How Are Alaskan Water Systems Interdependent with Other Infrastructure? A Systematic Literature Review

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ABSTRACT

The provision of water services is critical to ensure the vitality of Alaskan communities. Water systems in Alaska operate differently than those in the contiguous US given the Arctic climate, remote geography, and unique workforce limitations. For example, some communities rely on water delivered using trucks, and many households use traditional sources (e.g., rainwater, ice melt). This unique context reconfigures how water systems relate to other critical infrastructure services (CISs), such as transportation and electricity. For instance, the high energy costs needed to heat water systems in Alaska can exacerbate water insecurity. In another example, some communities with delivered water services can be limited by transportation challenges such as limited connectivity, roadway damage, and reduced visibility during winter weather. While we recognize that water-related challenges in Alaska are often linked to other CISs, it remains unclear how these interdependencies shape services—for instance, which connections are sources of vulnerability? Through a systematic literature review, we seek to understand the underlying network of interdependencies between water systems and other CISs in Alaska. We employ a qualitative content analysis of scholarly literature to identify relevant CISs and how they influence the provision of water services. By enhancing our knowledge about infrastructure interdependencies in Alaska, we can improve management by taking into account other relevant systems. Further, our work identifies key research gaps and opportunities, guiding future efforts to address the complex infrastructure challenges in Alaska.

Keywords: Critical infrastructure services, Interdependencies, Water systems, Alaska

INTRODUCTION

Critical infrastructure systems (CISs) including water, transportation, electricity, healthcare, and waste are essential for community well-being (CISA 2023). CISs are inherently connected with one another—these interdependencies influence each system's operations (Rinaldi et al. 2001). For example, energy plays a crucial role in the extraction, treatment, and distribution of drinking water (Chamberlin et al. 2021). At the same time, supply chain constraints could hinder the timely repair of water system outages (Spearing et al. 2022a). CISs in Alaska operate differently than those in the contiguous United States (US), primarily due to the isolated geography, limited employment opportunities, and harsh environment (Hickel et al. 2018). For instance, in Alaska, the arctic climate requires water distribution systems to be heat traced, demanding significant energy (Chamberlin et al. 2021; Rashedin et al. 2022). Based on interviews with stakeholders involved in the provision of water in Alaska, Spearing et al. (2022a) found that people reported that 60 to 80% of water system costs are related to energy.

Departing from typical systems in the contiguous US, there are multiple ways water is provided and accessed in Alaska. Water can be delivered through piped water systems (often in larger communities), via delivered water to a household tank, through a central watering point, or through traditional sources, such as ice melt (Chamberlin et., 2021; Lucas et al. 2021; Spearing et al. 2022a). Wastewater disposal and treatment methods include both piped and hauled systems that lead to wastewater treatment plants, as well as chamber pots (referred to as honey buckets; Chamberlin et al. 2021 and Mattos et al. 2021a). These distinctive features pose challenges in operating and managing water sector systems, creating unique interconnections with other CISs. For instance, delivered water services rely on water trucks and a reliable roadway system.

Previous studies mostly focus on managing water and wastewater systems in Alaska in isolation from other CISs (Eichelberger 2018; Lucas et al. 2021; Schubert et al. 2013). Some studies have explored connections with specific CISs, such as public health (Bressler and Hennessy 2018; Brubaker et al. 2011) or energy (Eichelberger 2010; Rashedin et al. 2022). For example, Chamberlin et al. (2021) explored the relationships between the water and energy sectors. They highlighted energy-intensive processes within the water sector, such as water extraction, treatment, and distribution. In another example, Eichelberger (2010) emphasized that the energy cost and consumption associated with hauling water systems play a significant role in determining water access and consumption in rural Alaska. Although researchers have started to explore infrastructure interdependencies in Alaska, certain sectors are often missing from the discussion (e.g., waste, transportation). A comprehensive study investigating linkages between water systems and other CISs in Alaska would help to fill epistemic uncertainty related to water sector operations. In this paper, we conduct a systematic literature review to understand how CISs influence water provision in Alaska. Through a qualitative content analysis, we identify knowledge gaps and propose steps for future research, offering insights to enhance the resilience of water services for consumers.

METHODS

We conducted a systematic literature review to understand infrastructure interdependencies in Alaska. We collected scholarly articles using the Web of Science, which covers a wide range of journals. Web of Science was chosen based on its extensive journal coverage and advanced search capabilities (Clarivate Analytics 2023). Given our focus on CISs interdependencies affecting water systems in Alaska, we used the keywords "water" AND "infrastructure" AND "Alaska". This search yielded 240 articles, which were then filtered based on title, abstract, and scope (see Figure 1 for more details). After excluding articles beyond the study's scope or inaccessible online, 25 articles comprised the final sample. The substantial number of out-of-scope papers occurred because many of them focus on the water section in isolation or are predominantly related to other fields such as climate change.

We qualitatively coded journal articles using a hybrid content analysis approach, with the article as the unit of analysis (Saldaña 2021; Spearing et al. 2022b). First, we coded statements based on which infrastructure system was interdependent with water, such as energy, public health, waste, transportation, and food. Table 1 shows the deductive coding dictionary, including sector definitions. Then, we inductively coded to identify emergent themes in each category, as shown in Figure 2. For example, mental and physical health emerged as subcodes of public health. Using our qualitative analysis results as a basis, we created a systems map illustrating CIS interdependencies (Rinaldi et al. 2001). Systems mapping is a useful tool to visualize complex system connections (Meadows 2008; Gray et al. 2013), such as infrastructure interdependencies. All codes were reviewed by a second researcher to validate the coding dictionary and system map.

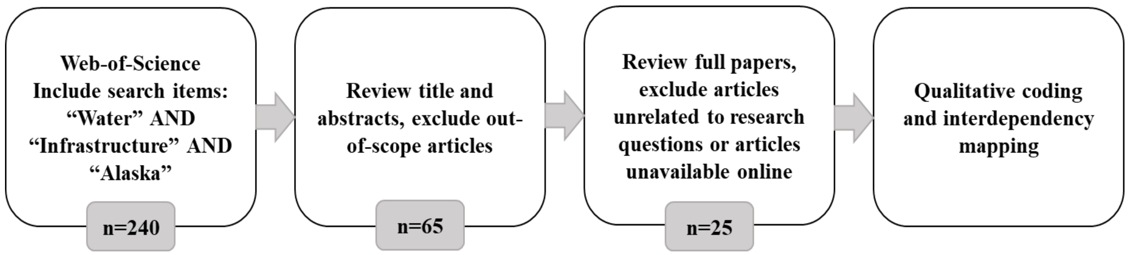

Figure 1. Overview of data collection and analysis

Table 1. Sector definitions (derived from CISA (2023)) and examples for deductive coding

Code	Definition	Example
Public health	System of healthcare facilities, suppliers, and manufactures that safeguard society from hazards like infectious disease outbreaks. This code addresses the impacts of water and wastewater systems issues on health.	"Higher respiratory and skin infection rates were associated with a lack of in-home water service." (Hennessy et al. 2008)
Energy	System of electricity, oil, and natural gas resources and assets that are used to maintain steady energy supplies. This code is related to energy consumption and cost of water systems.	"In the rural arctic and subarctic, a major barrier to accessing clean drinking water is preventing frozen pipes, which requires additional heating fuel, glycol, or electricity" (Chamberlin et al. 2021)
Transportation	Systems to move goods and people including aviation, roadway, maritime transportation, railroad, pipelines, and waterway shipping. This code is related to transportation and supply chain needs of water sector services.	"Households need a mode of transportation to haul water to and waste from the home" (Mattos et al. 2021a)
Food & Agriculture	System including farms, restaurants, and food manufacturing, processing, and storage facilities. This code is related to water consumption processes in the food sector.	"City water quality, availability, and access affect the agriculture and food security" (Stevenson et al. 2014)
Waste	System responsible for removing solid waste. This code is related to impacts of the waste system on water quality.	"The longer human waste sits outside the home, the more likely bags are to get ripped open by the elements or animals, the more likely waste is to spread onto nearby roads and waterways" (Mattos et al. 2021b)
Communication	Satellite, terrestrial, and wireless systems that provide connections for information sharing. This code is related to impacts of the communication system on water systems.	(No example was found on literature)

RESULTS AND DISCUSSION

Five different CISs (out of six sectors considered in the deductive coding dictionary; Table 1) in Alaska were found to be interdependent with the water sector based on existing literature. Table 2 shows the relative frequency of each infrastructure system. Most articles (80%) discussed interdependencies between the water sector and public health and 48% discussed connections between water and energy. Figure 2 shows the systems map of these infrastructure interdependencies.

Table 2. Qualitative coding results and frequency for each infrastructure sector

Sectors	No. of papers	Relative frequency of papers
Public health	20	80%
Energy	12	48%
Transportation	6	24%
Food & Agriculture	5	20%
Waste	1	4%
Communication	0	0%
Total	25	100%

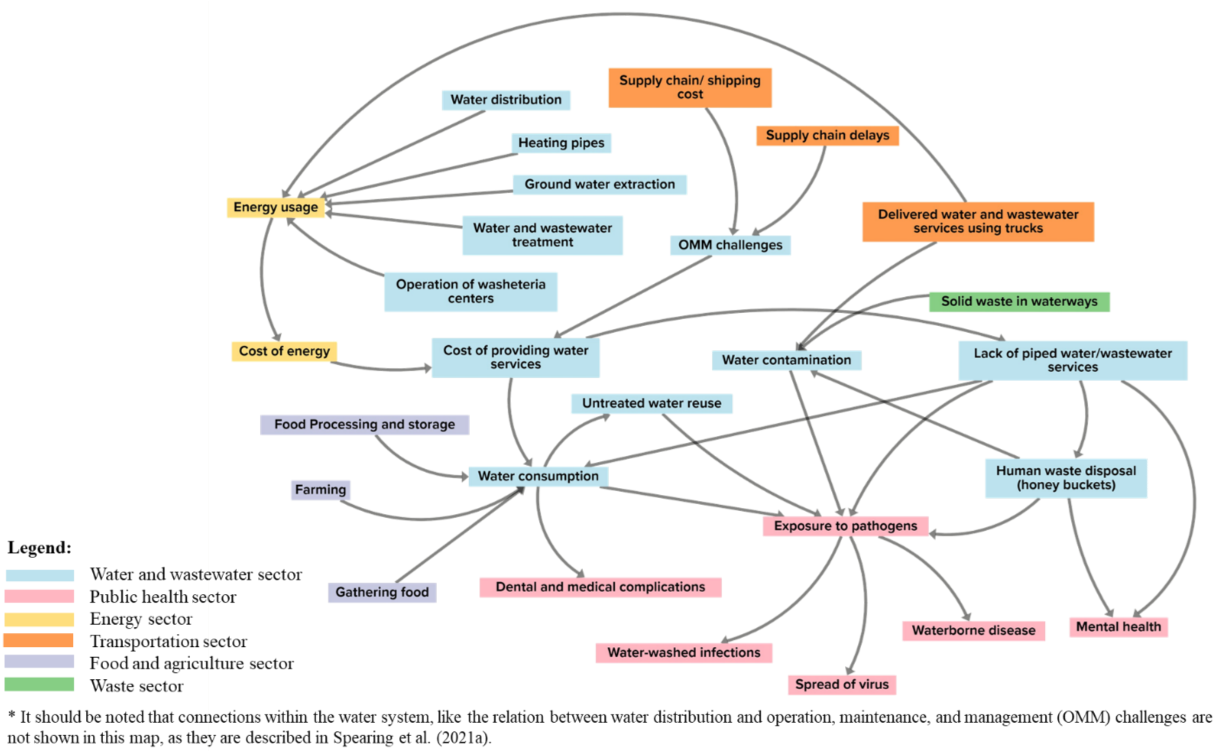

Figure 2. Systems map showing interdependencies between CISs and the water sector

Public Health

Twenty papers (80%) were coded as public health. The World Health Organization (WHO) recommends a per capita water consumption of more than 26.5 gallons per day to mitigate health concerns (Howard et al. 2020). In the US, the average water consumption is around 82 gallons per capita per day (EPA 2023). However, in a study of one rural Alaska community, researchers found that residents' average daily water consumption was significantly below both the national average and recommended levels (Eichelberger 2010). Factors such as the high cost of water, lack of piped water and wastewater services, and the labor intensity of hauling water contribute to reduced water consumption (Sohns et al. 2021; Hickel et al. 2018; Lucas et al. 2021). This, in turn, poses health risks, increasing the likelihood of disease—these connections are shown in pink in Figure 2 (Thomas et al. 2016; Mattos et al. 2021b). Moreover, the limited availability of water and low consumption rates drive individuals to opt for alternative, unhealthy beverages like soda and sugary drinks, leading to dental and medical complications (Sohns et al. 2021).

In addition to inadequate water consumption and lack of water and wastewater services, direct exposure to human waste through the use of honey buckets, reusing water multiple times, untreated water reuse, manual disposal of greywater, and direct contact during disposal result in pathogen exposure contributing to various public health issues (Bressler and Hennessy 2018; Brubaker et al. 2011; Eichelberger et al 2021; Hennessy et al. 2008; Mattos et al. 2021b). The resulting public health issues include water-washed infections (e.g., skin and respiratory infections), waterborne diseases (e.g., gastrointestinal illness), and a high rate of hospitalizations (Thomas et al. 2016; Hickel et al. 2018; Mattos et al. 2021a). Further, the COVID-19 pandemic underscored the critical importance of accessing sufficient and high-quality water while minimizing contact with wastewater, which was particularly challenging for some remote Alaska communities (Eichelberger et al. 2021; Hahn et al. 2022).

The interplay between water systems and healthcare services extends beyond physical health concerns to include mental health. The lack of piped water and wastewater systems, coupled with the reliance on hauling water and using honey buckets, contributes to mental challenges including discomfort, inconvenience, and heightened stress levels—mental health is shown in pink in Figure 2 (Schmidt et al. 2022b; Sohns et al. 2021). Consequently, issues related to water accessibility and quality can have a cascading impact on both physical and mental health.

Energy

Twelve papers mentioned energy—comprising 48% of the sample. The provision of water is contingent on an affordable and reliable energy supply (Chamberlin et al. 2021). Severe climate conditions in Alaska, combined with diverse water access methods, increase the energy needed for water and wastewater systems (Rashedin et al. 2022). Energy is critical for many water-related processes including the extraction of groundwater from wells and the operation of water and wastewater treatment plants—shown as connections between yellow and blue in Figure 2 (Chamberlin et al. 2021; Mattos et al. 2021a; Rashedin et al. 2022). Piped water and wastewater systems, in addition to treatment plants, require energy for pumping low-pressure water to end-users and pumping wastewater from homes to lagoons or treatment plants (Rashedin et al. 2022; Sambor et al. 2020). The subzero temperatures in Alaska require the circulation of water in pipes to prevent freezing, demanding additional energy for pumping or alternative measures such as heat tapes and below-torch heating on frozen pipes (Chamberlin et al. 2021; Rashedin et al. 2022).

Washeteria centers also contribute to energy consumption through lighting, heating, washing machines, dryers, and ventilation (Chamberlin et al. 2021). Communities relying on water and wastewater hauling to and from homes (shown in orange in Figure 2) often utilize energy-consuming equipment such as snow machines or all-terrain vehicles (ATVs), typically powered by diesel fuel (Sohns et al. 2021). The prevalent use of costly energy sources contributes to high water bills for Alaskan households (Her et al. 2021; Hickel et al. 2018; Penn et al. 2017; Schmidt et al. 2022a; Whitney et al. 2019).

Transportation

Transportation was referenced in 24% of the sample (six papers). Given the remote nature of many communities, there are notable supply chain and transportation challenges, including delays and increased costs in shipping materials. These issues cascade to cause vulnerabilities in water sector operations, maintenance, and management (OMM) (Spearing et al. 2022a). The high expenses related to shipping materials, construction equipment, and fuel contribute to increased water costs for households (Hickel et al. 2018; Spearing et al. 2022a). This relationship can be seen in Figure 2 where orange boxes representing supply chain are connected to blue boxes representing water OMM challenges. Delivered and hauled water systems, employed in some communities, utilize trucks and ATVs to deliver water to homes and transport wastewater to lagoons, establishing a direct interdependency between the water and transportation sectors in Alaska (Mattos et al. 2021a; Rashedin et al. 2022).

Food and Agriculture

Papers related to the food and agriculture sector account for 20% (five papers) of the sample. The availability, quality, and accessibility of water plays a pivotal role in growing, harvesting, and storing food—see the purple boxes in Figure 2 (Chamberlin et al. 2021; Stevenson et al. 2014). There are specific water quantity and quality requirements for many operations such as seafood processing plants (Whitney et al. 2019) and farming (Sambor et al. 2020). Also, as noted by Sohns et al. (2021), access to piped water and wastewater systems can afford people more free time to dedicate to gathering and hunting food given reduced time spent hauling water.

Waste

One paper discussed the waste sector. There has been limited exploration of the connection between water sector services and the solid waste sector. The interdependency identified is related to human waste being left outside of the home for long periods of time awaiting transportation, leading to heightened risk of waste contaminating nearby waterways (Mattos et al. 2021b). This relationship highlights the complex interconnections between multiple CISs (i.e., waste, solid waste, transportation, and public health).

Limitations and Future Research Opportunities

As with any systematic literature review, there are limitations. For example, Web of Science does not encompass all relevant journals; however, it is widely used in academic research and is recognized for its extensive coverage of scholarly literature (Aksnes and Sivertsen 2019; Clarivate Analytics 2023). To ensure a more comprehensive understanding of infrastructure interdependencies, future work should explore additional sources, including news media and grey literature. Results of this study revealed a lack of research exploring connections between water and communications, which is an important topic given possibilities to leverage remote water maintenance. Further, only a few studies explored interdependencies between transportation, waste, and water. Future work should incorporate a broader spectrum of CISs. Interviews with stakeholders involved in providing CISs could provide additional insight not available in the literature.

CONCLUSION

CISs are inherently connected to each other, creating vulnerabilities and opportunities for resilience. Although infrastructure interdependencies have been studied in the contiguous US, there is a gap in understanding about how interdependencies differ in Alaska, a unique context given the arctic climate and isolated geographical features. Within the distinctive context of Alaska, understanding the interconnections between the water sector and other CISs is fundamental for water utilities and policymakers to address the OMM challenges. Here, we conducted a systematic literature review of scholarly articles to identify CIS interdependencies related to the provision of water and wastewater services in Alaska. Through a qualitative analysis of 25 articles, we found that previous studies mainly focused on the relationship between water sector systems and public health, as well as with energy. However, there were limited studies focused on the connections between water and transportation, food and agriculture, and waste sectors, with no study specifically addressing communication systems. This gap calls for future research to broaden its scope and comprehensively investigate how water-related challenges interconnect with other CISs in Alaska. Practical recommendations include fostering cross-sector collaboration and advocating for integrated infrastructure planning. By addressing these areas, future initiatives can contribute to building more resilient CISs in Alaska, ensuring sustainable access to infrastructure services, and enhancing overall community resilience.

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