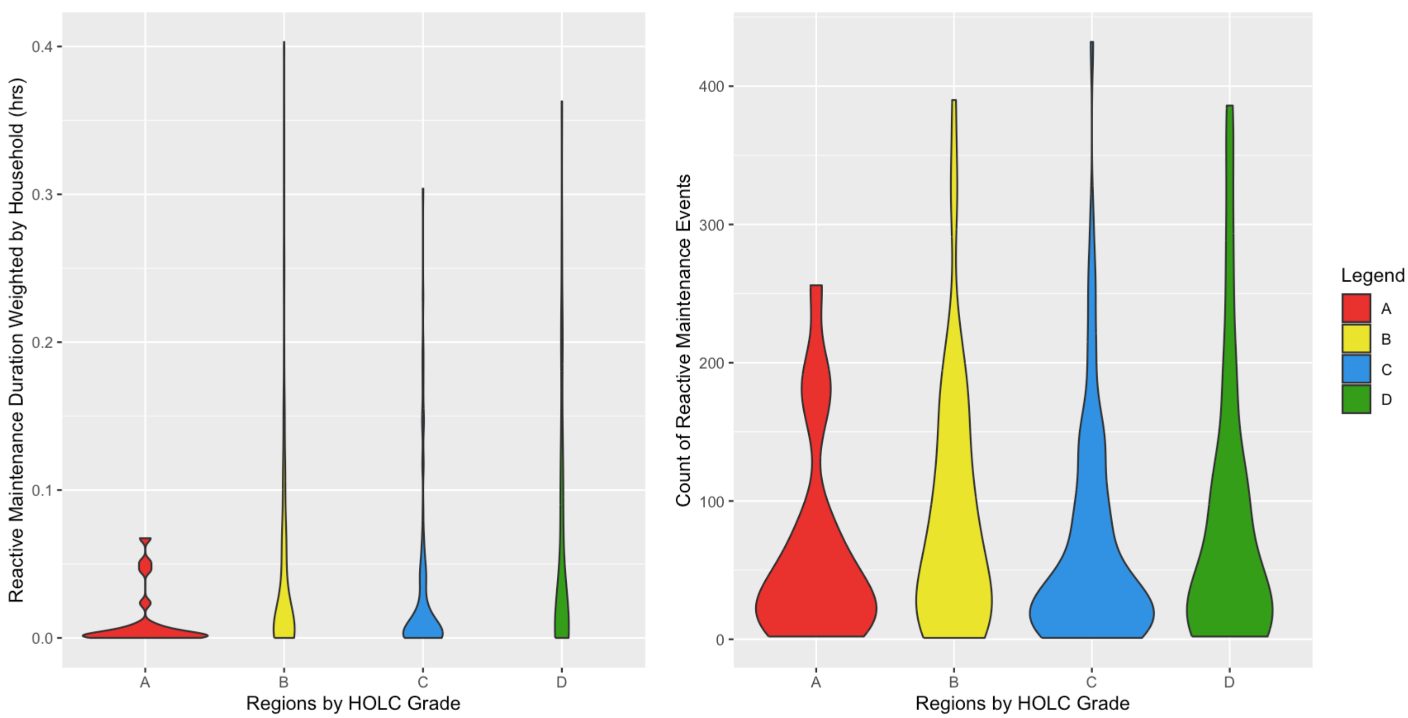

Figure C.4: Violin plots that display the distribution of the weighted maintenance durations (left) and number of maintenance events (right) for reactive maintenance alone

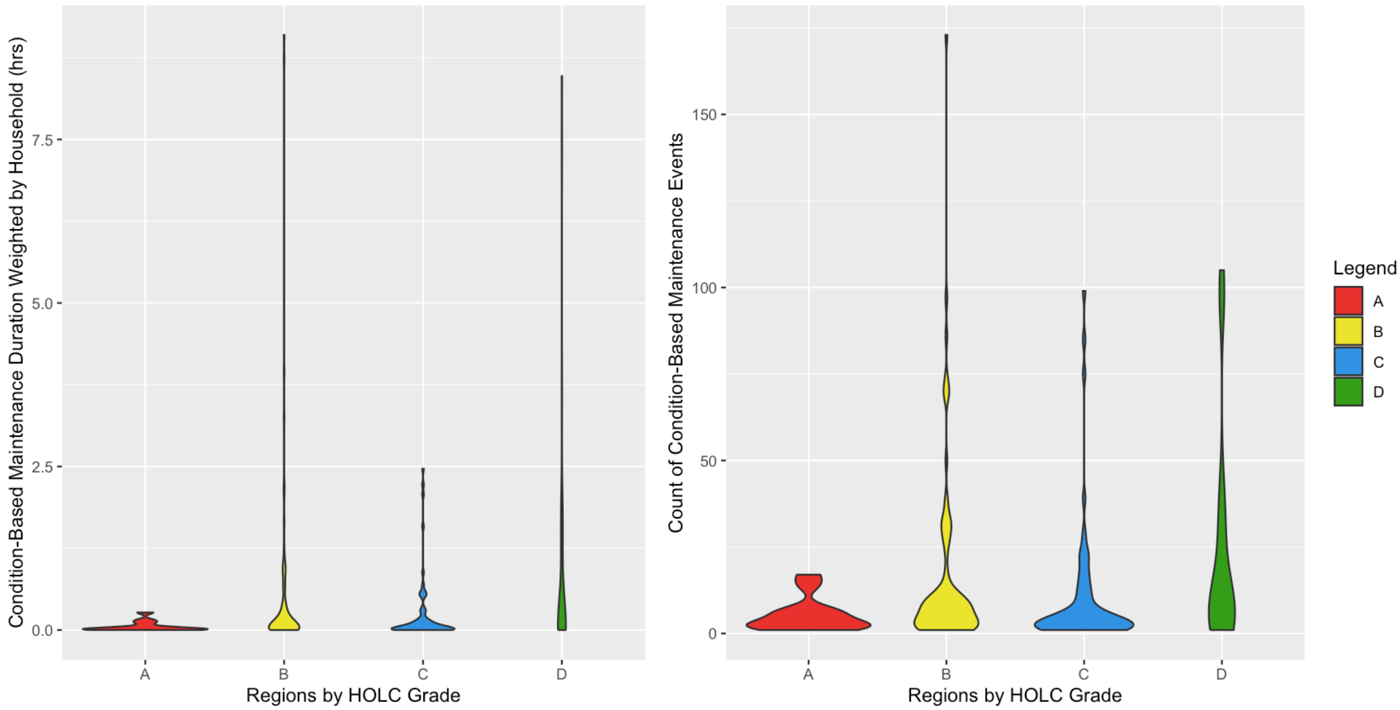

Figure C.5: Violin plots that display the distribution of the weighted maintenance durations (left) and number of maintenance events (right) for condition-based maintenance alone

Table C.1: Sensitivity Test - General Linear Model Regression Results of Mean and Median Weighted Maintenance Durations Associated with Redlining Distinctions for All Maintenance

Independent Variable	Rate (Median)	Rate (Mean)
A Redlining Distinction (Intercept)	0.3602***	0.3602***
B Redlining Distinction	2.058**	2.058**
C Redlining Distinction	1.236	1.236
D Redlining Distinction	2.296**	2.296**
Observations	274	274
Log Likelihood	-292.082	-292.082
Akaike Inf. Crit.	596.164	596.164

Note: *p<0.1; **p<0.05; ***p<0.01

Table C.2: Sensitivity Test - General Linear Model Regression Results of Weighted Maintenance Durations Calculated with Different Buffer Lengths Associated with Redlining Distinctions for All Maintenance

Independent Variable	5M Buffer Rate	10M Buffer Rate	20M Buffer Rate
A Redlining Distinction (Intercept)	0.3602***	0.3459***	0.3867***
B Redlining Distinction	2.058**	2.336***	2.567***
C Redlining Distinction	1.236	1.474	1.593
D Redlining Distinction	2.296**	2.962***	3.030***
Observations	274	254	243
Log Likelihood	-292.082	-294.543	-311.744
Akaike Inf. Crit.	596.164	601.085	634.488

Note: *p<0.1; **p<0.05; ***p<0.01

Table C.3: Sensitivity Test - General Linear Model Regression Results of Number of Maintenance Events Calculated with Different Buffer Lengths Associated with Redlining Distinctions for All Maintenance

Independent Variables	5M Buffer Rate	10M Buffer Rate	20M Buffer Rate
A Redlining Distinction (Intercept)	138.9***	133.2***	132.4***
B Redlining Distinction	1.524	1.639*	1.601*
C Redlining Distinction	1.056	1.121	1.126
D Redlining Distinction	1.012	1.121	1.103
Observations	274	254	243
Log Likelihood	-1,613.784	-1,494.170	-1,426.438
Theta	0.862*** (0.066)	0.900*** (0.072)	0.920*** (0.075)
Akaike Inf. Crit.	3,239.569	3,000.340	2,864.876

Note: *p<0.1; **p<0.05; ***p<0.01

R Code for Redlining and Drinking Water Infrastructure Analysis

Setting Up Data to be Analyzed

```
#Install and load required packages
install.packages('MASSExtra')
```

```
library(MASSExtra)

install.packages("stargazer")
library(stargazer)
```

#Import datafiles

```
WME_5M_Mean <- read.csv("WME_5M_Mean_V2.csv")
CBM <- read.csv("CBM_5M_Check_V2.csv")
RM <- read.csv("RM_5M_Check_V2.csv")
```

#Assign redlining hierarchy for files

```
WME_5M_Mean$holc_grade <-
  ordered(WME_5M_Mean$holc_grade,
          levels = c("D", "C", "B", "A"))

RM$holc_grade <-
  ordered(RM$holc_grade,
          levels = c("D", "C", "B", "A"))

CBM$holc_grade <-
  ordered(CBM$holc_grade,
          levels = c("D", "C", "B", "A"))
```

#Create dummy variables for the categorical redlining variable

```
WME_5M_Mean$A <- ifelse(WME_5M_Mean$holc_grade=='A',1,0)
WME_5M_Mean$B <- ifelse(WME_5M_Mean$holc_grade=='B',1,0)
WME_5M_Mean$C <- ifelse(WME_5M_Mean$holc_grade=='C',1,0)
WME_5M_Mean$D <- ifelse(WME_5M_Mean$holc_grade=='D',1,0)

CBM$A <- ifelse(CBM$holc_grade=='A',1,0)
CBM$B <- ifelse(CBM$holc_grade=='B',1,0)
CBM$C <- ifelse(CBM$holc_grade=='C',1,0)
CBM$D <- ifelse(CBM$holc_grade=='D',1,0)

RM$A <- ifelse(RM$holc_grade=='A',1,0)
RM$B <- ifelse(RM$holc_grade=='B',1,0)
RM$C <- ifelse(RM$holc_grade=='C',1,0)
RM$D <- ifelse(RM$holc_grade=='D',1,0)
```

#Check if the mean and variance are equal to determine what type of distribution to use (i.e., negative binomial vs Poisson distribution)

```
mean(WME_5M_Mean$wo_duration_household_hours)
var(WME_5M_Mean$wo_duration_household_hours)
```

Negative Binomial Regression Analysis (Number of Maintenance Events)

#Complete regression analysis for all maintenance counts

```
reg_main_l_count <- glm.nb(number_of_work_orders ~ B + C + D + population_density +
percent_below_poverty, data = WME_5M_Mean)
summary(reg_main_l_count)
(exp(coef(reg_main_l_count)))
```

stargazer(reg_main_l_count, type = "text", out = "AllMain_Count.txt", title = " General Linear Model Regression Results of Number of Maintenance Events Associated with Redlining Distinctions for All Maintenance")
exp(confint(reg_main_l_count))

#Complete regression analysis for reactive maintenance counts alone
reg_rm_l_count <- glm.nb(number_of_work_orders ~ B + C + D + population_density + percent_below_poverty, data = RM)
summary(reg_rm_l_count)
exp(coef(reg_rm_l_count))
exp(confint(reg_rm_l_count))
stargazer(reg_rm_l_count, type = "text", out = "RM_Count.txt", title = "General Linear Model Regression Results of Number of Maintenance Events Associated with Redlining Distinctions for Reactive Maintenance")

#Complete regression analysis for condition-based maintenance counts alone
reg_cbm_l_count <- glm.nb(number_of_work_orders ~ B + C + D + population_density + percent_below_poverty, data = CBM)
summary(reg_cbm_l_count)
exp(coef(reg_cbm_l_count))
exp(confint(reg_cbm_l_count))
stargazer(reg_cbm_l_count, type = "text", out = "CBM_Count.txt", title = " General Linear Model Regression Results of Number of Maintenance Events Associated with Redlining Distinctions for Condition-Based Maintenance")

Gamma-distributed Regression Analysis (Weighted Duration of Maintenance Events)

#Complete regression analysis for all weighted maintenance durations
reg_main_l <- glm(wo_duration_household ~ B + C + D + population_density + percent_below_poverty, family=Gamma(link="log"), data = WME_5M_Mean)
summary(reg_main_l)
(exp(coef(reg_main_l)))
stargazer(reg_main_l, type = "text", out = "AllMain_Duration.txt", title = "General Linear Model Regression Results of Weighted Maintenance Durations Associated with Redlining Distinctions for All Maintenance")
exp(confint(reg_main_l))

#Complete regression analysis for weighted maintenance durations for reactive maintenance alone
reg_rm_l <- glm(wo_duration_household_hours ~ B + C + D + population_density + percent_below_poverty, family=Gamma(link="log"), data = RM)
summary(reg_rm_l)
exp(coef(reg_rm_l))
exp(confint(reg_rm_l))
stargazer(reg_rm_l, type = "text", out = "RM_Duration.txt", title = "General Linear Model Regression Results of Weighted Maintenance Durations Associated with Redlining Distinctions for Reactive Maintenance")

#Complete regression analysis for weighted maintenance durations for condition-based maintenance alone reg_cbm_l <- glm(wo_duration_household_hours ~ B + C + D + population_density + percent_below_poverty, family=Gamma(link="log"), data = CBM)
summary(reg_cbm_l)

```
exp(coef(reg_cbm_l))
exp(confint(reg_cbm_l))
stargazer(reg_cbm_l, type = "text", out = "CBM_Duration.txt", title = "General Linear Model Regression Results of Weighted Maintenance Durations Associated with Redlining Distinctions for Condition-Based Maintenance")
```

APPENDIX D: Curriculum Vitae

Nathalie Thelemaque

nthele@uw.edu | (954) 205-9992 | linkedin.com/in/nthelemaque

Education

Doctor of Philosophy in Civil Engineering June 2024
The University of Washington | Seattle, Washington
Graduate Advisor: Dr. Jessica Kaminsky
Dissertation Title: *Community and Crisis: A Multiscale Analysis of Drinking Water Infrastructure Resilience in the Face of Slow-onset Disasters*
Master of Science in Civil Engineering June 2022
The University of Washington | Seattle, Washington
GPA: 3.98/4.00
Bachelor of Science in Civil Engineering May 2020
The University of Florida | Gainesville, Florida
Minor in Sustainability and the Built Environment
GPA: 3.52/4.00

Research Experience

Graduate Researcher June 2020 – Present
University of Washington | Seattle, Washington

- Engaged in research that uses quantitative and qualitative methods to examine the relationship between critical water infrastructure and marginalized communities through slow-onset disasters (Publications in ES&T Water, JCEM, JWRPM; Research funded by UW Fellowships)

Undergraduate Researcher December 2019 – April 2020
Bob Graham Center for Public Service | Gainesville, Florida

- Examined impacts of climate change on a Liberty County, Florida using both quantitative and qualitative data for Barometer Florida, a tool that provides information regarding effects of global warming

MIT Summer Research Program (MSRP) | Cambridge, Massachusetts June — August 2019

- Advisor: Dr. Desiree Plata
- Developed over 100 groundwater samples to determine the relationship between hydrocarbons and hydraulic fracturing through the headspace equilibrium method and computations using linear regression with the Plata Lab (Publication in ES&T)

Publications

1. **Thelemaque, N.** and Kaminsky, J. 2023. "Corporate Climate Pledges of High Revenue Design Firms and Contractors." *Journal of Civil Engineering and Management.* DOI: 10.1061/JCEMD4/COENG-13719
2. Li, Y., Siegel, H., **Thelemaque, N.,** Bailey, K., Moncrieffe, P., Nguyen, T., Clark, C., Johnson, N., Soriano Jr., M., Deziel, N., Saiers, J., Plata, D. 2023. "Conventional Fossil Fuel Extraction, Associated Biogeochemical Processes, and Topography Influence Methane Groundwater Concentrations in Appalachia." *Environmental Science and Technology.*
3. **Thelemaque, N.,** Spearing, L., Faust, K., Kaminsky, J. 2023. "Small Drinking Water Systems' Resilience: A Case of the COVID-19 Pandemic." *Environmental Science and Technology: Water.* DOI: 10.1021/acsestwater.2c00641

4. **Thelemaque, N.,** Cotherman, A., Pearson, R., Eichelberger, L., Neumann, R., Kaminsky, J. 2022. "Identifying the Built, Natural, and Social Factors of Successful and Failed Rural Alaskan Water Projects: Perspectives from State and Regional Professionals." *Environmental Science and Technology.* DOI: 10.1021/acsestwater.2c00201
5. Li, Y., **Thelemaque, N.**, Siegel, H., Clark, C., Ryan, E., Brenneis, R., Gutchess, K., Soriano Jr., M., Xiong, B., Deziel, N., Saiers, J., Plata, D. 2022. "Groundwater Methane in Northeastern Pennsylvania Attributable to Thermogenic Sources and Hydrogeomorphologic Migration Pathways." *Environmental Science and Technology.* DOI: 10.1021/acs.est.1c05272
6. Berglund, E., **Thelemaque, N.,** Faust, K., Kaminsky, J., Sela, L., Goharian, E., Lee, J., Keck, J., Giacomoni, M., Ernst van Zyl, J., Harkenss, B., Yang, Y., Cunha, M., Ostfeld, A., Kadinski, L., Spearing, L. 2021. "Water and Wastewater Systems and Utilities: Challenges and Opportunities during the COVID-19 Pandemic." *Journal of Water Resources Planning and Management*. DOI: 10.1061/(ASCE)WR.1943-5452.0001373
7. Spearing, L., **Thelemaque, N.,** Kaminsky, J., Katz, L., Kinney, K., Kirisits, M., Sela, L., Faust, K. 2020. "Implications of Social Distancing Policies on Drinking Water Infrastructure: An Overview of the Challenges to and Responses of US Utilities during the COVID-19 Pandemic." *Environmental Science and Technology: Water*. DOI: 10.1021/acsestwater.0c00229

Conference Publications (Critically reviewed prior to publication)

8. **Thelemaque, N.** and Kaminsky, J. "Describing Types of AEC Firms with Climate Pledges." Accepted by Construction Research Council, March 2024.
9. **Thelemaque, N.** Spearing, L., Faust, K., Kaminsky, J. "Water Utilities and the COVID-19 Pandemic: A Review of Pandemic-Related Research." Accepted by the Construction Research Council, March 2022. DOI: 10.1061/9780784483954.052
10. Spearing, L., **Thelemaque, N.,** Araya, F., Kaminsky, J., Faust, K. "Connecting Pre-existing Characteristics of Water Utilities to Impacts during the COVID-19 Pandemic." Accepted by the Construction Research Council, March 2022. DOI: 10.1061/9780784483954.026

Fellowships

William N. Allison Endowed Fund	2021
GSEE Fellowship	2020, 2023

Honors and Awards

Graduate School Medal, University of Washington	2024
Husky 100, University of Washington	2024
Best Presentation Award, Engineering Project Organization Conference	2023
Trail Blazer in Engineering Program Fellow, Purdue University	2022
Outstanding Woman in DEI Advocacy, UW Society of Women Engineers	2022
GEM Associate Fellow, GEM National Consortium	2020
Fulfilling the Legacy Scholarship, National Society of Black Engineers	2019
1st Place Poster, National Society of Black Engineers Region 3 Conference	2019

Teaching Experience

CEE 420 – Engineering with Developing Communities March 2023 – June 2023
Co-Instructor | University of Washington

- Adapted existing and created new course content for hybrid teaching on topics related to climate change, data in sustainable development, and water, sanitation, and hygiene (WASH)

CEE 307 – Construction Engineering September 2022 – March 2023
Teaching Assistant | University of Washington

- Developed course content relating social equity to civil infrastructure and hosted office hours and demonstrations for the software B2W

CEE 420 – Engineering with Developing Communities March – June 2022
Grader | University of Washington

- Collaborated with course teaching assistant to design a class assignment focused on climate activism, graded coursework, and completed administrative tasks associated with the course

Mentoring Experience

- Mentor for WiSE Bridge Program, University of Washington undergraduate students — Summer 2021 – Present
- Mentor for University of Washington graduate student — Summer 2021 – Present
- Mentor for 14 high school students, MIT Online Science and Technology, and Engineering Community (MOSTEC) program — Summer 2021 – December 2021

Service and Outreach

Team Lead October 2021 – Present
AVELA at the University of Washington

- Developed an interactive curriculum on environmental engineering concepts for high-school students in partnership with Hip Hop is Green

Speaker and Mentor July 2021 – Present
WE Rise at the University of Washington

- Spoke on panels and provided insights on the graduate engineering experience to first and second-year engineering students at various events, including the WiSE bridge program and WiSE conference

Outreaching Grad December 2020 – June 2021
GSEE at the University of Washington

- Worked with the Graduate Student Equity & Excellence office to recruit BIPOC students to the UW graduate school through presentations at prospective student events

Committee Member August 2015 – June 2023
Association of the Children of Regnier, Haiti

- Assisted in the coordination of various fundraising initiatives for the non-profit organization to help raise over $25,000 through the formation of fundraising galas, raffles, and book sales to provide tuition and food for deserving students in the region

Program Alumni Panelist 2021
MIT Office of Outreach Programs, College Academy

- Served as a panelist for multiple prospective/current student events to speak on experience as an underrepresented student in the engineering discipline

Presentations

Oral Presentations

1. **Thelemaque, N.** "Describing Types of AEC Firms with Climate Pledges." *Construction Institute and Construction Research Council Conference.* Des Moines, Iowa. 2024
2. **Thelemaque, N.** "On the Path Towards Environmental Justice." *Floyd Snider.* Seattle, Washington. 2023
3. **Thelemaque, N.** "Examining Infrastructure and Community Interactions During Slow-Onset Disasters." *Georgia Tech University.* Atlanta, Georgia. 2023
4. **Thelemaque, N.** "Redlining and infrastructure: Examining the legacy of historical zoning and its influence on current water infrastructure maintenance." *Engineering Project Organization Conference.* Berlin, Germany. 2023
5. **Thelemaque, N.** "Examining Infrastructure and Community Interactions During Slow-Onset Disasters." *UC Irvine.* Irvine, California. 2023
6. **Thelemaque, N.** "Understanding and Evaluating Critical Infrastructure and Social System Interactions." *CEE Rising Stars.* Pittsburgh, Pennsylvania. 2022
7. **Thelemaque, N.** "Examining the Corporate Climate Pledges of High Revenue Contractors and Design Firms." *Program on Climate Change Summer Institute.* Friday Harbor, Washington. 2022
8. **Thelemaque, N.** et al., "Water Utilities and the COVID-19 Pandemic: A Review of Pandemic-Related Research." *Construction Institute and Construction Research Council Conference.* Alexandria, Virginia. *2022*
9. **Thelemaque, N.** "From Coast to Coast: Mapping Out Your Journey Through STEM." *WiSE Bridge Program.* Seattle, Washington. 2021
10. **Thelemaque, N.** "Imposter Syndrome and How to Deal with It" *CEE 307 Construction Engineering.* Seattle, Washington. 2021
11. **Thelemaque, N.,** Li, Y., Bugher, N., Plata, D., "Something in the Water: Groundwater Methane Concentration in Relation to Hydraulic Fracturing." *ARC 1000 Architecture and Humanity.* Gainesville, Florida. 2019

Poster Presentations

12. **Thelemaque, N. "**Job Talk Poster - Understanding and Evaluating Critical Infrastructure and Social System Interactions." *Trail Blazers in Engineering Program.* West Lafayette, Indiana. 2022
13. **Thelemaque, N.,** Li, Y., Bugher, N., Plata, D., "Something in the Water: Groundwater Methane Concentration in Relation to Hydraulic Fracturing." *NSBE Region 3 Technical Research Exhibition.* Tampa, Florida *2019*
14. **Thelemaque, N.,** Li, Y., Bugher, N., Plata, D., "Something in the Water: Groundwater Methane Concentration in Relation to Hydraulic Fracturing." *MIT Summer Research Program Symposium.* Cambridge, Massachusetts. 2019

Industry Experience

Project Engineering Intern June – August 2023

Turner Construction Company | Seattle, Washington

Processed and reviewed RFIs, submittals, change orders, and specifications in support the construction phase of the SeaTac Airport C Concourse Expansion project

Structures Engineering Intern May — August 2018

The Boeing Company | Seattle, Washington

Interpolated data from previous aircraft and researched aircraft materials to compose a comprehensive stress note document analyzing a fitting on the side of body and wing joint on the 777x aircraft

Professional Memberships

National Society of Black Engineers 2016 – Present

American Society of Civil Engineers 2017 – Present