A Stakeholder-Systems Analysis of Water Provision in Rural Alaska

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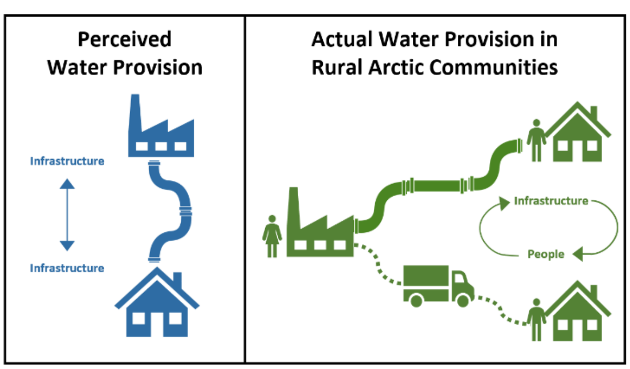
ABSTRACT

People are paramount in the operations of water infrastructure systems. While such processes are similar throughout most communities in the United States, including treatment and distribution, each community encounters localized challenges. In the Yukon-Kuskokwim (YK) Delta of Alaska, specifically, water sector professionals (e.g., water plant operators, water haulers) encounter unique and extreme challenges. The harsh Arctic weather makes road navigation dangerous for water haulers, and water plant operators must contend with a precarious supply chain when ordering supplies for maintenance. Such challenges can disrupt water provision for communities. In this study, we analyze semi-structured interviews with 24 Alaska water sector professionals, using qualitative content analysis and semi-cognitive mapping. We build a conceptual integration of systems and stakeholder theory to identify barriers to water provision and leverage points for improvement. We examine three components of the water provision process in rural Alaska communities: water treatment, hauled water distribution, and piped water distribution. We show that to increase workforce retention, limit worker burnout, and ensure reliable water provision, practices including training and certification need to become more localized. Moreover, working conditions and operating environment around the worker need to be more central in water system considerations, especially for water hauling where workers play a critical role in water distribution. This analysis reveals a key conclusion that underlies all our propositions: people are a leverage point for water provision improvement. In so doing, we contribute to the literatures in public administration and bureaucracy, sociotechnical systems, and stakeholder theory as applied to infrastructure systems, more generally, and water systems, more specifically.

Keywords: operations; infrastructure; stakeholders; systems; rural; Alaska; training

Synopsis: Training for water sector professionals in rural Alaska needs to become more localized to ensure reliable water provision for communities.

Abstract Art:



INTRODUCTION

Rural Alaska communities rely on a range of stakeholders to ensure water service provision, including water plant operators, water haulers, administrative workers, and end-users. While the design and physical integrity of infrastructure is essential, people are paramount for ensuring reliable water provision. For instance, water plant operators must understand how seasonal changes influence source water quality, ensuring they adjust chemical treatment accordingly. Workers in administrative roles create workforce schedules and process payments for end-users, ensuring reliable revenue for the utility. Community leaders develop long-term utility expansion plans to accommodate changing populations and system funding. End-users (i.e., the community residents) also hold an important role in water services, whereby they create a demand for water, monitor the aesthetics of water that reaches their homes, and contribute to revenue that supports the utility. In the Yukon-Kuskokwim (YK) Delta of Alaska, where many communities rely on hauled water distribution, water haulers deliver treated water to community residents via truck or all-terrain vehicles (ATVs), filling the essential role of distribution otherwise provided by piped infrastructure elsewhere.

The importance of stakeholders, especially the workforce operating the utility, is recognized by industry experts. In the 2023 State of the Water Industry Report, workforce concerns were prominent in the list of the top 20 issues facing the sector. For instance, "aging workforce/anticipated retirements" ranked at number 6 and "talent attraction and retention" at number 12 [1]. To contextualize the starkness of these challenges, a 2018 study noted that 30-50% of employees in the water sector are expected to retire in 5-10 years [2], [3]. To swiftly prioritize these concerns, the American Water Works Association (AWWA) is collaborating with several organizations and government agencies, such as the Water Environment Foundation (WEF), the

U.S. Environmental Protection Agency (EPA), and the U.S. Department of Agriculture (USDA) [4]. Such initiatives include the AWWA-WEF Work for Water program [5], the EPA Water Sector Workforce Initiative development grant scheme [6], and the EPA-USDA Memorandum of Agreement around rural water and wastewater services [7]; all of which prioritize water sector workforce development. The interagency cooperation demonstrated by these initiatives provides assurance that the industry and the government recognize the role of water sector professionals in water service provision, and seek to improve it.

While workforce challenges are acute in more "typical" operating conditions, they can be existential in more extreme operating conditions. The unique operating environment of rural Alaska presents significant constraints for water provision. Water sector professionals must contend with extreme weather conditions, precarious supply chains, and skill misalignments to ensure continuity of services [8]. Workers must prepare for the low temperatures and high winds that typify the Arctic. In many communities throughout the YK Delta—the region of focus in this study—water pipes are placed above the ground surface to avoid interference with permafrost [9]. These pipes can be damaged by vehicles, especially when covered by snowdrifts, requiring a great deal of knowledge, skills, and time from the water utility workforce to make repairs. Pipes can also be damaged by ground subsidence during freeze/thaw periods, an issue that is only further exacerbated by climate change [10]–[12]. Utility maintenance workers must regularly check and resecure pipes that have moved. Extreme temperatures necessitate the procurement of special materials and operations to prevent water within the distribution pipes and water treatment plant from freezing. These include but are not limited to the use of heat tape, glycol, as well as protocols to ensure water is continuously circulating to prevent blockages due to freezing [13], [14].

Other communities in the Delta employ water haulers to deliver water, rather than distributing the water through pipes. These specialized water sector workers must contend with icy roads, low visibility, and extreme cold while delivering water to homes [15]. The arctic weather requires those individuals who operate water utilities to have specialized knowledge and skills to properly maintain such systems. The lack of such knowledge and skills often results in infrastructure damage and service disruptions [16], [17].

Adding to these challenges, there are several communities in the YK Delta that are considered unserved, as defined by the Alaska Department of Environmental Conservation, where less than 55% of homes receive treated water through pipes, well, or a covered hauled service [18]. These households often must collect their own water, usually from a central community water point.

Adding to the environmental challenges, material and equipment needed for repairs and regular maintenance are not readily available or transportable in the rural Arctic [10], [17], [19]. When a replacement part is needed for a water pump, for instance, the likelihood that such a piece can be sourced from within the region, let alone in a timely manner, is low [20]. Because communities in the YK Delta are not connected via a highway system, materials are often shipped via air from Anchorage, if the parts are small enough. For larger equipment, water plant operators must place orders months in advance, and often wait for warm weather when a barge can access the area [21]. Amidst these habitual supply shortages, gaps, and delays, water sector workers in the region must develop the logistical skills to plan as much as a full year ahead for when materials and equipment is needed. Alternatively, when repairs must be made promptly to ensure water provision, and supplies cannot be procured, workers must innovate workarounds with readily available materials, such as utilizing coffee cans and other makeshift tools for repairs, which the researchers learned during tours of water treatment facilities in the region. This practice of recombining what is commonly available to innovate is known as bricolage, and in resource-constrained environments, this is not only common but often essential [22]–[24].

With water systems facing such extreme supply, social, and environmental conditions, one could argue more rather than less workforce is needed. Yet precisely due to these unwelcoming conditions, Alaska has some of the worst workforce shortages. In Alaska, job opening rates were as high as 11.2% in May 2022, almost twice that of the overall United States [25]. Strict certification testing, scheduling, and administrative requirements present additional barriers in communities with minimal internet access and a fairly informal local economy [26]. Moreover, in the YK Delta, where 85% of the population identifies as Alaska Native (AN) [27], many water sector workers take subsistence leave seasonally for hunting, fishing, and gathering. These subsistence practices are not only essential for preserving the local Indigenous culture, but are necessary for survival in these remote tundra communities [28]. With already existing shortages, most rural utilities cannot employ enough workers to fill important roles while others take subsistence leave, which only further stresses the system. Many workers are forced then to choose between their cultural and professional priorities [29], [30].

To explore the complexity of water delivery due to the extreme conditions that we have documented, we first highlight where such complexity critically intervenes in water distribution. Figure 1 details the components that centrally capture the diverse water delivery modes observed in rural Alaska water provision. Total household water supply is comprised of both treated and untreated water, the former of which can be provided by either piped or hauled distribution [18]. For piped water distribution, pipes transport treated water from a centralized water treatment plant to homes, with pipes typically placed above the ground surface to avoid disruption from shifting permafrost. For hauled water distribution, treated water is transported by the end-user or municipal worker via truck or ATV, and then stored in tanks inside homes. We posit that there are notable differences between these two service types, which impacts water provision as each mode requires different skills to maintain and operate, and are impacted differently by extreme Arctic weather. Although we focus on treated water in this study, we must acknowledge that traditional water collection practices, such as packing ice and collecting rainwater, contribute to a household's total water supply, although not managed or regulated by a professional workforce.

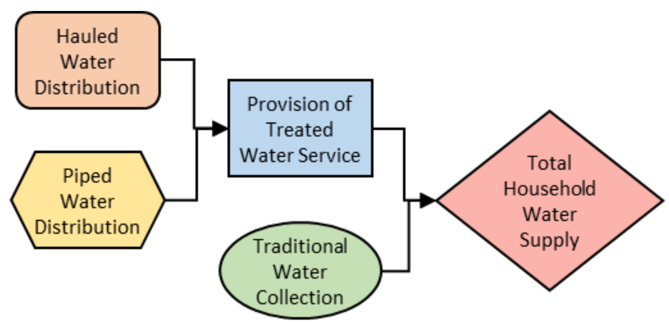


Figure 1. Components of water provision that lead to the total household water supply in rural Alaska communities. There are two supply types: treated and untreated water. Treated water can be distributed through either pipes or hauled service. All of these components contribute to the total household water supply.

Amidst such relentless complexity in water delivery, our study explores how water sector professionals work within and around water services in rural Alaska communities. Workers hold myriad essential roles in these water treatment and distribution processes, including management, operations, and administration of the utility. Prior work often does not holistically explore the worker and their impact on water provision, but rather focuses on issues such as sanitation [31] or infrastructure design [14]. In other words, the focus has been more on the water "hardware" and less so on the water "software". More specifically, workers are often the key means by which water systems are linked to key stakeholders (i.e., end users, government agencies, and community organizations). We have yet to fully characterize these interactions, especially amidst such extreme operating conditions. To these ends, we conduct an inductive study to identify such relationships. This study aims to identify salient relationships and synthesize them into testable propositions that can subsequently guide larger scale stakeholder-system analyses.

Enabling this study is the qualitative content analysis [32] of semi-structured interviews with 24 regional water sector experts who work in rural Alaska communities. These interview participants provide insight into the regular challenges and rewards of operating a rural Alaska water distribution network that could not be collected via other means. For example, the participants discuss the dynamics of workforce-community interactions, explaining the challenges of accessing private properties to deliver water. Other participants discuss workers' safety considerations of driving on icy roads in low visibility to deliver water. Building on this insight, we develop a semi-cognitive map [33], identifying relationships between factors that enable or inhibit water provision. Semi-cognitive maps provide a structure for knowledge that would otherwise "be loosely-linked, highly complex, or unavailable" [33]. These maps are especially useful in this analysis because they allow for a visual understanding of interactions among systems [17]. Using this information, we build a novel framework to understand the stakeholder-systems involved in water provision. We further utilize this information to provide recommendations for improvement to the water sector workforce to ensure reliable water provision, including training improvements and greater attention to workers' wellbeing.

POINTS OF DEPARTURE

Many studies have examined water infrastructure from various perspectives [14], [34], [35]. Such studies have evaluated planning [36], design [37], and resilience of water utilities [38]. Many studies focus on urban infrastructure, assessing deteriorating water networks and health impacts on communities [39]–[41]. This study departs from existing literature by focusing on the professionals supporting water provision in rural Alaska communities. Understanding water infrastructure here is especially important due to the populations' vulnerability, and the subsequent impact of water services [11], [26], [42].

There is a range of literature that explores water access in rural Alaska communities. Such studies provide insight into the barriers to water provision, highlighting environmental [43], economic [13], and cultural [44] factors that can hinder access to safe potable water. Brown et al. explore drivers of declining water access, identifying socioeconomic status as a significant barrier to water access in Alaska communities [10]. Other studies identify climate change and the resulting environmental impacts as barriers to reliable water provision [28], [45]. One challenge is how to understand the preferences of untreated water. There are two competing findings. The first is that some argue residents prefer untreated water, which can result in deleterious health impacts [43], [44], [46]. However, these studies are often conducted in settings where residents have and can afford a choice between treated and untreated water. The second is residents who use untreated water because they have no alternatives and so such practices are argued to be driven more from conservation than preference for such water delivery means [30], [42], [47]. For the purposes of our work, we are largely exploring a setting where both treated and untreated water are available.

We begin this study with a focus on water sector professionals, aiming to understand their impacts on the water provision in rural Alaska communities. Some researchers have analyzed stakeholders and infrastructure projects broadly, identifying who is a stakeholder [48], [49], the roles of key stakeholders [36], and even if stakeholders oppose projects [50], [51]. From these studies, we learn that stakeholder cooperation is pivotal in the successful implementation of a project. Such studies cover a range of infrastructure types, including transportation [52], real estate [53], and energy projects [50], demonstrating that commonalities exist across sectors. Some studies focus on rural areas [34], and others on urban areas [54], demonstrating that studies focused on specific regions and contexts yield different results. We build upon such research to evaluate the unique context of rural Alaska, where water sector stakeholders encounter significant challenges.

A select group of studies have explored stakeholders and water infrastructure [17], [36], [40], [48], arguing that stakeholders' roles must be understood for successful implementation of a water sector project. We learn from such studies that stakeholders with different backgrounds, careers, and motivations can impact infrastructure projects differently. For instance, Lienert et al. argue that stakeholders are disconnected from one another in water infrastructure planning, and that they need more coordination to ensure successful projects [48]. While most of these studies focus on the development and design of infrastructure [55], we depart from such studies to evaluate the stakeholders involved in water provision. To reiterate, while most focus on the water system "hardware" (i.e., infrastructure design and delivery), we also include the "software" (i.e., workers and stakeholders). Focusing on the provision of service allows us to understand this final step in the distribution process, and to identify possible intervention points, providing practical recommendations for water sector improvement.

We employ stakeholder theory in this study as a means to more systematically identify and better understand the stakeholders who are associated with water provision. Stakeholder theory, often used in business ethics and organizational studies, aids in identifying stakeholders for a project or organization [56]. The framework guides us in determining to whom the entity is responsible, considering factors such as safety, happiness, productivity, and finances. In identifying such stakeholders, the entity can better develop their strategy framework, determining which priorities drive success. Stakeholder theory further emphasizes the value of relationships between organizations and society [57]. As such organizations can create jobs, build infrastructure, and impact community wellbeing through these stakeholder relationships. Although not as commonly used in infrastructure studies, stakeholder theory is a useful tool here in the evaluation of water utility operations as it allows us to understand the system beyond just the technical perspective. When dealing with extreme operating conditions, a social perspective is arguably also consequential. Stakeholder theory enables us to identify relationships between utility owners, water sector workers, and community end-users. The literature that uses stakeholder theory to evaluate infrastructure projects primarily does so to identify stakeholders in the development of a new project, including transportation [49], [58], energy [50], and construction projects broadly [51], whereas we are focused on the roles of professionals throughout the daily operation and maintenance of a utility. More specifically, we see that stakeholder influences on service provision, and in our case water service provision, are missing from this scholarly dialogue. We use stakeholder theory to better understand the roles of water professionals in operations and management to fill this operational-focused gap in the literature.

This study's analysis of water infrastructure integrates system and stakeholder approaches. Defined by Meadows, a system is "an interconnected set of elements that is coherently organized in a way that achieves something" [59]. Systems thinking requires an understanding that systems are connected and do not function independently [59], [60]. Several studies have integrated this approach into their stakeholder analyses, recognizing that stakeholders will impact and be impacted by many interdependent systems [17], [58], [61], [62]. Much of the previous literature has evaluated water infrastructure from just one or two system types and underlying stakeholders. Here we build on a foundation of existing work that finds interdependencies among a wider set of financial, social, technical, and natural systems [60]. By integrating systems and stakeholder approaches, we can further understand the roles of water professionals and how they impact water provision. Ultimately, this more holistic approach will allow us to better identify solutions to the more extreme water challenges that typify rural Alaska communities.

This study provides contributions to literature in three key areas. The first contribution is in the literature on public administration around bureaucracies and the ways in which they administer public services such as water. The originating premise of this group of literature is that the processes for infrastructure service delivery are heavily influenced by those government agencies and bureaucrats nearest to the locus of access [63]–[65]. From that a plethora of literature has explored how such bureaucratic decisions affect delivery of services ranging from those pertaining to environmental protection [66], educational [67], water [68], hydroelectric facilities [69], all the way to even the approval of GMOs and wood pellets [70]. However, in this rich and growing literature, the focus is on detailed ethnographic studies and even when studied at larger scale, the focus is on the bureaucratic agency of interest. These studies are missing an understanding of the ways in which different stakeholder groups interact with such agencies. This is important as these stakeholders rarely act independently and often operate and deliver services as a coalition. In adopting a systems-based approach, we can take greater stock of the sociotechnical landscape around infrastructure services to better understand how multiple stakeholder groups interact to better gauge where there are barriers to service provision.

The second contribution is around the literature regarding sociotechnical analyses of water. This work tends to focus on individual preferences [43], [71], [72], how to build social acceptance [73], [74], and legitimacy [75]–[77]. While seemingly intuitive, few incorporate stakeholder theory into this arena [34], and when they do, they do not do so in a way that is actionable and can inform engineering decision-making. Our study advances not just a more structured incorporation of stakeholders into water systems but a methodology through which to chronicle where they are particularly important in the information flows of the system. Our study uses approaches in systems thinking to map where stakeholders interact with each other and other factors to identify where stakeholders have critical challenges and bottlenecks that if addressed, could improve system performance.

The third contribution is around stakeholder theory [56]. While much of this literature has focused on non-market strategy, namely the interactions between businesses and civic organizations such as non-profits and communities [78]–[80], this does not cover how these play out in infrastructure systems. This is surprising because there is a set of ethnographic work and more recent large-scale quantitative work that argues stakeholder contentions and interactions around infrastructure systems are especially important. Because infrastructure is often so taken-for-granted, they can have strong yet often obscured influence on how these systems operate, to the point they may skew resource access from these systems [81]–[83]. Here again, our approach to formalizing where precisely such stakeholder interactions play out and how they influence infrastructure systems helps expand the scope and applicability of stakeholder theory to these understudied infrastructure systems.

Overall, while many have recognized the value and influence of stakeholders, they do so generally and without a structured methodological approach. Our study helps formalize and structure an approach to more precisely understand where and how stakeholders influence infrastructure systems so as to better recognize and act upon such value and influence in ways that improve infrastructure system performance, better tailor to different stakeholder needs, and more equitably distribute the benefits.

METHODS

Data Collection

To better understand water provision in rural Alaska communities, we conducted semi-structured interviews with regional water sector experts from the YK Delta. These 24 experts held various roles within their communities, including administrative leadership, healthcare workers, water services operators, and others, as shown in Table 1. In line with Freeman's seminal work, we define a stakeholder as an entity that directly interacts with the water utility [56]. Participants included both members and non-members of Native Alaskan tribes. These interviews were conducted both remotely and in-person between November 2021 and August 2022. Before data collection, the project was reviewed by the Institutional Review Boards at the University of Texas at Austin, Carnegie Mellon University, and the Alaska Area IRB, as well as the YK Health Corporation Human Subject Review Board. Participants were compensated for their time. Interviews ranged in length from 11 to 123 minutes. The interviews were recorded (with permission), transcribed, and checked for quality through reviewing for transcription errors. One interview participant requested not to be recorded, but did agree to participate, and as such a debrief was recorded by the interviewer afterward to capture the discussion.

Table 1. List of interview participants, their community roles, and interview details.

Participant	Region of Experience	Organization	Role	Interview Mode	Interview Length
# 01	Rural Hub	Municipal Public Works	Water Hauler	In-Person	27 min
# 02	Rural Hub	Tribal Organization	Administrator	In-Person	38 min
# 03	Rural Hub	Municipal Public Works	Water Hauler	Remote	61 min
# 04	Rural Hub	Tribal Organization	Administrator	In-Person	68 min
# 05	Rural Village	Tribal Organization	Administrator	In-Person	123 min
# 06	Rural Village	Municipal Public Works	Water Plant Operator	In-Person	30 min
# 07	Rural Village	Municipal Administration	Administrator	In-Person	123 min

# 08	Rural Village	Municipal Public Works	Water Plant Operator	In-Person	31 min
# 09	Rural Village	Regional Health Organization	Healthcare Worker	In-Person	28 min
# 10	Rural Village	Regional Health Organization	Healthcare Worker	In-Person	28 min
# 11	YK Delta	Municipal Public Works	Water Hauler	In-Person	11 min
# 12	Rural Village	Municipal Administration	Administrator	In-Person	37 min
# 13	Alaska	Private Firm	Professional Engineer	Remote	59 min
# 14	Alaska	Municipal Public Works	Water Plant Operator	In-Person	90 min
# 15	YK Delta	Regional Health Organization	Public Health Worker	Remote	76 min
# 16	Rural Hub	Municipal Administration	Administrator	In-Person	79 min
# 17	YK Delta	Regional Health Organization	Administrator	Remote	80 min
# 18	YK Delta	Regional Health Organization	Public Health Worker	Remote	61 min
# 19	Rural Hub	Municipal Public Works	Water Hauler	Remote	62 min
# 20	YK Delta	Regional Health Organization	Public Health Worker	Remote	82 min
# 21	Rural Hub	Municipal Administration	Administrator	In-Person	60 min
# 22	YK Delta	Municipal Administration	Administrator	In-Person	108 min
# 23	YK Delta	Regional Health Organization	Water Plant Operator	Remote	73 min
# 24	Rural Hub	Municipal Administration	Administrator	In-Person	79 min

Interview questions were directed towards understanding the provision of water services broadly, the stakeholders involved in this process, as well as the unique barriers and impetuses to water provision in the YK Delta. As per prior exemplars in qualitative research, the core interview questions of interest were focused more on recounting facts and avoided leading questions [84]. Opinion or perception-based questions were asked to provide additional contextual information for which to situate the answers to the more core fact-based questions. Moreover, most interviews were conducted with at least two researchers present to enhance the internal validity and richness of the data collection as both the interview and additional observational data could be simultaneously collected [85]. When possible, additional data sources were used to triangulate our findings such as aforementioned observational data and archival data (e.g., media communications and policy documents). Our sampling strategy included two steps, as is typical in such work [85], [88]. We first identified professionals whose work is closely tied to water provision or decision-making in rural Alaska, and requested their participation. Next, we used snowball and convenience sampling to gather more participants with broad perspectives and experiences [32], [89]. Finally, we followed the principle of saturation, whereby we stopped conducting additional interviews as the focal participant's answer began to increasingly mirror the responses of past participants [90], informing our total of 24 participants. Given a sample as small as 10 can produce 95% of the salient information, our sample mirrors (and even arguably surpasses) that of prior practice [91].

Interview questions began with background information about the participant, both to build rapport and to understand their scope of expertise, asking about their community, their family, and their professional background. Next, participants were asked event and fact-based questions about their specific experience working in the water sector in the YK Delta, including daily tasks, challenges, and interactions with others. Finally, participants were asked about what they perceived to be the strengths and weaknesses of the water utility, and how they believed it could be improved. Several questions that are pertinent to the analysis here include:

- Can you walk us through a typical workday in your role?
- Who do you interact with most often in your role?
- What are some of the challenges you face in your role?

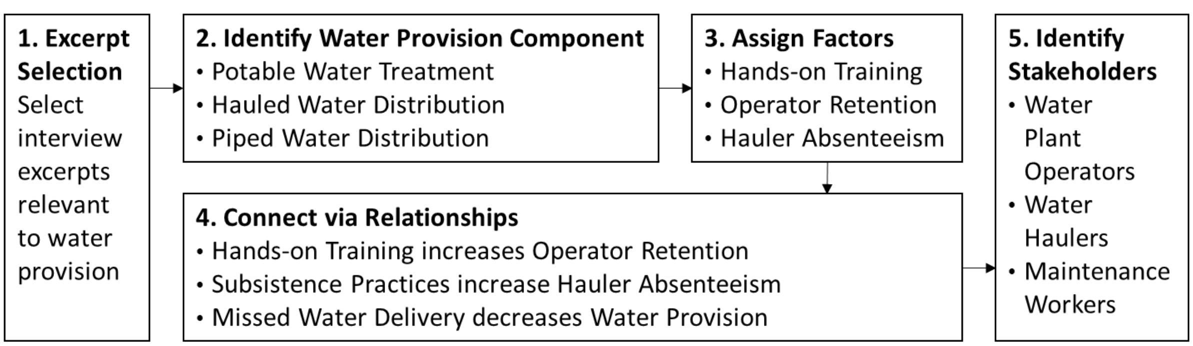


Figure 2. The qualitative coding process used in this study, including examples from interviews. We identified excerpts that included discussion of water provision and assigned each excerpt to a

component as applicable. Then we identified factors, relationships, and stakeholders relevant to water provision.

Qualitative Content Analysis

We employed qualitative content analysis using NVivo Software to evaluate interviews, as described in Figure 2 [32], [92], [93]. We identified excerpts that included discussion of water provision, then assigned distribution types and stakeholders as applicable. Employing inductive coding, we identified factors that drive or impede water provision and connected these via relationships, following similar work [17], [94]. The unit of analysis was the section of text pertaining to water provision, ranging from a phrase to a paragraph, and could be assigned multiple codes (i.e., simultaneous coding) [32]. Representative examples of interview excerpts with their coded stakeholders, factors, and relationships are included in Table 1. The coding was completed by one researcher who prepared a coding dictionary, then validated by a second researcher, resolving any discrepancies together.

Table 2. Examples of interview excerpts and the associated codes identified in the qualitative content analysis. Stakeholders, factors, and relationships are identified for each excerpt. Each relationship includes an associated polarity, indicating if the subsequent factor increases or decreases.

Excerpt	Stakeholders	Factors	Relationships
"They had problems where the boilers kept turning off. Our [Remote Maintenance Worker] came up, […] and they found the problem and fixed it."	• Water Plant Operators • Remote Maintenance Workers (RMW)	• RMW Assistance • Equipment Repairs • Water Treatment	• RMW Assistance **increases** Equipment Repairs • Equipment Repairs **increase** Water Treatment
"The average driver works between 8 and 10 hours a day on good times, and 14 to 15 for wintertime, […] so we just basically run our drivers to the	• Water Haulers	• Working Overtime • Worker Burnout • Hauler Attrition	• Working Overtime **increases** Worker Burnout

point where they don't want to work anymore, and then we try to find more.”			• Worker Burnout **increases** Hauler Attrition
“We have operators that will take subsistence leave, so sometimes summer times can be hard to find someone around to run the water plant.”	• Water Plant Operators	• Subsistence Practices • Operator Absenteeism • Number of Operators	• Subsistence Practices **increase** Operator Absenteeism • Operator Absenteeism **decreases** Number of Operators

Semi-Cognitive Mapping

Finally, we use the relationships identified in the previous step to develop a semi-cognitive map, shown in Figure 3. Cognitive mapping is a useful tool to study relationships between factors, and allows researchers to draw “conclusions about the belief systems of individuals and groups” [33]. In using this method, we aggregate understanding and experience from participants, piecing together otherwise loosely-linked information. We call the model developed in this study a “semi-cognitive map” due to the aggregation of knowledge from 24 participants, as well as the informed interpretation of the researchers. The development of this model allows us to identify shared knowledge. As shown in Figure 3, we begin with total household water supply at the center of the map (red diamond). We then add factors connected by arrows representing relationships. The map arrangement allows for a visual representation of the participants’ understanding of each component, stakeholder roles, and barriers to water provision. (See Figure 1 for a simplified version of this map.)

RESULTS

The semi-cognitive map shown in Figure 3 shows each component of water provision in rural Alaska, revealing distinct challenges as well as professionals impacting such challenges. Water plant operators, the key professional in water treatment, confront standardized regulations while working in localized contexts. Water haulers, the key professional in hauled water distribution, experience challenges from both working and operating contexts, ultimately leading to worker burnout. Discussion of the piped water distribution component largely omitted conversation around the people involved—an issue that needs to be explored further. All of the challenges identified in the semi-cognitive map can lead to or exacerbate service disruptions, decreasing water provision in communities. Here we discuss such challenges and propose solutions.

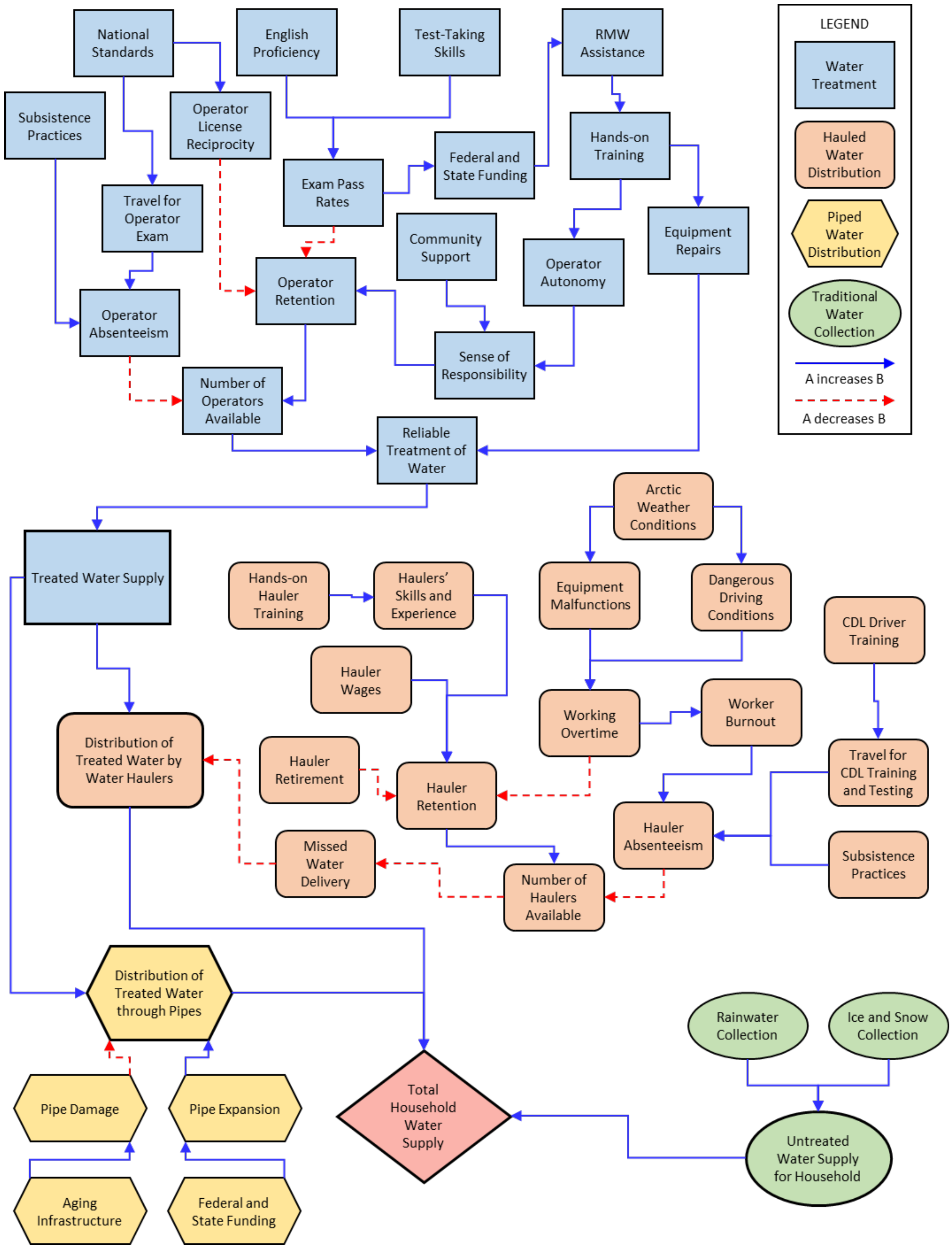

National Standards
English Proficiency
Test-Taking Skills
RMW Assistance
Subsistence Practices
Operator License Reciprocity
Federal and State Funding
Hands-on Training
Exam Pass Rates
Travel for Operator Exam
Community Support
Operator Autonomy
Equipment Repairs
Operator Retention
Operator Absenteeism
Sense of Responsibility
Number of Operators Available
Reliable Treatment of Water
LEGEND
Water Treatment
Hauled Water Distribution
Piped Water Distribution
Traditional Water Collection
A increases B
A decreases B
Arctic Weather Conditions
Treated Water Supply
Hands-on Hauler Training
Haulers' Skills and Experience
Equipment Malfunctions
Dangerous Driving Conditions
CDL Driver Training
Hauler Wages
Working Overtime
Worker Burnout
Distribution of Treated Water by Water Haulers
Hauler Retirement
Hauler Retention
Travel for CDL Training and Testing
Hauler Absenteeism
Missed Water Delivery
Subsistence Practices
Number of Haulers Available
Distribution of Treated Water through Pipes
Rainwater Collection
Ice and Snow Collection
Pipe Damage
Pipe Expansion
Total Household Water Supply
Untreated Water Supply for Household
Aging Infrastructure
Federal and State Funding

Figure 3. Semi-cognitive map showing the water provision process. The arrowheads on each relationship indicate directionality (i.e., A *leads to* B), and the line colors and type (solid blue: positive, dashed red: negative) indicate polarity (i.e., A *increases* B or A *decreases* B). Factors are arranged in the map according to the component of the water provision process (blue rectangles: water treatment, orange rounded rectangles: hauled water distribution, yellow hexagons: piped water distribution, green ovals: natural and traditional collection).

Water Treatment

One group of water professionals, water plant operators, are critical to the water treatment component of the overall water provision process. Before water can be distributed to residents, water plant operators use their extensive training and skills to treat water according to drinking water standards [95]. While the role of water plant operator is generally not unique to rural Alaska, rural operators are responsible for daily operations while often contending with extremely low temperatures, aging infrastructure, and limited supply chains [8], [19], [20]. Such challenges require skills, innovation, and perseverance to avoid service disruptions and ensure service provision for the community. The semi-cognitive map in Figure 3 reveals that the retention of water plant operators is an essential component of treated water provision. When operator retention is low, not only are there few individuals to perform essential duties, but experiential knowledge is lost. This continuity of knowledge is critical for reliable operations of water plants, ensuring water provision. Retention of water plant operators is a growing concern in the water sector [96], [97] and is even more acute in rural Alaska [98]. The semi-cognitive map shows that training and certification can impact operator retention, revealing two pathways. These pathways reveal a dichotomy in the water treatment component: standardization ("one size fits all") vs. situatedness ("tailoring for every circumstance"), as shown in Figures 4 and 5.

The first pathway, shown in Figure 4, focuses on the standardization of credentialing for water plant operators. A study participant who is very familiar with the certification requirements for operators explained that the State of Alaska previously certified operators through their own state-specific program. However, this process was changed to require operators to pass a nationally-recognized exam. Operators who pass this exam and meet the experience requirements can then obtain their operating license in the State of Alaska. The nationally-recognized exam covers a broad range of topics, familiarizing operators with water treatment processes used across the country. The exam is standardized to ensure that there is consistency and reliability amongst water plant operator licenses—those who are licensed have taken the same exam and conceivably possess the same knowledge. By making the exam nationally-recognized, operators can apply for reciprocity in some other states—where operators can transfer to work in another state once they are licensed in Alaska, and vice versa. As a participant explained, "That was done so that operators can enjoy reciprocity. That was supposed to be a good thing to standardize testing. […] but we lost uniqueness that would apply directly to us." While there are benefits to standardization and reciprocity for many operators in the contiguous United States, standardization mostly presents barriers for operators in rural Alaska. Interview participants emphasized that most rural water operators are unlikely to pursue reciprocity, as this would require living outside of their home communities.

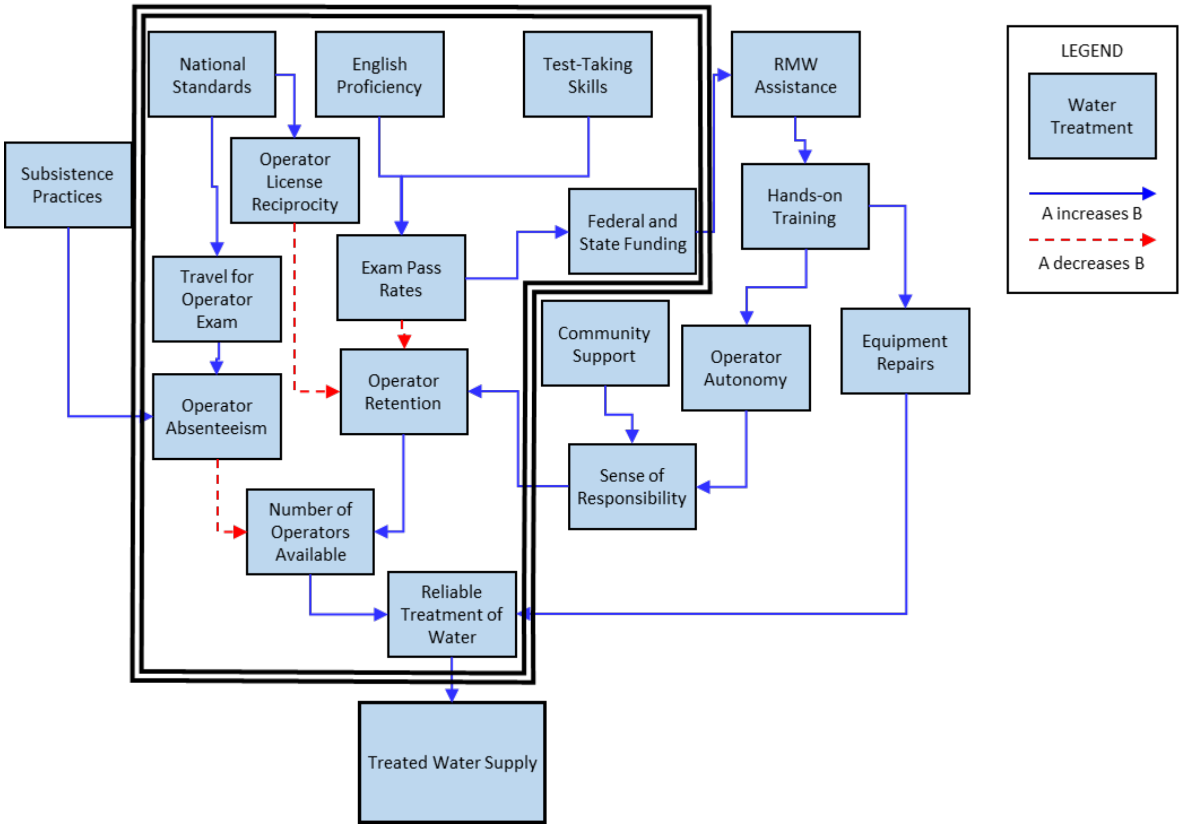


Figure 4. Semi-cognitive map focused on the water treatment component of the water provision process. The area inside the double lines includes the standardization pathways, focused on the nationally standardized operator exam and certification.

Many participants discussed the strict testing and certification requirements, and the low exam pass rates for rural Alaska operators. They explained, as shown in Figure 4, that test-taking skills and English proficiency were significant barriers to certification. Many operators living in rural Alaska communities struggle to align their traditional backgrounds with the regulatory requirements imposed by state and federal guidelines. The standardized exam created a greater barrier to certification for Alaska water plant operators, as the exam is more difficult and less applicable to rural Alaska infrastructure. Further, standardization of operator certification ignores the specific local context of rural Alaska communities, where utilities are generally smaller than others (usually serving just 100-1,000 people). These communities often use hauled water distribution, which is extremely uncommon in other areas of the United States. Perhaps most significantly, standardized certification requirements can impact funding. Having a licensed water plant operator on staff is a regulatory requirement for both state and federal agencies, and so many communities are refused funding when they cannot comply. There is a clear gap in understanding of Alaska water utilities, where state and federal agencies direct training and certification requirements without the local context informing such decisions.

Alternatively, the second pathway for water treatment focuses on building tacit knowledge and situating such skill-building in the local operational context. The semi-cognitive map in Figure 5 reveals that hands-on training is essential to skill-building for water plant operators. Such training often occurs in an operator's home water plant, with assistance from a Remote Maintenance Worker (RMW) [99]. RMWs are highly skilled and certified operators who travel to communities throughout the YK Delta, assisting local operators when significant challenges arise. Interview participants explained that this hands-on, in-person training is often the most useful form of training, as it enables operators to learn using the specific equipment that they operate every day. Figure 5 also reveals that community support and the operator's sense of responsibility positively impact service provision. As a participant explained, "I think most of the operators that are good at their job, they care about the position and they care about the job. […] They see it as a service to the community."

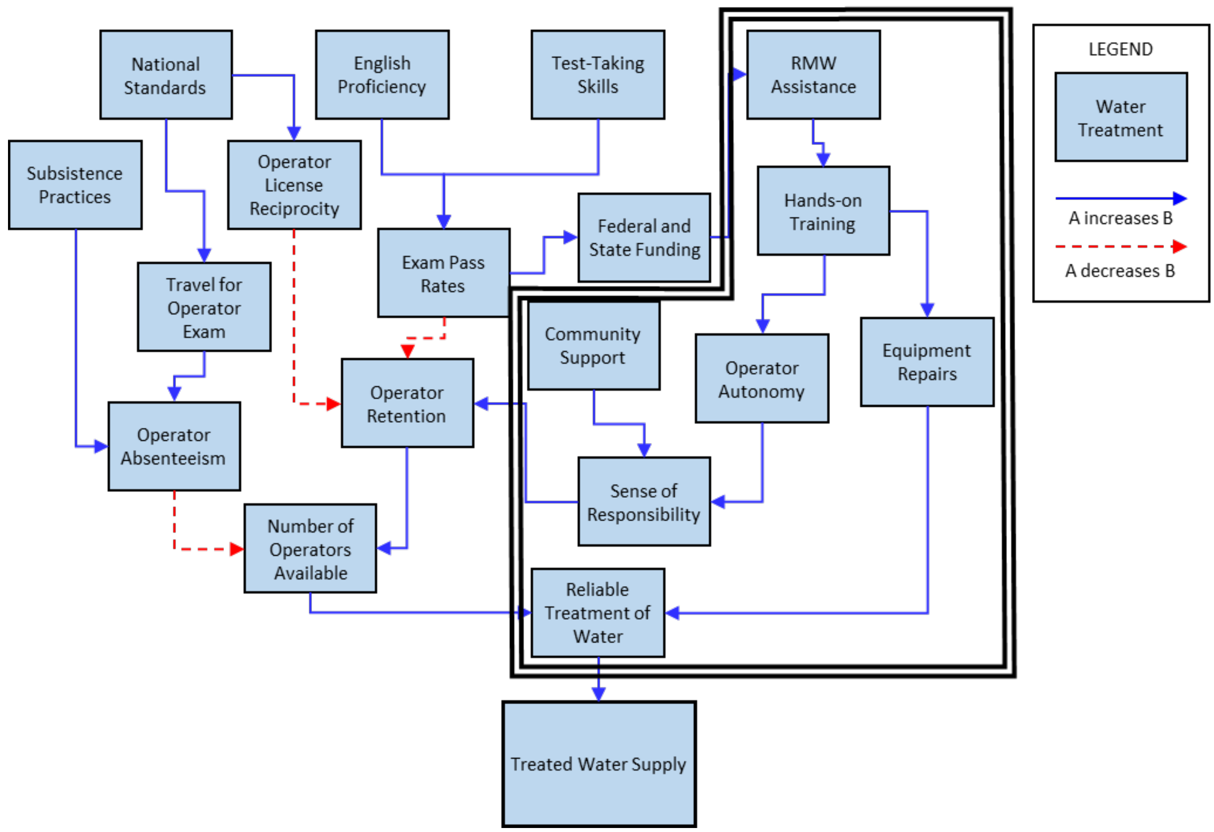


Figure 5. Semi-cognitive map focused on the water treatment component of the water provision process. The area inside the double lines includes the situatedness pathway, focused on the localized context of water plant operators' responsibilities.

The analysis here suggests that in the treatment and provision of potable water to residents in rural Alaska, there is a tension between standardization and situatedness [100]. Standardization, a "one size fits all" approach, ensures water operators are evaluated to a common set of guidelines. Such standardization can be valuable for many "typical" operating contexts to ensure uniformity of regulations and water quality, and can be especially helpful if operators move between water treatment plants. However, such standardization may not suffice when applied to extreme operating contexts which are fundamentally different from "typical" operating contexts. Rather, situatedness, a "tailoring for every circumstance" approach, can ensure local needs are better considered and served [100]. This suggests that operator training and certification requirements may need to be reassessed amidst this tension of approaches. Fortunately, the need for more localized training has been recognized by organizations in the state, like the Alaska Native Tribal Health Consortium [101]. A virtual training program has allowed rural operators to participate in training, without travel or time away from work. The importance of reciprocity for water plant operators may also need to be balanced with prioritization of local needs and preferences. Participants suggested modifications to the certification requirements, recommending that operators pass a site-specific certification test rather than a test determined by water treatment plant type. A participant explained, “Instead of them getting this huge general test that's for the whole nation, they would get tested on specific components that they have, and they would get certified to work in their plant.” While this may make deployment of tests more costly, such a change would empower local operators to build their skillset to operate their utility at a high level, ensuring water provision for local residents. This would also encourage retention in the water sector, as operators would not be pushed out of their roles for failure to pass a standardized exam. This all suggests the site-specific certification testing benefits (expanding cadre of operators available) may outweigh their costs (more localized site testing) in such extreme contexts.

Hauled Water Distribution

The analysis revealed that water haulers are the key water professionals associated with hauled water distribution in rural Alaska communities. In larger communities (e.g., the hub community in the YK Delta), water haulers transport water from the water treatment plant to homes via a water truck, often holding over 3,000 gallons of potable water. In smaller communities, water haulers transport potable water via small tanks and ATVs from the central water treatment plant to residents’ homes. Without water haulers, residents of rural Alaska communities would likely need to haul their own water, creating a labor burden, as well as a significant barrier to access for many residents [13], [102]. Indeed, water haulers directly impact service provision in communities that utilize the hauled water distribution process. As shown in Figure 6, a major finding emerges—worker retention impacts water provision via hauled distribution. Workers are affected by pathway A (working context) and pathway B (operating context) leading to overtime, burnout, and ultimately attrition. Following these two pathways, we can identify leverage points for improving working conditions and increasing retention. Ultimately, worker retention can improve service provision via hauled distribution.

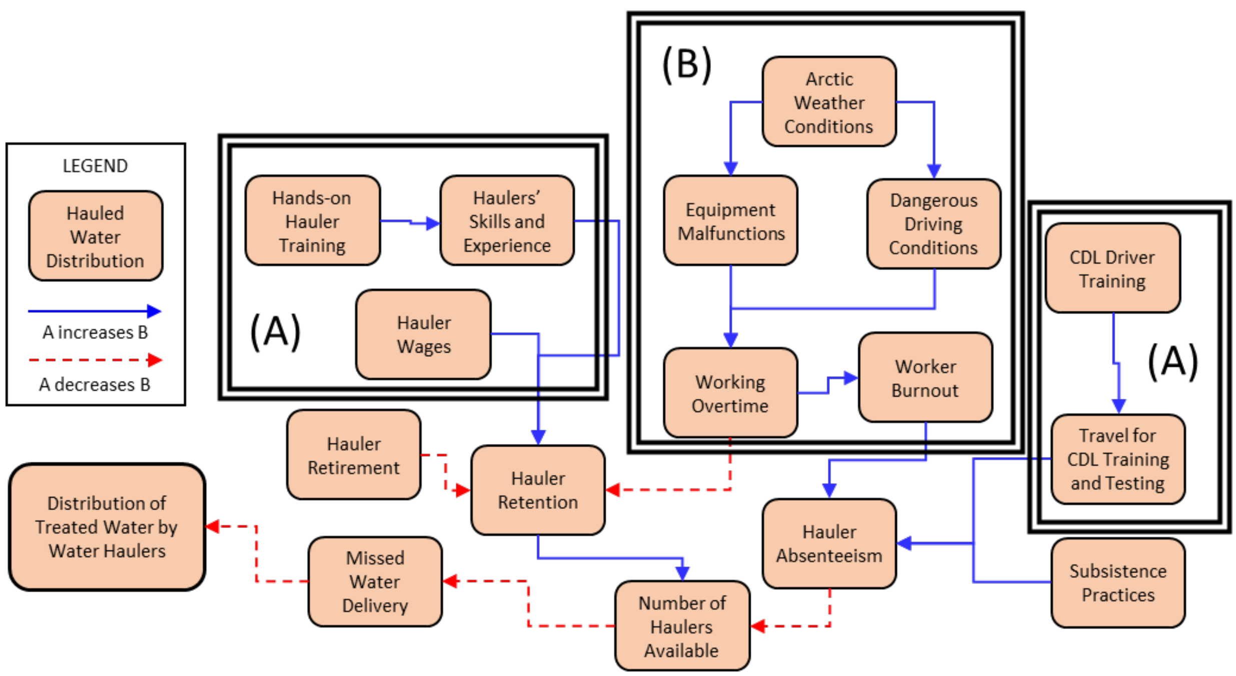


Figure 6. Semi-cognitive map focused on the hauled water distribution component of the water provision process. Pathway A inside the double lines shows the working context. Pathway B inside the double lines shows the operating context.

The working context primarily includes training and licensing requirements for water haulers. Water haulers in rural Alaska communities must develop specific skills for their work due to the unique context. Participants explained that water haulers must be able to navigate icy roads, manage deliveries to 40 to 60 homes in one shift, and monitor the water levels in both home tanks and the delivery tank. Without such skills, haulers are more likely to make mistakes, fall behind schedule, or miss houses on their delivery schedule, hindering service provision. To avoid these errors, water haulers participate in training, both formally and informally. In communities that use large water trucks, water haulers are required to obtain a commercial driver's license (CDL) before beginning work [15], [103]. Once hired, haulers participate in hands-on training, where they shadow and work with an experienced driver. A participant explained that this is the most effective training method for drivers to learn: "They ride in the right seat and learn the job. They can see how it's done; we put them with an experienced driver. […] As far as the pumps go, 40 to 60 houses a day, you see it turned on and turned off that many times every single day; you'll pick it up." This one-on-one hands-on training is an essential component of building skills for water haulers. As they develop those skills, and practice them both while supervised and independently, haulers can ensure more reliable service provision for their community.

In the operating context, the natural environment emerges as a significant contributor to water provision barriers. While most studies utilizing stakeholder theory solely consider people as stakeholders [104], we follow some researchers who take a broader approach to stakeholder definitions [105], [106]. We define the natural environment as a key stakeholder in hauled water distribution due to its impact on workers, end-users, and infrastructure. This interpretation aligns with the understanding in many indigenous communities that the natural environment is interdependent with other systems [107]. We learn from the Alaska Native communities in the region who hold similar traditions and practices that foster a familial relationship with the natural environment.

The semi-cognitive map relates Arctic climate conditions to worker burnout, which then results in water provision gaps that place more stress on the infrastructure and operations. More specifically, Arctic weather and icy roads can lead to difficult working environments and ultimately worker burnout. In turn, worker burnout can increase missed water deliveries, which can further decrease service provision. Burnout, categorized by the World Health Organization as an occupational phenomenon, results "from chronic workplace stress that has not been successfully managed" [108]. Burnout can include symptoms such as fatigue, semi-cognitive impairments, and emotional dysregulation [109]. When experiencing burnout, workers are more likely to make mistakes and are often less effective in their job tasks. Workers might work more slowly than usual, which would require them to work longer days to complete all of their deliveries, or skip deliveries when they run out of time on their shift. Mistakes or accidents can further increase the number of missed deliveries, as water haulers will not be able to complete deliveries if they are injured or their vehicle is damaged. Before reaching burnout, water haulers are likely to experience long work hours due to low staffing and difficult working conditions due to the extreme Arctic weather. For instance, the Arctic environment creates extreme low temperatures, strong winds, and icy conditions, requiring extra precautions to avoid accidents or injuries. The additional time and energy required in such situations contributes to the overload of workplace stress. In addition to safety hazards, extreme weather can cause water haulers to take more time for each delivery, navigating icy driveways and frozen pipes, leading to longer workdays. These long workdays contribute to worker stress and burnout.

Piped Water Distribution

The analysis of piped water distribution reveals that there are two major contributors to water provision via pipes—pipe damage (negative) and pipe expansion (positive), as shown in Figure 7. While these technical factors emerged from the interviews, we intuitively understand that there are factors missing in this map. Specifically, actions by water professionals must be largely inferred, as they were not explicitly discussed amongst most participants. This is interesting as we can infer that there are water professionals who specialize in the piped infrastructure, including maintenance workers, as described in studies of different system types [110], [111]. Such maintenance workers would require specialized knowledge to build, maintain, and repair water distribution pipes in the Arctic conditions of rural Alaska. Due to the extreme weather, maintenance workers are likely essential to monitoring the Arctic pipes for leaks, which are a key disruption to piped water provision [112]. We can assume that these essential workers were overlooked in discussions because of a larger focus on challenges and barriers to hauled water provision. The water treatment and hauled distribution processes currently present significant challenges for those working in the water sector, and so participants who were familiar with the distribution process likely biased their responses toward more pressing issues. In the semi-cognitive map shown in Figure 7B, we add two factors, in bright yellow and dotted-line outlines, that include actions by pipe maintenance workers. To mitigate pipe damage, and subsequent service disruptions, maintenance workers must make repairs to pipes. Additionally, when funding becomes available for new pipe construction, construction workers are heavily involved in that process. Future work can explore piped water distribution further, and the specific challenges faced by workers within these system components.

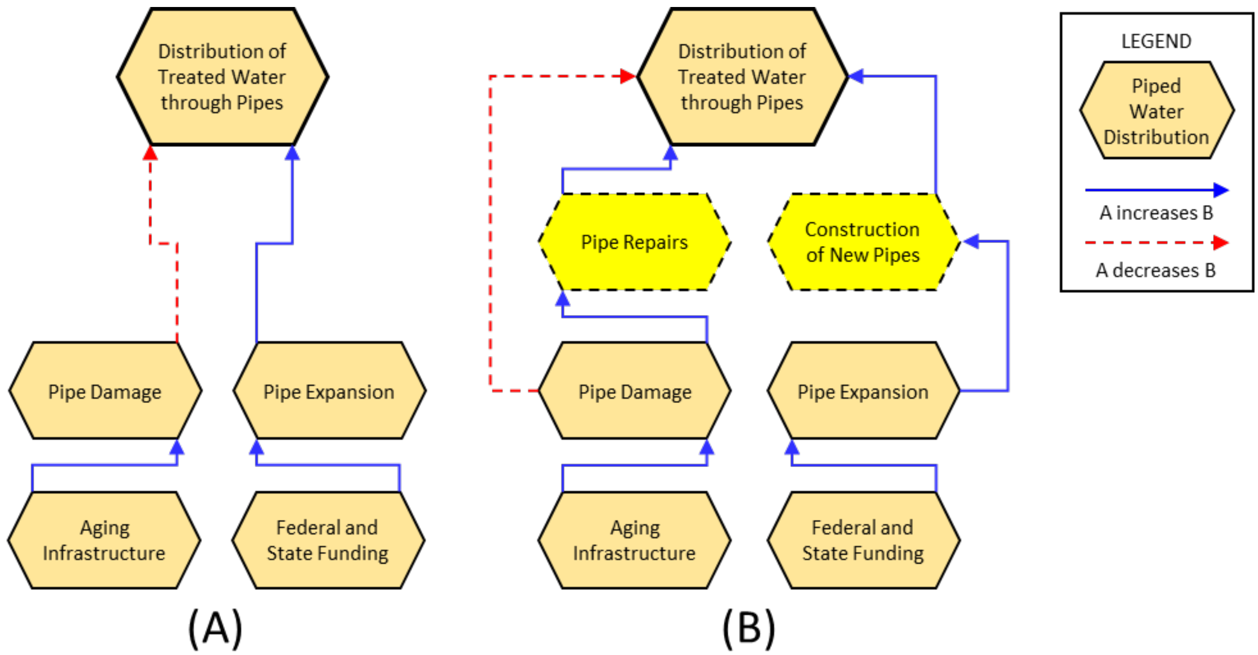


Figure 7. Piped water distribution process. Part A shows the factors that emerged from the interviews in this study. In Part B, we add two factors that we can infer, but are missing from the interviews. This gap indicates a need for future discussion.

The work required of piped distribution maintenance workers is likely more arduous in rural Alaska than in other communities due to the extreme Arctic weather. As discussed in the previous section, the natural environment has emerged as a significant stakeholder in rural water provision. For the piped distribution process, the natural environment intervenes at many points to create barriers to provision. For instance, freezing temperatures can lead to frozen pipes if not maintained properly (i.e., constantly circulating water, utilizing heat tape). To maintain water utilities properly, energy costs can be exorbitant [113], [114]. The structural supports for water pipes can sustain damage from intermittent permafrost, further damaging pipes and hindering distribution [11], [43], [115]. Such challenges result in decreased water provision via piped service for communities. An intervention point here may be greater attention to the tasks of maintenance workers. While the interviews conducted in this study do not shed adequate light into the working conditions and responsibilities of these workers, their omission in of themselves are insightful.

DISCUSSION

We now synthesize our results into propositions which can guide future work. This study revealed that while many stakeholders likely impact water provision as a whole, there are select stakeholders who are more associated with specific components of water provision. For instance, water plant operators are essential for water treatment and water haulers are essential for hauled water distribution. Maintenance workers are likely essential for piped water distribution. As such:

> *Proposition 1: In extreme environments, stakeholders differ between components of water provision (i.e., water treatment, piped water distribution, hauled water distribution).*

We further identified factors that contribute to water provision, as perceived by regional water sector experts. Such experts provided useful insight, as they interact with water operations daily, confronting challenges in water provision. The analysis revealed that the factors impacting water provision are different based on the specific component, including water treatment, piped water distribution, and hauled water distribution. For instance, the national operator certification is an important factor impacting water provision in the water treatment component. As such:

> *Proposition 2: In extreme environments, stakeholders perceive different factors that impact water provision, depending on the specific component (i.e., water treatment, piped water distribution, hauled water distribution).*

We explored the differences in the architecture of water provision contributing to total household water supply in rural Alaska. We define the architecture of such systems as the interfaces among components of the interdependent systems, including social, natural, technical, and financial systems. Factors that lead to or prevent water provision are often related to one another and interact across systems [13], [17], [26]. For instance, extreme Arctic weather (natural system) leads to frozen overflow pipes (technical system) which can lead to water haulers working overtime (social system). The analysis revealed that components of water provision differ in terms of (inter)dependencies among factors. We investigated the interactions among factors that contribute to water service provision for end-users, as viewed by regional water sector experts. As such:

> *Proposition 3: In extreme environments, the architecture of (inter)dependent systems differs for components of water provision (i.e., water treatment, piped water distribution, hauled water distribution).*

Our study identified pathways that differentiated stakeholders as well as components of water provision. Regarding water treatment and water plant operators, there is tension between standardization and situatedness in water provision. In the standardization pathway, state and federal agencies tend to dictate decisions, while in the situated pathway, local leaders drive decisions [100]. Regarding hauled water distribution and water haulers, the localized pathways further split into a tension between working and operating contexts. In the working context, local workers and leaders acting within the utility dominate. In the operating context, the natural environment as a stakeholder, acting outside the utility, tends to dominate. The piped distribution pathways are still fairly unclear as these were not discussed as extensively in interviews. This piped section of the semi-cognitive map requires more detail focused on the water professionals.

> *Proposition 4: In extreme environments, pathways can be identified and differentiated amongst various contexts and components of water provision (i.e., water treatment, piped water distribution, hauled water distribution).*

PRACTICAL APPLICATIONS

This study demonstrates that specific water professionals are essential to water provision in the YK Delta in three key components: water treatment, hauled water distribution, and piped water distribution. As such, changes can be made in each of these categories to enable professionals to perform their work more effectively, contributing to reliable water provision. Water plant operators, who are responsible for the treatment of potable water in rural Alaska communities, are limited by state and national standards for testing and certification. Such requirements hold them to standards that are designed for communities in the contiguous United States as these certification exams include significant content that is not necessarily aligned to their work in Alaska. Rather than requiring such certification that prioritizes standardization and reciprocity, Alaska policymakers may consider implementing local component-specific requirements for operators. Situated changes to the certification requirements would include more tailored standards regarding the equipment, chemicals, and processes used in rural Alaska water treatment plants. Operators would spend more time studying their treatment process and practicing inside their own water treatment plant, enabling the workforce to be more qualified to provide water to their rural community. Long-term, operators may participate in continuing education programs that cover broader water treatment concepts over time, after learning their utility-specific requirements.

Water haulers, who are responsible for delivering water in hauled water distribution, are largely overlooked in the literature regarding water infrastructure in rural Alaska. Because these workers are critical to water provision, conditions can be improved to aid in retention of this workforce. Greater attention to hands-on training practices can help improve haulers' safety and well-being, as well as mitigate missed water delivery. Improved training would be best in one-on-one settings, without formalized testing or certifications. Rather, haulers would benefit from hands-on, on-the-job mentoring and training. In response to this finding, the research team plans to develop an innovative training guide in the next phase of this study. The guide will hopefully serve as a reference for water haulers in the YK Delta and will be developed in collaboration with the local workforce to capture key aspects of their work. Maintenance workers, who are likely essential to piped water distribution in rural Alaska communities, are largely overlooked. Due to the extreme weather conditions of rural Alaska, water distribution pipes should be monitored for damage and resulting leaks, which can help mitigate service disruptions. Future studies can examine in greater depth the roles of these professionals.

Beyond the YK Delta, these results provide valuable insight for utility operations in extreme conditions more broadly. The analysis here revealed that extreme weather can lead to worker burnout, which has negative impacts on the system performance. The analysis approach used here better identifies and incorporates extreme factors and connects them to system components. In identifying relationships and developing semi-cognitive maps, we were able to uncover linkages not just between human stakeholders, but between human and non-human stakeholders. This approach may be adapted to other studies seeking to find links between infrastructure system factors and the extreme conditions in which they are placed.

CONCLUSION

This study analyzed semi-structured interviews with 24 regional water sector experts in the Yukon-Kuskokwim Delta of Alaska, using qualitative content analysis and semi-cognitive mapping. We built a unique conceptual integration of systems and stakeholder theory to identify bottlenecks to water provision and leverage points for improvement. In this framework, we expanded our understanding of both stakeholders and infrastructure systems. Here we examined three components of treated water provision in rural Alaska communities: water treatment, hauled water distribution, and piped water distribution. We identified that within the water treatment process, water plant operators confront a tension between standardization and situatedness in the examination and certification process. While state and federal regulators have increasingly pushed for standardizing exams, rural operators would benefit from situated, localized material. Such changes would allow for greater autonomy and ownership over each component of their water provision process.

Further, water haulers, the key professionals in hauled water distribution, confront challenges that lead to high rates of attrition, divided between the working context and the operating context. Within the working context, water haulers are subject to CDL testing and hands-on training for their job tasks. Within the operating context, haulers are subject to the harsh Arctic environment. The weather conditions in the YK Delta lead to more dangerous working conditions and longer workdays, as the ice and snow take more time to navigate safely. Finally, piped water distribution was largely overlooked by interview participants, likely due to other pressing issues. We can, however, infer that water maintenance workers play a key role, and require greater attention.

This analysis reveals a key conclusion that underlines each of our propositions: *people are often the critical leverage point for water provision improvement.* To improve water provision in rural Alaska communities, consideration must center significantly more on people (i.e., workers). Localized and context-specific training will improve the performance of both water treatment and hauled water distribution. Future work must examine workforce retention in the rural Alaska water sector, as retention directly impacts water provision.

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