What Impacts Water Services in Rural Alaska? Identifying Vulnerabilities at the Intersection of Technical, Natural, Human, and Financial Systems

Lauryn A. Spearing,[1] Prachi Mehendale,[1] Leif Albertson,[2] Jessica A. Kaminsky,[3] and Kasey M. Faust[1,*]

[1] Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 301 Dean Keeton C1752, Austin, TX 78712, USA

[2] Institute of Agriculture, Natural Resources and Extension, University of Alaska Fairbanks, 1751 Tanana Loop, P.O. Box 756180, Fairbanks, AK 99775-6180

[3] Civil and Environmental Engineering, The University of Washington, 3760 E. Stevens Way NE Seattle, WA 98195

*Corresponding Author: faustk@utexas.edu

KEYWORDS: Alaska water infrastructure, water access, systems of systems, arctic communities, climate change

ABSTRACT

Thousands of homes in rural Alaska do not have access to in-home water services and those that are served often experience disruptions. Such gaps in service lead to extreme water conservation and water quality issues, causing health disparities in Native communities that have been historically disenfranchised. Water sector challenges in rural Alaska stem from a variety of conditions that create a complicated operating context, such as the extreme climate, limited funding, small workforce, and remote settings of the communities. It is imperative to holistically understand the nature of water sector challenges in Alaska, bringing together proxy views to gain an understanding of overall system operations. In turn, our research objectives are to 1) identify challenges within the financial, human, natural, and technical systems involved in the provision of water services in rural Alaska, and 2) use a systems thinking approach to identify interdependencies between systems. Specifically, we identify the cascading impacts caused by the arctic environment and by climate change, and the factors contributing to the increase of unserved communities and system failures. To do so, we performed a deductive-inductive qualitative content analysis on semi-structured interviews with 19 stakeholders that work with water infrastructure in rural Alaska. Findings show that climate change exacerbates the Arctic operating context, straining financial and technical systems (e.g., flooding impacts source water quality). Additionally, we found that service disruptions are often caused by a lack of operations and maintenance funding; communities are only able to pay for repairs using emergency funds that become available after system failures. Here, we outline policy, engineering, and management leverage points that can be used to improve water services in rural Alaska. For instance, we recommend auditing funding systems to ensure equitable allocations and further exploring the water-energy nexus in arctic communities.

1. INTRODUCTION

Although in-home water plumbing is the expected level of service in the U.S., this is not always the reality, as observed in rural regions of Alaska that are experiencing declining levels of water access (Brown et al., 2022). Over 3,300 rural Alaska homes lack running water and a flush toilet (Alaska DEC, 2022a). Such gaps in water service make Alaska the state with the highest proportion of homes without water and sewer services (U.S. Arctic Research Commission, 2017). In fact, there are more than 30 unserved communities, where 45% or more homes are not served by piped, septic tank and well, or covered haul systems (Alaska DEC, 2022b). These unserved communities are largely located in rural areas that house mostly American Indian/Alaskan Native (AI/AN) populations. Communities without in-home plumbing must haul water to the household (often from a central watering point called a washateria), increasing mental and physical burdens (Eichelberger, 2017, 2010). The time and physical intensity of hauling water can lead to extreme water conservation in many households (Thomas et al., 2016a), impacting sanitation and hygiene practices. Further, researchers found associations between access to piped water and rates of respiratory, skin, and gastrointestinal illnesses (Hennessy et al., 2008; Thomas et al., 2016b). In addition to low water use in the home, communities may be exposed to pathogens through other pathways, including untreated water reuse and inadequate waste disposal (Mattos et al., 2021).

Providing water services to unserved communities in Alaska is challenging due to the geographic isolation (Hickel et al., 2018), extreme and changing climate (Cozzetto et al., 2013; Hickel et al., 2018; Marino et al., 2009; Melvin et al., 2017; Thomas et al., 2016a), and economic constraints (ASCE, 2017; Hickel et al., 2018; Penn et al., 2017; Sohns et al., 2021), among other factors. For example, the small size of communities and the limited revenue sources make it hard to fund the construction of piped water systems due to the lack of economies of scale. Additionally, the Arctic environment leads to more complex and expensive systems to build (Hickel et al., 2018; Marino et al., 2009; Thomas et al., 2016a). In short, the communities that are yet to be served are the hardest to serve. Acknowledging the challenges of constructing piped systems, researchers studied alternative methods to provide water in unserved communities (Hickel et al., 2018; Lucas et al., 2021; Mattos et al., 2021b), but it is important to note that these systems face challenges with social sustainability (e.g., maintenance; Kaminsky and Javernick-Will, 2014).

Even when piped systems exist, a myriad of challenges for sustaining and maintaining services are present. Researchers have documented how community characteristics (e.g., subsistence-focused lifecycle, small number of people) make operations challenging (Hickel et al., 2018; Penn et al., 2017). For instance, some communities have a subsistence-focused lifestyle, challenging water system operations (Marino et al., 2009). With a limited cash economy, it is difficult to collect revenue from end-users, hindering utilities' ability to purchase materials needed for system operations. Additionally, communities are often challenged to hire and retain a certified water operator due to the limited labor pool and certification challenges (Hickel et al., 2018; Sohns et al., 2021). The impact of climate change on physical infrastructure has been widely studied (e.g., ASCE, 2017; Cozzetto et al., 2013; Hickel et al., 2018; Melvin et al., 2017; Sohns et al., 2021; Thomas et al., 2016a), finding that permafrost melt, increased flooding, and erosion, among other climate impacts, will damage (or has already damaged) systems. Suter et al. (2019) quantified the cost of climate change in Alaska, finding that Alaska will incur $2.56 billion in increased maintenance costs and $3.5 billion in climate damages by 2050. Many of these climate changes are directly affecting Alaskan Native communities' water sources (e.g., increased turbidity and algae blooms), creating pressing equity concerns (Cozzetto et al., 2013). The unique operating context in Alaska has led to widespread service disruptions in served communities (e.g., frozen pipes; Eichelberger, 2010) that often lead to long-lasting access challenges (Eichelberger, 2017) or seasonal outages (Mattos et al., 2021). Even when water is provided, some people do not want to use treated water due to cultural preferences, aesthetic issues, or disapproval of treatment chemicals (Marino et al., 2009; Penn et al., 2017; Sohns et al., 2021). Instead, community members may rely on traditional sources, such as ice melt.

Although researchers have explored specific challenges surrounding the provision of water services in rural Alaska, most studies fail to explore how such challenges are related to each other, limiting current literature. Limited studies have used a broader lens to capture how these challenges compound or are related to each other (Eichelberger, 2010; Penn et al., 2017; Sohns et al., 2021). Penn et al. (2017) used an environmental security framework to understand water security in the rural North, leveraging community members' perspectives to understand narratives around access. The authors found, for instance, that harsh weather conditions (e.g., cold temperatures, flooding) make operations and maintenance (O&M) of water systems difficult and expensive, creating affordability concerns (Penn et al., 2017). In a different study, Eichelberger studied water and energy insecurity in parallel, discovering that *"soaring electricity and heating bills place a strain on household finances and deepen the situation of water insecurity"* (Eichelberger, 2010, p. 1016). Sohns et al. (2021) used causal loop modeling to understand how stakeholders conceptualize water vulnerability in rural Alaska. Their model revealed that environmental barriers restrict the economy and consequently impact water access and that there is a need for more funding to operate and maintain systems. Although Sohns and colleagues (2021) explored economic, environmental, infrastructure, social, and health themes, their analysis was largely focused on policy instead of physical infrastructure systems. The current study complements their analysis by studying the interfaces between engineered systems and other systems in-depth (i.e., using an engineering lens), and allows for the identification of specific points of intervention.

Here, we use a systems approach to understand the nature of water infrastructure challenges in rural Alaska. We frame water services as a system, or "an interconnected set of elements that is coherently organized in a way that achieves something" (Meadows, 2008, p. 11). We acknowledge that physical infrastructure (i.e., the technical system) exists within a complex operating environment that is influenced by the human, financial, and natural systems. In other words, multiple systems work together to provide water services in rural Alaska, forming a systems-of-systems. Such a systems approach required multiple stakeholders' perspectives and proxy views, so we conducted interviews with 19 water-sector stakeholders to inform this study. Specifically, we identify interdependencies between financial, human, natural, and technical systems to answer four specific questions about the nature of water services in Alaska. These questions (shown below) were developed based on the existing literature and shed light on factors that influence the level of service in rural Alaska.

1. *What are the cascading impacts of the arctic environment on Alaska water services?*

   The arctic environment (i.e., climates that commonly experience low temperatures, ice and snow cover, or permafrost) in Alaska creates a unique and especially challenging operating context to provide water services, which has been documented in literature (Hickel et al., 2018; Marino et al., 2009; Thomas et al., 2016a). Literature tends to focus on direct impacts of the arctic climate (e.g., heating requirements for piped systems), but it is imperative to understand how these factors cascade to impact the entire system.

2. *What are the cascading impacts of climate change on Alaska water services?*

   Researchers have explored how climate change impacts water systems in Alaska (e.g., ASCE, 2017; Cozzetto et al., 2013; Hickel et al., 2018; Melvin et al., 2017; Sohns et al., 2021; Thomas et al., 2016a). Knowing there are notable climate change impacts (e.g., water quality changes, increased erosion damaging physical infrastructure), we want to understand how these impacts are related to other system challenges.

3. *Why are there <u>unserved communities</u> in Alaska?*

Providing services to unserved communities has been a priority in Alaska for many decades (Alaska DEC, 2022a; USARC, 2015) because of the health implications stemming from a lack of water access in the home. Here, we explore what factors contribute to the continued lack of service in communities to understand indirect, and possibly unexpected, connections.

4. *Why are there <u>system failures and service disruptions</u> in served communities?*

Service disruptions are common in communities that have a water system in place. Such disruptions (e.g., pipe breaks, service outages; Eichelberger, 2010; Mattos et al., 2021a) impact the community's quality of life. For instance, water service disruptions in rural Alaska have impacted schools' schedules, sometimes causing the school year to be delayed (Joling and Thiessen, 2012). In turn, we want to understand what contributes to such disruptions or failures to better understand how to prevent them.

By mapping interdependent challenges, the current study identifies leverage points (i.e., "places in the system where a small change could lead to a large shift in behavior"; Meadows, 2008, p. 145; e.g., funding and policy changes) that can be used to restructure the system and improve water services in Alaska. Further, understanding the cascading impacts of the Arctic environment and climate change, as well as the factors contributing to both the absence of services and service disruptions, will enable decision-makers to proactively make policy and funding changes.

2. MATERIALS AND METHODS

To understand factors influencing water services in rural Alaska, we conducted 18 semi-structured interviews with 19 practitioners involved in the water sector in Alaska. We performed a hybrid, deductive-inductive qualitative content analysis on the interview data to identify challenges to provide services. Additionally, we analyzed interdependencies between financial, human, built, and natural systems (Rinaldi et al., 2001) to understand how challenges cascade between systems.

2.1 DATA SOURCES AND COLLECTION

Eighteen semi-structured interviews with 19 stakeholders involved in the provision of water services in rural Alaska were conducted from January 25th to June 28th, 2021. In one interview (Interview 8 in Table 1), two stakeholders participated. Anonymized interview data can be found online in the Arctic Data Center (Spearing et al., 2022). Before data was collected, the project received institutional review board (IRB) approval from The University of Texas at Austin, The University of Washington, and the Alaska Area IRB. Interviewees were selected using snowball and convenience sampling and were conducted until theoretical saturation was met and no new information emerged from additional interviews (Corbin and Strauss, 2008; Saldaña, 2013). Interviews were conducted via teleconferencing or phone and were an average of 55 minutes long. The interviews were recorded (with permission), transcribed, and checked for quality (i.e., reviewed for transcription errors). Interviewees worked at various institutions including state and federal government agencies, non-profit organizations, and research institutions. Interviewees' experiences in the Alaska water sector ranged from two to over forty years. Table 1 shows anonymized information about interviewees. To further validate our results, we sent interviewees a summary of the findings and asked for their feedback, which was incorporated into the manuscript. This ensures that the analysis is consistent with subject-matter experts' experiences and opinions. We also presented findings to an advisory board (consisting of eight individuals who are familiar with water infrastructure in Alaska, but not involved in the interview process) and they reviewed the results for accuracy.

Table 1: Information about Interviewees

Interviewee Number	Organization	Role
1	Federal Agency (Infrastructure)	Program Manager
2	Federal Agency (Health)	Division Director
3	Federal Agency (Environmental)	Program Manager
4	Federal Agency (Development)	Engineer and Environmental Coordinator
5	Consultant/Federal Agency (Infrastructure)	Consultant and Co-Chair*
6	State-Level Agency (Environmental)	Program Manager
7	State-Level Agency (Health)	Program Manager
8**	State-Level Agency (Environmental)	Program Manager
	State-Level Agency (Environmental)	Program Manager
9	State-Level Agency/Consultant	Engineer and Regulatory Specialist*
10	Non-Profit Organization (State, Health)	Engineer and Quality Roles
11	Non-Profit Organization (State, Health)	Director of Standards and Innovation
12	Non-Profit Organization (State, Health)	Engineer
13	Non-Profit Organization (State, Health)	Project Manager and Engineer
14	Non-Profit Organization (State, Health)	Director of Standards and Innovation
15	Non-Profit Organization (Regional, Health)	Director of Environmental Health and Engineering
16	Non-Profit Organization (Regional, Community Support)	Program Manager
17	Regional Organization & Non-Profit Organization (Water)	Superintendent and Director of Non-Profit
18	Academic	Researcher

*Interviewee is retired, role shown is previous role prior to retirement.
** Interview involved two participants

The interview protocol (shown in the Supplemental Information (SI)) was designed to create an understanding of water infrastructure challenges present in Alaska, specifically focusing on rural access because these areas face especially unique challenges compared to urban areas (e.g., isolation) and house many unserved communities. Interviewees were first asked broad questions, such as:

- What water infrastructure challenges are you aware of in regard to access or levels of service in rural Alaska?
- What water infrastructure challenge do you think is the most important to address (i.e., what would you prioritize)?

Next, detailed questions about topics of interest were asked. For example, such questions include:

- What workforce challenges do you face with your water infrastructure systems' operations and maintenance in rural Alaska?
- How does climate change impact water infrastructure systems in your region?
- Can you describe service disruptions or failures that commonly occur?
- Do utilities commonly experience issues with supply chain (i.e., acquiring materials needed to collect, treat, and distribute drinking water)?

2.2 QUALITATIVE AND SYSTEMS ANALYSIS

Using a hybrid, deductive and inductive content analysis approach (L. A. Spearing et al., 2022), we first used a deductive framework based on our research questions—identifying challenges within the technical, human, natural, and financial systems (see Table 2 for definitions of each system). We then let specific themes emerge within each system, taking an inductive, data-driven approach (Saldaña, 2013). The unit of analysis was a complete response to the interviewer's question and each unit could be assigned multiple codes (i.e., simultaneous coding; Saldaña, 2013). Qualitative coding and analysis were performed using NVivo Software (NVivo, 2020). The coding was completed by one researcher and validated by another researcher who coded a set of interviews independently using a codebook (shown in the SI). After coding one interview, the researchers met to update the codebook and discuss any discrepancies. Using two interviews, the authors achieved a Mezzich's kappa of 0.65, which is considered suitable for qualitative research (Burla et al., 2008; Everitt, 1996). Mezzich's kappa was chosen for its ability to validate simultaneous coding because it does not have a requirement that each excerpt can only be assigned to one code (Eccleston et al., 2001; MacPhail et al., 2016; Mezzich et al., 1981).

Table 2: System Definitions and Examples (Full Coding Dictionary in the SI)

Code	Definition	Example
Financial	Related to finances or funding water systems (e.g., billing, funding).	"It's more isolation of the communities resulting in high construction costs and the size of the communities is very small. When you have a small number of a denominator entailed, you get a [really high cost]."
Human	Related to people and society, including topics such as community experiences, management, and workforce challenges.	"[Community members are] going to their traditional water sources which have a higher risk for them than chlorine, but they just don't like the taste of it, they don't like the idea of a chemical being in their drinking water."
Natural	Related to the natural environment, including climate, weather, and geographic location.	"One thing that's happened pretty immediately with climate change is volumes of water. In some cases, there's been maybe a huge increase in water at certain times a year because of faster thawing."
Technical	Statements about technical aspects of water systems. This may include designing, constructing, operating, and sustaining systems. Workforce is not included here, but instead in the human code.	"The construction, I mean, it's difficult in Alaska, so it's cold, the construction season is limited. Sometimes you have to construct in the winter."

In addition to coding challenges unique to each system, we took a systems-thinking approach to understand dependencies and connections between systems (Meadows, 2008; Rinaldi et al., 2001). Similar to work done in other contexts (Spearing and Faust, 2020), each unit of analysis was coded as a relationship (i.e., dependency) between factors (and systems). These relationships emerged inductively. For instance, the excerpt below was coded as a relationship between the "Climate change" and "Service disruptions, failures, and damages" code within the Natural and Technical systems.

"We have definitely seen that impact [of climate change], melting permafrost has caused settling of buildings, water treatment plants, water sourcing pipe, and especially above-ground utilidors. You're seeing the stands on which the pipes are sitting shifting, and then you get bellies or humps, and that [causes] the freeze up."

Coding relationships between themes allows us to create cognitive system maps rooted in qualitative data (see Section 3.2). Additionally, we quantified the number of times each relationship was mentioned in the dataset. When mapping dependencies, the lines are weighted by the number of references in our dataset (i.e., thicker lines were mentioned more often in interviews, but do not necessarily show the strength of the connection), and the arrowheads indicate the directionality of the relationships. When answering the four research questions (see Section 1.2), the maps stopped at third-order effects (see Rinaldi et al., 2001 for more information) to ensure the system structure was clear and understandable. For instance, a third-order effect can trace climate change to alternative water use. First, "Climate change" leads to "Water quality and treatment problems" (first-order), which leads to a "Lack of public acceptance" (second-order), which leads to "Alternative water use" (third-order). Mapping such dependencies based on qualitative data allows for an understanding of indirect relationships in financial, technical, human, and natural systems.

2.3 LIMITATIONS

As with any study, there are limitations present in this work. This analysis only includes perspectives from regional, state, and national water sector stakeholders that could be reached virtually due to COVID-19 pandemic travel restrictions during the time of data collection. In turn, it is important to acknowledge the biases that may be introduced based on the stakeholders interviewed. Despite this, our results provide valuable insight into water services in Alaska by integrating viewpoints from multiple stakeholders from varying institutions. This work should be paired with community-level insights in the future. Additionally, this work is focused on Alaska specifically, limiting the generalizability outside of the state. We argue that Alaska-specific studies are warranted because of the unique operating context and poor levels of service.

When quantifying qualitative datasets, it is important to note that the frequency of responses does not necessarily mean that certain themes are more important or challenging. It may be that these questions were discussed more frequently or that the interviewees were more aware of certain trends. Knowing this, we do not rely solely on the frequency of codes, but also include the number of interviews that the challenge was mentioned in.

3. RESULTS AND DISCUSSIONS

3.1 CHALLENGES TO PROVIDE WATER SERVICES

Here, we discuss the challenges present to provide water services in each system—financial, human, natural, and technical (see Table 2 for system definitions). Table 3 shows the frequency of excerpts coded to each system, as well as the emergent codes. The discussion focused on cascading impacts between systems is confined to Section 3.2.

Table 3: Frequency Table of Challenges to Provide Water Services in Rural Alaska

Code	Number of Interviews Mentioned	Relative Frequency of Interviews	Number of References	Relative Frequency of References
Total Challenges	**18**	**100%**	**841**	**100%**
Financial	**18**	**100%**	**190**	**23%**
Expenses or costs for water systems	*18*	*100%*	*78*	*41%*
High cost of construction	15	83%	25	32%
High operational costs	15	83%	37	47%
Unaffordable costs per household	12	67%	16	21%
Funding or financial capacity	*17*	*94%*	*112*	*59%*
Billing issues	6	33%	7	6%
Communities' ability to financially support systems	15	83%	41	37%
Funding system shortcomings	10	56%	21	19%
Insufficient capital funding	8	44%	15	13%
Lack of outside O&M funding	9	50%	19	17%
Limited cash economy	4	22%	9	8%
Human	**18**	**100%**	**251**	**30%**
Community experiences, characteristics & perceptions	*18*	*100%*	*110*	*44%*
Cultural expectations and subsistence activities	8	44%	13	12%
Health implications	9	50%	16	15%
Lack of public acceptance	8	44%	16	15%
Small populations	10	56%	14	13%
Underserved communities	8	44%	9	8%
Unserved communities	14	78%	34	31%
Use of alternative sources	5	28%	8	7%
Management and regulations	*15*	*83%*	*66*	*26%*
Communication and collaboration	9	50%	18	27%
Community capacity to manage & maintain systems	11	61%	25	38%
Determining the service method	5	28%	7	11%
Lack of oversight and support during operations	4	22%	7	11%
Rigid regulatory environment	7	39%	9	14%
Workforce	*17*	*94%*	*75*	*30%*
Few operators and high turnover	17	94%	26	35%
Lack of workforce mobility	4	22%	4	5%
Loss of institutional knowledge	4	22%	5	7%
Operator certification and training challenges	9	50%	19	25%
Operator expertise and knowledge	9	50%	21	28%

Natural	**18**	**100%**	**127**	**15%**
Arctic environment	*18*	*100%*	*46*	*36%*
Climate change	*18*	*100%*	*43*	*34%*
Climate variability	*5*	*28%*	*6*	*5%*
Fires	*3*	*17%*	*4*	*3%*
Remote, rural environment	*13*	*72%*	*28*	*22%*
Technical	**18**	**100%**	**273**	**32%**
Design and construction	*16*	*89%*	*71*	*26%*
Challenges with standards	3	17%	5	7%
Complex piped systems to design and construct	10	56%	22	31%
Construction scheduling issues	4	22%	7	10%
Supply chains constraints	15	83%	32	45%
Need to adapt infrastructure systems	4	22%	5	7%
Operations	*18*	*100%*	*123*	*45%*
Complex systems to operate and	9	50%	19	15%
Identifying and sustaining a water	8	44%	15	12%
Heating water systems	16	89%	25	20%
Inability to address issues or implement capital projects	8	44%	13	11%
Inefficient operations	4	22%	5	4%
Maintaining decentralized systems	6	33%	7	6%
Meeting water quality regulations	10	56%	11	9%
Water quality and treatment	13	72%	28	23%
System sustainability	*18*	*100%*	*79*	*29%*
Need to relocate systems (due to climate change)	7	39%	10	13%
Poorly built or designed systems	5	28%	9	11%
Service disruptions, failures, or	11	61%	26	33%
System failures in decentralized	3	17%	4	5%
Systems degrading or aging	15	83%	30	38%

*Relative frequency is the percent of all excerpts coded to each parent code.

3.1.1 Financial System

All interviewees discussed financial challenges surrounding the provision of water services in rural Alaska; 23% of all references were coded as Financial. 59% of excerpts in this category were about the financial capacity to support systems due to a myriad of factors such as insufficient capital funding (13% of excerpts coded to Funding or Financial Capacity) and a lack of outside O&M funding (17%). This is not surprising, as a lack of funding for water services in rural Alaska has been documented in both grey and scholarly literature (e.g., Alaska DEC, 2022b; ASCE, 2017;

Penn et al., 2017; Sohns et al., 2021). Many respondents emphasized the importance of providing O&M funding, something that is largely lacking. One interviewee explained this challenge: *"There are several grants that we can use to send operators to hub communities (i.e., larger communities) for training, but as far as the operations and maintenance to pay the operator [and to] pay for routine maintenance, I mean, we run into problems all the time with routine maintenance. Whole systems can fail because somebody didn't put oil in a pump. And I'm not exaggerating. That's a literal issue. It happens quite frequently but if we could find money, that would be great, but there are no grants that we have that allow [for O&M funding]."*

Ten interviewees mentioned challenges with the way funding was distributed (i.e., the funding system). For instance, an engineer described how funding the lowest cost alternative impacts sustainability: *"Sometimes they only fund projects that are the lowest cost alternative. You might have three alternatives, but they're only going to pay for the least cost alternative, but the least cost alternative may not be the ideal solution. If it's not done right, the least cost alternative might be a terrible solution. But that's what gets funded. And then it's like, all right, well, now we've got to go build this because that's where we got funding for when that really was not what we should have been doing to begin with."* This indicates that policy changes that impact *how* money is spent could be a successful leverage point to improve services within the existing funding constraints. Additionally, results showed that high construction and operational costs make it increasingly hard to financially support systems.

3.1.2 Human System

Three themes emerged within the human system—"Community experiences, characteristics, and perceptions" (44% of codes in the Human System); "Workforce" (30% of codes in the Human System), and "Management and regulations" (26% of codes in the Human

System). Within community experiences, we found that public acceptance of water systems was a challenge (mentioned in 44% of the interviews). Interviewees discussed that community members often disapprove of the chemicals used to treat water, often (incorrectly) believing that chlorine used in water treatment is harmful to their health. In turn, people rely on alternative water sources (e.g., rivers, rainwater catchment), creating health concerns (Mattos et al., 2021). In this case, despite being informed of the risks, the familiarity and sense of security surrounding the use of alternative sources (a challenge mentioned in 28% of interviews), outweigh the perceived dangers of consuming untreated water (Marzec et al., 2013). This shows that health education alone will be insufficient to effect long-term behavioral change.

"Community capacity to manage and maintain systems" (within the "Management and regulations" parent code) was mentioned extensively by interviewees (in 61% of interviews). This may be due to the small number of people in communities or the limited cash economy, among other reasons. In addition to the lack of O&M funding discussed in Section 3.1.1., interviewees also noted that there was a lack of oversight and support to manage systems. Programs such as the Remote Maintenance Worker Program that provide operational support to rural water systems are a great step towards addressing this challenge (Alaska DEC, 2022c). Communication and collaboration challenges were discussed in half of the interviews. Many interviewees discussed that there is a gap in communication between community members and decision-makers. This results in systems that are not designed based on community needs, reducing social sustainability (Kaminsky and Javernick-Will, 2014). Additionally, our data revealed that a lack of collaboration between organizations results in inefficient decision-making. Often agencies *"swim in their own lane"* and do not integrate various perspectives into decisions (i.e., focus on holistic community development).

Management of water systems is also challenged by the rigid regulatory environment. Alaska water systems must adhere to the same water quality requirements as the rest of the U.S. (i.e., the Lower 48) despite the unique and challenging operating context. Interviewees often wrestled with this challenge, weighing the importance of regulations to maintain public health and equity with the fact that regulations may hinder water access. For instance, this perspective was articulated here: *"Half of me thinks, 'Boy, it would be really nice to have a different set of regulations, that [small communities] didn't have to meet these really high standards, but then you get into the question of environmental justice. And because you live in a small community, because you don't have adequate resources, are you less entitled to have safe drinking water? And the answer to that has to be no. We're all entitled to have safe drinking water. It's this big conundrum of applying the standards but realizing that there are some communities that are never ever going to [be in compliance]."*

Workforce challenges in rural areas were a common theme in our data. Interviewees noted that it was difficult to retain a trained operator because the job pool is small, the job is challenging, and operators are perceived to be underappreciated. One interviewee described that it is hard to be a water operator because: *"You're paid just enough to not be eligible for benefits, but not enough to live. You're paid probably part-time but working way longer. You can't engage in subsistence because every day you have to be at the utility. Then people are complaining about the chlorine level and in the meantime, the state is mad at you because you didn't fill out this paperwork. Like [this is] a day in the life [of an operator so there is] huge burnout."* In turn, operator turnover, and the loss of institutional knowledge associated, makes managing water systems difficult. In addition to the number of operators, limitations in operator expertise and training were mentioned in half of the interviews. Standardized exams are used for certification and a broad range of information is needed to pass the test, yet many rural operators may never encounter components that are covered in the test. One interviewee mentioned that an *"operator who is doing a good job, has the skills and the knowledge to be able to operate their system, can't pass the exam."* The cascading impacts of such workforce challenges are discussed further in Section 3.2.

3.1.3 Natural System

Much discussion surrounding the natural system was focused on the arctic climate and climate change creating a particularly challenging operating context in Alaska. Additionally, interviewees mentioned that many villages are in remote, rural areas, which inhibits water services (as discussed further in Section 3.2). Climate variability (both seasonally and geographically) was mentioned in five of the interviews. For instance, one interviewer mentioned that *"you might be [designing a system] up north in a very severe Arctic climate or you might be down in Southeast Alaska where you essentially have semi-rain forest, cold rain forest environment with mountains…permafrost up north, and essentially a lot of bad soil in between and then you've got nothing but rock in other places. The variety is very challenging."* This variation in conditions requires diverse engineering solutions, which makes it difficult to create standards or a best practices manual. *"It is not a one size fits all thing. You have to tailor each standard to each set of unique environmental and geotechnical conditions."* In summary, the natural system in Alaska constrains water systems design, construction, operations, and management.

3.1.4 Technical System

Three themes surrounding technical system challenges emerged: Design and construction, Operations, and System sustainability (26%, 45%, and 29% of excerpts coded to the technical system, respectively). In over half of the interviews, respondents discussed that piped systems were complex to design and construct and that construction often faced scheduling issues and supply chain challenges. Additionally, water systems in Alaska must operate in a unique natural environment, impacting technical considerations. For instance, in many systems, water must be heated during treatment and distribution (as mentioned in 89% of the interviews). Water quality and treatment problems were mentioned in many interviews (72%). For instance, some water systems cannot afford to remove secondary contaminants (U.S. EPA, 2017), causing aesthetic issues, while other communities struggle to meet regulatory testing requirements due to logistical and weather issues. In addition to quality problems, communities often struggle to identify and sustain a water source.

Lastly, long-term technical challenges emerged in our data. Aligning with literature, we found that many systems (both centralized and decentralized) experience service disruptions, failures, and damages. Reasons for these disruptions are explored in Section 3.2.4. Additionally, existing water systems are degrading and aging, which is not surprising given the arctic conditions. Notably, some interviewees discussed that existing systems were poorly built or designed for the context, hindering sustainability. For instance, *"some systems were overbuilt, meaning that they overestimated population growth, water usage or other features"* and now these communities incur higher operating costs, making systems unaffordable for the community.

3.2 CASCADING SYSTEMS IMPACTS

Here, we discuss the cascading system impacts of the arctic climate (Section 3.2.1) and climate change (Section 3.2.2) and study what factors cause there to be unserved communities in rural Alaska (Section 3.2.3), as well as system failures and disruptions (Section 3.2.4). We map system dependencies in Figures 1-4. It is important to note that only relationships mentioned more than once are included in these figures to ensure claims were supported by the data. The full cognitive systems map is shown in the SI.

3.2.1 Cascading Impacts of the Arctic Climate

Figure 1 shows the cascading impacts of the arctic climate on water infrastructure systems in rural Alaska. The arctic environment cascades to the technical system, which indirectly impacts human and financial systems. The arctic environment necessitates complex infrastructure systems with difficult operation and maintenance requirements, which hinders communities' ability to manage and maintain systems, which eventually causes systems to degrade and age. For example, (1) the freeze and thaw which occurs every year (and sometimes multiple times a year), (2) weakens physical infrastructure by expanding the materials beyond their tensile strength as water freezes and then shrinks rapidly upon water melt, (3) which causes infrastructure to deteriorate faster than systems outside the arctic.

Through multiple pathways, we see that the arctic environment increases costs to construct, operate, and maintain water systems. For example, (1) the Arctic environment creates both supply chain constraints and a need to heat water systems which (2) increases both operational and construction costs. Interviewees noted the water-energy nexus throughout the dataset. For instance, one interviewee mentioned that *"60% to 80% of the cost of [water system] operations in rural Alaska are energy"* due to the unique need to heat water during treatment and distribution. These high costs, paired with insufficient outside funding, hinder communities' financial capacity to support systems, leading to affordability and access issues. Overall, we see that the arctic climate creates cascading impacts that ultimately impact the level of water services provided in rural Alaska. In fact, *"the normal challenges that you would have in a regular climate in the Lower 48 [i.e., contiguous US] are just exacerbated and multiplied living [in Alaska] just because of the climatic conditions"*. Although we cannot change the arctic nature of this region, by mapping the cascading impacts of the arctic climate, we can mitigate the effects through tailored engineering, research, and policy recommendations (see Section 4).

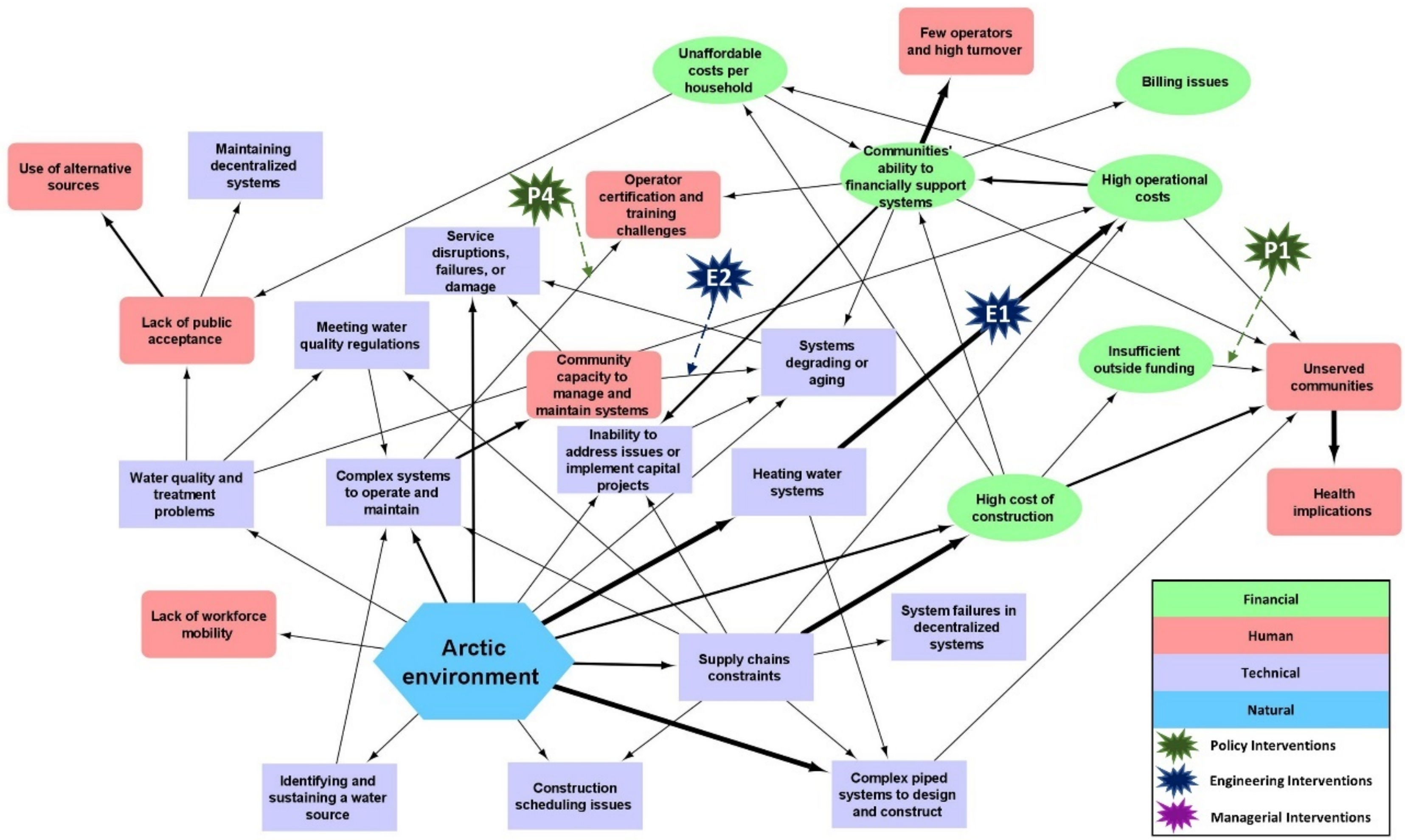


Figure 1: Cascading Impacts of the Arctic Environment on Water Infrastructure in Alaska.
Lines are weighted based on the number of coded references (thicker lines were mentioned more often).

3.2.2 Cascading Impacts of Climate Change

A cognitive map of the cascading impacts of climate change is shown in Figure 2. Direct (i.e., first-order) impacts from climate change were mostly to the technical system. Many climate change impacts were centered around water quantity or quality. For instance, increased flooding causes turbidity issues in surface water sources, earlier thaws cause pathogens to release earlier in the year which warrants increased chemical treatment, and erosion has caused some water sources to become obsolete. Water treatment plants are designed for a specific operating context, so when this context changes, the system may not always be able to adapt. Such a situation was described by one interviewee: *"If you're designing a water treatment facility for a surface water source, as engineers, we always look in the rearview mirror and we use historic data to project future events. But, yeah, this historic data is changing. How can we then forecast a future event? If we design a water treatment facility to not produce significant levels of disinfectant byproducts [DBPs] and organic carbon concentration of eight milligrams per liter max in your water source, what happens when that organic carbon concentration jumps to 16 milligrams per liter? Well, all of a sudden, your treatment system is not capable of removing those levels. Now you've got a DBP problem."* Such (1) water quality issues can cascade to the human system by (2) reducing public acceptance of water systems, which, in turn, (3) leads people to use alternative water sources. Water quality problems also make meeting regulatory requirements more challenging and increase operational costs.

Results reveal that climate change is making an already challenging operating context worse, and in turn, it will be *"harder and harder to serve these areas that are already the most underserved"*. For instance, as described in Section 3.2.1, the arctic climate creates supply chain constraints, but such constraints are made worse due to climate change. This was evident in one community that no longer can be accessed by fixed-wing aircrafts because there is not enough sea ice to make a runway, which was the main way of accessing the community previously. A similar trend is present with aging infrastructure systems—already aging systems are being strained by permafrost melt, erosion, and other climate changes. These challenges also cascade to the financial system—climate change is making water systems construction and operations more costly. A similar trend (i.e., economic impacts of climate change) has been proven in other contexts (e.g., Texas; Chen et al., 2001). This supports previous work discussed above that has brought to light the potential costs of climate change in Alaska (Cozzetto et al., 2013; Suter et al., 2019). Additionally, (1) climate change has created the need for some communities to relocate, which is often an extensive process. Once a community decides to relocate, (2) receiving any funding for its existing water system is difficult. In turn, (3) these communities are experiencing service disruptions and deterioration as they wait to relocate, something that takes many years.

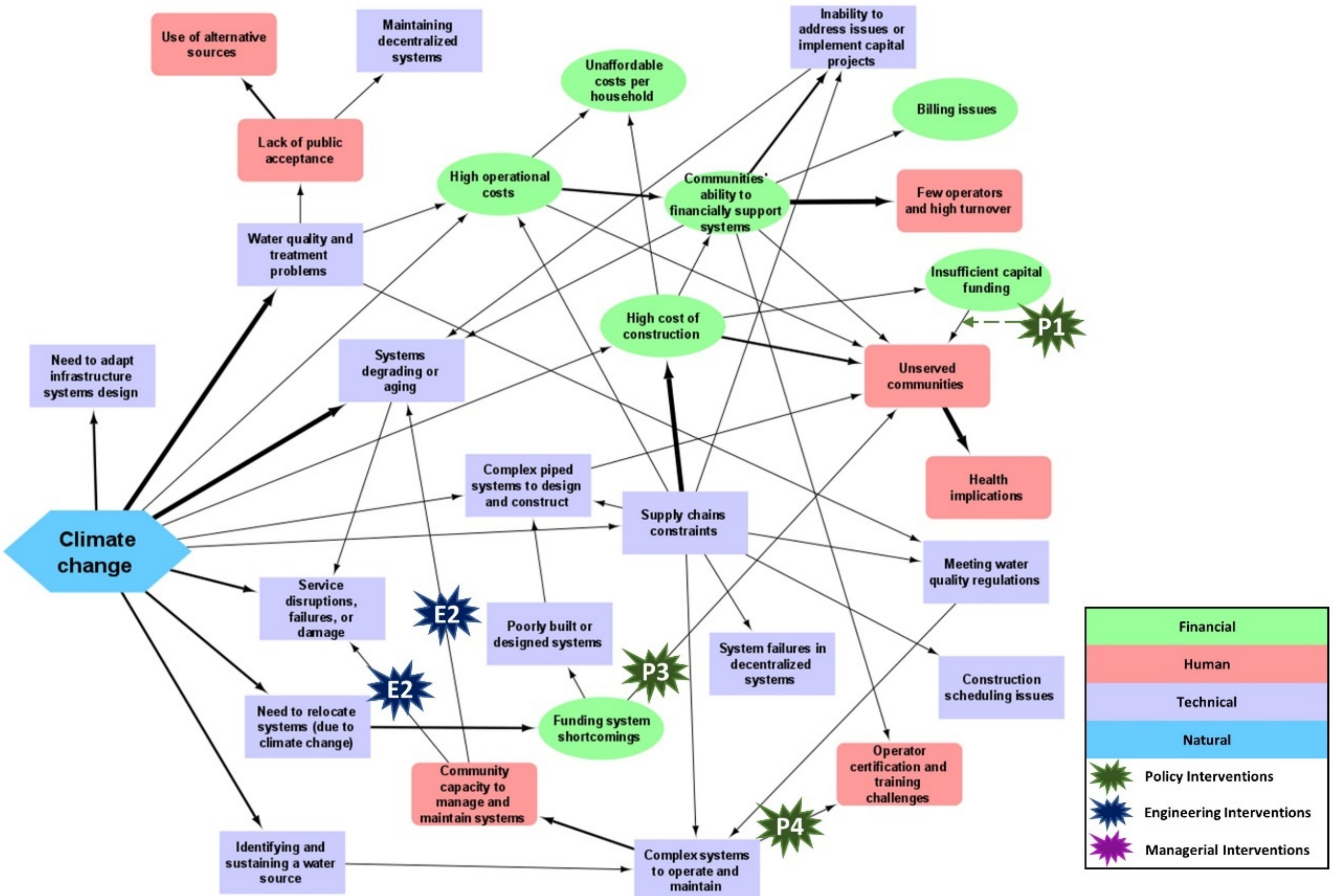


Figure 2: Cascading Impacts of Climate Change on Water Infrastructure in Alaska. Lines are weighted based on the number of coded references (thicker lines were mentioned more often).

3.2.3 Factors Contributing to Unserved Communities in Alaska

Figure 3 shows what factors contribute to unserved communities in Alaska. Finances are directly tied to underserved communities (see the green boxes in Figure 3). First, we see that there is insufficient capital funding to build new systems, which was described as a *"constant game of catch up"* where the need is greater than funds. High construction and operational costs make serving some communities incredibly expensive to serve. Such high costs are difficult for stakeholders and communities to understand. For example, it is hard to justify to Congress that constructing expensive piped systems is the best use of federal funding despite the environmental justice concerns (i.e., communities deserve quality services). Affordability is also a concern—community members must be able to pay for water services once in place (often over $200 a month). These financial issues compound, leaving communities unserved.

When the intricate relationships between factors are mapped, we see that it is not only the amount of funding that is a problem but *how* funding is distributed. To build a new system, the community must be able to financially sustain the system (per the Best Practices System; Alaska DEC, 2022). This policy is put in place to ensure that capital projects are sustainable, but an unintended consequence of this action is that it hinders the communities that are *most* in need from receiving funding. Additionally, projects may not receive funding because estimated water bills after construction are deemed unaffordable (i.e., the community would have to pay high bills to sustain the system, something common for piped systems). Although these affordability metrics are put in place to protect the public, in some cases, it is hindering communities' ability to construct piped systems that provide more reliable and consistent services. This finding reveals the need for water economic studies in Alaska as the problem cannot be solved with technology or management advances alone (Griffin, 2012).

Many unserved communities have a limited cash economy and are very small, making it difficult to successfully manage a water system. Additionally, there is a small pool of people who can serve as an operator and an even smaller pool who are willing to take the job (as the pay is often low and it interferes with subsistence activities). In turn, it is difficult for these communities to show that they have the financial and managerial capacity (e.g., a certified operator) to maintain a system, making it difficult to receive funding. For instance, one interviewee described this here: *"There are about 3,300 homes or about 30 communities that cannot or do not presently qualify [for funding] because of capital cost caps or O&M cost caps or both. They are not in a position* *to receive funding, and we call these the last mile communities. They're in this position because it's a difficult environment to design and construct facilities, just their economic conditions locally, or they're very poor and just can't afford it. In the US, that's the way it works. The government will build the system, but they won't pay to operate it. They expect operation and maintenance to be locally supported."* This funding process *"penalizes the communities that are the poorest and have the highest percentage natives,"* contributing to the systematic disenfranchisement of vulnerable populations.

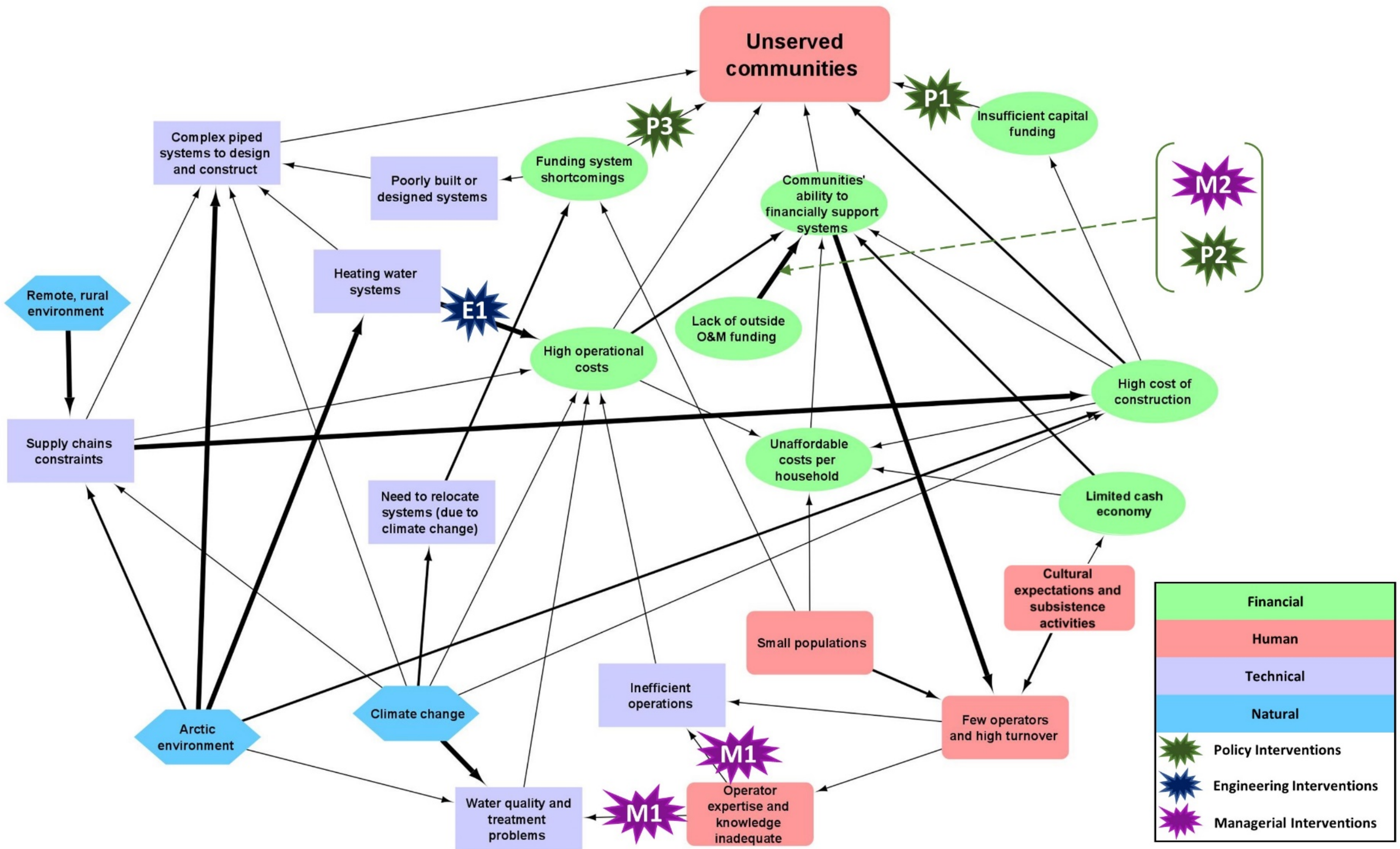


Figure 3: Factors Contributing to Unserved Communities in Alaska.
Lines are weighted based on the number of coded references (thicker lines were mentioned more often).

3.2.4 Factors Contributing to Service Disruptions and Failures

Once a water system is put in place, service disruptions, failures, and damages occur. As discussed previously, the natural system directly causes some service disruptions (e.g., pipe breaks, fires), while sometimes disruptions occur because the water system and supporting facilities (e.g., power generators) are aged and have deteriorated. This deterioration is often driven by the natural environment, a lack of proactive management, and a lack of funding for capital projects or repairs. Many systems are operating in a financial deficit because systems are expensive to operate, and communities cannot afford to cover the costs. Increasing their water rates to be able to operate systems will create affordability concerns, but without increasing rates, water systems fall into disrepair. On the other hand, increasing rates may cause people to stop participating in the water system, reducing overall financial capacity. Due to the existing funding structure that supports new projects and not the maintenance of existing systems, systems may fall into disrepair because of a lack of capital improvements. After such failure, emergency funding is often used to restore service. This leads to increased federal spending because it costs less to maintain infrastructure than to replace it. This finding, again, points to the importance of providing O&M funding.

System failures also occur because of poor management or operator errors. Such operational challenges were caused by a lack of operator expertise and training as well as the fact that there are limited operators and a high turnover rate, leading to a loss of institutional knowledge. For instance, in one community, an operator moved, and nobody replaced them, so now there is *"nice equipment [in the community] that still makes the same poor-quality water that they were making before we gave them the system."* In other cases, the technology put in place is too complex for the average operator to use, making it hard for operators to diagnose issues.

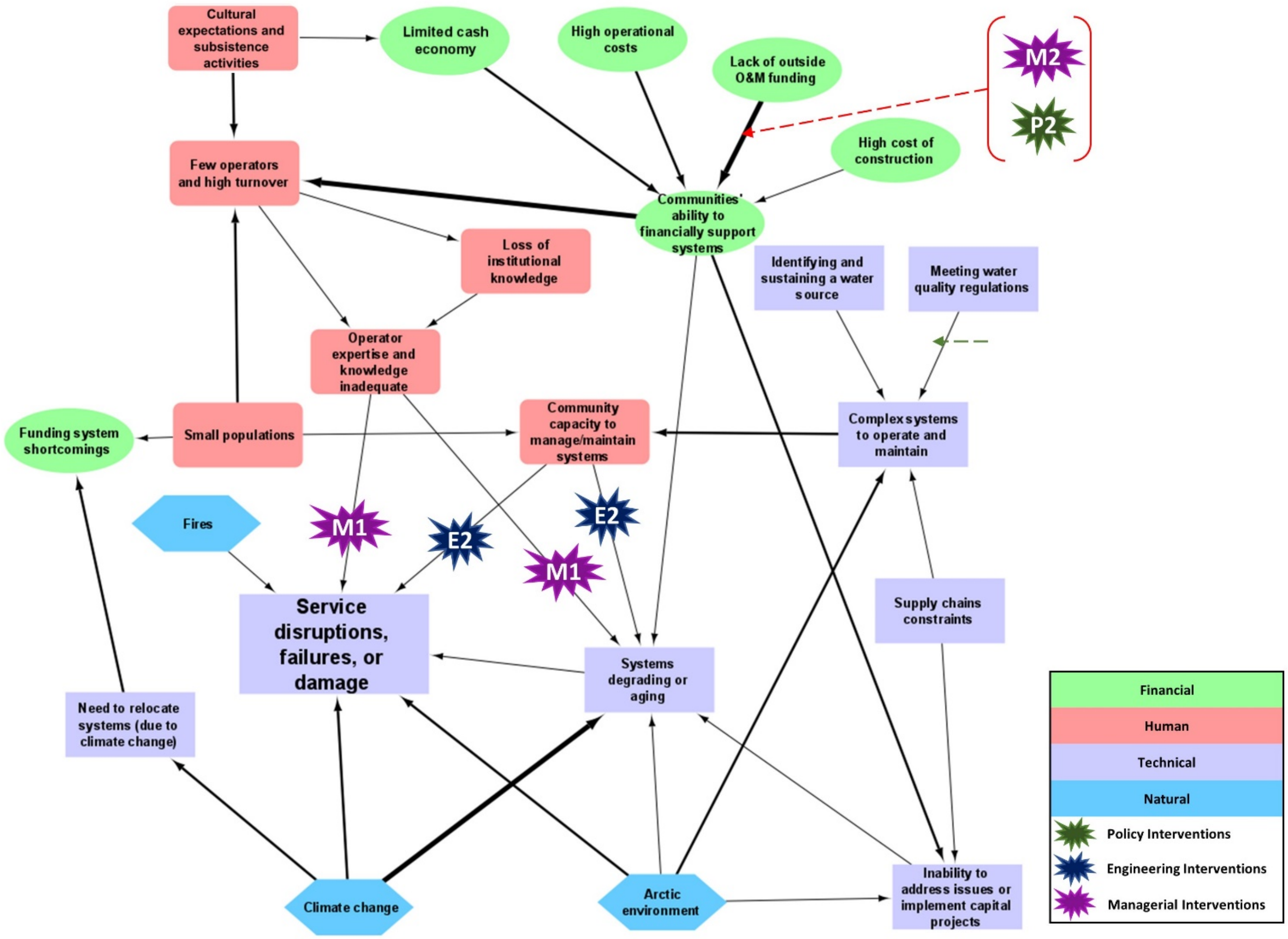


Figure 4: Factors Contributing to Water Service Disruptions or Failures in Alaska. Lines are weighted based on the number of coded references (thicker lines were mentioned more often).

4. RECOMMENDATIONS: SYSTEM LEVERAGE POINTS

By mapping complex relationships surrounding water system issues in rural Alaska, we identified points of intervention or leverage points in the system (i.e., places in the system structure where a small change could lead to a large shift in the system's performance; Meadows, 2008, p. 145). See Figures 1-4 for the corresponding location of each leverage point in the system structure. Here, we outline policy, engineering, and managerial recommendations.

4.1 POLICY INTERVENTIONS

P1. There is an urgent need to increase overall funding for water systems in rural Alaska. Although policy changes such as the Infrastructure Investment and Jobs Act (H.R.3684) are a good step towards addressing these issues, there needs to be continued investment in providing quality services to underserved communities, something outlined extensively in literature (Brubaker et al., 2011; Mattos and Blanco-quiroga, 2020; Sohns et al., 2021).

P2. Following discourse in literature (Penn et al., 2017; Sohns et al., 2021), we recommend that state or federal funding should be allocated for O&M of water systems (e.g., subsidize O&M in rural communities). If water systems are going to be built, there needs to be both financial and managerial support to help maintain and operate these systems. It is cheaper to maintain systems before they fail, so funding O&M activities would be a more cost-effective way to serve communities.

P3. Requirements for communities to receive project funding (i.e., Best Practices System; Alaska DEC, 2022d) should be reviewed to ensure there is an equitable system in place that does not disenfranchise vulnerable populations. Researchers should explore funding frameworks to fund sustainable and equitable systems.

P4. Operator certification testing should be tailored to specific systems or the Alaska context. Standardized tests designed for the Lower 48 are not appropriate for the workforce and systems present in Alaska.

4.2 ENGINEERING INTERVENTIONS

E1. Research and development should prioritize innovations that reduce energy costs to operate water systems in the arctic, as energy costs exacerbate water insecurity (Eichelberger, 2010). Such innovations may include solar technologies, wind turbines, and ways to capture and use waste heat. It is important to note that for these technologies to be successful, the original system must be optimized to reduce energy use, as well as operations and maintenance.

E2. The human system in which technical systems operate must be considered in the design process. Technologies and infrastructure systems being developed should be simplified and easy to operate.

4.3 MANAGERIAL INTERVENTIONS

M1. Remote monitoring and maintenance programs, such as the State of Alaska's Remote Maintenance Worker Program, should be expanded as it is a way to mitigate operational problems that may stem from a lack of operator training or expertise. Researchers should explore how virtual remote maintenance may be feasible in this context (e.g., virtual reality, remote monitoring), something largely unexplored in literature. Notably, there should be support for remote maintenance workers to travel and help communities with repairs that go beyond local capacity.

M2. Private managerial support for water systems should be explored further. This has been successful in some cases. For instance, companies engaged in mining in the region are assisting communities by helping with O&M of water systems. It is important to note that private support must be sustainable, and companies must commit to long-term support.

5. CONCLUSION

The arctic environment, remoteness, climate change, and social characteristics in rural Alaska create a unique and especially challenging operating environment for water systems. In turn, there are notable service gaps in rural Alaska, with some communities unserved and other communities experiencing service outages. These water infrastructure issues can lead to health impacts, including an increase in water burden and respiratory illnesses. Water infrastructure operates within multiple systems, including the technical, human, natural, and financial systems. To holistically understand the nature of water sector challenges in rural Alaska, we first identified challenges within each system and then studied how such challenges cascade between systems.

Results reveal that financial limitations result in unserved communities and service disruptions in served communities. It is not only the amount of money but how funding is distributed that causes such issues. For instance, funding is traditionally allocated to build new systems, but not for O&M, something particularly challenging for rural communities with limited financial and human resources. We also found that climate change is impacting multiple facets of water systems, such as accelerating the aging of systems and creating water quality and quantity concerns. Using cognitive system maps, we identified policy, engineering, and managerial leverage points that may improve the provision of water services in rural Alaska. For instance, we recommend that requirements to receive funding for a new water system be reviewed and replaced with a framework that ensures communities most in need are not getting penalized. Overall, our study documents water challenges in rural Alaska, bringing awareness to pressing environmental justice concerns.

ASSOCIATED CONTENT

The following files are available free of charge.

Table S1: Coding Dictionary for Challenges to Provide Water Services in Rural Alaska

Figure S1: Systems Conceptualization of Challenges to Provide Water Service in Rural Alaska

AUTHOR INFORMATION

Corresponding author: faustk@utexas.edu

First author: lspearing@utexas.edu

Author Contributions

The manuscript was written through contributions of all authors, as follows: Conceptualization and design: L.S., L.A., J.K., and K.F.; Data collection: L.S., J.K., and K.F.; Data coding and analysis: L.S. and P.M.; Coding validation: P.M. and K.F.; Writing - original draft: L.S.; Writing - review and editing: All authors; Supervision: K.F. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interests.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 2022666/2022177.

REFERENCES

Alaska DEC, 2022a. Alaska Water and Sewer Challenge [WWW Document]. URL https://dec.alaska.gov/water/water-sewer-challenge/ (accessed 11.30.22).

Alaska DEC, 2022b. Rural Alaska Unserved Communities [WWW Document]. URL https://dec.alaska.gov/water/water-sewer-challenge/rural-communities/

Alaska DEC, 2022c. Remote Maintenance Work Program [WWW Document]. Alaska DEC. URL https://dec.alaska.gov/water/remote-maintenance/ (accessed 2.13.22).

Alaska DEC, 2022d. Operations and Maintenance Best Practices [WWW Document]. URL https://dec.alaska.gov/water/technical-assistance-and-financing/best-practices/ (accessed 4.27.22).

ASCE, 2017. Infrastructure Report Card.

Brown, M.J., Spearing, L.A., Roy, A., Kaminsky, J.A., Faust, K.M., 2022. Drivers of Declining Water Access in Alaska. Environmental Science & Technology Water. https://doi.org/10.1021/acsestwater.2c00167

Brubaker, M., Berner, J., Chavan, R., Warren, J., 2011. Climate change and health effects in Northwest Alaska. Glob Health Action. https://doi.org/10.3402/gha.v4i0.8445

Burla, L., Knierim, B., Barth, J., Liewald, K., Duetz, M., Abel, T., 2008. From Text to Codings. Nurs Res 57, 113–117. https://doi.org/10.1097/01.nnr.0000313482.33917.7d

Chen, C.-C., Gillig, D., McCarl, B., 2001. Effects of Climatic Change on a Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer. Clim Change 49, 397–409.

Corbin, J., Strauss, A., 2008. Basics of Qualitative Research (3rd ed.): Techniques and Procedures for Developing Grounded Theory. SAGE Publications, Thousand Oaks, CA. https://doi.org/https://dx.doi.org/10.4135/9781452230153

Cozzetto, K., Chief, K., Dittmer, K., Brubaker, M., Gough, R., Souza, K., Ettawageshik, F., Wotkyns, S., Opitz-Stapleton, S., Duren, S., Chavan, P., 2013. Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S. Clim Change 120, 569–584. https://doi.org/10.1007/s10584-013-0852-y

Eccleston, P., Werneke, U., Armon, K., Stephenson, T., MacFaul, R., 2001. Accounting for overlap? An application of Mezzich's κ statistic to test interrater reliability of interview data on parental accident and emergency attendance. J Adv Nurs 33, 784–790. https://doi.org/10.1046/j.1365-2648.2001.01718.x

Eichelberger, L., 2017. Household water insecurity and its cultural dimensions: preliminary results from Newtok, Alaska. Environmental Science and Pollution Research 25, 32938–32951. https://doi.org/10.1007/s11356-017-9432-4

Eichelberger, L.P., 2010. Living in utility scarcity: Energy and water insecurity in Northwest Alaska. Am J Public Health 100, 1010–1018. https://doi.org/10.2105/AJPH.2009.160846

Everitt, B.S., 1996. Making sense of statistics in psychology: A second-level course. Oxford University Press.

Griffin, R.C., 2012. The origins and ideals of water resource economics in the United States. Annu Rev Resour Economics 4, 353–377. https://doi.org/10.1146/annurev-resource-110811-114517

Hennessy, T.W., Ritter, T., Holman, R.C., Bruden, D.L., Yorita, K.L., Bulkow, L., Cheek, J.E., Singleton, R.J., Smith, J., 2008. The relationship between in-home water service and the risk of respiratory tract, skin, and gastrointestinal tract infections among rural Alaska Natives. Am J Public Health 98, 2072–2078. https://doi.org/10.2105/AJPH.2007.115618

Hickel, K.A., Dotson, A., Thomas, T.K., Heavener, M., Hébert, J., Warren, J.A., 2018. The search for an alternative to piped water and sewer systems in the Alaskan Arctic. Environmental Science and Pollution Research 25, 32873–32880. https://doi.org/10.1007/s11356-017-8815-x

Joling, D., Thiessen, M., 2012. Alaska village short of water as winter approaches [WWW Document]. The Associated Press. URL https://www.nbcnews.com/id/wbna49373022 (accessed 2.13.22).

Kaminsky, J.A., Javernick-Will, A.N., 2014. The internal social sustainability of sanitation infrastructure. Environ Sci Technol 48, 10028–10035. https://doi.org/10.1021/es501608p

MacPhail, C., Khoza, N., Abler, L., Ranganathan, M., 2016. Process guidelines for establishing Intercoder Reliability in qualitative studies. Qualitative Research 16, 198–212. https://doi.org/10.1177/1468794115577012

Marino, E., White, D., Schweitzer, P., Chambers, M., Wisniewski, J., 2009. Drinking water in northwestern alaska: Using or not using centralized water systems in two rural communities. Arctic 62, 75–82. https://doi.org/10.14430/arctic114

Marzec, M.L., Lee, S.P., Cornwell, T.B., Burton, W.N., McMullen, J., Edington, D.W., 2013. Predictors of behavior change intention using health risk appraisal data. Am J Health Behav 37, 478–490. https://doi.org/10.5993/AJHB.37.4.6

Mattos, K., Blanco-quiroga, T., 2020. Water Infrastructure Brief Opportunities and challenges for washeterias in unpiped Alaska communities.

Mattos, K.J., Eichelberger, L., Warren, J., Dotson, A., Hawley, M., Linden, K.G., 2021. Household Water, Sanitation, and Hygiene Practices Impact Pathogen Exposure in Remote, Rural, Unpiped Communities. Environ Eng Sci 38, 355–366. https://doi.org/10.1089/ees.2020.0283

Meadows, D., 2008. Thinking in Systems: A Primer. Earthscan.

Melvin, A.M., Larsen, P., Boehlert, B., Neumann, J.E., Chinowsky, P., Espinet, X., Martinich, J., Baumann, M.S., Rennels, L., Bothner, A., Nicolsky, D.J., Marchenko, S.S., 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proc Natl Acad Sci U S A 114, E122–E131. https://doi.org/10.1073/pnas.1611056113

Mezzich, E., Kraemer, H.C., Worthington, D.R.L., Coffman, G.A., 1981. Assessment of Agreement Among Several Raters Formulating Multiple Diagnoses. J Psychiatr Res 16, 29–39.

NVivo, 2020. NVivo [WWW Document]. QSR International Pty Ltd. URL https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software

Penn, H.J.F., Loring, P.A., Schnabel, W.E., 2017. Diagnosing water security in the rural North with an environmental security framework. J Environ Manage 199, 91–98. https://doi.org/10.1016/j.jenvman.2017.04.088

Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K., 2001. Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. IEEE Control Systems Magazine 21, 11–25.

Saldaña, J., 2013. The Coding Manual for Qualitative Researchers (2nd Ed.), 2nd ed, SAGE Publications Inc. Sage Publications, London. https://doi.org/10.1017/CBO9781107415324.004

Sohns, A., Ford, J.D., Adamowski, J., Robinson, B.E., 2021. Participatory Modeling of Water Vulnerability in Remote Alaskan Households Using Causal Loop Diagrams. Environ Manage 67, 26–42. https://doi.org/10.1007/s00267-020-01387-1

Spearing, L., Kaminsky, J., Faust, K., 2022. Interview Data from January-June 2021: What Impacts Water Services in Rural Alaska? Arctic Data Center. https://doi.org/doi.org/10.18739/A2VH5CK3M

Spearing, L.A., Bakchan, A., Hamlet, L.C., Stephens, K.K., Kaminsky, J.A., Faust, K.M., 2022. Comparing Qualitative Analysis Techniques for Construction Engineering and Management Research: The Case of Arctic Water Infrastructure. J Constr Eng Manag 148, 1–12. https://doi.org/10.1061/(asce)co.1943-7862.0002313

Spearing, L.A., Faust, K.M., 2020. Cascading System Impacts of the 2018 Camp Fire in California: The Interdependent Provision of Infrastructure Services to Displaced Populations. International Journal of Disaster Risk Reduction. https://doi.org/https://doi.org/10.1016/j.ijdrr.2020.101822

Suter, L., Streletskiy, D., Shiklomanov, N., 2019. Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. Polar Geography 42, 267–286. https://doi.org/10.1080/1088937X.2019.1686082

Thomas, T.K., Hickel, K., Heavener, M., 2016a. Extreme water conservation in Alaska: limitations in access to water and consequences to health. Public Health 137, 59–61. https://doi.org/10.1016/j.puhe.2016.06.002

Thomas, T.K., Ritter, T., Bruden, D., Bruce, M., Byrd, K., Goldberger, R., Dobson, J., Hickel, K., Smith, J., Hennessy, T., 2016b. Impact of providing in-home water service on the rates of infectious diseases: Results from four communities in Western Alaska. J Water Health 14, 132–141. https://doi.org/10.2166/wh.2015.110

U.S. Arctic Research Commission, 2017. Alaska Rural Water and Sanitation Working Group.

U.S. EPA, 2017. Secondary Drinking Water Standards: Guidance for Nuisance Chemicals [WWW Document]. URL https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals#table-of-secondary (accessed 2.13.19).

USARC, U.S.A.R.C.A.R.W. and S.W., 2015. Alaskan Water and Sanitation Retrospective 1970-2005 26.

Supplemental Information *for*

What Impacts Water Services in Rural Alaska? Identifying Vulnerabilities at the Intersection of Technical, Natural, Human, and Financial Systems

Lauryn A. Spearing, Prachi Mehendale, Leif Albertson, Jessica A. Kaminsky,

and Kasey M. Faust

Contents:

Interview Protocol

Role and Organization:

- What is your current role? How long have you been in your role?
- What are your main responsibilities?
- What entities/agencies do you usually work with?
- Please tell me about your organization.

General Water Infrastructure:

- What water infrastructure challenges are you aware of in regards to access or levels of service in rural Alaska?
- What water infrastructure challenge do you think is the most important to address (i.e. what would you prioritize)?
- Can you describe service disruptions or failures that commonly occur?
    - How are disruptions or failure in service responded to?

Adapting to Arctic Challenges

- What challenges are unique to Alaska due to the arctic conditions?
- What solutions have been implemented to address these challenges in providing water service in rural areas?
- What do people from outside of your community not understand about water infrastructure in your area?

Climate Change

- How does climate change impact water infrastructure systems in your region?
- How are you adapting to these changes?
- Looking back on how you adapted to challenges, what do you think was done well?
    - What do you think could have been done better?
- What adaptations would you like to see happen in regulations or management?
- What should others know about what climate change means for water systems?

Workforce

- What workforce challenges with water infrastructure system operations and maintenance in rural Alaska have you heard of?
- What do you need to better respond to these changes (e.g., funding, increased training for operators)?

Supplemental Table 1: Coding Dictionary for Challenges to Provide Water Services in Rural Alaska (Examples Only Shown for Child Codes)

Code	Definition	Example
Financial	Related to finances or funding water systems (e.g., billing, funding).	
Expenses or costs for water systems	Statements about expenses or costs for water systems.	
High cost of construction	Statements referencing the high cost of construction.	"It would cost approximately $26 million to replace their distribution system. So, it's really expensive."
High operational costs	Statements about high operational costs (e.g., from heating the system).	"There are two primary challenges for providing service to an unserved community, [they are] capital costs and O&M costs."
Unaffordable costs per household	Statements about the high costs of service for each user or household and affordability issues. Focuses on the overall affordability not just high costs.	"Yeah, so if you build a water treatment plant that costs five million dollars…if you're serving a small community, you divide that by a small number, and they'd be in a cost that's really high. It's more isolation of the communities resulting in high construction costs and also the size of the communities is very small. When you have a small denominator, you get a [really high] cost."
Funding or financial capacity	Statements about funding or a community's financial capacity for water systems.	
Billing issues	Statements about challenges to bill users (e.g., no meters, trouble collecting).	"Some communities have been successful in implementing rates, rate charges for water, and wastewater. But if people don't even have a job to get some cash income, they're not able to pay a water bill, and then it's their neighbor, or their uncle, or their grandmother, or someone that they're very close to that would have to make the decision to turn off their water because they haven't paid their bill."
Communities' ability to financially support systems	Statements about a community's overall ability to financially support a water system. This can be attributed to various causes such as the high cost of service or the economy in the area.	"The operations and maintenance costs of the system are incredibly burdensome; a lot of our communities are not a traditional cash-based economy—they are subsistence-based."

Funding system shortcomings	Issues with funding systems (usually at the state and federal level). This may include issues with decision making, ranking projects, or funding coming from different organizations. This is not including the overall amount of money.	"But that's what gets funded. And then it's like, all right, well, now we've got to go build this because that's where we got funding for when that really was not what we should have been doing to begin with."
Insufficient capital funding	Statements about a lack of sufficient capital funding (e.g., state, and federal funding) for water systems.	"How many projects we can fund, because of this high cost, could be limited. So, we may not be able to get to the community's needs as quickly as we would hope."
Lack of outside O&M funding	Statements about a lack of (or absence of) operations and maintenance funding from sources outside of the community (e.g., state agencies, private sector).	"There is no funding to pay for the operations and maintenance of the systems. Once we build these systems, then it's on the community to be able to pay to operate and maintain the systems."
No cash economy	Statements about communities lacking a cash economy and, in turn, having limited spending capacity.	"A lot of our communities are not a traditional cash-based economy—they are subsistence-based. And so the burden of $150 or $200 a month water and sewer bill is just excessive."
Human	Related to people and society, including topics such as community experiences, management, and workforce challenges.	
Community experiences, characteristics, and perceptions	Statements regarding community experiences with water systems (aside from management, workforce, and financial challenges). This may include their level of service, perceptions towards systems, and community characteristics.	
Cultural expectations and subsistence living	Regarding the culture and lifestyle of communities, such as subsistence living (i.e., traditional uses of fish and wildlife like for food or clothing; Alaska Department of Fish and Game, 2022)	"For a lot of these rural areas really for people to survive, they need to engage in subsistence, gathering or hunting, to provide food."

Health implications	Statements about the health risks and implications related to water and wastewater issues.	"We have the highest rate of respiratory syndromes in the state. We have high levels of skin infections. We don't have a lot of documented waterborne disease outbreaks, as far as salmonella, Shigella, those kinds of things, but we do have a higher level of waterborne disease burden."
Lack of public acceptance	Statements about communities not accepting the water services or having issues with the water provided (e.g., taste, smell, perceptions of safety).	"I would say probably a majority of [people] do [use water services], but there's quite a few folks that don't like the treatment in it."
Small populations	Statements mentioning the small size of communities (i.e., limited number of people).	"It's more isolation of the communities resulting in high construction costs and also the size of the communities is very small. When you have a small number of a denominator entailed, you get a cost, they're really high."
Underserved communities	Communities that receive services through fee-based closed-haul systems where water is hauled to the home and sewage is hauled away." (Alaska DEC, 2022)	"We do have a number of systems, a number of communities that have had for 20 or more years, a flush tank haul type system where there's water hauled to the home, the sewage is collected and hauled away."
Unserved communities	Communities where under 55% of the community is served; communities receive water through a central watering point (i.e., washeteria) and often use honey-buckets. (Alaska DEC, 2022)	"I'll first address the question of unserved communities. A community that has a washeteria and a watering point that doesn't actually have running water within their homes [is unserved]. There's approximately 30 of those in Alaska."
Use of alternative sources	Statements about community members using alternative water sources or sanitation methods (e.g., ice melt) despite services being provided.	"[Instead, people are] going to their traditional water sources which has a higher risk for them than chlorine. But they just don't like the taste of [their treated water], they don't like the idea of a chemical being in their drinking water."
Management and regulations	Pertaining to managing construction, providing support during operational stages, or regulations. This does not include aspects related to the workforce and employee training.	

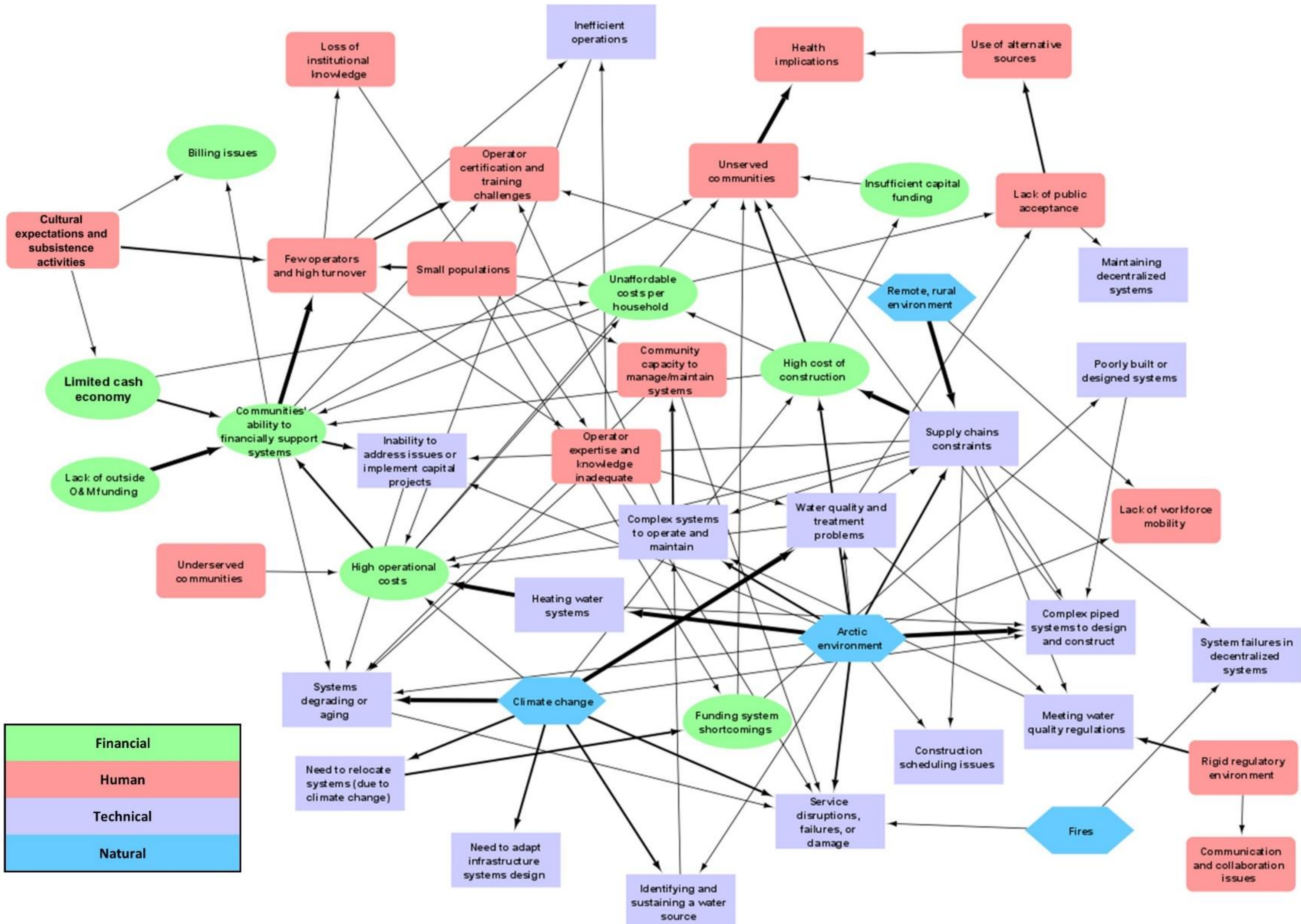
Communication and collaboration issues	Statements about communication or collaboration challenges between different institutions and communities.	"I don't think technology is the problem because I think we can get their technology. I think what it comes down to, is people and communication. There is an annual water and sanitation working group. And it's very rarely people from rural areas are included"
Community capacity to manage and maintain systems	Statements about the community's ability to manage and maintain systems, aside from financial considerations. These statements are not specifically about operators.	"You're just going to leave it and say, 'Here you go people. Have fun.' And we know that they [the community doesn't] have the capacity to maintain it properly.'
Determining the service method	Challenge to determine the right technology or method of service for communities. This is not inclusive of general discussions of service provision.	"I think one of the things that all of us as practitioners struggle with here in the state is what's an appropriate technology for small communities."
Lack of oversight and support during operations	Statements about a lack of management oversight and support during operations from outside institutions (e.g., State government).	"I'm trying to think of what we're addressing, obviously qualified and competent staff at the local level…they need a cooperative or some other way of dealing with issues. But generally, there's not a lot of oversight in terms of expectations of what the operators do by city council or utility board."
Rigid regulatory environment	Statements about the regulatory environment being rigid and not adaptable.	"I found it challenging with the ever-increasing regulatory requirements on water treatment. I remember back in the nineties, we were all ticked off that EPA had a requirement that every year they had to list 25 more things to test for and it seemed like it just made it more difficult for us to develop systems that were hardened for the Arctic, and that could be easily maintained."
Workforce	Related to the workforce (e.g., operators). This includes workforce training and knowledge.	
Few operators and high turnover	Mentions challenges with having enough water system operators and backup operators. This code includes mentions of high operator turnover.	"Our operator turnover is really high. I think our average, I guess lifespan, is probably not the correct term, but an operator typically stays on the job for three years."

Lack of workforce mobility	Statements about the lack of mobility of people working in the water sector (e.g., operators, engineers accessing communities).	“We have a remote maintenance worker program that's funded by our state revolving loan fund, but sometimes they can't even get out to these places because of the weather.”
Loss of institutional knowledge	Statements about a loss of knowledge when the workforce (e.g., operators, engineers) turns over.	“Then all of a sudden, nobody's passed the baton. Nobody's passed on that knowledge of how to run that system, how to maintain it.”
Operator certification and training challenges	Challenges with operator certification and training.	“Then as far as training, it's definitely still a big challenge for people to get their initial certification and then keep their certification.”
Operator expertise and knowledge inadequate	Mentions that the operator's expertise and knowledge are inadequate to manage the system.	“But unfortunately, most operators in rural Alaska can't accommodate changes like that (i.e., from climate change), they are not generally well versed or trained to respond to changes.”
Natural	Related to the natural environment, including climate, weather, and geographic location.	
Arctic environment	Related to the arctic environment and weather patterns (e.g., weather patterns, temperature).	“We also have kind of unconventional needs here too, just because of the climate…We have a lot of instances where our services are provided in above-ground utilidors with Arctic pipe.”
Climate change	Related to climate change (e.g., erosion, permafrost melt) that is from both natural and man-made causes.	“Climate change does affect the existing infrastructure that's out there, mainly in the arctic and sub-arctic areas because we see thawing permafrost.”
Climate variability	Related to the variability in climate throughout the state of Alaska (e.g., Arctic, temperate) based on geography.	“That's very true that your toolbox is quite large, you might be up north in a very severe Arctic climate, or you might be down in Southeast Alaska where you essentially have semi-rain forest, cold rain forest environment with mountains. So permafrost up north, and essentially a lot of bad soil in between and then you've got nothing but rock in other places. So their variety is very challenging.”
Fires	Related to fires. This could be induced or influenced by climate change or caused by human errors.	“I think a lot of this has made it into the Lower 48 news, but we had a couple of really big fires up here.”

Remote, rural environment	Related to the remote and rural nature of communities in rural Alaska.	"It's more isolation of the communities resulting in high construction costs and also the size of the communities is very small."
Technical	Statements about technical aspects of water systems. This may include designing, constructing, operating, and sustaining systems. Workforce is not included here, but instead in the social code.	
Design and construction	Statements about designing or constructing water systems.	
Challenges with standards	Statements that discuss a lack of design standards or issues developing them for water systems in Alaska.	"It's difficult to create standards. It's a not a one size fits all thing. You have to tailor each standard to each set of unique environmental and geotechnical conditions. Sometimes even economic and cultural as well."
Complex piped systems to design and construct	Statements about how piped systems are complex to design and construct.	"The construction, I mean, it's difficult in Alaska, so it's cold, the construction season is limited. Sometimes you have to construct in the winter, which is expensive, so logistics are difficult, it's expensive to ship materials out to communities."
Construction scheduling issues	Statements about the limited timeframe of construction (e.g., seasonal, challenges during the winter) or that it takes longer for construction.	"Obviously it's not just the harsh climate, but we would have a little bit more limited construction season compared to Lower-48, because of our weather and environmental factors."
Supply chains constraints	Challenges associated with supply chain (i.e., acquiring and transporting materials needed for construction or operations).	"It's not necessarily a winter thing. But because they're isolated and small, even getting a replacement pump or something small like that may take weeks because of fog or snow weather. Even in the spring and the fall when the ice is thawing, thaw is the problem."
Need to adapt infrastructure systems design	Statements that the way infrastructure is designed needs to be adapted for both future projects and repairs.	"Look you're not going to get the freeze back, so we've got to change your foundation a little bit or change construction techniques, issues like that."
Operations	Statements about operating water systems; this does not include specifics about workforce (that is in the social code).	

Complex systems to operate and maintain	Statements about how water sector systems are complex to operate and maintain.	"Another challenge is the technical complexity of the systems trying to operate a very complex system that heats water and circulates it year-round in a community of say 200 to 300 people where the technical capacity of that community is very limited. You walk into some of these plants, and it's truly overwhelming in terms of the technical complexity to keep the water flowing, to meet regulatory standards."
Identifying and sustaining a water source	Statements about finding, accessing, and sustaining a reliable water source.	"Now we have climate change where we have huge banks sloughing off into water sources, turbidity spikes that we've never encountered before, and now that's compounded the ability to treat local sources and developed them into adequate sources of water, not only quality wise, but quantity wise."
Heating water systems	Statements that talk about the need to heat systems during operations or how this makes systems energy dependent.	"We're running boilers 24 hours a day and heating the main line 24 hours a day, which means we're burning diesel fuel 24 hours a day. And so, the community has to be able to afford to do that."
Inability to address issues or implement capital projects	Statements that mention communities' inability to address issues, implement capital projects, or keep the backups needed to sustain water systems.	"None, nobody has a spare $1 million sitting around or $10 million for replacement of that water treatment plant, if it breaks."
Inefficient operations	Statements about inefficient operations of water systems, such as excessive energy use.	"You don't always operate your system as if it's minus 32, it's a huge waste of energy. And many of the systems have fixed operational plans, which don't really allow the operators any variability and responding to actual conditions of usage and or temperature and that kind of thing."
Maintaining decentralized systems	Challenges associated with maintaining and operating decentralized systems (e.g., PASS, wells).	"I think a decentralized system is going to have some of the same issues as community (i.e., piped) systems do. You have this issue or the struggle to do the operation and maintenance."
Meeting water quality regulations	Challenges associated with meeting water quality regulations.	"[A community's] water source is basically runoff from the rocks, but it's a rookery, a sea bird rookery. They have really high levels of nitrate and high levels of arsenic in their source water. And they are always out of compliance because they can't get samples back to the mainland to get them to a lab."

Water quality and treatment problems	Challenges associated with treating water and maintaining adequate water quality. This is up to the point of service.	"One of the big issues that we run into is for systems that add fluoride. We are the only state in the country that's ever had somebody actually die from a fluoride overfeed in a drinking water system. It happened in one of our villages in 1992, and so we do require a certified operator if the community is going to be adding fluoride."
System sustainability	Statements about system sustainability or issues. For instance, if there are system failures or if systems are degrading.	
Need to relocate systems (due to climate change)	Statements about existing systems being put at risk and the need to relocate.	"We have a couple of systems that are, communities, whole communities that are just going into the river or going into the sea. They need to be they need to be relocated."
Poorly built or designed systems	Existing systems are poorly built, underbuilt, or overbuilt.	"Sometimes they only fund projects that are the lowest cost alternative, so you might have three alternatives, but they're only going to pay for the least cost alternative. The least cost alternative may not be the ideal solution. And if it's not done right, the least cost alternative might be a terrible solution."
Service disruptions, failures, or damage	Statements about damage, failures, or service disruptions in water systems or services.	"Whole systems can fail because somebody didn't put oil in a pump. And I'm not exaggerating. That's a literal issue."
System failures in decentralized systems	Failures in decentralized systems such as flush and haul.	"I know there are some communities that have a washeteria as the only source of piped water, or potable water, I guess. There was a community recently, Tuluksak, where their washeteria burned down. So, now they have to fly in with a cargo plane water, which, that's issues."
Systems degrading or aging	Statements about systems degrading over time or aging naturally.	"I think that one of the main issues right now with [water systems] is the age of them, where some of them have been in place maybe 30 years already. And so now we have to worry about the pipes breaking down over time, and the connections breaking down."



Supplemental Figure 1: Systems Conceptualization of Challenges to Provide Water Service in Rural Alaska. Only relationships mentioned more than once are shown. Lines are weighted based on the number of coded references (thicker lines were mentioned more often).

References

Alaska DEC. (2022). *Rural Alaska Unserved Communities*. https://dec.alaska.gov/water/water-sewer-challenge/rural-communities/

Alaska Department of Fish and Game. (2022). *Customary and Traditional Use - Subsistence Information*. https://www.adfg.alaska.gov/index.cfm?adfg=subsistence.customary