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A sociotechnical systems approach to water infrastructure decision making

Rachel Lane Pearson

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Abstract

Sociotechnical systems approach to water infrastructure decision making

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The increasing complexity and interdependence of global water and energy systems demand innovative approaches to ensure sustainable infrastructure. This dissertation examines the sociotechnical interactions shaping water and energy infrastructure through a systems lens. It highlights how decision-making by both organizational stakeholders and individual users impacts infrastructure sustainability, resilience, and equity. This research comprises three studies that explore the intersection of human behavior, technical operations, and infrastructure outcomes. First, a case study in Addis Ababa, Ethiopia, evaluates the successes and challenges of WASH behavior change programs, focusing on their influence on student and teacher engagement. Second, semi-structured interviews with stakeholders in rural Alaskan communities reveal the decision-making processes behind water source selection in drinking water projects, emphasizing the interplay of technical feasibility and community needs. Lastly, the integration of renewable energy into water treatment systems is investigated using energy audit data and HOMER software to assess the technical and economic viability of solar microgrids. By combining qualitative and quantitative methods, this dissertation bridges gaps in existing literature that often focus on technical or social dimensions in isolation. It contributes to the field by advancing the eco-sociotechnical systems framework, offering actionable insights into how infrastructure design and operation can align with user behavior, stakeholder priorities, and sustainability goals. The findings underscore the need for holistic approaches that integrate technical innovations with a deep understanding of human and social factors to achieve equitable and resilient infrastructure systems.

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DEDICATION

To Meaghan

CHAPTER 1: INTRODUCTION

In 2015, the United Nations created the Sustainable Development Goals, a set of 17 universal goals that address economic, political, and environmental challenges (United Nations, 2024b). These goals aim to end poverty and hunger, combat inequalities, build peaceful societies, protect human rights, and protect the planet and its natural resources at a global scale, not only in developing countries. This dissertation focuses on Sustainable Development Goals 6 and 7, which are to ensure availability and sustainable management of water and sanitation and to ensure access to affordable, reliable, sustainable, and modern energy for all respectively.

According to the World Health Organization, as of 2022, 27% of the world's population lacks access to safely managed drinking water services, 3.5 billion people are without safely managed sanitation services, and 2 billion people do not have handwashing facilities at home (WHO, 2024). A 2019 survey revealed that emergency preparedness is among the top 10 concerns in the water industry (ASCE, 2021). As climate change exacerbates the challenges of resilience and equity in water infrastructure, infrastructures need to be understood and designed with a systems approach. For example, incorporating the water-energy nexus in design is increasingly essential. The water-energy nexus describes the interdependence between water and energy resources, where energy is required for water collection, treatment, and distribution, and water is necessary for energy extraction, operation, and distribution. This highlights the complex interconnections that exist across systems, which have traditionally been operated and managed independently (Aggarwal, 2022; Feldman et al., 2021; Griffiths-Sattenspiel, 2009; Guy et al., 2001; IEA, 2022; Pincetl & Porse, 2016; Sambor et al., 2022; Vakilifard et al., 2018).

Humans play a crucial role in the resilience of infrastructure, both individually and collectively, as these systems are shaped by human decisions and the social, economic, and institutional contexts that influence those decisions (Williams & Edge, 1996). Engineering design not only modifies constraints and provides essential services but also relies on humans for design, operation, and maintenance. Therefore, there is a strong interconnection and interdependence between critical infrastructure systems and human stakeholders (Laugé et al., 2015; Moore et al., 2019; J. E. Thomas et al., 2019).

This dissertation adopts an eco-sociotechnical systems approach to infrastructure, examining infrastructure decision making on both the operational and stakeholder level. While much of the existing engineering literature focuses on either the technical and operational efficiency of infrastructure systems (Aggarwal, 2022) or user experiences in isolation (Harris-Lovett et al., 2018), this research bridges the gap by exploring how these dimensions interact. It highlights how technical decisions—such as energy integration, water source selection, and system design—are influenced by and, in turn, affect user behaviors, community needs, and social contexts. I draw on both qualitative and quantitative methods and a wide range of contexts to demonstrate the implementation of this perspective and its value in water and energy infrastructure systems.

1.1.DISSERTATION SUMMARY

The proposed dissertation will explore three research questions, each addressed in separate publications. The first, Chapter 1, investigates the successes and failures implementation of infrastructure by studying the users of WASH behavior change program in Addis Ababa, Ethiopia. The second chapter utilizes qualitative methods to analyze how water officials make decisions regarding water sources in rural Alaskan drinking water projects. The final chapter examines the integration of renewable energy into water treatment systems, employing HOMER software to analyze energy audits. The overarching theme of this dissertation is understanding how water and energy infrastructure stakeholders impact the sustainability of infrastructure systems. Figure 1 visually summarizes the work done in this dissertation. The various methods used to explain these questions are explained in more detail in the following sections.

Research Question: How do operational and user decisions influence each other in the design, implementation, and success of infrastructure systems?

	Decision Makers/ Stakeholders	Research Question	Method	Data
Chapter 1	Users	What are the barriers and facilitators of handwashing among primary and secondary school students?	Semi- strucutred interviews, qualitative coding	Interview data with 12 teachers and 48 students in Splash schools in 2022
Chapter 2	Operators, planners, and managers	What factors influence water source choice for drinking water in rural Alaskan communities?	Semi- strucutred interviews, qualitative coding	Interview data with 21 Alaskan water officials collected from 2020 to 2021
Chapter 2	Designers, operators, and planners	What are the 24-hour and annual energy loads of water treatment plants in rural Alaska? How does solar energy integrate into these systems? How do these loads and integration vary across regions and system types?	Energy demand analysis, quantitative exploratory study	Energy audits done in 13 rural Alaskan communities done by ANTHC through 2024

Figure 1. Overview of dissertation chapters and research design

1.2.RESEARCH CONTEXT

This dissertation integrates various aspects of water and energy infrastructure systems, including resilience, sustainability, and systems thinking. The combination of the three research papers allows for a deeper understanding of water and energy infrastructure systems and positions this research to better assess interactions between infrastructure and its decision makers.

This research examines infrastructure through the lens of decision-makers, recognizing that infrastructure requires significant upfront investments that are challenging to recover. Poor decisions in this domain can be costly and difficult to reverse (Marlow et al., 2010; Too & Too, 2010). While historically, engineers often approached infrastructure decision-making from a technocratic perspective (Fischer 1990; Parkin, 1994), there is a growing recognition of the need to adopt a broader sociotechnical approach. This dissertation explores how decisions made by both organizational stakeholders and users influence each other and shape infrastructure outcomes.

From an organizational perspective, stakeholders such as engineers, operators, planners, and policymakers determine the types of systems, their operations, and placement. These decisions significantly affect both the functionality and the lives of the users who depend on the infrastructure. However, such decisions come with inherent risks due to the unpredictability of user behavior. Mitigating these risks requires a deeper understanding of user needs and preferences. Chapter 3 focuses on the choices made by water officials in rural Alaskan communities, examining the factors influencing their selection of water sources for drinking water projects and the potential consequences of these choices for local residents.

On the user side, decision-making can directly impact the effectiveness and sustainability of infrastructure systems. Community engagement with water and energy systems influences their cost, longevity, and overall success. Chapter 2 of this dissertation investigates how students and teachers interact with WASH infrastructure, analyzing their perceptions of its successes and failures and its impact on student behavior. Insights from this analysis highlight how infrastructure use contributes to outcomes and how user-focused adjustments could improve organizational strategies.

Chapter 4 bridges the gap between organizational and user perspectives by examining system operations and usage patterns. It explores energy trends in water treatment systems to identify technical modifications, such as solar energy integration, that can enhance system efficiency and reduce costs for communities. It also identifies ways to change operational approaches in the systems to better incorporate renewable energy.

This dissertation employs a sociotechnical systems approach, combining technological and social perspectives to better design infrastructure systems that serve both users and organizations. By analyzing infrastructure through a social lens, we can create systems that effectively meet the needs of the people and institutions they support (W. R. Scott, 2008). Organizational theory, particularly sociotechnical systems theory, provides a framework for understanding the interplay between social and technical components of infrastructure (Ottens et al., 2006). This theoretical approach helps explain how decisions made by organizational stakeholders interact with user behavior to influence the design, construction, operation, and management of resilient and equitable infrastructure systems.

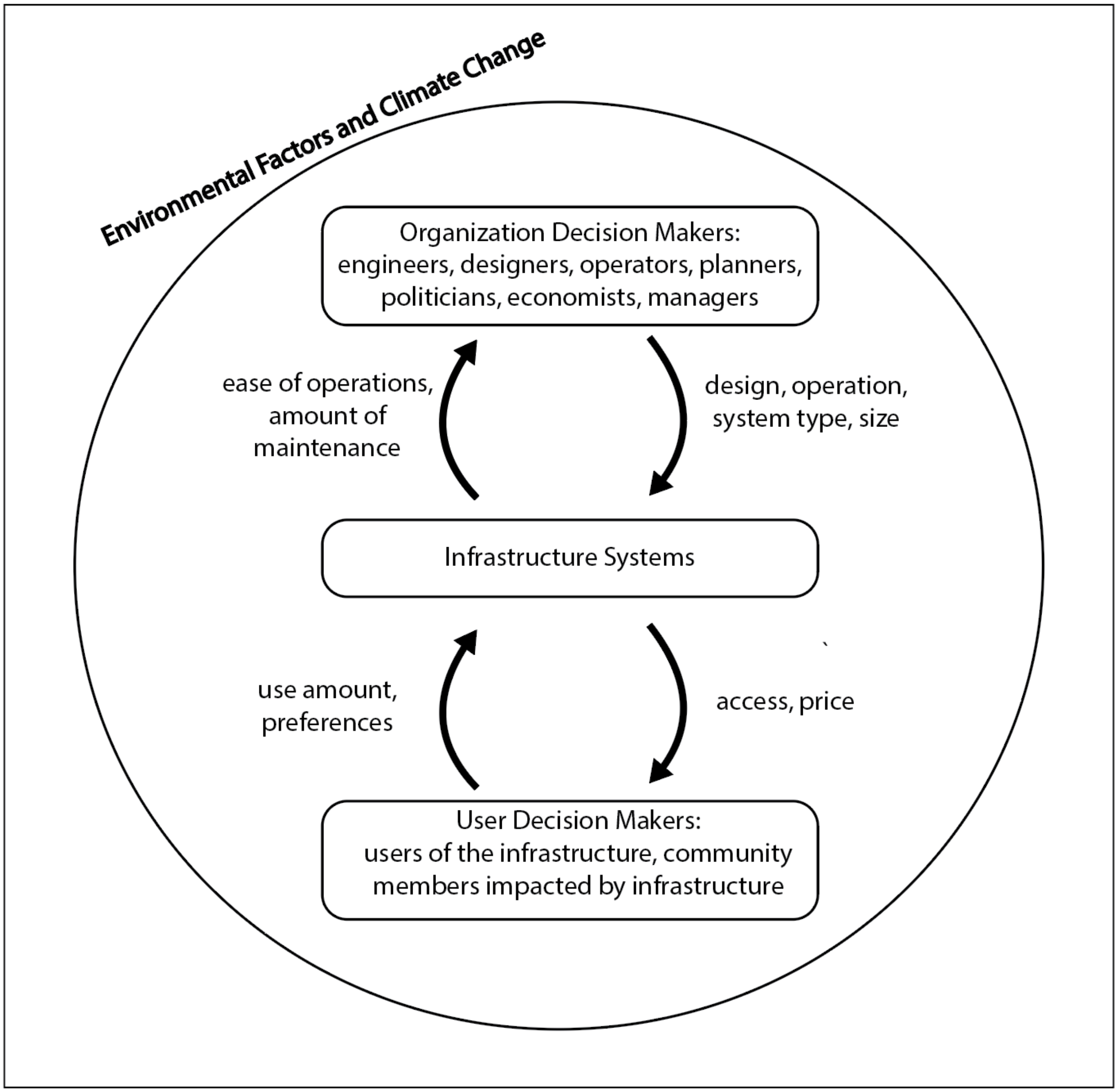

Figure 2. Diagram showing sociotechnical systems and how organizational decision makers and infrastructure systems impact each other and infrastructure systems and user decision makers impact each other. Both are impacted by environmental factors.

1.3. RESEARCH METHODS

This section introduces the methodological approaches I will be using to answer my research questions. My proposed dissertation uses quantitative and qualitative methods.

1.3.1. DATA COLLECTION: INTERVIEWS

Chapters 2 and 3 of the proposed dissertation use interviews from two separate interviews. In Chapter 2 interviews were done with teachers and students at schools in Addis Ababa, Ethiopia and in Chapter 3 interviews were done with stakeholders involved in drinking water projects in rural Alaska. The datasets used semi-structured and in-depth interviews. The interview guides for each interview will be in the appendices of the proposed dissertation.

1.3.2. DATA COLLECTION: OPEN DATA

Chapter 4 uses open data from the Alaskan Native Tribal Health Consortium (ANTHC) (ANTHC, 2024). ANTHC conducted energy audits at 144 locations in rural Alaska and published the results of these audits. We collected data from 13 communities that had energy loads for water treatment plants every 15 minutes for an entire year.

1.3.3. DATA ANALYSIS: QUALITATIVE CODING AND ANALYSIS

My dissertation employs qualitative coding to analyze interview datasets using the qualitative coding software NVivo (*NVivo*, 2022a). Additionally, I applied a combination of deductive and inductive approaches to categorize themes within the interview transcripts. Parent codes were derived from research questions or theoretical frameworks, while child codes emerged from the themes identified during the interviews (Spearing et al. 2022a).

1.3.4 DATA ANALYSIS: HOMER MODELING

In Chapter 4 we performed an optimization analysis of load data and system cost estimation used Hybrid Optimization of Multiple Energy Resources (HOMER) software (HOMER Pro, 2024). This tool simulates a microgrid for an infrastructure system using technical, economic, and environmental data to simulate and optimize a renewable grid. We also performed an energy demand analysis to create load profiles with the data (Kini, 2011).

1.4. DISSERTATION FORMAT

This dissertation will use the publication-based approach. Chapter 2 has been accepted for publication in Environmental, Science, and Technology: Water (ES&T Water). Chapters 2 and 3 are being prepared to be published. The supplementary information for the three chapters is compiled at the end into the appendices.

CHAPTER 2: ANALYSIS OF FACTORS INFLUENCING TEACHER AND STUDENT WATER, SANITATION, AND HYGIENE KNOWLEDGE AND BEHVAIORS IN ADDIS ABABA, ETHIOPIA

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2.1. ABSTRACT

Water, sanitation, and hygiene (WASH)-related diseases pose significant health challenges for children worldwide, with schools serving as critical settings for WASH investments. This paper examines the perceived barriers and facilitators for handwashing behavior change in the context of a school-based WASH program implemented by the nonprofit Splash International in Addis Ababa, Ethiopia. We identified influential factors using the Behavior Centered Design framework to qualitatively code teacher and student semi-structured interview data. Our findings indicate that knowledge-based, emotional, and social interventions were perceived to encourage handwashing, while physical infrastructure constraints and time limitations were considered impediments. These results underscore the necessity of adopting comprehensive approaches that address both hardware and software factors of handwashing behavior change. We recommend that future school WASH research and practice further examine the effects of time constraints and water intermittency on WASH behaviors to inform intervention design.

2.2. INTRODUCTION

Water, sanitation, and hygiene (WASH) conditions are important determinants of child health (Aiello et al., 2010; Wolf et al., 2014). School WASH can be incredibly influential given the time children spend in this setting exposed to germs and behaviors that can impede healthy development (McMichael, 2019). Previous research suggests access to WASH services in school can reduce rates of diarrheal diseases (Dreibelbis et al., 2014; McMichael, 2019) and respiratory infections (McMichael, 2019). Achieving these and other benefits requires reliable services, which we define as consistently available safe drinking water, well-maintained sanitation facilities, and handwashing stations equipped with soap and water. This study focuses on hand hygiene promotion, which is a highly effective health intervention for reducing mortality and morbidity among children (Matta et al., 2022). Evidence suggests that regular handwashing can reduce diarrheal diseases by nearly 50% (Curtis & Cairncross, 2003) and mitigate the risk of acute respiratory infections (Ryan et al., 2001).

Studies have examined the availability of handwashing facilities and predictors of good hygiene practices among students in Addis Ababa, Ethiopia (Melaku & Addis, 2023), as well as the effects of school-based WASH interventions on diverse health and educational outcomes such as diarrhea, respiratory infections, and school attendance (Caruso et al., 2014; Chard et al., 2018; Dreibelbis et al., 2013; Freeman et al., 2014). However, few studies have investigated the extent to which these interventions have resulted in changes in specific hygiene behaviors (Dreibelbis et al., 2016; Okello et al., 2019). This study aims to contribute to the existing literature by examining which components of interventions effectively change handwashing behavior and identifying areas needing improvement, with a focus on the school setting in Addis Ababa, Ethiopia.

The aim of our study is to examine such mediating factors in the context of a school-based WASH program in Addis Ababa, Ethiopia. Specifically, we answer the question: What are the barriers and facilitators of handwashing among primary and secondary school students? We used qualitative methods informed by the Behavior Centered Design (BCD) approach to analyze the perspectives of teachers and students from schools that received the WASH program. Based on our results, we offer practical suggestions for school-based intervention design.

2.3. METHODS

2.3.1. Intervention

Splash International is a nonprofit organization that has been working to change handwashing and other school WASH conditions in Addis Ababa, Ethiopia since 2008. Their school-based intervention known as Project WISE, or WASH in Schools for Everyone, creates positive behavior-changing environments (Matta et al., 2022) primarily through infrastructure improvements and health education. Schools typically receive upgraded water storage, sanitation facilities, and handwashing and drinking water stations while students and teachers are trained in the associated behaviors such as handwashing with soap, point-of-use water treatment, toilet use and cleaning, and menstrual hygiene management. Splash helps schools form student hygiene clubs led by a trained focal teacher to encourage school-wide behavior change.

2.3.2. School selection

We collected data from six primary schools in Addis Ababa that had received Splash's full intervention. Eligible schools were non-boarding primary schools included during the third wave of Project WISE from 2020 to 2022, when Splash implemented its latest handwashing measurement technique. We divided the sample of eleven eligible schools into two groups based on handwashing infrastructure sufficiency pre-implementation, as we assumed this condition would affect the post-implementation behaviors in which we are interested. We labelled schools as "infrastructure insufficient" if Splash could not conduct handwashing observations during its pre-implementation infrastructure assessment due to either water unavailability, the absence of any handwashing station, or the absence of a functioning handwashing station.

We then selected three schools from each group according to student population size. We chose this criterion due to the influence that the number of students can have on intervention implementation (e.g., the effect of an intervention may be slower in larger schools). We calculated student population percentiles across the list of eligible schools and chose an infrastructure sufficient and insufficient school close to the 25th, 50th, and 75th percentiles. Selecting schools in this way allowed us to capture a broad spectrum of contexts.

2.3.3. Participant selection

We recruited 48 students, evenly distributed across the six schools. To select students, we first chose one class from both the 4th and 8th grades at each school. Classes were randomly selected from a list by the interviewers. Teachers within each chosen class were responsible for recruiting one girl and one boy volunteer who were not members of the hygiene club (representing the typical student). The chosen volunteers were responsible for selecting a friend of the same gender who was also not a hygiene club member to make up a "friendship pair." Friendship pair interviewing is a technique where the participant is encouraged to bring a friend to the interview session. This approach aims to create a comfortable and non-intimidating atmosphere for children during data collection (Cartwright et al., 2016). The friendship pair is then interviewed together. The 48 students we interviewed were part of 24 friendship pairs, 12 of pairs for each gender. We discovered during data analysis that some of the students selected were hygiene club members; six students mentioned their involvement during the interviews. As we did not systematically ask students about their involvement, the actual number of hygiene club members interviewed may be larger than those who mentioned it in passing. We discuss the implications of this oversight in the limitations section.

In addition, we recruited six focal teachers and six non-focal teachers, one type of teacher at each school. School principals facilitated the recruitment of these teachers. Focal teachers are those who work with Splash to implement their program and oversee the hygiene club. Non-focal teachers are those who are not directly involved in implementing the program. We intended for more-experienced and less-experienced non-focal teachers to be interviewed, but only experienced teachers were interviewed. We also discuss the implications of this sampling constraint in the limitations section. We believe that we reached theoretical saturation data (Glaser & Strauss, 2017) with 12 teacher interviews and 24 student friendship pair interviews.

Data collection: In-depth interviews

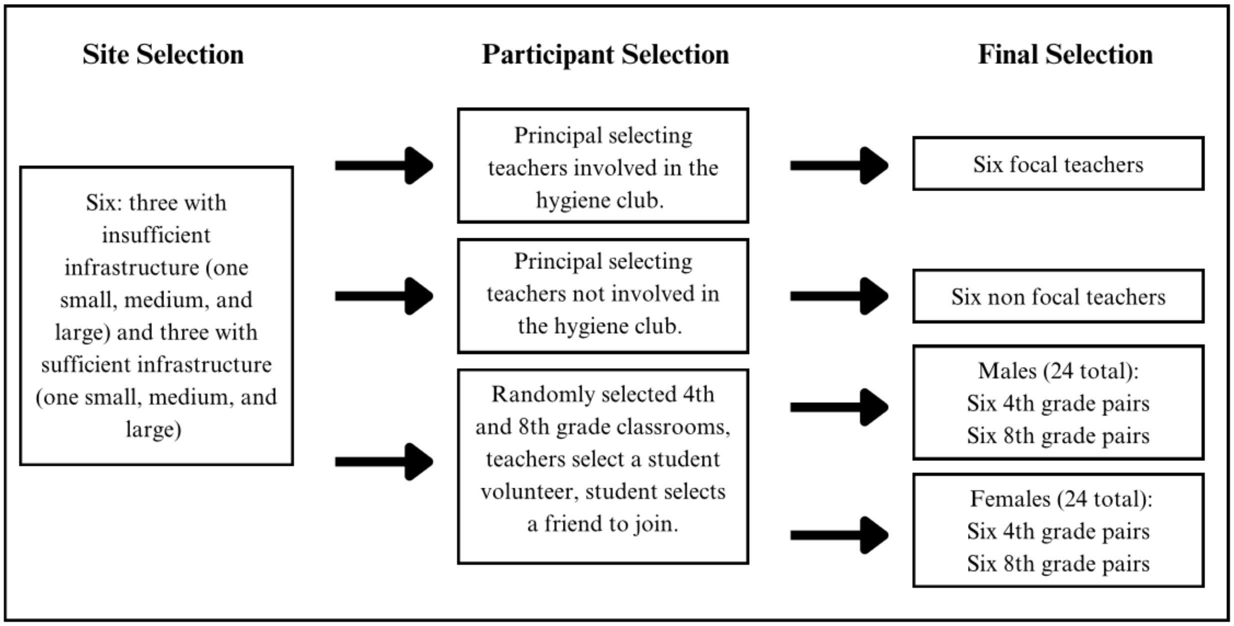

Figure 3. Outline of the selection process for schools and participants

Data collection was between July and August 2022 and consisted of in-person semi-structured interviews conducted by an external data collection firm. All interviews were private, one-on-one interviews with a member of the data collection firm, except for those with friendship pairs. Interviews were done in Amharic and typically lasted 30 to 60 minutes. Audio recordings of the interviews were transcribed and translated into English. All participants gave their verbal consent before the start of the interview; students also presented a signed parental permission form.

The University of Washington Institutional Review Board and the Government of Addis Ababa Ethical Clearance Office approved all data collection activities.

The three classes of interviews collected a diverse set of perspectives on Splash's program. Interviews with students gathered information on their knowledge regarding handwashing with soap, their motivation to wash their hands, and which lessons they gained knowledge. We interviewed focal teachers to understand the strengths and weaknesses of Splash's program from their unique position as head of the hygiene club. We asked focal teachers about their knowledge of Splash's program, their motivation and confidence in their role as focal teachers, and their perceptions of the program's effectiveness and sustainability. We asked questions similar to those of non-focal teachers about their knowledge, experience, and perceptions of program effectiveness to understand how teachers' perspectives are a function of their involvement. Our interview guide was designed primarily based on the interview guide from a paper assessing the Mikono Safi intervention schools in Tanzania (Okello et al., 2019). Please see the Supporting Information for the full interview guides.

2.3.4. Data analysis

The research team uploaded all interview transcripts into NVivo 14 software (*NVivo*, 2022b) and analyzed them using a hybrid inductive-deductive thematic approach. (Spearing, Bakchan, et al., 2022). Deductive coding is a structured approach to qualitative data analysis that allows researchers to apply existing knowledge, theories, or research objectives to categorize and make sense of qualitative data (Bingham, 2023; Crabtree & Miller, 1999). In inductive analysis, researchers engage in the iterative process of examining the data to discern codes, categories, patterns, and themes as they organically unfold (Miles & Huberman, 1984; Saldana, 2021).

2.3.5. Behavior Centered Design framework

We derived our deductive codes from Splash's behavior change program process model based on the Behavior Centered Design framework. In brief, this holistic framework offers a structured model for understanding and programming behavior change interventions based on theories from reinforcement learning, evolutionary biology, and social ecology (Aunger & Curtis, 2016). The accompanying BCD checklist is a tool summarizing the framework's factors, such as the social environment, motivation, physiology, and norms. Splash uses a simplified checklist consisting of five factors abbreviated as: physical, social, executive, motivated, and reactive. Figure 2 shows how these factors map onto the different components of Splash's program. Physical factors encompass all the infrastructural or material elements introduced by Splash's program. Social factors leverage influential figures such as teachers and peer models to promote and advocate for behavior change. Executive factors focus on educating students about WASH health and safety through classroom lessons or extracurricular activities. Motivated factors are designed to trigger behavior change through emotional incentives, including evoking feelings of disgust, nurturing, and affiliation. Reactive factors are those that serve as reminders, prompting and reinforcing healthy WASH behaviors. In WASH practice parlance, the physical and reactive components can be thought of as the hardware, while the executive, motivational, and social factors are the software.

Physical	**Social**	**Executive**	**Motivated**	**Reactive**
Handwashing stations Soap drives Drinking stations Filter systems Sanitation Trash bin and water buckets	Hygiene clubs Soap drive Training of teachers Handwashing pledge	Germs germs everywhere Clean hands/ dirty hands Safe water sources Toilet beauty standards	Disgust Clean hands/ dirty hands Handwashing pledge Status and affiliation	Posters Vests Mirrors Trash bins

Figure 4. Splash's program organized under the BCD framework

BCD factors—physical, social, executive, motivated, and reactive— are accompanied by subcategories representing the activities, lessons, and enhancements implemented by Splash. For instance, under motivated, considerations such as "Status and affiliation" represent students' concerns about the influence of their hygiene practices on their social life. Additionally, ''Germs germs everywhere" under executive and ''Clean hands/dirty hands" under motivated are classroom behavior change lessons.

2.3.6. Coding approach

We qualitatively coded the interviews by first applying the five BCD factors as our parent, or main, codes (e.g., physical, motivated). Two rounds of coding were conducted for each BCD factor. We then assigned each segment of text to one or more program components, or child codes (e.g., Handwashing stations, Disgust). If there were no factor or relevant program component but an emergent pattern in the data, we inductively coded the data under the parent code "Other" and assigned it a new child code. Two rounds of coding were undertaken for the subcategories.

An example of this hybrid coding approach was in relation to students' handwashing knowledge. Some students brought up lessons about germs that seemed to originate from Splash's intervention, but no student explicitly mentioned Splash. Students may not know the difference between Splash's lessons and the WASH lessons created by their teachers. We coded text describing handwashing knowledge that could be reasonably connected with the content of Splash's lessons under "executive, germs germs everywhere." Otherwise, we coded handwashing knowledge inductively under a new child code "executive, general germ."

We organized the parent-child code combinations into the categories of facilitator or barrier. We defined barriers as the components of Splash's program that were discussed as impeding students' handwashing. Facilitators were the program elements discussed as supporting handwashing. The purpose of this categorization was to examine the perceived effects of each BCD component. We conducted an additional two rounds of coding for the facilitators and barriers.

2.4. LIMITATIONS

Our study presents several limitations. First, it was conducted with a relatively modest sample size of schools, teachers, and students. The sample was further limited in that we did not interview everyone we intended to. As previously mentioned, our student sample included hygiene and non-hygiene-club members, and our teacher sample was only more-experienced instructors. Hygiene club members and more-experienced teachers may be relatively more aware of what goes on at the school, including Splash's work. One possible implication is that Splash's impact may seem more pronounced than it is in reality, or that it is from the perspectives of less-experienced teachers and non-hygiene-club members only, though it is hard to say without these data. Our sample may consequently be less generalizable to other intervention schools in Addis Ababa, as it may not capture the typical student or teacher. However, a counter-balancing strength of our sample is that it represents a range of schools in terms of size and infrastructure conditions, two factors Splash knows affect the implementation of its program. Furthermore, there is the potential for courtesy bias since our participants knew the study was carried out by Splash. This awareness may have influenced their responses, potentially leading them to provide answers they believed would be well-received. Nevertheless, it is noteworthy that we encountered a high degree of consistency in responses across both students and teachers, and respondents spoke candidly about challenges, such as the difficulty maintaining a reliable supply of soap. There may also be courtesy bias from focal teachers about hygiene clubs since these clubs are led by focal teachers. Focal teachers and students spoke candidly about the barriers of these programs and there was a high degree consistency across focal teacher responses.

2.5. RESULTS AND DISCUSSION

Table 1 summarizes the highest-frequency child codes for the five BCD factor parent codes categorized through our deductive thematic analysis. While the frequency of reporting each factor does not inherently signify its relative importance, it can offer insights into a factor's perceived impact.

In the following sections, we consider each BCD factor more closely, revealing their barriers and facilitators to handwashing, examining their frequencies across participants, and offering representative quotations to illustrate critical points. Given the similar results and themes in responses from focal and non-focal teachers, comparing them proved unproductive, hence consolidating them was the appropriate decision. We lightly edited some of the quotations for readability while retaining the text's original meaning.

Table 1. Facilitators and barriers by BCD factor mentioned by teachers and students[1]

BCD Factor	Facilitators	Barriers
Physical	Handwashing station: Well-designed Handwashing station: Perceived positive health effects from the separation of handwashing and drinking water stations Water supply: Increased supply due to storage tanks	Handwashing station: Overcrowded Soap drive: Inconsistent supply (students often steal it) Soap drive: Students dislike watered-down soap Handwashing station and soap drive: Students damage infrastructure and soap Water supply: Inconsistent supply Other: Non-focal teachers' concern for the sustainability/maintenance of new WASH infrastructure
Reactors	Mirrors: Help students to wash their hands and faces Posters: Students often recall posters as being present and helpful handwashing reminders	None
Social	Training: Teacher trainings, lead by Splash, help them to feel knowledgeable and comfortable educating students on hygiene Handwashing pledge: Mini-media is a compelling handwashing reminder Hygiene club: An effective communication channel for hygiene and means of involving students in the program	Hygiene club: Focal teachers' challenge of fulfilling duties due to competing priorities Soap drive: Inconsistent supply (students often steal it)
Motivated	Disgust: Students want to be perceived as clean	None

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[1] Table 1 presents the factors identified as barriers and facilitators categorized by each BCD factor. Only factors mentioned by more than 10% of interviewees are included in this table.

Executive	General germ: Students know handwashing decreases germs and improves health General germ: Many students care about protecting the health of their friends and family through handwashing Handwashing steps: Many students remember and can explain the difference/importance of washing your hands with water versus water and soap	None

Table 2 provides an overview of the relative frequencies of various facilitator types discussed by teachers and students. We found that teachers most mentioned facilitators within the categories of physical, reactive, and social. In contrast, students most frequently discussed executive, motivated, and social factors as facilitators.

Table 2. Frequency of each factor categorized as a facilitator of handwashing[2]

		Facilitators				
		Teachers			Students	
Code		Number of interviewees	Number of responses (relative frequency)		Number of interviewees	Number of responses (relative frequency)	
Handwashing facilitators		12	204	(100.0%)	114	214	(100.0%)
Executive		7	10	(4.9%)	17	59	(27.6%)
	Clean hands, dirty hands	3	3	(1.5%)	9	13	(6.1%)
	General germ	5	7	(3.4%)	15	46	(21.5%)
Motivated		1	1	(0.5%)	5	13	(6.1%)
	Disgust	1	1	(0.5%)	5	13	(6.1%)
Physical		10	33	(16.2%)	8	10	(4.7%)
	Handwashing station	7	14	(6.9%)	3	3	(1.4%)
	Soap drive	1	1	(0.5%)	4	5	(2.3%)
	Water tanks	6	16	(7.8%)	2	2	(0.9%)
	Other	2	2	(1.0%)	0	0	(0.0%)
Reactive		10	23	(11.3%)	3	3	(1.4%)
	Mirrors	10	16	(7.8%)	0	0	(0.0%)
	Handwashing monitors	2	3	(1.5%)	0	0	(0.0%)
	Posters	4	4	(2.0%)	3	3	(1.4%)
Social		11	35	(17.2%)	9	22	(10.3%)
	Friday cleaning	1	1	(0.5%)	4	5	(2.3%)
	Handwashing pledge	6	7	(3.4%)	3	3	(1.4%)
	Hygiene club	7	12	(5.9%)	5	10	(3.7%)
	Soap drive	1	1	(0.5%)	2	2	(0.9%)
	Handwashing monitors	2	3	(1.5%)	2	2	(0.9%)
	Teacher training	6	11	(5.4%)	0	0	(0.9%)

Table 3 provides an overview of the relative frequencies of various barrier types discussed by teachers and students. Overall, the results show that the physical and social factors were mentioned at the highest frequency. There was almost no mention of executive or motivated factors hindering the success of handwashing.

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[2] Table 2 displays the frequency of factors mentioned as facilitators to handwashing in schools. The factors and their subcategories are shown under the "Code" column. The "Number of Interviewees" column indicates how many interviewees (teachers or pairs of students) mentioned each factor. The "Number of Responses" column indicates how frequently that factor was mentioned overall, with the "Relative Frequency" showing how often that response was given compared to other factors.

Table 3. Frequency of each factor categorized as a barrier to handwashing

		Barriers					
		Teachers			Students		
Code		Number of interviewees	Number of responses (relative frequency)		Number of interviewees	Number of responses (relative frequency)	
Handwashing barriers		60	82	(100.0%)	92	130	(100.0%)
Executive		0	0	(0.0%)	1	1	(0.8%)
	Clean hands, dirty hands	0	0	(0.0%)	0	0	(0.0%)
	General germ	0	0	(0.0%)	1	1	(0.8%)
Motivated		1	1	(1.2%)	2	2	(1.5%)
	Disgust	1	1	(1.2%)	2	2	(1.5%)
Physical		10	25	(30.5%)	19	46	(35.4%)
	Handwashing station	3	5	(6.1%)	5	6	(4.6%)
	Soap drive	4	7	(8.5%)	10	15	(11.5%)
	Water tanks	5	6	(7.3%)	14	25	(19.2%)
	Other	5	7	(8.5%)	0	0	(0.0%)
Reactive		2	4	(4.9%)	2	2	(1.5%)
	Mirrors	1	1	(1.2%)	2	2	(1.5%)
	Handwashing monitors	2	3	(3.7%)	0	0	(0.0%)
	Posters	0	0	(0.0%)	0	0	(0.0%)
Social		6	11	(13.4%)	11	14	(10.8%)
	Friday cleaning	0	0	(0.0%)	0	0	(0.0%)
	Handwashing pledge	0	0	(0.0%)	0	0	(0.0%)
	Hygiene club	4	5	(6.1%)	6	7	(5.4%)
	Soap drive	3	3	(3.7%)	5	6	(4.6%)
	Handwashing monitors	2	3	(3.7%)	1	1	(0.8%)
	Teacher training	0	0	(0.0%)	0	0	(0.0%)

2.5.1. Executive

We found students perceived executive factors exclusively as facilitators. Executive factors include lessons that teach students about the hygiene practices and germs. Lessons taught by Splash like germs germs everywhere and clean hands dirty hands teach students how handwashing removes germs, therefore helping their health. The students exhibited proficiency in articulating correct hand hygiene practices, demonstrating a solid understanding of the circumstances warranting soap usage and most of the handwashing steps. We found that 17 student pairs (71%) showed some knowledge of the difference between handwashing with water alone and handwashing with soap and water. For example, an eighth grade boy stated:

"Washing with water only will not remove the germs from our hands. To completely clean our hands, we use soap to remove and clean germs from our hands. Thus, washing with only water will not clean your hands, but washing your hands with water and soap will do."

Moreover, nine students (38%) explicitly mentioned that their awareness of germs and soap had improved because of lessons done at school. We asked students about the consequences of not washing their hands, and they were able to articulate the connection between hand hygiene and the risk of infections, as illustrated by this quotation from a fourth grade girl:

"If we wash our hands with only water, our hands will not be cleaned, and different viruses may remain in our hands. But if we wash with soap, the viruses in our hands will be cleaned and removed to some degree. Thus, washing hands with only water will be disadvantageous while washing hands with soap will be advantageous."

The majority of students reported germs and health as the principal drivers behind their commitment to handwashing. Students also conveyed concerns about safeguarding their well-being and that of their families and friends through diligent handwashing. When comparing the perspectives of students and teachers, we observed that teachers placed less emphasis on the executive drivers of handwashing (seven; 58% teachers compared to 17; 71% of student pairs).

Research suggests that comprehending the rationale behind handwashing is crucial for effective HWWS practices (Almoslem et al., 2021). This finding is consistent with others indicating that children's grasp of health-related knowledge serves as a catalyst for handwashing and encourages greater adherence to the practice (Jetha et al., 2021). These studies bolster the idea that interactive educational activities can enhance both the understanding and execution of handwashing among students. Our study's results are in line with research conducted by (Okello et al., 2019), who utilized the COM-B behavior change framework to explore the factors influencing handwashing among students in Tanzanian schools following the implementation of a WASH program. Their findings emphasize the significance of educational interventions in fostering handwashing behavior among students. By imparting knowledge about germs through educational lessons, students are equipped with a solid foundation for comprehending the importance of handwashing.

2.5.2. Motivated

Motivating factors include situations where students are driven to wash their hands due to the perceptions or judgments of their peers. Our findings revealed that five student pairs (21%) reported experiencing feelings of disgust or perceived judgment from their peers regarding handwashing practices. Motivation emerged primarily as a facilitator for handwashing, as students expressing it stated that it increased their inclination to wash their hands. Students articulated feelings of being unclean, malodorous, or embarrassed when they neglected handwashing. While this sense of shame or disgust might incentivize handwashing, some students also indicated experiencing peer pressure against handwashing, especially when hurrying to engage in activities or meals. One 4th-grade boy explained feeling pressure to wash his hands for fear of the social consequences:

"I feel bad because some people are afraid of washing for fear of the cold water, but they eventually smell bad, so if I become like them, my friends will stay away from me."

Conversely, teachers rarely (one; 8%) mentioned motivating factors. We hypothesize that these factors are internal emotions or peer influences that students experience, making them challenging for teachers to observe or address directly.

Research has pointed to the efficacy of emotions, particularly motivational factors, in influencing hygiene behaviors (Biran et al., 2014; Rabie & Curtis, 2006; B. Scott et al., 2007). For instance, the SuperAmma study conducted in India demonstrated significant enhancements in hygiene behaviors by addressing motivational drivers independently of health education (Biran et al., 2014). Our study concurs with these findings, illustrating how emotional drivers can serve as motivators for handwashing. However, our findings suggest that emotional drivers may be perceived to have a lesser impact on handwashing behaviors than executive factors. Additionally, the influence of motivational drivers could be contingent upon the presence of sensory cues. As these cues were absent during the interviews, individuals may not have experienced sensations of disgust, uncleanness, or a perceived threat to their health. It is worth noting that motivational factors were mentioned less frequently than executive factors, which may contribute to their limited emphasis. We remain uncertain whether motivational factors genuinely have less influence on handwashing or if they are simply less considered in the absence of sensory cues.

2.5.3. Physical

Physical factors of handwashing were the most cited barriers and facilitators among teachers and students. Approximately 10 teachers (83%) and 19 student pairs (79%) discussed physical aspects as barriers, while 10 teachers (83%) and eight student pairs (33%) discussed them as facilitators. One focal teacher explained how the additional water storage infrastructure installed by Splash helped increase handwashing at their school:

"Prior to Splash, there was only one tanker, and the school water supply was available once or twice per week. When this tanker was finished, there was no other option for handwashing. But when Splash fixed the water stations, it provided the school with six big tankers. There is also a generator that pumps water up. But before that, there was a time when water could not be filled. Now, all tankers can be filled with water due to the generator. Thus, it is perceived that problem of water shortage is minimized."

Students similarly discussed the connection between water storage and handwashing. As explained by an 8th-grade girl:

"To begin with there is a severe scarcity of water in our school. Water is available here for a maximum of three days a week only. That could be a reason for not washing our hands. Everybody likes to wash his/ her hands if adequate water is available."

Another 8th-grade girl complained about the soap quality, which is part of the quality of handwashing station infrastructure as a whole:

"I used water only to wash my hands because the quality of the soap was not good. The soap was made available in liquid form. The soap will make the color of our skin white. I am allergic to a soap that has a bad quality."

Interestingly, while the facilitators were distributed somewhat evenly across different factors, a significant portion of the barriers fell within the physical category. This result may suggest that physical factors pose as a relatively large challenge to the success of Splash's program. Yet, physical factors may also be the most frequently mentioned simply because they are the most apparent. We do not believe the interview questions were disproportionately about physical infrastructure.

Consistent with findings from other WASH interventions, our findings suggest that physical infrastructure is necessary to program success (Okello et al., 2019). Reliable access to clean water and quality soap is imperative for promoting healthy hand hygiene practices. However, in urban areas like Addis Ababa, water supply is often intermittent, with different parts of the city receiving water on a rotating basis (Danilenko et al., 2014). Moreover, many water utilities in low- and middle-income countries are susceptible to power outages, making it challenging to maintain pressure in the system and increasing the risk of contamination from groundwater intrusion (Debela et al., 2018). Water quality in Addis Ababa exhibits high variability. Addressing water insecurity in schools necessitates collaboration with city utilities to enhance connections to the broader distribution system and improve infrastructure. Schools may also need to augment their water storage capacity to mitigate the impact of unreliable water delivery. Intermittent water supply exacerbated by poor maintenance forces consumers, including schools, to navigate uncertainties and adapt their behaviors to cope with shortages (Espira et al., 2023). This can significantly impact handwashing practices among students and teachers, hindering their ability to maintain consistent hygiene routines. Some schools have unreliable water intermittency, which can be further impacted by poor maintenance requiring the consumer to make choices under uncertainty, requiring greater behavioral, emotional, and physical defenses to cope with shortages (Cord et al., 2022; Galaitsi et al., 2016). Intermittent water supply impacts both students' and teachers' behavior, hindering their ability to maintain consistent handwashing practices. While research suggests that routines increase handwashing compliance, further investigation is needed to explore the specific impacts of intermittent water supply on handwashing behavior change (Gillebaart et al., 2022).

2.5.4. Reactive

Reactive factors, like mirrors or posters, are used to remind students to wash their hands. In our investigation, teachers noted that reactive elements were viewed positively in their influence on handwashing habits. Specifically, 10 teachers (83%) highlighted the effectiveness of mirrors installed by Splash above handwashing stations. While these mirrors were originally installed as a handwashing reminder, some teachers observed that they also encouraged students to wash their faces. Interestingly, when students were questioned about their handwashing motivations, mirrors and posters reminding them to wash their hands were not cited. Instead, students emphasized personal feelings of cleanliness or their understanding of health reasons.

One focal teacher discussed how the students interact with the mirrors:

“After the children washed their hands and their face in the fixed basin, they look at their face through the mirror to make sure they are clean and good-looking. But it is not permitted to touch the mirror by hand. There are six cleaners in the school who make sure that the students don’t put their hands in contact with the mirror. I feel happy when I observe the children looking at their image through a mirror.”

Students might find themselves washing their faces more frequently when there are mirrors behind the sinks, as seeing their reflection may cause them to notice any dirt or imperfections, prompting them to clean their faces. The strategic placement of mirrors and the awareness of facial hygiene can contribute to the prevention of diseases like trachoma (Tidwell et al., 2019a). Given the insights from our interviews regarding the influence of mirrors on face washing habits, future initiatives aimed at promoting face washing should continue incorporate the deliberate use of mirrors as a reinforcement mechanism. Students may have not mentioned mirrors as a reminder to handwashing because it could be a subconscious reminder. Unlike germ knowledge and feeling dirty, a mirror is a tool at the handwashing station subconsciously reminding students to wash their hands.

2.5.5. Social

Hygiene clubs and teacher trainings were the most frequently mentioned social factors. Teachers mentioned hygiene clubs and teacher trainings as facilitators at 58% (seven teachers) and 50% (six teachers) prospectively while students mentioned hygiene clubs at 21% (five student pairs), but did not mention teacher trainings. Despite students perceiving hygiene clubs as effective training for its members, there was a lack of awareness among students outside the club about its existence. This is shown through the six (25%) student pairs that perceived them as a barrier because of the lack of awareness in their school. Teachers emphasized that the training enhanced their understanding of handwashing, drinking water, and other health-related topics. They reported that this knowledge empowered them to confidently teach their students. For example:

"Thus, I have gained a lot of knowledge during the training which is a huge input for me; because we were washing with only water; but now, when we wash with soap, the things that come off our hands, even the water we drink, the foods we eat, could cause different health problems. Due to this knowledge, I have had good change in my life.

In alignment with other school behavior change studies (Azizan et al., 2021; Pu et al., 2022) our findings suggest that well-trained teachers impact the perceived success of the handwashing initiative. Additionally, it underscores the importance of teachers serving as influencers in the executive factor, as they play a crucial role in spreading WASH knowledge to their students. The impact of Splash's hygiene club varied among schools, showing inconsistency in its effectiveness. This finding may suggest that hygiene clubs are less crucial than teachers in promoting school-wide handwashing, which is contrary to studies done by (Berhanu et al., 2022; Beya et al., 2022). While hygiene-club students are perceived to be engaged in initiatives promoting handwashing, the level of activity and visibility of these hygiene clubs varies greatly among schools. This variance may stem from the limited time available to focal teachers in some schools to dedicate to hygiene club activities, with their sustainability often relying heavily on the involvement of a single focal teacher. To address this issue, we would recommend implementing a system that does not heavily rely on a singular teacher. This arrangement could involve hiring additional staff members to support hygiene club activities or dispersing responsibilities among multiple teachers to ensure sustainability and effectiveness across schools.

2.5.6. Scheduling and routine

Time within a schedule emerged as a frequently discussed factor that was perceived as a barrier to handwashing. Overcrowded handwashing stations and limited time to wash hands before activities were common themes in the data. Fifty percent of the teachers mentioned that some students are compelled to either use outdated handwashing infrastructure or forgo handwashing altogether due to overcrowding at Splash stations. One non-focal teacher estimated that half of her school's population uses the older facilities to avoid the congestion at the new handwashing stations. Students also mentioned instances where their peers skipped handwashing before meals, as they rushed to get their lunch and were reluctant to wait in line at the crowded handwashing stations. A 4th-grade boy explained:

"Sometimes there is crowding at the handwashing station so that students might leave without washing."

Overcrowded facilities can result from a lack of physical infrastructure facilities and proper scheduling and time. Additionally, water intermittency further exacerbates the challenge of maintaining handwashing routines in schools. In environments where water availability fluctuates unpredictably, students and teachers may struggle to integrate handwashing into their daily schedules. Without consistent access to water, it becomes difficult to establish regular handwashing practices (Namara et al., 2020). We encourage the consideration of time constraints in school WASH behavior change programming. Schools may need to consider establishing routines and schedules that prioritize handwashing times. Furthermore, future research should explore the impact of water intermittency on handwashing behaviors to underscore the importance of routine in handwashing initiatives.

2.6. CONCLUSIONS

Our qualitative study examined the determinants of school handwashing behavior using the BCD framework. We found that most students understood the importance of handwashing with soap, some saying this knowledge improved through hygiene lessons taught at school. We also observed motivational and social factors, especially teacher trainings, were perceived to facilitate handwashing. Discussion surrounding the hardware components emphasizes the importance of improvements in school infrastructure, such as water storage facilities and innovative handwashing stations. These enhancements address common challenges like intermittent water supply and ensure consistent access to drinking water and water for handwashing. The data suggest that infrastructure improvements are perceived to increase access to hygiene practices. It is worth noting that the school context amplifies the importance of these improvements. Challenges related to physical and social aspects were also identified, including soap availability, overcrowding at handwashing stations, and irregular water supply. Soap quality and quantity and water availability were among the most common perceived barriers, highlighting the importance of addressing hardware-related issues for improved handwashing.

In conclusion, our qualitative exploration provides valuable insights into the multifaceted nature of school handwashing behavior. Our study underscores the importance of comprehensive strategies that address both knowledge gaps and infrastructural deficiencies. Moving forward, interventions aimed at promoting handwashing in schools must integrate educational initiatives with tangible improvements in infrastructure and scheduled handwashing time to ensure sustained behavioral change and enhance overall hygiene outcomes.

2.7. ASSOCIATED CONTENT

Complete interview guide (Table S1).

2.8. ACKNOLEDGMENTS

As authors, our workplaces are on the ancestral homelands of the Coast Salish, the land which touches the shared waters of all tribes and bands within the Duwamish, Puyallup, Suquamish, Tulalip and Muckleshoot nations. We would like to thank the busy teachers and students who we interviewed who made time to share their perspectives. We would like to thank Splash International and their private donors for funding and supporting the planning, data collection, and data analysis done in this project. We would also like to thank Dr. Leigh Hamlet for her support on the project and Deep Dive for enumerating and translating interviews.

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2.9.1. Funding

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2.9.2. Conflicts of interests

Rachel Pearson's work on this paper was funded by Splash International and Megan Williams works for Splash International. The rest of the authors have no conflicts of interest.

Chapter 3: WATER SOURCE AND SYSTEM CHOICE IN RURAL ALASKAN COMMUNITIES: PERSPECTIVES FROM STATE- AND REGIONAL PROFESSIONALS

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3.1. ABSTRACT

Despite an abundance of water, the unique context in rural Alaska makes providing access to in-home water services to be challenging. Inadequate access to treated water can be a danger to communities' health. This study aims to understand how officials and community members choose water sources and systems in rural areas of Alaska. Using data from interviews with 21 individuals working within the water industry in rural Alaska, we show factors that lead to communities choosing to use surface water or groundwater infrastructure systems for their drinking water. Results showed groundwater is often easier to treat, maintain, and comply with regulations. Still, natural factors like geography and climate change impact the availability of water sources, leading to a lack of choice in some regions.

3.2. INTRODUCTION

While piped water has come to be an expectation in the U.S., thousands of homes in rural Alaska do not have access to water services (L. Eichelberger, 2014). Alaska contains more than 30 communities where at least 45% of the homes are not served by piped, septic tank and well, or covered haul systems, making Alaska the state with the highest proportion of homes without water and sewer services in the United States (Alaska Department of Environmental Conservation Division of Water, 2017). Rural Alaska faces a myriad of challenges when providing safe drinking water, including the remoteness of the communities, economic constraints, climate change, and harsh climate (Cozzetto et al., 2014; Hickel et al., 2018a; Lucas et al., 2021; Sohns et al., 2021a). Many of these impacts disproportionally affect Alaskan Native communities (Brubaker et al., 2011; Cozzetto et al., 2014; McOliver et al., 2015).

Understanding which water source and system works best for each community is complicated with complex climate, geographic isolation, and other challenging factors. Many rural and geographically isolated communities in Alaska depend on groundwater as their primary drinking water source due to its reduced likelihood of freezing during the winter and its fewer regulatory treatment requirements than surface water (Health Resources and Services Administration, 2002). However, groundwater can contain elements like arsenic, manganese, and iron (i.e., geogenic elements), which naturally exist in soils and aquifer sediments and can be excreted into the surrounding water under the right chemical conditions (Erickson et al., 2019). Manganese and iron give water an unpleasant taste, odor, and color, and arsenic is carcinogenic, posing a risk to human health. Although groundwater can contain geogenic elements, many rural communities use groundwater wells for drinking water because it is less likely to be affected by freezing temperatures than surface water (Erickson et al., 2019). Surface water has more regulations than groundwater, but it is the only option in some communities with little groundwater.

Researchers have begun to address the challenges of providing clean drinking water to rural Alaska. Studies have found associations between proportions of home water services and rates of raspatory, skin, and gastrointestinal illnesses (Gessner, 2008; Hennessy et al., 2008; T. K. Thomas, Ritter, et al., 2016). For example, Hennessy et al. found significantly higher hospitalizations in households without water and wastewater services, providing further evidence of the correlation between water service and community health.

Other researchers have used a systems approach to analyze drinking water infrastructure in rural Alaskan communities. A systems approach requires an evaluation of social, financial, institutional, environmental, and technological factors and an understanding that multiple factors may influence the success of drinking water infrastructure. Limited studies explain how these factors interact in rural Alaskan drinking water projects (L. P. Eichelberger, 2010; Penn et al., 2017; Sohns et al., 2021a; Thelemaque et al., 2022a). Some studies have used systems approaches and the resiliency framework to explain the factors affecting these projects (Spearing, Mehendale, et al., 2022; Thelemaque et al., 2022a). For instance, Thelemaque et al. (2022) identified themes contributing to the success and failure of these initiatives, while Spearing et al. (2022) highlighted how certain factors have led to increasing numbers of unserved communities and system failures. Both studies emphasized the significant role of social factors and underscored climate change as a critical environmental challenge exacerbating these issues. Additionally, Sohns et al. (2021) used causal loop modeling to explore how stakeholders perceive water vulnerability, revealing that environmental challenges constrain the economy, affecting water access and highlighting the need for more funding to maintain and operate systems. Although these studies have continued to address drinking water in rural Alaska, there have been calls for more systems approaches to WASH infrastructure projects, especially studies that evaluate interactions or relationships between factors in a system (Valcourt et al., 2020).

Few researchers have examined water infrastructure systems in rural Alaska. Eichelberg et al. conducted a case study to assess whether decentralized water and sanitation systems could provide adequate water supply. Their findings showed that in-home water systems when supplemented by centralized facilities for showers, laundry, and hygiene, could meet water quantity goals. Another study compared centralized water systems with traditional water source use in two rural Alaskan communities, concluding that environmental factors and cultural practices influence water system choices (Marino et al., 2009). Both studies emphasized that adopting a community-based approach to system selection leads to better outcomes.

Due to Alaska's unique climate and geographic location, further research is needed in this region. While previous studies have examined the challenges of delivering drinking water to rural Alaska, the factors influencing water source selection remain underexplored. This study aims to fill that gap by analyzing the perspectives of 21 Alaskan water officials to understand better how and why communities choose between surface water, groundwater, or traditional water sources. In this paper, surface water is defined as any body of water on the Earth's surface, including saltwater from the ocean and freshwater from rivers, streams, and lakes. Groundwater refers to water found underground in saturated zones. A traditional water source involves individuals collecting water, snow, or ice and treating it at home. By exploring the advantages and disadvantages of each option, this research will offer insights to guide future projects and improve decision-making. Additionally, understanding the challenges associated with each water source will help develop strategies for enhancing system sustainability. This study will deepen understanding of the factors influencing water source choice for drinking water and provide practical solutions for addressing related issues.

3.3. MATERIALS AND METHODS

3.3.1. Data sources and collection

Twenty-four semi-structured interviews with 21 individuals working with water services in rural Alaska were conducted from October 27, 2020, to May 20, 2022. The project and interview questions received institutional review board (IRB) approval from the University of Washington. Interviewees were chosen through convenience and snowball sampling and continued until theoretical saturation of the information was met (Parker et al., 2019). Interviews were recorded with consent over video conferencing and phone calls. Most interviews were approximately 60 minutes long, were digitally transcribed, and coded with NVivo software. Additional information, including demographics, about the interviewees are in Tables 4 and 5.

We interviewed the first 21 individuals to understand their perspectives on water projects in rural Alaska. The initial interview questions were designed to facilitate conversation about successes, failures, and factors of drinking water projects in rural Alaska. A sample of interview questions is provided as a reference:

1. What is your experience with drinking water in rural Alaska?
2. How would you define success for water supply projects in the rural Alaska context?
3. What factors matter for rural Alaska drinking water supply projects (or systems)?
4. How is climate change impacting water resources and water supply systems?
5. What do people outside the rural Alaska context not understand about groundwater supply projects in rural Alaska communities?
6. From your perspective, are there any equity or inclusion issues impacting rural Alaska water supply projects or systems?

After the initial analysis, we interviewed four individuals again to go into more depth about choosing a water source. A sample of interview questions is provided as a reference:

1. Can you describe the difficulties remote communities face in adhering to drinking water regulations?
2. In the communities you work with or are familiar with, what drives the usage of centralized or decentralized water infrastructure?
3. In the communities you work with, are people choosing their traditional water source over water from a treated system?
4. If yes, which systems are they choosing traditional sources over?
5. What type of contamination (e.g., fecal, water-borne diseases) is usually seen in untreated/traditional water in rural communities?

Table 4. Occupation information of interviewees

Number of Interviewees	*Current Roles**	*Combined Years of Applicable Experience*
1	Geophysicist	25
2	Water pump service provider	92
2	Researcher in engineering, Alaskan rural water, or Arctic research	21
7	Engineer/project manager/construction manager	176
9	Director/program manager for environmental health, drinking water, facilities, operator certification, and/or remote maintenance	147

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

Table 5. Demographic information of interviewees

Gender		
Category	*Number*	*Percentage*
Woman	2	10%
Man	12	55%
Preferred not to Respond	7	35%
Race		
Category	*Number*	*Percentage*
White (including Middle Eastern)	11	55%
Asian	1	5%
American Indian or Alaskan Native	2	5%
Other	1	5%
Preferred not to Respond	6	30%

3.3.2. Qualitative analysis

The data analysis for this study was done using NVivo Software to code the interview transcripts qualitatively. The analysis consisted of a hybrid, deductive content analysis with additional inductive coding (Azungah, 2018; Kallio et al., 2016; Proudfoot, 2023; Spearing, Bakchan, et al., 2022). While the research team used a list of questions to facilitate interviews, a predetermined list of coded categories was not generated to maintain impartiality to all study outcomes. Instead, we allowed themes in the data to emerge throughout the analysis (Saldana & Omasta, 2016; D. Thomas, 2006).

First, we analyzed the semi-structured interviews using deductive content analysis. To understand how technical water officials and community members make water source choices, we coded the interviews into two categories: groundwater and surface water. After coding the data into water source categories, the researchers used inductive content analysis to find new and emergent themes (Spearing, Bakchan, et al., 2022; D. Thomas, 2006). Inductive coding was used to categorize and describe the deductive content analysis further. Child codes emerged as themes emerged for the three water sources. One researcher did the coding, and a second researcher helped with the intercoder reliability check based on one, or 5%, of the excerpts. The intercoder reliability test helps reduce bias and identify code weaknesses (De Vries et al., 2008). The coding was further validated by a kappa value of 0.754, which is considered satisfactory in qualitative research (De Vries et al., 2008).

In addition to coding factors that lead to the selection of different water sources, we also coded the relationships between the factors and their water source. Once these relationships were coded, cognitive systems maps were created to understand how the factors related to each water source (Meadows, 2009; Rinaldi et al., 2001). One cognitive map was made to reflect how groundwater and surface water factors influence water officials' water treatment choices to understand how and why water officials choose water sources and technologies. The factors from the cognitive maps are shown in a table in relation to surface water and groundwater. Frequency tables were made for each coded category to show the category's prevalence from the interviewees' perspective. Frequency does not necessarily indicate importance; a category's discussion frequency may reflect the interviewee's willingness or ability to discuss the subject.

3.4. LIMITATIONS

The interviews continued until the theoretical saturation of ideas was met, and the results of this study reflect the interviews we conducted, which showed a limited understanding of drinking water sources in Alaska. The analysis involved thematic coding to target important ideas and themes discussed in the interviews. Because the interviewees' knowledge and awareness of the themes varied, the frequency of coded themes and ideas may not directly represent the significance of the theme. Furthermore, there may be variations in drinking water projects in other communities and regions.

The interviewees for this study are individuals who manage drinking water projects in rural Alaska and often do not reside in the communities in which they work. The results of this study should be interpreted as knowledge and ideas from individuals in management and not those who are community members directly affected by these projects. This dataset will be supplemented during the second phase of this study, which will center on direct community engagement and include in-person community outreach and engagement to include community voices in this study. Nevertheless, we believe this initial study provides knowledge and insight into important ideas from Alaskan water officials.

3.5. RESULTS

Table 6 reports the themes identified through the qualitative analysis for factors that are perceived to contribute to the choice of water source for drinking water projects. The table illustrates each theme's relative frequencies and number of coded excerpts.

Table 6. Frequency table of water source choice, preference, or factors

	Water source			
Code	Groundwater		Surface water	
	Number of interviewees	Number of responses (relative frequency)	Number of interviewees	Number of responses (relative frequency)
Factors	20	107 (100%)	20	58 (100%)
Availability	5	6 (6%)	6	7 (12%)
Chemical content	14	25 (23%)	5	5 (9%)
Financial considerations	5	8 (7%)	2	2 (3%)
Geographic location	2	3 (3%)	3	3 (5%)
Groundwater under the influence of surface water	4	10 (9%)	0	0 (0%)
Health	0	0 (0%)	0	0 (0%)
Preference	10	14 (13%)	6	8 (14%)
Quality	4	10 (9%)	9	14 (24%)
Regulations	2	4 (4%)	1	1 (2%)
Seasonal influences	2	2 (2%)	2	3 (5%)
Taste	2	2 (2%)	2	4 (7%)
Technical system considerations	13	23 (21%)	7	11 (19%)

3.5.1. Technical System Considerations

Technical system aspects of water system infrastructure emerged as a central topic, discussed by 70% of interviewees. There was a notable inclination towards decentralized systems, particularly groundwater wells, for water treatment and delivery. Interviewees favored these systems due to their perceived simplicity, cost-effectiveness, and lower operational burden. One interviewee expressed their preference for groundwater wells, highlighting their consistency in water quality and the relatively straightforward treatment processes, "*I like them (wells) a lot better than surface water generally speaking, because it's more consistent water for treatment. It usually requires a less complex treatment system. And so it's less expensive to operate, and then the operator doesn't require as higher as high level of certification difficult sometimes to get water plant operators who stick around long enough to get a certification level the time that meet the level of the plant permission to run plants. Just makes the system a little bit more sustainable I think when they're using well water."*

Additionally, 35% of respondents discussed the technical systems considerations related to surface water utilization. A recurring theme was the difficulty in training and retaining operators for treatment plants, with a staggering 64% turnover rate reported in 2022 (Alaska Department of Environmental Conservation, 2022). According to the interviews, turnover is attributed mainly to the high stress and low remuneration associated with the job. Moreover, the complexity of treatment plants for surface water, compounded by regulatory requirements and the dynamic nature of surface water, presents ongoing challenges in maintenance and operation.

Moreover, 65% of interviewees cited challenges associated with the technical systems of wells. One major difficulty of these systems is drilling operations for groundwater wells in remote Alaskan regions, which are made difficult by permafrost and unpredictable subsurface conditions. The logistical complexities of transporting drill rigs to remote areas and uncertainties regarding subsurface composition and chemical content present significant obstacles to groundwater extraction and utilization. As one interviewee noted,

"*They may drill a hole and the ground is dry, and then they may go 15 feet another direction and it will be flowing and so that glaciated nature of the subsurface and the unexpected of what is there is quite a challenge."*

3.5.2. Water Quality

Respondents highlighted various challenges associated with water quality, ranging from geogenic contamination to variability in quality. Approximately 70% of respondents noted the presence of chemicals such as mercury, iron, and manganese in groundwater, especially in areas near mining activities. Consequently, many communities grappling with high concentrations of contaminants have shifted to surface water sources to address operational challenges. For instance, one respondent mentioned,

"*They had groundwater that was very high in arsenic and ended up failing cartridge removal system and have since gone to surface water source largely in part because the operational challenges they've promoted*."

45% of interviewees also mentioned difficulties in surface water quality. Surface water quality exhibits significant variability, particularly during extreme weather events such as droughts and floods. These events can compromise water quality, necessitating additional treatment measures and storage solutions to maintain safe drinking water standards.

3.5.3. Surface Water Infiltrating Groundwater

25% of the interviewees expressed concerns regarding surface water infiltration into groundwater, particularly in regions of Alaska where this phenomenon is more prevalent. For instance, in the southeast region, groundwater utilization is nearly impossible due to its location on ocean bedrock. Furthermore, interviewees noted the exacerbating effects of climate change on groundwater infiltration. Surface water infiltrates groundwater within permafrost regions through open taliks, which act as conduits connecting the ground surface to the unfrozen material below, allowing for the exchange of water between surface and subsurface reservoirs (Haeberli et al., 1993). When surface water infiltrates groundwater, treatment protocols must adhere to surface water regulations, which accommodate a wider range of water quality variations. One interviewee discussed issues of surface water infiltrating groundwater,

"*A lot of our subsurface in a lot of places is peat for a long way and peat can be quite frozen in many of these instances and if, as it thaws and creates new pathways to get surface water into groundwater. I think many of our groundwater systems are going to be more and more affected by groundwater under the influence of surface water*."

3.5.4. Geographical Location

The geographical location plays a crucial role in determining the available water sources. In regions like the southeast coast of Alaska, groundwater utilization faces severe limitations due to the presence of ocean bedrock, restricting groundwater availability. Conversely, in northern regions where rivers and streams freeze most of the year, accessing surface water becomes challenging, affecting drinking water availability. Additionally, in locations situated atop ocean bedrock, groundwater may be susceptible to infiltration by surface water, thus limiting groundwater options. In contrast, groundwater may emerge as the preferred option for drinking water provision in areas with frozen rivers and streams.

3.5.5. Financial Considerations

Both well-based and surface water systems entail specific financial considerations. The logistical challenges of transporting drill rigs to remote areas and maintaining treatment plants in isolated communities impose substantial financial burdens for wells. Interviewees also highlighted the expenses associated with piping water from centralized surface water systems, particularly during seasons requiring regular pumping to prevent pipe freezing, which can incur significant costs. Treatment of surface water is often energy-intensive, contributing further to operational expenses. Additionally, storing water, especially during shoulder seasons, adds to the overall operational costs of water provision systems.

3.5.6. Regulations

Respondents familiar with the utilization of drinking water regulations in Alaska observed that compliance with groundwater regulations proved more manageable than those pertaining to surface water. Surface water presents challenges due to the need to account for fluctuating turbidity levels. Sampling frequency for surface water varies based on population size and facility type, with some instances requiring continuous sampling (Alaska Department of Environmental Conservation Division of Water, 2024). Consequently, treatment protocols vary from sample to sample. In contrast, groundwater treatment necessitates less frequent sample testing. It exhibits less variability in treatment requirements due to its comparatively stable chemical composition (Alaska Department of Environmental Conservation Division of Water, 2024). Moreover, specific groundwater sources may not require treatment owing to their inherent purity (Alaska Department of Environmental Conservation Division of Water, 2024). Consequently, opting for groundwater as a drinking water source is often the more feasible choice for rural communities.

3.5.7. Seasonal Effects

Seasonal variations significantly influence the availability and quality of surface water. Partial ice melt during shoulder seasons, such as fall and spring, often renders surface water sources inaccessible, posing challenges to water provision. During these periods, water storage becomes essential, increasing costs associated with maintaining heated tanks. Additionally, extreme weather events like droughts and floods exacerbate surface water challenges, impacting availability and quality. For instance, one interviewee highlighted the difficulties faced during cold seasons when surface water freezes for a significant part of the year. Communities are compelled to store water throughout the year in large tanks, resulting in subsidence and shifting due to the weight of stored water. This underscores the logistical and financial challenges of seasonal surface water availability and quality variations.

Alaska has also suffered from extreme weather events like droughts and floods. A respondent described how, during a drought, several communities' reservoirs went dry and how, during a rainstorm, a significant mudslide affected the quality of surface water. An interviewee described the problems faced during cold seasons,

"*The surface water freezes for a significant part of the year, so they can only make water one year a year and so they have to make all of their water and store it in big giant storage tanks, and you can imagine the subsidence and the shifting of the storage tanks because the water is extremely heavy."*

3.5.8. Taste and Community Preference

The interviewees perceived that some community members preferred traditional water sources over treated water due to taste preferences. The dislike of the chlorine taste or appearance of piped water systems often influences the choice of traditional water sources, such as snow/ice melt or rain catchment systems.

While many communities in rural Alaska have treated water systems, some people in this region choose to drink their traditional water sources, such as ice/snow melt, boiling water, and rain catchment systems. The interviewees discussed why some people in rural Alaska choose their traditional drinking water over a treated water source. Traditional drinking water sources include snow/ice melt, rain catchment systems, and gathering water from a surface water source like a river or creek. According to the interviewees, the most common reason people chose to drink from a traditional water source was the dislike of the chlorine taste or appearance of piped water systems. Other community members use their traditional water source because it is cultural or traditional. For example, one respondent explained,

"*It's again ingrained in culture to do some rainwater catchment and because it's here and I don't have to even walk across the city, so people use rainwater. Sometimes people go cut ice out of rivers, again, it's a traditional experience and activity."*

While communities' cultural preferences are widespread in rural Alaska, water officials noticed a trend in communities that have had access to treated water systems for longer periods are less likely to use traditional water sources. One water official explains,

"It's *a function of time a lot of the communities that recently got piped water and sewer are using traditional water sources more than the communities that have had piped water for years. They don't use traditional water sources as much."*

Some health concerns exist in using traditional water sources instead of treated water. One interviewee pointed out,

"*There is no way a snow catchment will ever be able to collect enough water to provide the per capita water use that you're going to get with having pipes in your house*."

Traditional water sources are often insufficient in quantity, and their quality can pose health risks. Several respondents noted that if individuals return to using these untreated sources after implementing a water treatment system, they view it as a project failure, as it indicates a failure to protect public health.

3.5.9. Climate Change Impacts

Climate change inherently impacts technical officials and community members' choices of drinking water. Things like permafrost melt and seasonal effects impact the availability and quality of water sources. One technical official explained climate change's impacts on groundwater, "*Climate change is a big deal when you talk about melting permafrost because you might have had groundwater well at depth and the permafrost may have been present but shallow enough to still support groundwater wells that permafrost then melts. I can't imagine it not impacting the groundwater in some way.*"

The interviewee discussed how difficult it can be to predict the impacts of melting permafrost on a groundwater well, but the impacts will be there on either the quality of the water or the system's structure. Water quality can cause problems in meeting regulatory requirements when climate change causes surface water to leak into the groundwater, creating difficulties for built technical systems. Climate change also has a cascading impact on community members' drinking water choices. When water quality is threatened, and the acceptability of a water system is reduced, people are more likely to use their traditional water sources.

Surface water systems can also be impacted by climate change. Respondents discussed how systems need to be built in a way that is resilient to permafrost and or weather changes. Climate change can impact surface water quality, making it more difficult to predict and treat. Periods of heavy rain or drought impact the turbulence of surface water and its availability.

3.6. DISCUSSION

3.6.1. Factors leading to water source choice

The results underscore the multifaceted considerations influencing the choice of drinking water sources in rural Alaska, ranging from technical and financial challenges to regulatory constraints and geographical limitations. These findings provide valuable insights into the complexities of water resource management in remote regions, highlighting the need for tailored solutions to address the diverse needs and challenges faced by communities reliant on groundwater and surface water sources.

Figure 5 shows the overall preference for water source choice by water officials. Each arrow points towards the source that is easier or better to use according to each factor.

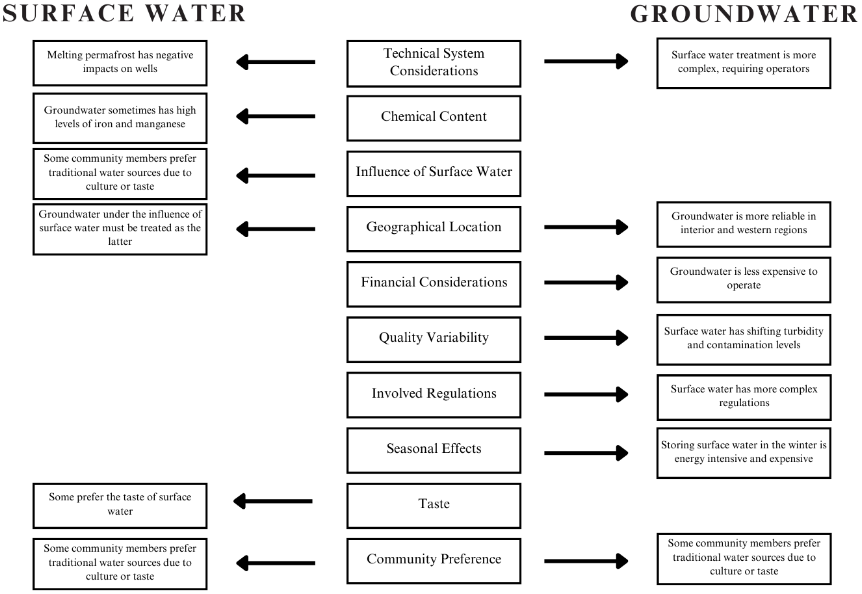

Figure 5. How water officials perceive social, environmental, and built factors to influence their decision on water sources for drinking water projects

Despite the inherent challenges, half of the respondents specifically preferred groundwater over surface water due to its relative stability and lower treatment requirements. In contrast, only 19% of respondents explicitly preferred surface water. This sentiment reflects a broader inclination towards groundwater as a more sustainable and dependable drinking water source in rural communities, notwithstanding the technical and regulatory complexities associated with its extraction and treatment. Factors like technical system considerations, geographical location, financial considerations, quality variability, regulations, and seasonal effects make using groundwater the preferred choice. On the other hand, technical system considerations, chemical content, the influence of surface water on groundwater, location, and taste can make surface water preferred in some instances.

3.6.2. Drinking Water Methods

The results show that when available, groundwater is often the best choice for communities because of the cost, ease of system use, less complicated regulations, and less quality variability. Groundwater is not always available due to geographical, environmental, or culturally specific constraints. With climate change increasing these constraints, we look to solutions to some of the barriers that arise to the success of surface water systems. In this section, we discuss potential solutions to issues with surface water systems. We recognize that there may be different viewpoints on solving these problems and different constraints for different communities. We present four possible solutions and how they can be applied to surface water systems in rural Alaskan communities. We summarize the solutions in Table 7.

Table 7. Solutions for issues in using surface water in drinking water infrastructure

	Solution 1	**Solution 2**	**Solution 3**	**Solution 4**
Example Changes:	Water Quality Regulation Changes	Increase or Reallocate Funds	Increase Operation and Maintenance Support	Technical Infrastructure Improvements
Possible presuppositions: How might a community define the nature of the problem?	Regulations make surface water difficult to treat, leading to complicated infrastructure systems	There are not enough funds or the funds are being allocated to building infrastructure instead of operation and maintenance or water costs	Challenges in hiring, training, and retaining operators due to community size and location	Current infrastructure does not fit the community's needs
Example solution:	Changing water quality regulations	Increase money for operation and maintenance and subsidies for water costs	Supplying communities with people to run the plants or ongoing training and support for operators	Incorporating renewable energy decreases energy costs
Objectives: What are the main goals of the proposed solution?	To increase access to higher quantities of water and make infrastructure more simple	To allow more community members to afford water and make the infrastructure more sustainable	To increase the sustainability of water infrastructure and decrease operator turnover	To increase the efficiency and sustainability of infrastructure and decrease costs
Pros: Why might a community choose this solution?	An increase in water quantity has positive health outcomes, and simplifying treatment may allow for more successful infrastructure	It increases sustainability of the infrastructure and decreases the cost of water	Increases the sustainability of the infrastructure	Increases sustainability of the infrastructure, decreases the cost of water, and/or provides locally specific solutions
Cons: Why might a community not choose this solution?	A decrease in water quality may impact the health of community members	It does not address simplifying treatment or	It does not address simplifying treatment or the cost of water	There may still be issues with operators or costs, and the perfect

		operator difficulties		solution may not exist yet

3.6.3. Solution 1: Regulation changes

Regions close to the ocean or with groundwater under the direct influence of surface water are forced to use surface water systems (West Virginia Department of Health, 2024). The Environmental Protection Agency screens wells to understand the extent to which groundwater may be under the direct influence of surface water, deeming it needs to be treated using surface water regulations (US EPA, 2015a, 2024). Regions near the ocean or with groundwater under the direct influence of surface water are forced to use surface water treatment regulations (West Virginia Department of Health, 2024). The Environmental Protection Agency does screenings of wells to understand the extent to which groundwater may be under the direct influence of surface water, deeming it needed to be treated using surface water regulations (US EPA, 2015a, 2024).

Due to these complex regulations surrounding its treatment, surface water is generally more difficult and costly to manage. If treatment challenges were less demanding, surface water could present a more viable option for rural communities, as it is easier to transport than groundwater. This raises the critical question of whether surface water quality in rural Alaska indeed poses a significant health concern. If regulations were adjusted to simplify the treatment process, there is potential for improved success in surface water treatment facilities. Such regulatory changes could enhance water quantity, even if it means balancing that with water quality considerations. While safe drinking water is crucial, water also serves other vital purposes, including cooking, bathing, laundry, and sanitation. These uses are directly linked to overall public health. The current regulatory framework operates on an "all or nothing" basis, meaning that if a community fails to meet strict water quality standards, it cannot receive piped water (T. K. Thomas, Ritter, et al., 2016). Some researchers argue that prioritizing water quantity over strict quality control may yield better outcomes for rural households (Cairncross, 1987; T. K. Thomas, Ritter, et al., 2016). By increasing the available water supply, households could meet essential daily needs—such as washing, cooking, and hygiene—without constant concern over water conservation. In light of this, this option recommends that regulators consider a shift in focus. By prioritizing water quantity and exploring innovative solutions for piped water systems, policymakers may better serve the needs of rural Alaskan communities while still safeguarding public health.

3.6.4. Solution 2: Increase or reallocate funds

Insufficient funding for rural Alaskan drinking water projects has been highlighted in numerous studies (ASCE, 2017; Penn et al., 2017; Sohns et al., 2021b; Spearing, Mehendale, et al., 2022; Thelemaque et al., 2022a). Tribal nations across the U.S. often face funding challenges and must rely heavily on federal grant programs (Jones et al., 2007). This solution aims to increase financial support for rural Alaskan communities to address their specific drinking water infrastructure needs. Research indicates that both community members and water professionals have expressed concerns about the distribution of funds (Brown et al., 2022; Jones et al., 2007; Spearing, Mehendale, et al., 2022; Thelemaque et al., 2022a). This solution emphasizes not only the total amount of funding but also its allocation according to the unique needs of each community. Studies have identified that funding for operation and maintenance and water cost subsidies are notably lacking (Spearing, Mehendale, et al., 2022; Thelemaque et al., 2022a).

3.6.5. Solution 3: Increase operation and maintenance support

Challenges in operating and maintaining systems were a typical response in our data, aligning with findings from other studies (Spearing, Mehendale, et al., 2022). Both our research and numerous other studies have identified challenges in hiring and retaining certified operators for the infrastructure (Hickel et al., 2018b; Sohns et al., 2021b; Spearing, Mehendale, et al., 2022; Thelemaque et al., 2022a). These issues stem from limited labor availability in small communities, challenging certification processes, low wages, and the high-stress nature of the job. This solution provides the necessary resources, training, and funding to operate and maintain water treatment systems effectively. Potential strategies include providing the personnel to staff water treatment plants, offering funding to maintain systems, and providing proper training programs and pay to reduce turnover and ensure systems are managed effectively.

3.6.6. Solution 4: Technical infrastructure improvements

Our study found that the challenges of treating surface water and the complexity of the associated systems were significant factors in the decision to use groundwater. Beyond the difficulties in surface water treatment, harsh weather conditions and remoteness make it difficult and costly to design, build, and maintain drinking water infrastructure (Cozzetto et al., 2014; Hickel et al., 2018b; Melvin et al., 2016; Penn et al., 2017; Sohns et al., 2021b; T. K. Thomas, Hickel, et al., 2016). By focusing solutions on technical infrastructure improvements, we could potentially address issues such as cost and operational challenges.

There are both established and emerging solutions to these technical problems. One possible approach is integrating automation into water systems, which could reduce the reliance on human operators—an element that has repeatedly posed challenges in various communities. Although automation has been increasingly adopted in urban water systems (Yuan et al., 2019), rural Alaskan communities' unique climate and context may complicate its implementation. Another option is incorporating renewable energy into the system, which could reduce customer costs since energy is costly in the Arctic. Systems should be tailored to meet the specific needs of each community, similar to the approach in Eichelberger et al.'s (2020) case study, which combined in-home water treatment for drinking with centralized water for hygiene purposes. These customized solutions could help address rural communities' environmental and social barriers.

3.6.7. Future Work

Water officials frequently highlighted traditional water sources such as snowmelt, rain catchment systems, and river water collection. While their insights into community preferences are valuable, future research should involve direct interviews with community members to understand their preferences better firsthand. Ongoing research is also needed to advance technologies suited to the unique conditions of rural Alaska. This includes developing systems that are resilient to climate change, affordable, and simple to operate.

3.7. CONCLUSION

Providing access to treated drinking water in rural Alaska is uniquely challenging due to a combination of natural, built, and social factors exacerbated by climate change. This increasing complexity can lead to adverse health outcomes from a lack of access to safe drinking water. This study examined the nuanced considerations that influence water source selection within these communities. Through 21 semi-structured interviews with engineers, project managers, service providers, operation managers, and researchers involved in water management, we identified key themes and factors affecting the choice of water sources. Our findings reveal a notable preference for groundwater as a source; however, groundwater is not always viable. We presented four solutions for situations where a community must use surface water in their drinking water infrastructure: regulation changes, funding, operation and maintenance support, and technical system advances. These options integrate locally specific needs for more sustainable drinking water infrastructure systems.

3.8. CREDIT AUTHOR STATEMENT

Rachel Pearson: Writing – Original Draft, Writing – Review & Editing, Formal Analysis. **Nathalie Thelemaque:** Formal analysis. **Laura Eichelberger:** Conceptualization, Resources, Formal analysis, Writing – Review & Editing. **Rebecca B. Neumann:** Conceptualization, Investigation, Writing – Review & Editing. **Jessica Kaminsky:** Conceptualization, Investigation, Writing – Review & Editing.

3.9. ACKNOWLEDGEMENTS

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CHAPTER 4: THE POTENTIAL OF RENEWABLES FOR MEETING THE ELECTRICAL DEMANDS OF WATER TREATMENT AND DELIVERY IN RURAL ALASKA

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4.1. ABSTRACT

This study explores the integration of solar power into water treatment systems in rural Alaska, addressing gaps in understanding how renewable energy can be effectively utilized in these distinct environments. We analyzed energy audit data from 13 rural communities, developing 24-hour and annual electrical load profiles. We then assessed the feasibility of incorporating solar energy by using HOMER software and comparing the results across different regions, system types, and water sources. The findings show that while solar energy can reduce the cost of energy for all system types and regions, it is not sufficient to meet the full energy demands of these water infrastructure systems without the use of electrical grids or storage batters. This is due to the misalignment between peak solar production and system load profiles, with seasonal peaks occurring in winter to prevent freezing, and daily peaks in the afternoon and evening, which fall outside solar generation hours. The study offers valuable insights into load profiles that can inform energy planning for rural Arctic water utilities and has broader implications for renewable energy integration in similar remote regions.

4.2. INTRODUCTION

Water treatment plants represent a significant opportunity to enhance energy demand management, particularly given their role as large consumers of energy. Approximately 7% of global electricity consumption is attributed to drinking water and wastewater treatment (Chini & Stillwell, 2018; Plappally, 2013). Energy utilities have long been incentivizing customers, including water treatment plants, to manage their energy use during periods of peak demand or grid instability, thus reducing the need for dispatchable resources and enhancing grid reliability (Palensky & Dietrich, 2011). Additionally, by shifting energy consumption to times when renewable energy generation is abundant, water treatment plants can help increase renewable energy integration and contribute to reducing greenhouse gas emissions (Paterakis et al., 2017). Facilities capable of shifting their energy loads are well-positioned to act as demand resources that support a more sustainable energy grid (Wimmler et al., 2017).

Energy consumption at water treatment plants is strongly influenced by pollutant loading, with a positive correlation between the two (Simon-Várhelyi et al., 2020). Both energy demand and loading exhibit seasonal and diurnal variations, with higher pollutant loads generally occurring in the summer and daily peaks observed in the late morning and early evening (Thompson et al., 2008). Energy expenses in remote Alaskan communities are approximately ten times higher than the U.S. national average, driven by the extreme cold temperatures and the logistical challenges associated with delivering energy and water services in these isolated regions (Aggarwal, 2022). While many water treatment plant loads are higher in the summer, Alaska's cold winters cause higher loads then other regions. Alaskan water distribution systems often require substantial energy for heating and continuous water recirculation to prevent freezing during the harsh winters, adding to the already high operational costs (Wu et al., 2018).

The energy-water nexus in rural Alaskan communities has attracted research, exploring the challenges posed by high energy costs and limited water access. Previous studies have examined energy consumption in water treatment and distribution systems, emphasizing the need for alternative solutions like renewable energy integration. Aggarwal et al. (2022) explored energy use in rural Alaskan communities, illustrating how various distribution systems influence energy demand, with distinct system components contributing to these loads. They showed that different distribution systems have different energy loads and different aspects of the system contributing to these loads. Chamberlin et al. (2021) demonstrated the feasibility of renewable energy integration into Alaskan water treatment systems, noting the seasonal potential for solar and wind energy in different regions of the state. Their findings highlighted the promise of renewables for improving energy, water, and food security in these communities.

However, gaps remain in understanding how renewable energy, particularly solar power, can be optimally integrated into water treatment systems in Alaska. While energy audits and models have been applied to specific water treatment plants, there is a lack of comprehensive statewide analyses that account for regional, system-type, and water-source variability. Moreover, we lack 24-hour and annual synthetic load profiles for these plants that aid water engineers in matching the energy demands of water treatment to variable renewable energy supply. This study seeks to fill these gaps by addressing the following research questions: What are the 24-hour and annual electrical loads of water treatment plants in rural Alaska? How do these loads compare to the available solar irradiance across different regions, system types, and water sources? And how does solar energy integrate into these systems? How does its effectiveness vary based on regional, system-type, and water-source characteristics?

4.3. MATERIALS AND METHODS

4.3.1. Data Sources and Collection

We analyzed energy audit data from 13 rural communities provided by the Alaskan Native Tribal Health Consortium (ANTHC) through their Remote Monitoring Program (ANTHC, 2024). ANTHC conducts technical audits of water treatment facilities across 144 communities in Alaska. Among these, 13 communities had comprehensive electrical data covering a full year, either from 2023 or 2024. This data, recorded at 15-minute intervals, was accessed and downloaded via ANTHC's Remote Monitoring platform. We focused exclusively on water treatment facilities with complete annual datasets. Once downloaded, the data was converted into kilowatts to ensure consistency during analysis. To address any missing data points caused by sensor downtime or malfunctions, we applied a Python-based linear interpolation function (Allik & Annuk, 2017; *The Python Language Reference*, 2024). This approach provided consistent load estimates by filling gaps in the dataset.

Using the latitude and longitude of each community with load data, we downloaded solar irradiance datasets. from NASA's Data Access Viewer (NASA, 2024). Python was then used to process and organize this data, producing spreadsheets detailing the hourly, daily, and monthly load profiles for each community. We also calculated average load values for each time interval to support further analysis. Please see the Supporting Information for code detailing these data preparation procedures.

The communities included in this study vary in terms of their distribution system type, region, water source, and population size. Located across Alaska's diverse regions, these communities rely on a mix of piped circulating, closed haul, and individual well systems for water distribution. The majority of the communities use groundwater as their water source, with a few utilizing surface water. Population sizes range from very small communities like Crooked Creek with 57 residents to small ones like Gambell and Savoonga with populations over 600. Poverty rates also vary significantly, with some communities, such as Brevig and Napakiak, having high poverty rates above 50%, while others, like Gulkana and Nanwalek, have relatively lower poverty levels. This diversity in community characteristics is essential for understanding the variability in energy demand and renewable energy integration potential across different regions of Alaska.

Table 8. Descriptions of the 13 communities and their water treatment plants used in this study. Population and poverty are from the 2020 census (World Population Review, 2024) and the distribution system type, region, and water source are from ANTHC data (ANTHC, 2024)

City	Distribution System Type	Region	Water Source	Population	Poverty
Brevig	Piped Circulating	Northern	Groundwater	429	53.93%
Crooked Creek	Closed Haul	Interior	Groundwater	57	28.57%
Gambell	Piped Circulating	Northern	Groundwater	642	35.45%
Gulkana	Individual Wells	Gulf Coast	Surface water	83	1.45%
Kipnuk	Piped Circulating	Southwest	Surface water	360	33.22%
Napakiak	Individual Wells	Southwest	Groundwater	355	59.10%
New Kasigluk	Piped Circulating	Southwest	Groundwater	414	46.02%
Savoonga	Piped Circulating	Northern	Groundwater	833	33.78%
Shishmaref	Closed Haul	Northern	Surface water	573	31.51%
Togiak	Piped Pressure	Southwest	Groundwater	816	16.03%
Holy Cross	Piped Circulating	Interior	Groundwater	177	18.05%
Nanwalek	Piped Circulating	Gulf Coast	Surface water	213	7.56%
Anvik	Piped Circulating	Interior	Groundwater	73	27.03%

4.3.2. Load Profiles

To develop the load profiles for water treatment systems, we utilized 15-minute interval electrical load data collected from the studied facilities. Using Python, we processed this data to calculate the average electrical consumption at hourly, daily, and monthly scales. The method involved aggregating the 15-minute interval data into hourly averages to create a representative hourly load profile. These hourly averages were then compiled to compute daily averages, and the daily data was further aggregated by month to determine average monthly load profiles.

To analyze general patterns and trends, we first calculated the average load profiles for individual facilities, then aggregated these to determine the overall average load profiles across all studied systems. When an outlier community was identified, we excluded it to compute an adjusted average trend without its influence. Outliers were identified by plotting the load profiles and visually identifying profiles that looks different from the others. One outlier was identified – Crooked Creek. Additionally, we calculated the median peaks and valleys to compare with the averages, providing insight into the reliability of the identified peaks, valleys, and overall load trends. This analysis was conducted in Python, utilizing libraries such as pandas for data manipulation and visualization tools to validate the trends visually (*The Python Language Reference*, 2024). This systematic approach ensures reproducibility and offers a robust framework for deriving average load profiles to support energy planning and renewable energy integration. See Supporting Information for the code that documents these procedures.

4.3.3. Levelized Cost of Energy (LCOE) and Interpretation of Cost Figures

The Levelized Cost of Energy (LCOE) is a financial metric used to assess the cost-effectiveness of energy generation technologies over their lifespan. It represents the average cost per unit of energy (typically measured in \$/kWh) that needs to be charged to cover both the capital and operational costs of a particular energy generation system, considering factors such as installation, maintenance, and energy production efficiency. LCOE allows us to compare the cost of energy from different sources on a consistent basis, regardless of their individual capital costs or operational characteristics.

LCOE is calculated using this formula:

LCOE = Total Lifetime Costs / Total Lifetime Energy Produced

Where:

- **Total Lifetime Costs** include the upfront capital cost (such as the cost of equipment and installation), ongoing operational and maintenance costs, and any additional costs like financing.
- **Total Lifetime Energy Produced** is the total amount of energy the system is expected to generate over its operational life.

As described below, we calculated the LCOE for integrating solar power into the energy supply of water treatment systems in rural Alaskan communities. The LCOE is used to compare the cost of energy produced from solar installations to the cost of energy purchased from the local grid. A lower LCOE indicates a more cost-effective energy source, which helps guide decisions on whether solar energy integration reduces or increases overall energy expenses for the community.

4.3.4. HOMER Simulation

We utilized HOMER, a simulation tool developed by the National Renewable Energy Laboratory, to determine the optimal sizing of solar components and evaluate the cost implications of transitioning from the existing system to a renewable energy-based system (HOMER Pro, 2024). HOMER is a widely adopted, standardized, and replicable method for modeling and optimizing micro-power systems. It simulates system performance over extended periods, assessing specific configurations of components, their operational strategies, and their interactions under given conditions. This tool ensured consistent and replicable LCOE calculations across all the included communities.

HOMER's simulation capabilities enable both optimization and sensitivity analyses. During simulation, the tool evaluates various system configurations, including combinations of photovoltaic (PV) arrays, wind turbines, hydro-turbines, generators, battery banks, ac-dc converters, and hydrogen storage tanks. Systems can be grid-connected or autonomous and can serve ac and dc electrical loads as well as thermal loads. The simulation process ensures two key objectives: (1) determining the feasibility of a system by verifying its ability to meet energy demands and user-defined constraints, and (2) calculating the system's life-cycle cost, encompassing all installation and operational expenses over its lifespan.

Optimization involves running multiple simulations with different configurations. Our simulation ran two configurations – one with only electricity and one with solar. HOMER discards infeasible systems that fail to meet user-specified constraints and ranks feasible configurations based on their total net present cost. The configuration with the lowest total cost is identified as the optimal solution. To enhance accuracy, empirical weather data including solar insolation and wind speed was used in the simulation. This approach provides a comprehensive evaluation of both technical and economic feasibility for renewable energy system design.

We utilized datasets from 13 communities to develop 13 energy system models using HOMER software. Each model included solar photovoltaic (PV) panels, grid connections, and inverters or converters to simulate real-world energy system configurations. Only water treatment electrical demands were included as demands in these models. We did not exclude any outliers in this analysis.

For the HOMER analysis, we inputted the load data and configured three key system components. First, we selected the community's location and imported the solar resource data for that region from the National Renewable Energy Laboratory (National Renewable Energy Labratory, 2024). We then imported the load data for the year 2023, aligning with the load dates. Next, we added the grid components for the system, connecting it to the local grid. Electricity cost data were sourced from the Alaska Energy Authority (Alaska Energy Authority, 2023) and incorporated into the model, with net metering selected as the system's operational mode, reflecting the practices in Alaska (Renewable Energy Alaska Project, 2024). For the solar panel configuration, we allowed the system to scale solar capacity from 0 to the total load and set the capital and operation and maintenance costs to be twice that of solar panel in the continental United States (Schwabe, 2016). Finally, a converter was included to enable energy exchange between AC and DC systems.

HOMER optimized the system configurations to minimize costs while reliably meeting the water infrastructure systems' electrical demands. Outputs included detailed energy balances, cost summaries, (LCOE), and the percentage of load met by solar energy. These simulations provided insights into the economic feasibility of integrating solar power into rural Alaskan water treatment systems.

4.3.5. HOMER Result Comparisons

We chose to compare the decrease in cost and amount of solar integration across several factors, including region, distribution system type, and water source, to better understand how these variables influence renewable energy integration. The environmental and solar conditions vary significantly across Artic regions, which impacts the feasibility of solar power. For instance, northern regions experience shorter daylight hours in the winter and longer days in the summer, so we aimed to determine how solar availability affects renewable integration differently across these regions. Additionally, we compared across system types, as research has shown that different distribution systems—such as piped versus wells—have varying energy demands and load profiles, which could influence how effectively solar energy can be integrated (Aggarwal, 2022). Similarly, we considered both surface water and groundwater systems, as the treatment processes for these water sources differ, potentially affecting their compatibility with solar power integration.

4.4. LIMITATIONS

This analysis was based on data from only 13 rural Alaskan communities, which limited the scope of the study. The small sample size restricted our ability to perform statistical comparisons across different system types, water sources, and regional factors. A larger dataset would provide more robust comparisons and enhance the reliability of the findings. However, to our knowledge, this is the largest dataset of this kind available or analyzed to date. As the ANTHC dataset becomes more comprehensive in the coming years, this analysis should be updated to reflect these additional data.

This analysis focused solely on electrical energy demands, as consistent data were only available for this energy source. While some systems also incorporate other energy demands, such as those for water reuse or heat recovery, the scope of the analysis was limited to electricity. These other energy demands were not included because they are typically used for ancillary processes rather than directly powering water treatment operations. While this approach allows for a focused assessment of the primary energy demand, future studies incorporating a wider range of energy sources and demands could provide a more holistic perspective.

The datasets contained missing data points due to sensor downtime on certain days. Although Python-based interpolation techniques were used to estimate these missing values, such corrections may not fully reflect the actual electrical loads during those periods, introducing some degree of uncertainty.

Additionally, the presence of outliers in the load profiles means that with a larger dataset, a more accurate average load could be calculated, potentially shedding light on whether these outliers are truly exceptional cases or whether certain treatment plants have distinct load patterns. A more comprehensive dataset could also provide further insights into the factors influencing these variations.

The load profiles represent a specific subset of water treatment systems—small utilities in the Arctic region—so the findings may not be directly applicable to larger or more diverse systems in other parts of the country. Expanding the study to include water treatment plants of varying sizes and locations could enhance the generalizability of the results and provide a broader understanding of energy planning for water utilities.

Another limitation arises from the differing units and scales used for solar irradiance and electrical load. Solar irradiance is measured in watts per square meter (W/m^2), while electrical load is expressed in kilowatts (kW). These metrics are not directly comparable, and the figures presented primarily illustrate the timing of peak availability of solar energy and energy demand, rather than assessing whether solar energy can fully meet the load at any given time.

Additionally, HOMER optimization software seeks the lowest-cost solution for meeting energy demands, which can result in designs with different levels of solar generation depending on the design targets set for each system. Alternative design targets, such as prioritizing energy security or reducing environmental impact, would likely result in different system sizes, costs, and amounts of solar energy generated.

While this study did not include pollutant loading as a variable, incorporating this factor in future research is crucial for a more comprehensive analysis.

These limitations underscore the need for continued data collection and further research to validate the results and explore additional variables that could influence the integration of renewable energy into rural water systems.

4.5. RESULTS

Our findings include an analysis of load profiles and the outcomes of the HOMER simulations. The load profiles are examined across different regions and system types and are presented at both the 24-hour and annual scales. Additionally, we compare the percentage of load that uses solar and cost reductions across various regions and system types.

4.5.1 Load Profiles

Figure 6 displays the average 24-hour load profile alongside the individual load profiles for 13 communities for reference. The community load profiles generally exhibit a similar pattern, with peaks occurring in the afternoon or evening and valleys in the early morning. The average 24-hour load profile peaks at 5:00 PM and reaches its valley at 6:00 AM. The average peak time across the 13 communities is 2:55 PM, and the average valley time is 7:51 AM. Most community peaks occur between 11:00 AM and 10:00 PM, with the exception of Nanwalek, which peaks at 4:00 AM. Similarly, most valleys fall between 1:00 AM and 10:00 AM, except for Nanwalek and Gulkana, which have valleys at 6:00 PM and 8:00 PM, respectively.

To assess the reliability and representativeness of the average load profiles, the median peak and valley times were also calculated. The median peak occurs at 3:00 PM, and the median valley at 8:00 AM, closely aligning with the averages. This similarity between median and average values suggests that the load profiles are relatively consistent across communities, with minimal skew or extreme variability influencing the aggregated results. These findings underscore the robustness of the identified load patterns, which can reliably inform energy planning and renewable energy integration strategies.

Notably, load peaks frequently, though not always, coincide with daylight hours, likely reflecting operational preferences for running systems during the day rather than at night. While some load profiles may appear visually flat due to the scale of representation, plotting these profiles individually reveals that they follow a similar pattern to other communities, with discernible peaks and valleys. This reinforces the general consistency of load behaviors across the studied communities.

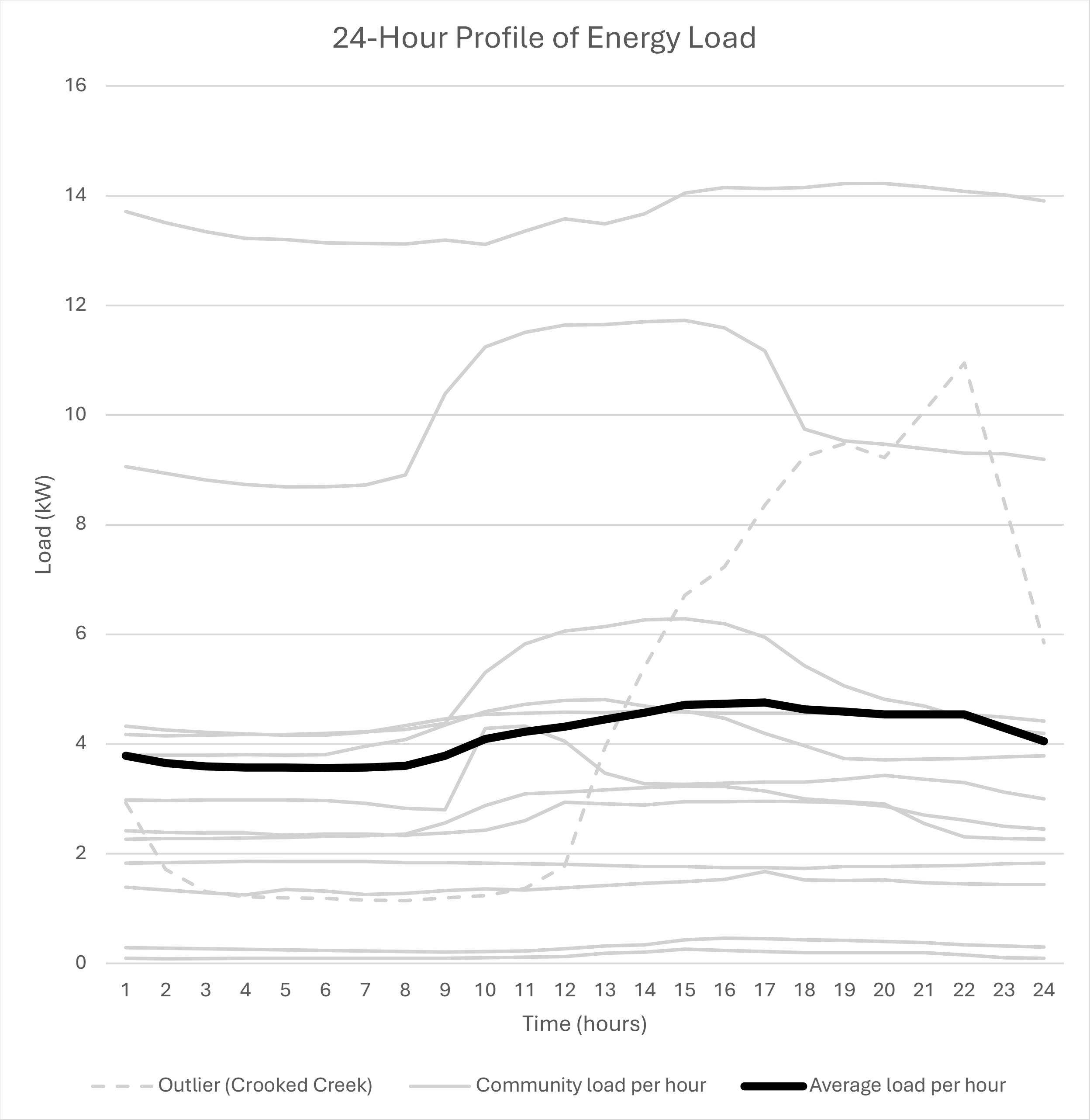

Figure 6. 24-hour profile of Electrical loads showing the average load as the thicker black line and each of the 13 communities as the thin grey lines.

Figure 7 presents the average 24-hour load profile for the water treatment systems across the studied communities, excluding the Crooked Creek outlier. The peak load in the average profile occurs at 3:00 PM, while the valley is observed at 6:00 AM, reflecting typical energy demand patterns for water treatment in these regions. Crooked Creek, with its smaller population and significantly higher electricity costs, exhibits a distinctly different load profile compared to the other communities. The unique characteristics of this community, including its high electrical costs and electrical usage patterns, set it apart from the others in the study. By excluding Crooked Creek, the revised average load profile provides a more representative view of this dataset, possibly offering a clearer understanding of the general trends in energy consumption for rural water treatment systems in Alaska.

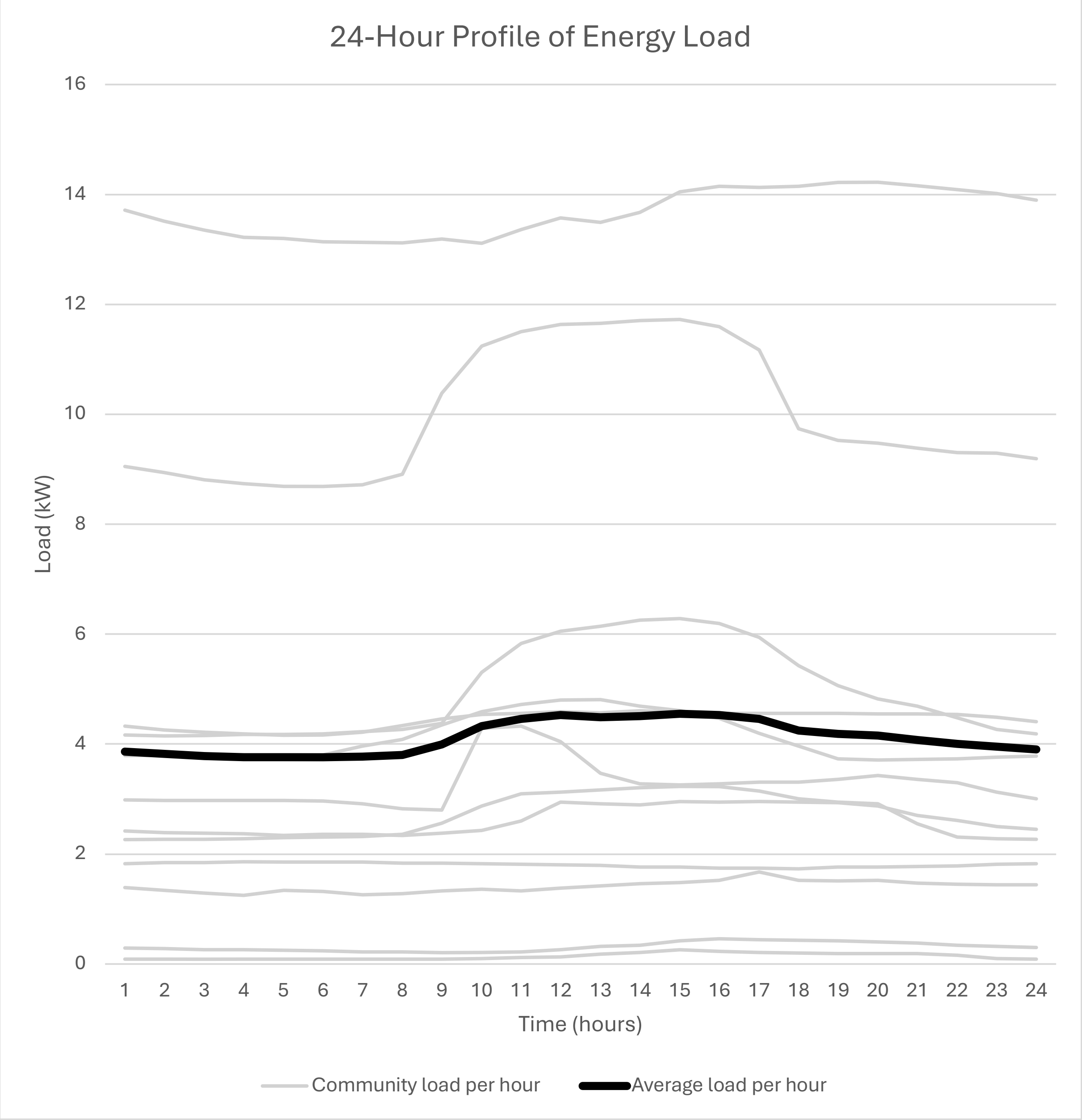

Figure 7. 24-hour profile of electrical loads showing the average load as the thicker black line and each of the 12 communities as the thin grey lines. This profile does not include the outlier community, Crooked Creek.

Removing this outlier demonstrates that the average and median peak and valley loads, as well as the overall load profile, are not significantly affected. Therefore, the remainder of our analysis will include the outlier to present the full dataset, while acknowledging the limitations of the small sample size and the potential influence of outliers.

Figure 8 illustrates the 24-hour load profile for each month of the year. The shape of the load profiles remains consistent throughout the year. Peaks typically occur between 2:00 PM and

4:00 PM, while valleys are observed between 2:00 AM and 6:00 AM. November, December, January, February, and March, the coldest months of the year (US Climate Data, 2024), have the highest load profiles and are grouped together, while June, July, August, and September, the hottest months of the year (US Climate Data, 2024), exhibit the lowest loads and are similarly grouped. The remaining months fall in between, with load values that are moderate in comparison. Unlike many other regions where summer loads tend to be higher due to increased turbidity (Thompson et al., 2008), Alaska's harsh winter conditions result in elevated energy demands during the colder months.

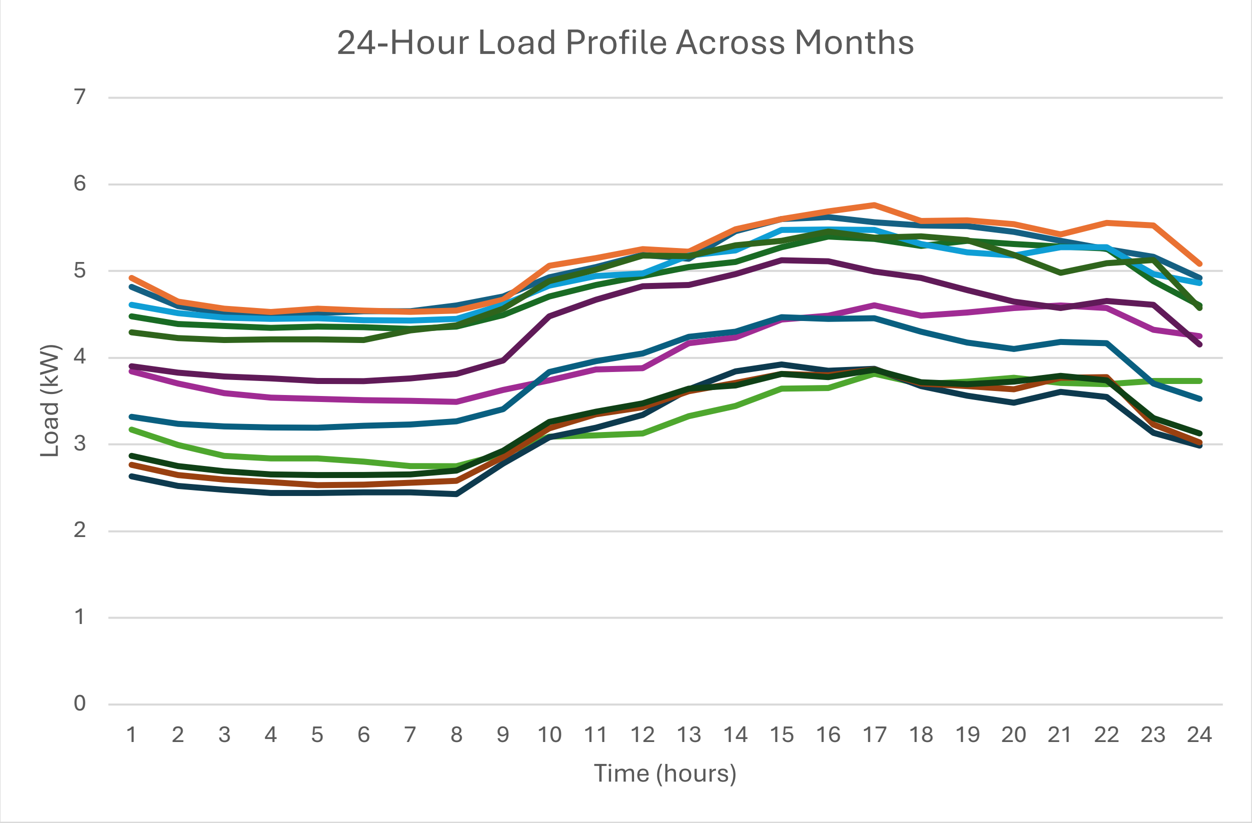

Figure 8. 24-Hour load profiles of each month of the year as an average of the communities.

Figure 9 through 13 compare the average profiles of solar irradiance (measured in W/m²) and electrical load (measured in kW). These two metrics use different units and scales, with solar irradiance representing the intensity of sunlight per square meter and electrical load representing the total power demand of the water treatment systems. The y-axes are therefore not directly comparable in magnitude. The figures are intended to illustrate these trends in timing rather than assess whether solar energy can fully meet the energy demand at different times.

Figure 9 presents the average solar irradiance alongside the average electrical load over a 24-hour period. Solar irradiance reaches its peak at 12:00 PM and its lowest point at 1:00 AM.

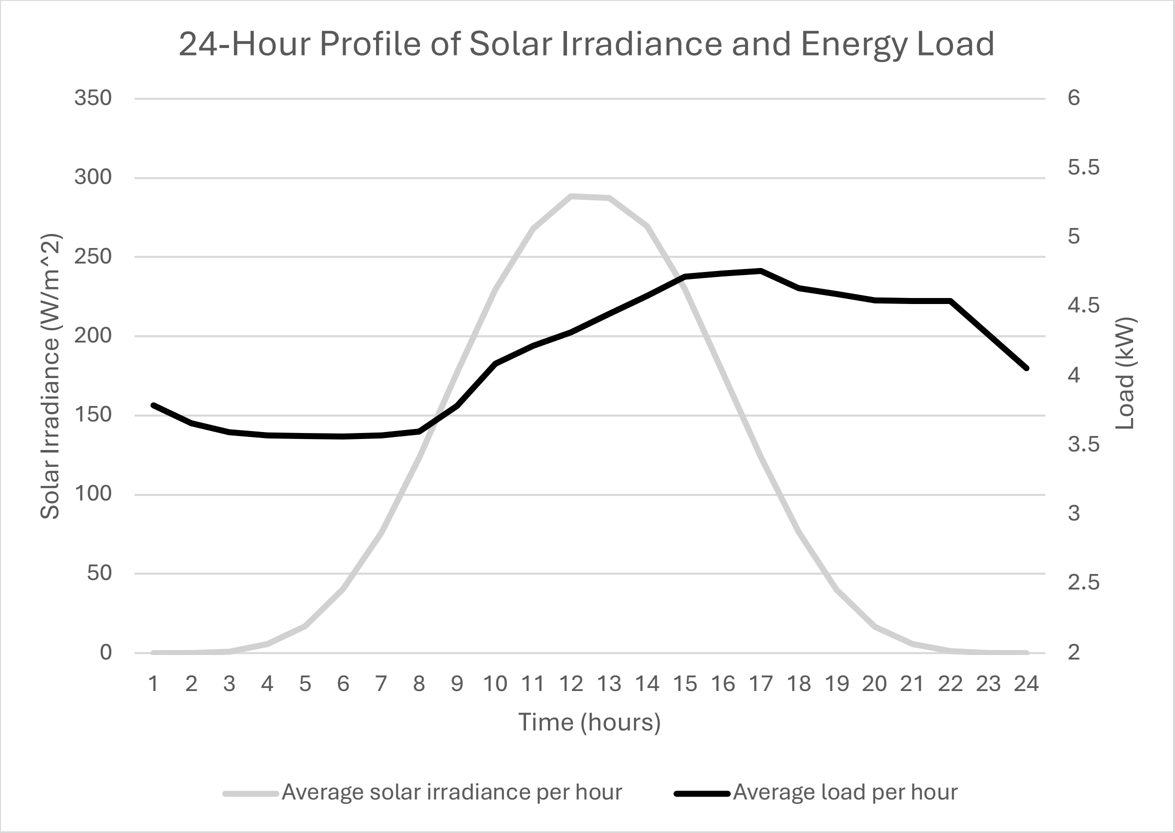

Figure 9. 24-Hour profile of solar irradiance and electrical load

Figure 10 presents the annual profiles of average monthly electrical loads and average monthly solar irradiance, based on data from the 13 communities. Solar irradiance is highest between April and August, while electrical loads are greatest between December and April. This highlights a seasonal mismatch between solar availability and energy demand for Alaskan water systems, where the periods of highest solar potential coincide with lower energy use, and peak energy needs occur during times of reduced solar availability.

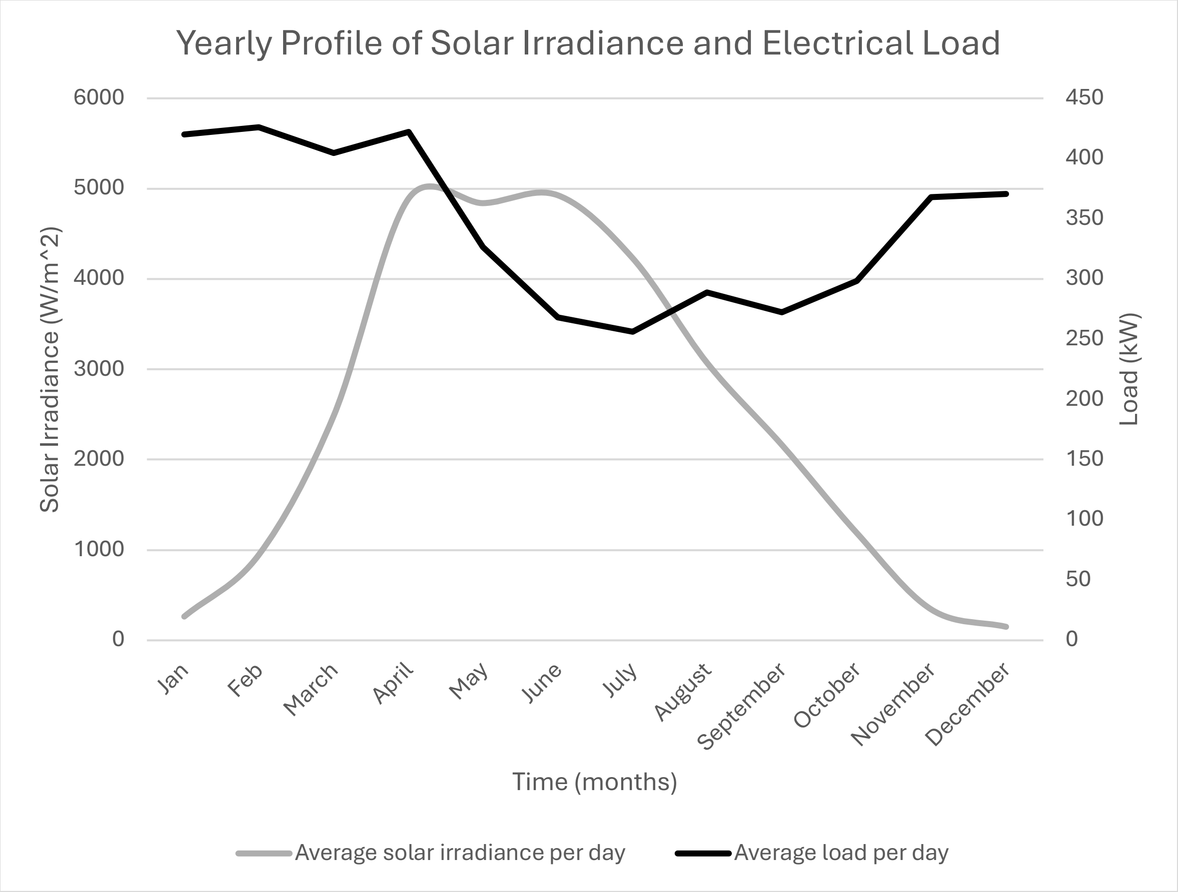

Figure 10. Yearly profile of solar irradiance and electrical load

Figures 11 though 13 illustrate the annual electrical load profiles and solar irradiance, categorized by region, distribution system type, and water source. Regionally, the electrical load profiles have similar shapes, but the northern region exhibits higher electrical loads compared to other regions, despite having lower solar irradiance availability. When categorized by water source, electrical loads for surface water systems are lower than those for groundwater systems, while solar availability remains consistent across both. Regarding system type, individual well systems show lower electrical loads compared to piped circulating, piped pressure, and closed-haul systems. Other researchers have found that piped circulating distribution systems have much higher loads than piped pressure and closed haul systems (Aggarwal, 2022).

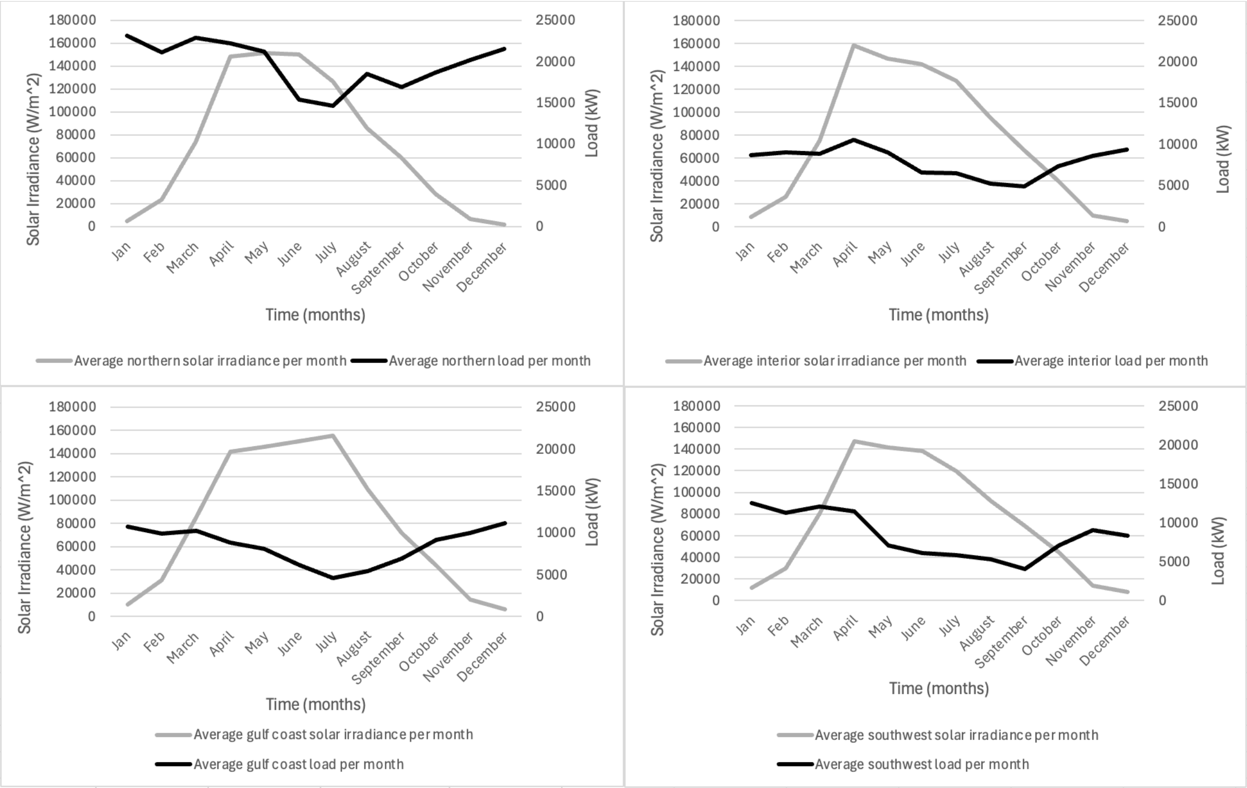

Figure 11. Yearly profile of solar irradiance and electrical load by region

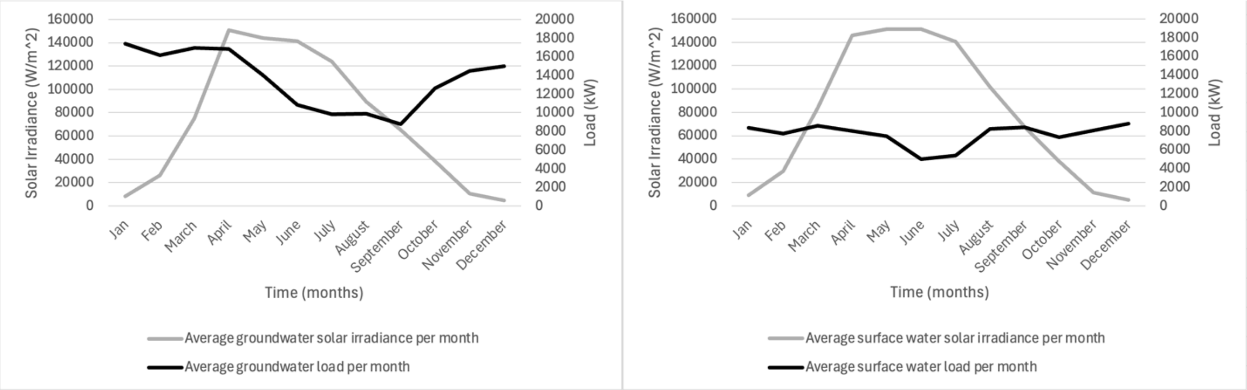

Figure 12. Yearly profile of solar irradiance and electrical load by water source

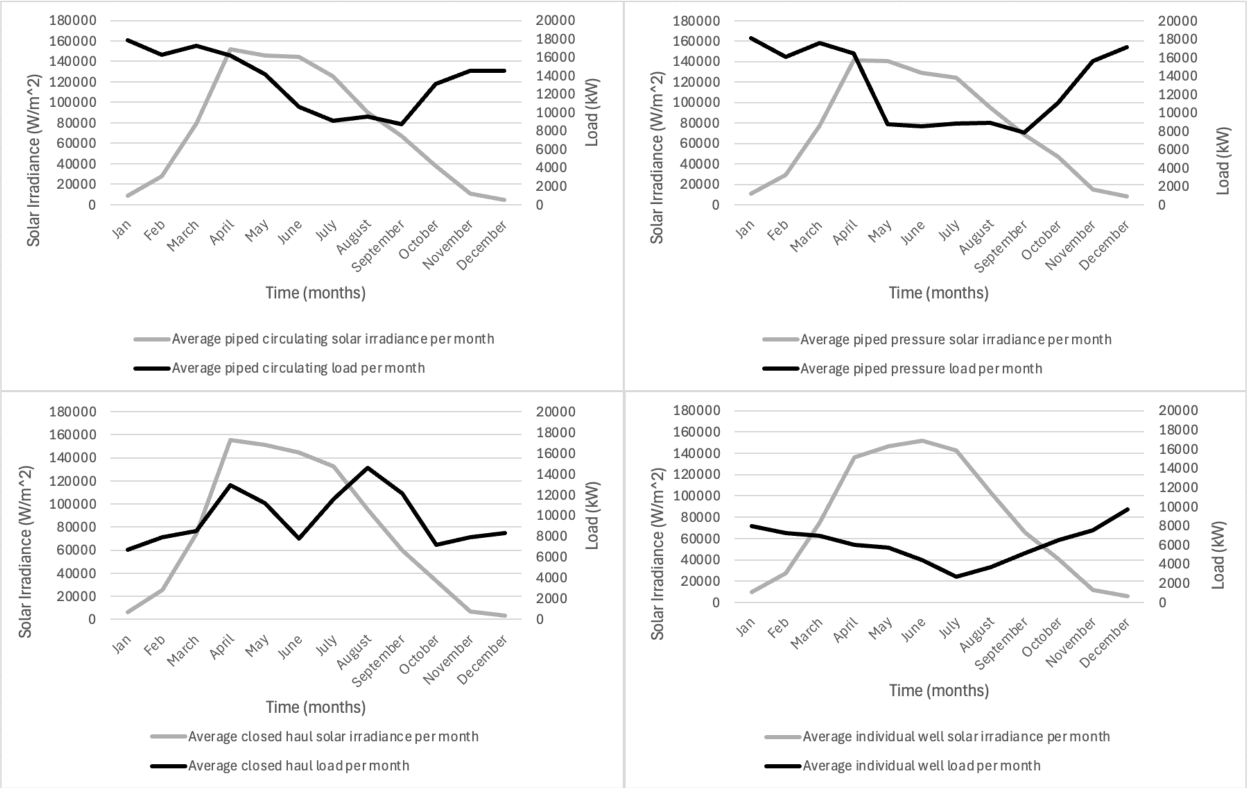

Figure 13. Yearly profile of solar irradiance and electrical load by system type

4.5.2. Region

Figures 14 and 15 summarize percentage of solar integration and cost changes across four regions: Northern, Interior, Gulf Coast, and Southwest. The Northern region had a mean percentage of solar integration of 45% with low variability (standard deviation = 0.72%). Cost changes ranged from \$0.16 to \$0.21, with a mean of \$0.19 and a standard deviation of \$0.02.

The Interior region showed a higher mean percentage of solar integration of 59% and more variability (standard deviation = 5%). Cost changes ranged from \$0.25 to \$1.16, with an average increase of \$0.58 and a standard deviation of \$0.51, representing the highest cost variability among the regions observed in this dataset.

The Gulf Coast had a mean percentage of solar integration of 39%, with substantial variability (standard deviation = 12%). Cost changes were lower, ranging from \$0.03 to \$0.20, with a mean of \$0.12 and a standard deviation of \$0.12. The Southwest region had a mean percentage of solar integration of 49% and moderate variability (standard deviation = 9%). Cost changes ranged from \$0.14 to \$0.51, averaging \$0.30 with a standard deviation of \$0.17.

Regions with higher percentage of solar integration, such as the Interior and Southwest, show greater potential for solar integration but also exhibit more variability in cost changes. Conversely, the Northern region demonstrates lower solar integration and smaller cost improvements, reflecting the challenges posed by its geographic and climatic conditions. It is important to note that while regional differences are shown, these variations may also be influenced by factors such as electricity costs, system types, and system sizes. Nevertheless, as expected based on geographic conditions, the typical Northern system tends to have a lower percentage of solar integration and smaller related cost improvements.

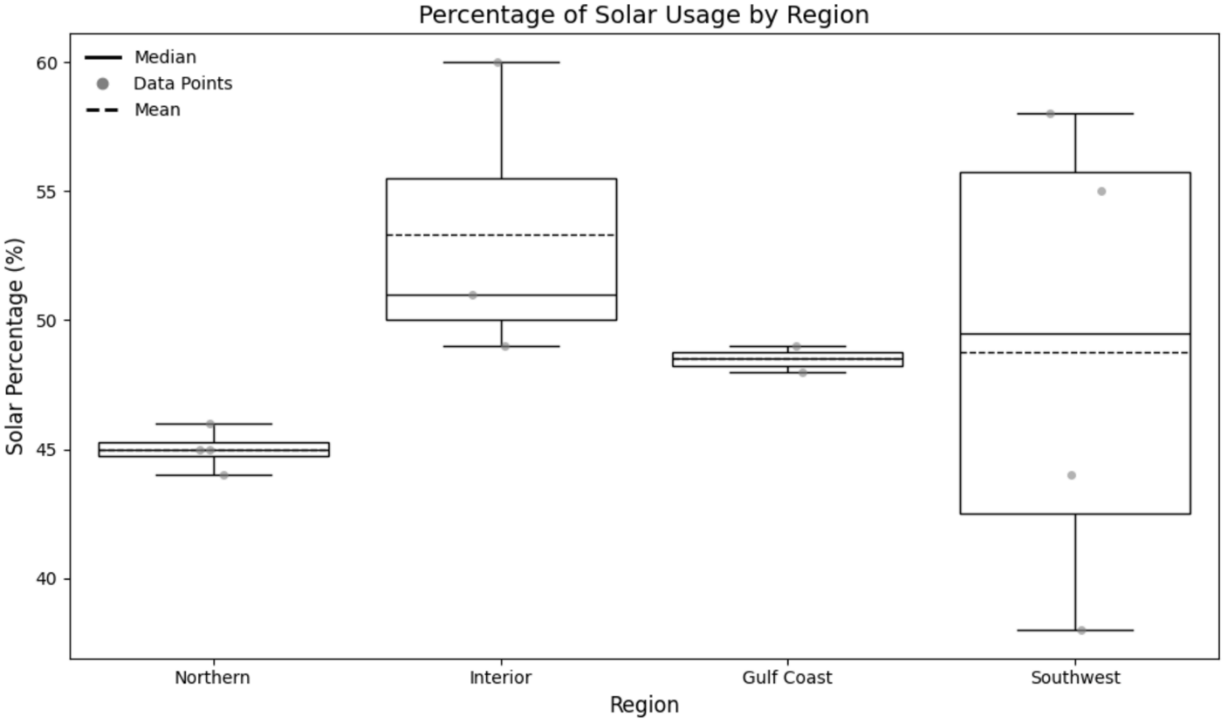

Figure 14. Percentage of solar usage by region

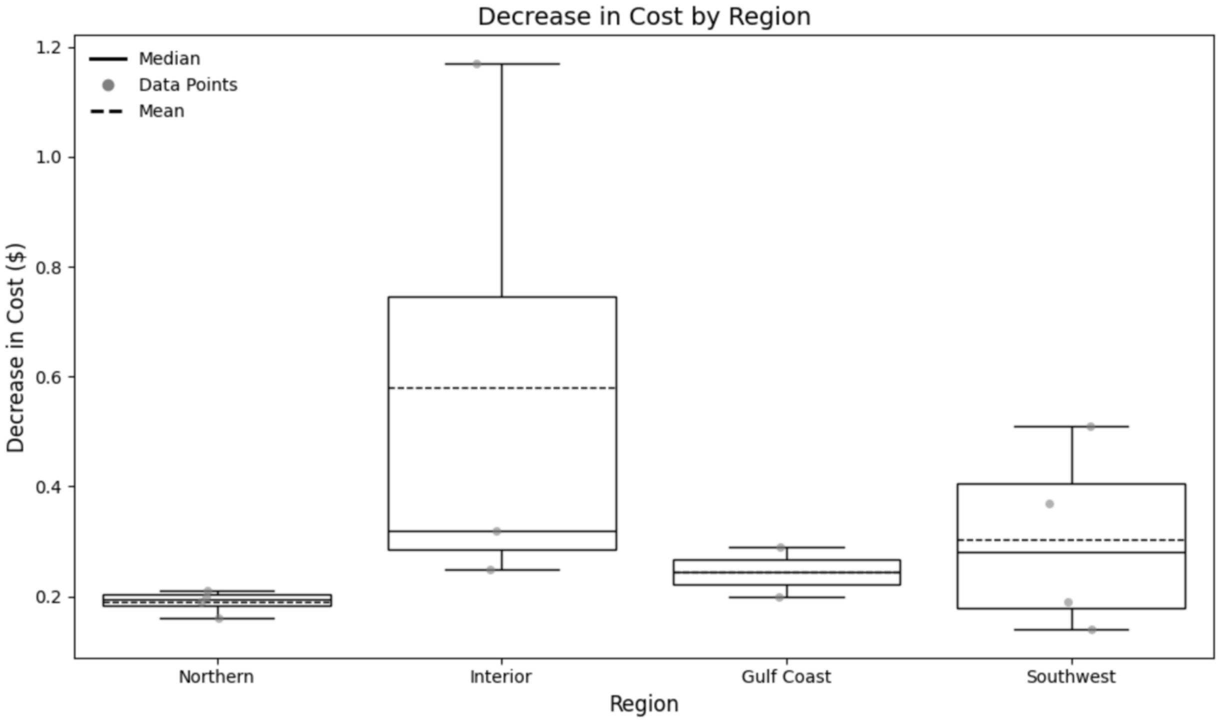

Figure 15. Decrease in cost by region

4.5.3. Water Source

We compared the percentage of solar integration used in the system and the decrease in cost from electricity to the system's LCOE by water source. Figures 16 and 17 summarize the percentage of solar integration and associated cost changes for groundwater and surface water. Groundwater exhibited a mean percentage of solar integration of 49% with a standard deviation of 7%, ranging from 38% to 59%. The associated change in cost varied significantly, ranging from $0.14 to $1.16, with a mean of $0.37 and a standard deviation of $0.34, indicating substantial cost variability. Surface water, with a mean percentage of solar integration of 44% and a higher standard deviation of 10%, ranged from 30% to 55%. Cost changes for surface water were lower and more stable, ranging from $0.03 to $0.37, with a mean of $0.20 and a standard deviation of $0.14.

Groundwater systems show higher average percentage of solar integration but with greater variability in both solar use and cost savings, likely reflecting differences in system design, size, or location.

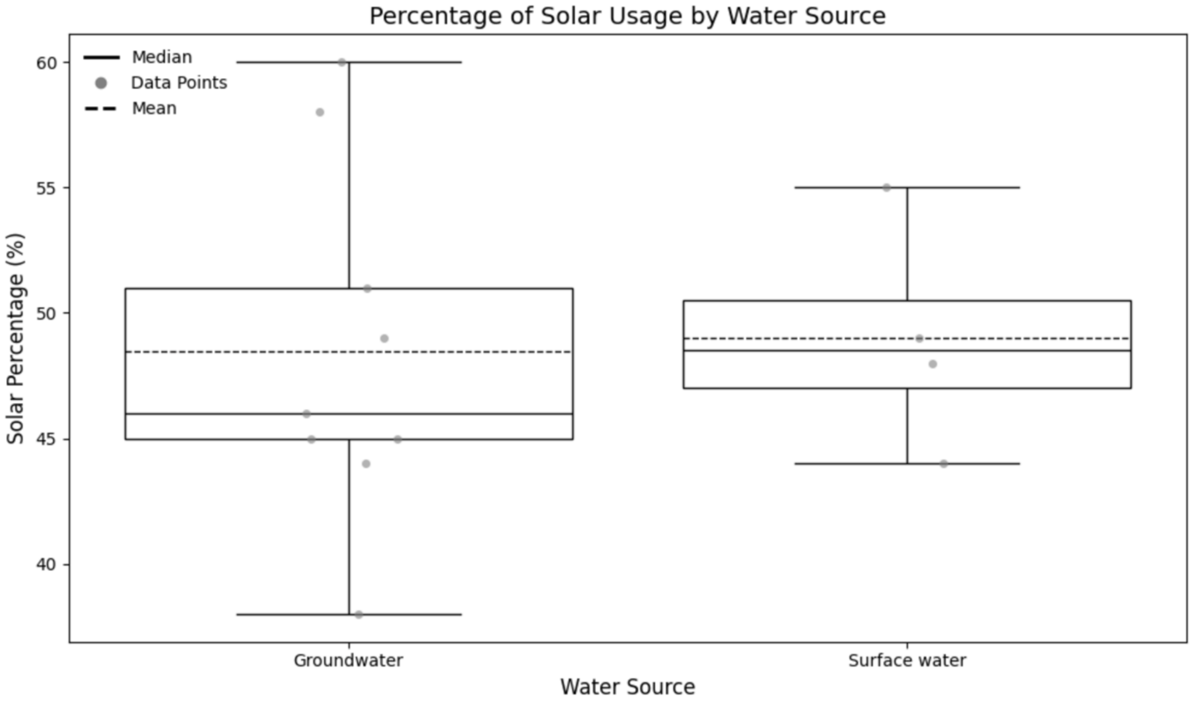

Figure 16. Percentage of solar usage by water source

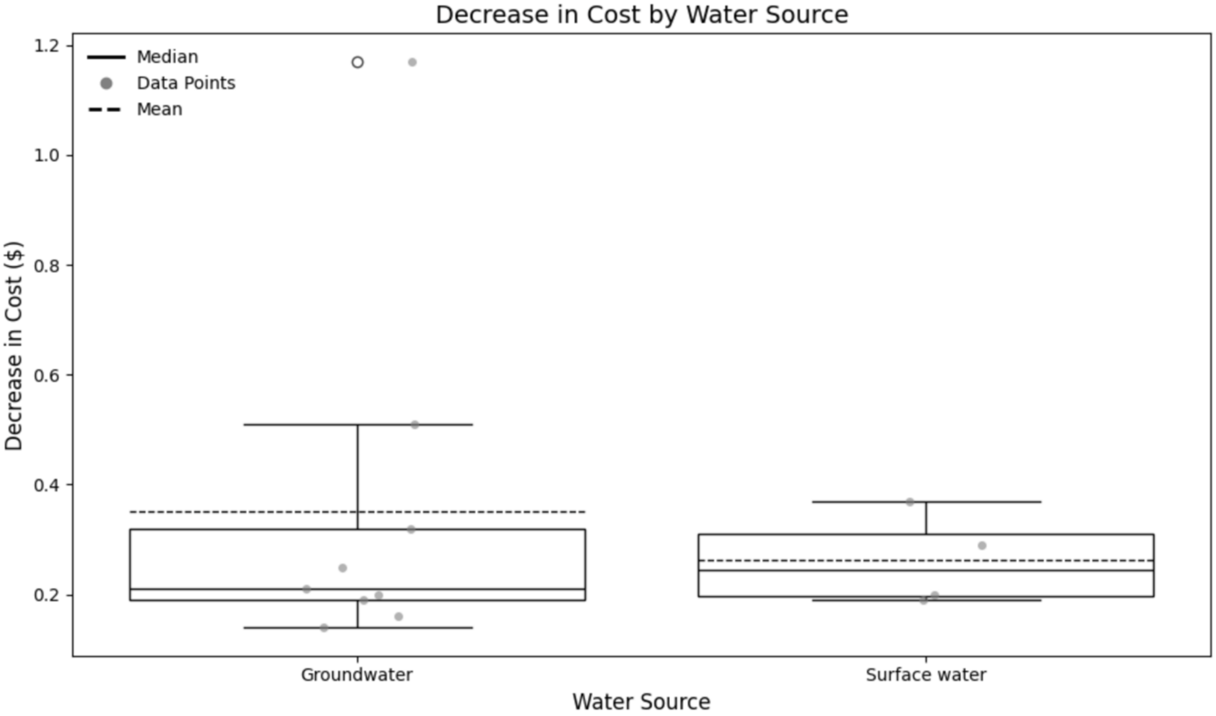

Figure 17. Decrease in cost by water source

4.5.4. System Type

Figures 18 and 19 presents data on percentage of solar integration and cost changes for four system types: Piped Circulating, Closed Haul, Piped Pressure, and Individual Wells. Piped Circulating had a mean percentage of solar integration of 47% with a low standard deviation (2%), indicating consistent solar energy usage. Cost changes ranged from \$0.16 to \$0.32, averaging \$0.22 with a standard deviation of \$0.06.

Closed Haul showed a higher mean percentage of solar integration of 51% and notable variability (standard deviation = 11%). Cost changes for this system ranged from \$0.19 to \$1.16, with a mean increase of \$0.68 and a standard deviation of \$0.69, indicating higher cost variability.

Piped Pressure had a mean percentage of solar integration of 41% and a standard deviation of 4%, suggesting moderate variability. Cost changes were stable, ranging from \$0.14 to \$0.19, with a mean of \$0.16 and a standard deviation of \$0.03. Individual Wells had a fixed percentage of solar integration of 30% and consistently low-cost changes of \$0.03, demonstrating no variability in either metric.

Piped Circulating and Closed Haul systems generally achieve higher percentage of solar integration compared to Piped Pressure and Individual Wells. However, Closed Haul systems exhibit the greatest variability in both percentage of solar integration and cost changes, suggesting that their performance is highly sensitive to specific conditions. In contrast, Individual Wells show the most consistency, with fixed percentage of solar integration and minimal cost variability, indicating limited potential for solar integration.

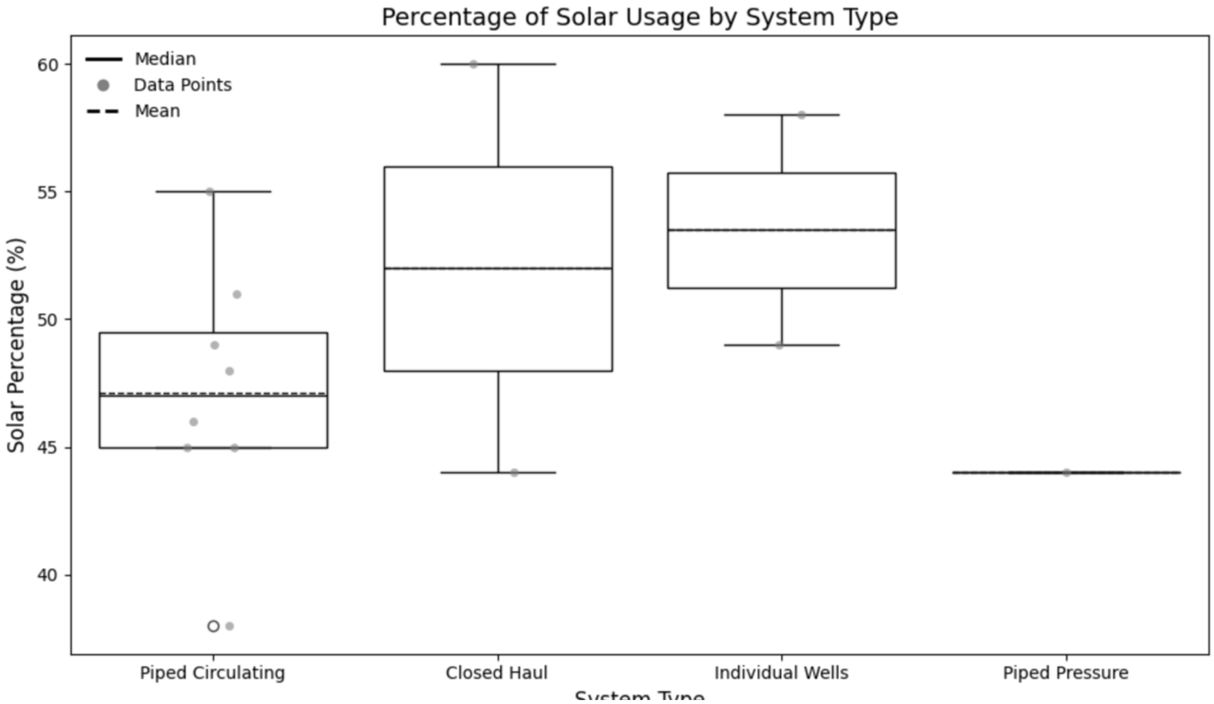

Figure 18. Percentage of solar usage by system type

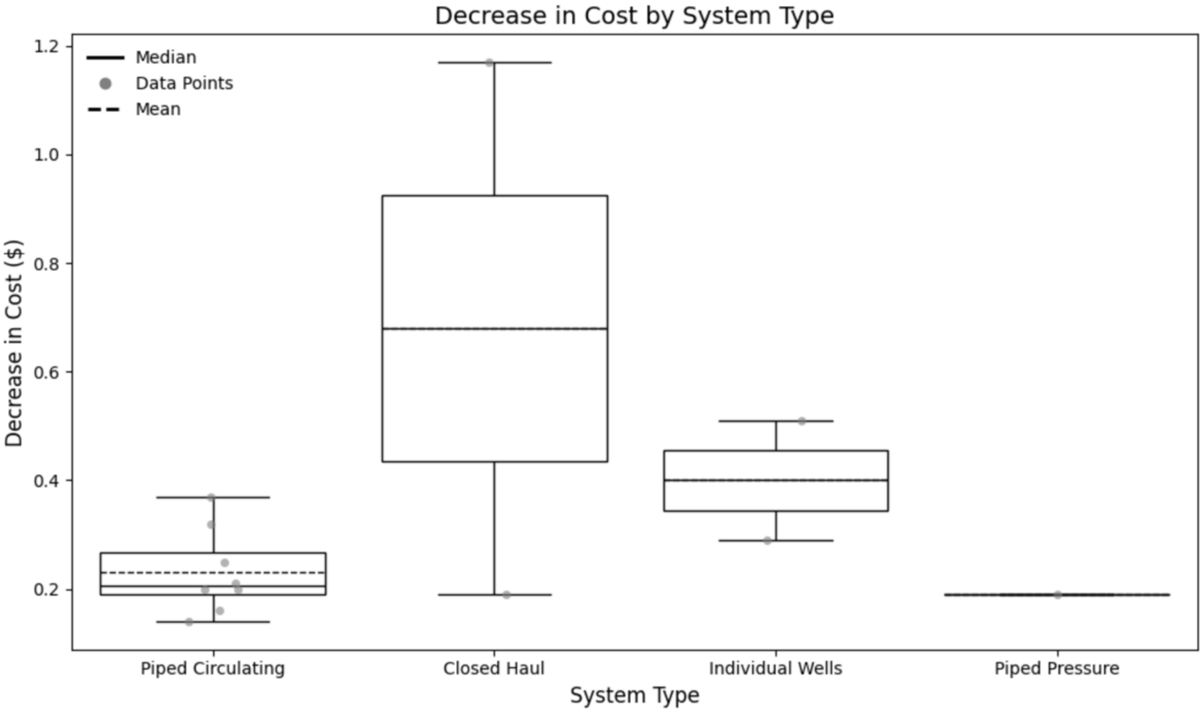

Figure 19. Decrease in cost by system type

4.6. DISCUSSION

To synthesize the key findings from this study, Table 9 summarizes the major insights into load profiles, solar energy integration, regional and system-specific variations, economic impacts, and planning applications. These headline results provide a concise overview of the critical takeaways, highlighting the challenges and opportunities associated with integrating renewable energy into rural Arctic water infrastructure systems.

Table 9. Key insights discussed from the results discussed in the discussion section

Category	**Key Insights**
Load Profiles	- Seasonal peak loads occur in winter months due to Arctic climate conditions, driven by pipe circulation needs to prevent freezing. - Daily peaks typically occur around 5 PM, outside peak solar production hours.
Solar Energy Integration	- Solar reduces LCOE in all examined cases, regardless of system type or region. - Solar energy cannot meet water system loads alone, due to misalignment with energy demand and extreme variability in daylight hours. - Energy storage (e.g., batteries) or complementary sources (e.g., wind, grid electricity) are necessary.
Regional Variability	- Interior regions showed the highest percent solar integration and LCOE reduction, largely driven by higher grid electricity costs. - Northern regions had the lowest percent solar integration, limited by reduced winter sunlight availability.
System-Specific Insights	- There is similar solar potential for groundwater and surface water systems. - Greater cost reductions were observed in groundwater systems, primarily due to these communities' higher baseline electricity costs rather than groundwater energy demand characteristics.
Economic Impacts	- Installing solar at individual water treatment plants can unintentionally increase community electricity costs or destabilize energy utilities by removing large customers from the grid. - Community-scale renewable energy projects are recommended to avoid adverse economic impacts.
Planning Applications	- Load profiles developed in this study support energy planning for rural Arctic water utilities, especially small systems with unique challenges (e.g., inefficiency, financial constraints). - Hourly and monthly multiplier tables (Table 10 and 11) allow for scalable energy demand estimation, aiding in the integration of renewables in water infrastructure design and operation.

4.6.1. Load profiles

Developing load profiles for water treatment systems represents a significant contribution to the literature, as these profiles facilitate better planning of system operations and energy requirements. To our knowledge, this is the first time the electrical load profiles of water treatment plants have been described in the literature. Previous studies have demonstrated example yearly load profiles for individual systems (Chamberlin et al., 2021). Profiles averaged across multiple systems or detailed at the 24-hour level are needed for engineering applications involving renewable energy sources, which by nature are variable (Kang et al., 2023). The development of average load profiles is essential for enabling engineers to optimize the integration of renewable energy sources and water infrastructure systems.

Water treatment plants maintain relatively steady energy demand throughout the day compared to residential electrical loads, which typically peak in the mornings and evenings (Zipperer et al., 2013). This consistency in energy use reflects the operational requirements of continuously heating, circulating, and treating water. However, it also highlights the distinct challenges these systems face in aligning energy use with intermittent renewable sources like solar power.

Despite the promise of solar energy, one key insight from Figures 9 and 10 and from the HOMER simulations is that even substantial solar installations cannot meet the energy demands of water treatment systems on their own. The extreme variation in daylight hours—long days in summer and very short days in winter—complicates the alignment of solar energy availability with energy demand. This variability makes it difficult to size renewable energy systems to meet loads without the inclusion of storage batteries, further emphasizing the importance of careful system planning for Arctic water treatment systems.

While these profiles offer valuable insights, it is important to recognize that they represent a specific type of water treatment system. The 13 communities included in this study serve an average population of 387 individuals. According to the U.S. Environmental Protection Agency (EPA), water systems are classified based on the population they serve (US EPA, 2015b):

- **Very small water systems**: 25–500 people
- **Small water systems**: 501–3,300 people
- **Medium water systems**: 3,301–10,000 people
- **Large water systems**: 10,001–100,000 people
- **Very large water systems**: Over 100,000 people

Nine of the 13 communities in this study are classified as very small water systems, while the remaining four are classified as small water utilities. Studies have shown that smaller water utilities are generally less efficient than their larger counterparts, facing challenges related to supply chains, financial stability, and personnel management, which existing vulnerabilities can exacerbate (Peda et al., 2013; Thelemaque et al., 2022b). This highlights the critical need for improved planning tools, such as load profiles, tailored to the specific requirements of small water utilities. It also suggests the need for future research that robustly describes energy demand profiles for larger water utilities.

Additionally, the load profiles developed in this study reflect the unique characteristics of utilities operating in Arctic regions. The results indicate that electrical loads peak during the winter months, a trend supported by prior research and consistent with the Arctic climate. In these regions, water must be actively circulated during harsh winters to prevent pipes from freezing, which increases energy demand. This contrasts with water treatment plants in other climates, where energy loads often peak in summer due to the need to treat more turbulent surface water (Thompson et al., 2008).

Tables 10 and 11 can be used to estimate the daily and monthly electrical loads for water treatment plants for future planning. As just described, the unusual characteristics of the communities included in this dataset must be considered during the application of these research results.

4.6.2. Hourly Multiplier Table

This table was created from the average hourly electrical loads. It allows users to estimate the electrical load for each hour of the day by applying a multiplier to the total daily load. The multipliers were found by dividing the hourly load by the total daily load. The hourly multiplier reflects the proportion of the daily load occurring at a specific hour. The For example:

If the daily load is **100 kW** and the multiplier for **8:00 AM** is **0.0358**, the load at 8:00 AM can be calculated as:
Hourly Load=100×0.0358=3.58 kW

Table 10. Hourly multiplier table

Hour	Hourly Multiplier
1:00	0.0380
2:00	0.0367
3:00	0.0360
4:00	0.0358
5:00	0.0358
6:00	0.0357
7:00	0.0358
8:00	0.0361
9:00	0.0379
10:00	0.0410
11:00	0.0423
12:00	0.0433
13:00	0.0446
14:00	0.0459
15:00	0.0473
16:00	0.0475
17:00	0.0477
18:00	0.0464
19:00	0.0460

20:00	0.0456
21:00	0.0455
22:00	0.0455
23:00	0.0431
0:00	0.0406

4.6.3. Monthly Multiplier Table

This table was created from the average monthly electrical loads. The monthly multiplier table represents the proportion of the annual electrical load that occurs in each month. The multipliers were found by dividing the Monthly load by the total yearly load. This allows for the estimation of monthly loads by multiplying the total annual load by the multiplier for a given month. For example:

If the annual load is **100,000 kWh** and the multiplier for **January** is **0.1098**, the estimated load for January can be calculated as:
Monthly Load=100,000×0.1098=10,980kW

Table 11. Monthly multiplier table

Month	**Monthly Multiplier**
January	0.1098
February	0.0978
March	0.1042
April	0.0988
May	0.0777
June	0.0605
July	0.0574
August	0.0696
September	0.0648
October	0.0747
November	0.0906
December	0.0938

These tables provide useful approximations for hourly and monthly loads, helping engineers and planners design water treatment systems that align with energy demands while accounting for renewable energy integration. However, they should only be used in the absence of empirical data specific to a given system, particularly given the outliers identified in this dataset.

4.6.4. Shifting Loads for Enhanced Integration with Renewables

Water treatment plants, as large energy consumers in small communities, present a significant opportunity to participate in energy demand management through load shifting to align better with renewable energy availability (Musabandesu & Loge, 2021). Shifting energy-intensive operations to periods of higher solar irradiance could enhance solar energy integration into water treatment processes, reducing the reliance on costly battery storage solutions. This strategy is particularly relevant given that this data shows the daily peak electrical load for many systems occurs at 5:00 PM, which is typically outside of peak solar production hours.

Research has highlighted how the type of water distribution system affects electrical consumption. In rural Alaskan water systems, for instance, energy use varies significantly depending on whether the system includes piped circulating systems or other types of distribution. For piped systems, water circulation represents the primary energy demand, whereas for other systems, space heating is often the largest consumer of energy (Aggarwal et al., 2022). Other major contributors to energy demand include raw water heating, tank heating, ventilation fans, air compressors, lighting, and miscellaneous plug loads.

Among the processes within water plants, energy requirements for primary treatment, which largely involve pumping, are relatively low compared to secondary treatment, where energy-intensive aeration systems are employed to maintain microbial health (Plappally & Lienhard, 2012). Pumps play a particularly important role in water treatment plant operations, performing functions such as transporting water from sources to storage tanks, maintaining chemical balances, cleaning sand filters, and ensuring continuous water circulation in piped distribution systems (Aggarwal, 2022). These pumping activities constitute a substantial portion of electrical energy use, and their timing is one of the most adaptable aspects of plant operations.

Pumps, due to their operational flexibility, offer the greatest potential for load shifting in alignment with renewable energy sources. Scheduling pump usage during daylight hours, when solar irradiance is at its peak, could shift the electrical load earlier in the day. This would allow solar energy to offset a larger proportion of the plant's energy demand without the need for extensive storage. In other applications, pumps powered by solar energy have already proven effective in bringing water into systems, suggesting that similar strategies could be adapted for water treatment plants.

Despite this potential, certain components of water systems—such as space heating, ventilation, lighting, and tank heating—are more challenging to reschedule. These operations are driven by temperature, sunlight, or the need for continuous functionality. However, the flexibility offered by pumps, combined with modeling efforts to predict energy consumption (Mannina et al., 2019) and effluent quality (Gernaey et al., 2004), creates an opportunity to optimize system operations to better align with renewable energy production.

4.6.5. Solar integration comparisons across region, system type, and water source

Comparing the analysis results across regions, the interior region showed the highest solar integration and the greatest reduction in costs. This outcome may be partially attributed to an outlier dataset from Crooked Creek, Alaska, where electricity costs are significantly higher than in the other communities studied. Electricity in Crooked Creek is $0.95 per kWh higher than the average across the other communities, which allows for a substantial cost reduction when transitioning from traditional electricity costs to the LCOE associated with solar integration.

In contrast, the northern region had the lowest percentage of solar integration and the smallest cost reduction. The northern arctic region experiences limited sunlight during winter months, making it challenging to generate sufficient solar energy to power large portions of the plants throughout the year as shown in other studies (Chamberlin et al., 2021). While prior research suggests that combining renewable resources such as wind and solar could address this limitation (Heide et al., 2010), wind power is not an optimal solution for rural Alaskan communities due to various logistical and operational constraints.

The percentage of solar utilization in groundwater and surface water systems was nearly identical, indicating that solar energy is viable for both types of systems. The observed greater cost reduction in groundwater systems compared to surface water systems may be more reflective of the higher electricity costs associated with these particular communities rather than a difference in their ability to incorporate solar energy. Previous studies have demonstrated the successful use of solar energy in both contexts, including applications for pumping in groundwater systems (Gao et al., 2013; Meah et al., 2008; Wang et al., 2019) and for powering surface water systems. Future research and more data are needed to explore this result.

4.6.6. Solar incorporation impacts and realities

Members of ANTHC discussed with our research team that integrating solar systems directly into small community water systems can have unintended negative consequences for the broader community (O.Pfeifer, personal communication, October 23, 2024). The ANTHC previously installed solar panels on water treatment plants to reduce energy costs. However, this approach inadvertently harmed communities by removing one of the largest customers from the local utility grid. As a result, the burden of covering the fixed costs of electricity generation shifted to other community members, particularly businesses, since residential energy costs are often subsidized under the Power Cost Equalization program. This redistribution led to even higher electricity costs for the remaining customers. Given these challenges, the focus has shifted toward implementing community-scale renewable energy projects using the Independent Power Producer model. This approach ensures that renewable energy benefits are distributed across the entire community grid rather than isolating water treatment systems. While system-specific changes remain relevant, they can also be effectively applied within the context of community-wide renewable energy integration to avoid negative economic impacts on the broader community.

4.6.7. Future work

This study contributes to the literature by presenting detailed electrical load profiles of water systems in rural Alaskan communities. However, there are several areas for future research that could enhance the understanding and application of renewable energy integration in these systems.

First, there is a need for more granular data on the electrical loads of specific components within water infrastructure systems. Such data would enable the creation of 24-hour load profiles for individual components, such as pumps, heating systems, and ventilation fans. Understanding the distinct load patterns of these components could provide clearer insights into which operations are most suitable for shifting to align with solar irradiance, thereby maximizing solar utilization and reducing dependence on storage solutions.

Expanding the scope of the study to include more communities would allow for more robust comparisons across regions, system types, and water sources. A larger dataset could help validate the observed trends and provide a more comprehensive understanding of how geographic and system-specific factors influence electrical loads and solar integration potential.

Incorporating data on overall community electrical loads is another critical avenue for research. Understanding how water infrastructure systems interact with broader community energy demands would facilitate the design of renewable energy strategies that consider the entire community grid. This approach could mitigate the potential negative impacts of isolating water infrastructure systems from the grid, such as those previously observed when water treatment plants in Alaska adopted solar installations without community-scale integration. By analyzing community-wide load profiles, researchers could identify synergies between residential, commercial, and water treatment and distribution energy demands, optimizing renewable energy deployment for the entire grid.

4.7. CONCLUSION

This study provides critical insights into the electrical demands of rural Alaskan water infrastructure systems and explores the potential for solar energy integration to reduce costs and improve sustainability. By analyzing electrical load profiles and leveraging HOMER simulations, we created load profiles representing water infrastructure system electrical data over 24-hours and a year and identified regional and system-specific variations in renewable energy applicability. The results show that solar energy has the potential to significantly reduce LCOE needed for remote Alaskan water infrastructure, particularly but not only in southern regions. They also underscore the challenges of direct integration into water infrastructure systems because of variable solar availability. Future research should focus on expanding datasets, examining detailed load profiles of individual system components, and exploring the interactions between water infrastructure systems and community-wide energy demands to optimize renewable energy strategies for rural and remote settings.

4.8. ACKNOWLEDGEMENTS

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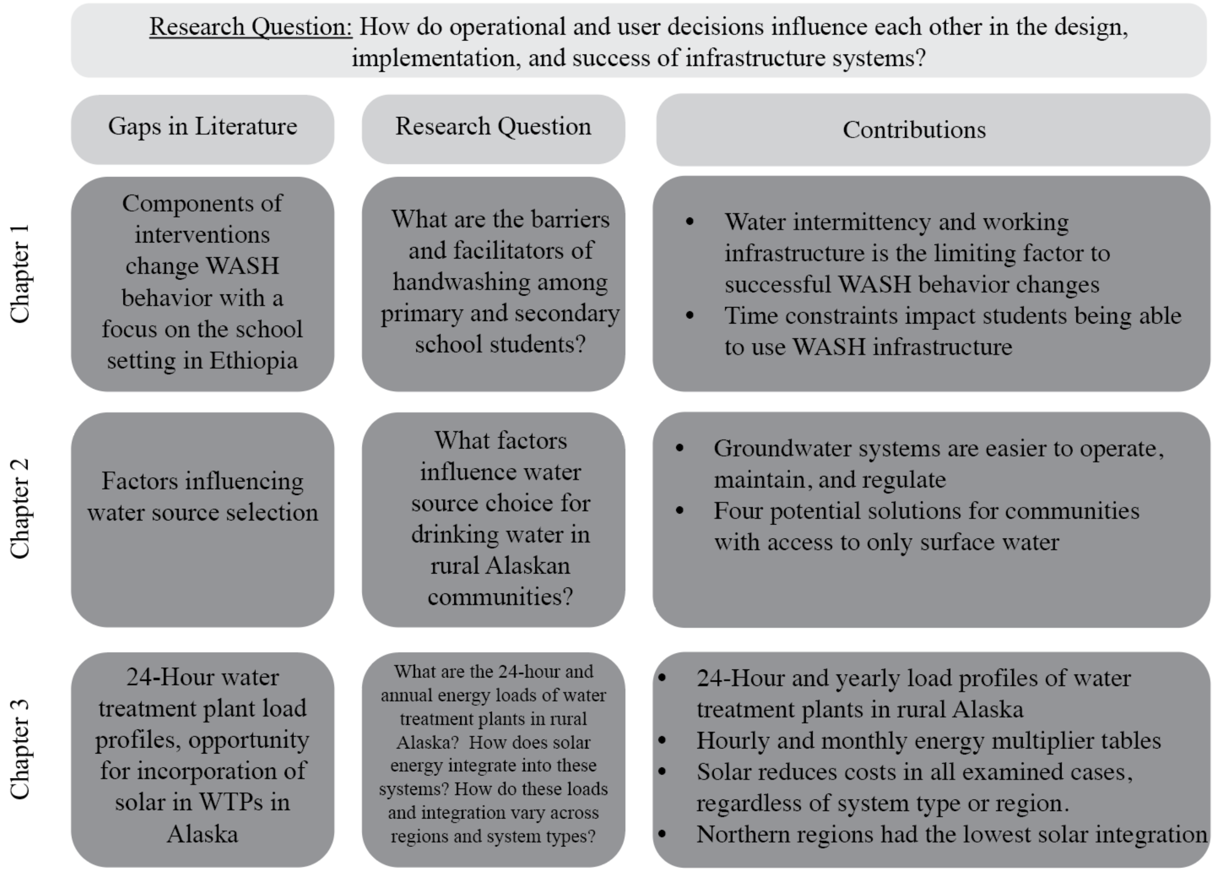
CHAPTER 5: SUMMARY AND CONCLUSIONS

The overarching goal of this dissertation is to explore how decision-making processes shape infrastructure systems by considering the perspectives of various stakeholders, including users, project decision-makers, and technical designers. By examining sociotechnical infrastructure across these lenses, this research seeks to inform decisions and develop tailored solutions that align with the environmental and social contexts of specific communities.



Research Question: How do operational and user decisions influence each other in the design, implementation, and success of infrastructure systems?

	Gaps in Literature	Research Question	Contributions
Chapter 1	Components of interventions change WASH behavior with a focus on the school setting in Ethiopia	What are the barriers and facilitators of handwashing among primary and secondary school students?	• Water intermittency and working infrastructure is the limiting factor to successful WASH behavior changes • Time constraints impact students being able to use WASH infrastructure
Chapter 2	Factors influencing water source selection	What factors influence water source choice for drinking water in rural Alaskan communities?	• Groundwater systems are easier to operate, maintain, and regulate • Four potential solutions for communities with access to only surface water
Chapter 3	24-Hour water treatment plant load profiles, opportunity for incorporation of solar in WTPs in Alaska	What are the 24-hour and annual energy loads of water treatment plants in rural Alaska? How does solar energy integrate into these systems? How do these loads and integration vary across regions and system types?	• 24-Hour and yearly load profiles of water treatment plants in rural Alaska • Hourly and monthly energy multiplier tables • Solar reduces costs in all examined cases, regardless of system type or region. • Northern regions had the lowest solar integration

Figure 20. Summary of Dissertation Contributions

In Chapter 2, we used deductive and inductive methods to investigate the barriers and facilitators of a WASH program designed to promote handwashing with soap in schools. By capturing the perspectives of students and teachers, we identified critical distinctions between hardware (physical infrastructure) and software (organizational and behavioral) components. While students adopted handwashing behaviors, these behaviors were hindered by inconsistent access to water and handwashing infrastructure, rendering behavior change lessons less effective. Additionally, the findings emphasized the importance of time and scheduling, as routines are crucial for sustained behavior change. Future research should examine the broader impacts of inconsistent water supply on behavior adherence, particularly how such disruptions influence long-term handwashing habits among students.

Chapter 3 examined water source selection in drinking water projects for rural Alaskan communities. Through interviews with water officials, we identified the factors influencing the decision to use groundwater or surface water. While groundwater systems are often more practical and cost-effective, environmental conditions sometimes render them unsuitable, necessitating reliance on surface water. To address the unique challenges faced by surface-water-reliant communities, we proposed four tailored solutions to improve the feasibility and effectiveness of surface water systems. These solutions aim to enhance the sustainability and resilience of drinking water infrastructure while addressing community-specific needs.

In Chapter 4, we utilized energy audits from water treatment plants in rural Alaska, conducted by the ANTHC, to explore opportunities for integrating renewable energy into these systems. By analyzing 24-hour and yearly load profiles, we highlighted patterns in energy demand, including peaks and valleys, and compared these to solar energy availability across different regions, system types, and water sources. Using HOMER software, we conducted simulations to evaluate energy consumption patterns and develop strategies for optimal solar energy integration. We found that solar integration is possibly across system types and regions, but that northern regions have the lowest amount of solar integration. The findings offer design guidelines for water infrastructure systems that incorporate renewable energy, considering local weather conditions and material availability. They also allow for the use of an hourly and monthly energy multiplier table to help make energy load profiles for similar systems. This research provides actionable insights to better incorporate renewable energy and a better understanding of solar opportunity in Alaska.

5.1 LIMITATIONS AND THE PATH FORWARD

While this dissertation provides valuable insights into sociotechnical infrastructure decision-making, it is important to acknowledge the limitations of the studies and outline potential directions for future research. Each chapter addresses distinct aspects of infrastructure decision-making, but the scope and methodologies of the research inherently introduced certain constraints.

Chapter 2 focused on a modest sample of schools, teachers, and students in Addis Ababa, Ethiopia, which may limit the generalizability of the findings to other intervention schools or regions. This sampling approach, while useful for understanding implementation successes, may not fully capture the perspectives of less-experienced teachers or non-hygiene-club students. Additionally, there is potential for courtesy bias, as participants were aware that the study was conducted by Splash, the organization implementing the interventions. Nevertheless, the consistency of responses across students and teachers and their candid acknowledgment of challenges, such as unreliable soap supplies, lends credibility to the findings.

Future research could address these limitations by expanding the sample size to include more schools, students, and teachers, and by intentionally capturing the perspectives of those less directly engaged with WASH interventions. Incorporating longitudinal data collection would also provide insights into how WASH behaviors and infrastructure effectiveness evolve over time. Additionally, examining the relationship between resource availability (e.g., water and soap) and behavior change in more diverse educational contexts could further validate and expand the findings.

Chapter 3 relied on interviews with water project managers in rural Alaska to explore decision-making processes related to drinking water sources. The study captured the perspectives of managers who do not reside in the communities they serve, meaning the findings represent managerial viewpoints rather than those of community members directly impacted by the water projects.

The next phase of this research should incorporate direct community engagement to include the voices of those who experience these projects firsthand. In-person outreach and interviews with community members could provide a more comprehensive understanding of how water source decisions affect daily life, resilience, and sustainability at the local level. Expanding the geographic scope of the study to include other regions with similar challenges would also enhance the applicability of the findings.

Chapter 4 leveraged energy audit data from 13 rural Alaskan communities to explore renewable energy integration into water treatment systems. However, the research faced limitations due to missing data points from sensor downtime, which were addressed using interpolation techniques. While these methods mitigated the issue, the estimates may not fully capture actual energy loads. Additionally, the relatively small sample size limited the ability to perform statistical comparisons across variables such as system type, water source, and regional differences.

Future research could focus on expanding the dataset to include more communities and additional monitoring to reduce data gaps. Conducting comparative analyses with a larger sample would enable more robust statistical testing and potentially uncover patterns related to infrastructure types and regional contexts. Incorporating other renewable energy sources, such as wind or geothermal energy, into the HOMER simulations could also provide a broader understanding of how to optimize energy sustainability for rural water systems.

5.2. SO WHAT, WHAT NEXT?

This dissertation began as an exploration of decision-making processes in infrastructure systems and evolved into a comprehensive investigation of how organizational, technical, and user-driven factors interact to shape the success of water and energy infrastructure in diverse contexts. The studies highlight the importance of aligning infrastructure design and operations with the environmental and social realities of specific localities, offering actionable insights for improving both the performance and equity of these systems.

By applying sociotechnical systems thinking, this dissertation underscores the interconnectedness of infrastructure decision-making at multiple levels—from individual users to technical designers to policymakers. The findings show that there is no one-size-fits-all approach to water and energy infrastructure; instead, context-specific solutions are crucial for addressing operational challenges and advancing sustainability. Whether examining the barriers and facilitators of WASH implementation in schools, the decision-making processes behind water source selection in rural Alaskan communities, or the integration of renewable energy into water treatment systems, each study highlights the need to balance technical, social, and environmental considerations.

Reflecting on the overarching themes of this dissertation, a critical lesson is the importance of adopting an integrated approach to decision-making in infrastructure systems. The findings underscore that decisions cannot be made in isolation; they are inherently shaped by the interplay of technical constraints, organizational priorities, and user behaviors. This sociotechnical lens not only improves our understanding of how systems function but also provides a framework for designing solutions that are more resilient and equitable. While the studies in this dissertation focused on water and energy systems, the principles of context-specificity, stakeholder inclusion, and adaptability have broader applicability across diverse infrastructure domains.

A key insight from this work is the role of sociotechnical systems thinking in addressing global challenges like those outlined in the United Nations Sustainable Development Goals (SDGs). Many initiatives around the SDGs, such as improving access to clean water (Goal 6) and affordable energy (Goal 7), already exhibit sociotechnical characteristics by recognizing the interdependence of technical solutions and social contexts. However, these efforts often fall short of fully embracing the integrated decision-making processes required to tackle systemic challenges. For example, while the SDGs highlight the importance of equitable access to water and energy, they do not always provide guidance on how to navigate trade-offs between technical feasibility, environmental sustainability, and social equity. By embedding sociotechnical principles into the implementation of SDG initiatives, decision-makers can better align global targets with the specific needs and realities of local communities.

Recent reports indicating regression in achieving many SDG targets highlight the urgency of rethinking strategies to accelerate progress (Halkos & Gkampoura, 2021; United Nations, 2024a). The synergies between water and energy systems, as explored in this dissertation, offer a compelling opportunity to address multiple SDGs simultaneously. If advising on SDG implementation, particularly regarding water and energy integration, a key recommendation would be to prioritize systemic approaches that leverage cross-sectoral systems. This includes:

1. **Promoting Co-Designed Solutions**: Engage local communities, technical experts, and policymakers in co-designing infrastructure systems to ensure that solutions are both context-appropriate and scalable.
2. **Incentivizing Renewable Energy in Water Systems**: Develop policies and funding mechanisms that encourage the adoption of renewable energy technologies in water infrastructure, particularly in underserved regions where resource constraints are most acute.
3. **Strengthening Data and Monitoring Systems**: Invest in robust data collection and analysis tools to better understand the dynamic interactions between water and energy systems and to track progress toward integrated sustainability goals.
4. **Fostering Interdisciplinary Collaboration**: Encourage partnerships across engineering, social sciences, and policy domains to create holistic strategies that address both technical and societal dimensions of infrastructure challenges.

Ultimately, this work highlights the transformative potential of sociotechnical systems thinking. As the world is impacted with the dual challenges of advancing sustainable development and mitigating the impacts of climate change, the integration of technical innovation with social inclusivity and cross disciplinary collaboration will be essential. My hope is that the insights from this dissertation can inspire practitioners and researchers to prioritize both sustainability and justice in future infrastructure planning, operations, and management, fostering systems that meet the needs of all stakeholders while adapting to the challenges of a rapidly changing world.

CHAPTER 6: REFERENCES

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APPENDIX A: SUPPORTING INFORMATION FOR CHAPTER 2

Table A1. Complete Interview Guide

To be completed by the interviewer	
Date	**Date____**/Month____/Year______
Time	**Start________ End: ___________**
Place	**Sub city : _________**
	Woreda: ___________
	Name of school : ____________
	Participant interviewee: - **Focal teacher _____** - **Non-focal teacher _____ New ____ Experienced ___** **(UW researchers recommend that the “new” non-focal teacher should be one that has been at the school for at least the length of time Splash’s program has been in effect.)** - **Paired boy students _____ Grade 4___ Grade 8 ___** - **Paired girl students _____ Grade 4___ Grade 8 ___** **(UW researchers recommend that one pair of boys and one pair of girls be interviewed FOR EACH GRADE. So, a total of 4 friendship pair interviews per school.)**
Interviewer:	**Code: ________________**
Supervisor:	**Code: ____________**

Table A2. In-depth Interviews (IDIs) guides for Focal teachers

Data variables (information want to obtain)	**Interview questions**
Knowledge and experience of Splash’s program	1. Can you describe Splash’s program at your school? a. What is your role in implementing the handwashing part of the program?
Motivation, confidence, and time spent in their role as focal teacher	1. How do you feel about the program being used in your school? a. Why? 2. What are your roles and responsibilities as a focal teacher? a. What kind of training have you been given? b. What were the positive aspects of training? c. Anything missing? d. If anything was missing, what was it?

	3. Are you confident that you are successfully carrying out your role as focal teacher?
	  a. What gives you that level of confidence (or lack of confidence)?
	  b. What resources are lacking that may hinder you from carrying out your focal teacher responsibilities?
	4. How much time per week do you spend on your focal teacher responsibilities?
	  5. How do you feel about this time commitment?
	6. In your work as a focal teacher, what motivates you to maintain Splash's program at your school?

Perceptions of how the program influenced students' handwashing behavior	1. How would you describe students' handwashing behavior in general
	  a. **Before** Splash's intervention?
	  b. A**fter** Splash's intervention?
	2. After Splash's intervention who in the school is…
	  a. Most likely to wash their hands?
	7. Least likely to wash their hands?

perceptions of the program's **reach** in their school Please tell me how handwashing lessons are delivered to students outside of the hygiene club.	

Perceptions of the program's **reach** in their school *(*Have interviewer start this section of interview by saying something like, *"Now, thinking about the role of the hygiene club in influencing student behavior…")*	8. What were the most effective student-led hygiene activities performed by the hygiene club to successfully engage non-hygiene club members?
	  a. What about these activities made them so effective?
	9. Were there any hygiene club activities performed at this school that did not turn out to be effective to successfully engage non-hygiene club members?
	  a. What about these activities made them so ineffective?
	10. Please tell me how handwashing lessons are delivered to students outside of the hygiene club.

Perceptions on the effectiveness non-curricular elements of HW program	3. Do posters influence students' handwashing behavior at school?
	  a. If yes, why? If not, why not?
	4. Do mirrors influence students' handwashing behavior at school?
	  a. If yes, why? If not, why not?
	5. Do handwashing station placement and design influence students' handwashing behavior at school?
	6. If yes, why? If not, why not?

Perceptions of the program's **sustainability** in their school	7. Is there a sustainability strategy to ensure all WASH activities started in year one are sustained over the next few years? a. If yes, what is this strategy? b. What are this strategy's plans for… i. Replacing or repairing WASH fixtures? ii. Acquiring enough soap to be placed at every handwashing station every day? iii. Sustaining the hygiene club? iv. Replacing focal teachers if they leave the school? c. How do you plan to monitor your school's sustainability? d. What could be challenges in making your school's WASH activities sustainable?

Table A3. In-depth Interviews (IDIs) guide for Non-focal teachers

Data variables (information want to obtain)	**Interview guiding questions**
Knowledge and experience of Splash's program, specifically as it relates to focal teacher and hygiene club	1. Can you describe Splash's program at your school? 2. How do you feel about the program being used in your school? e. Why? 2. Who do you ask if you have questions about the handwashing program or your role in its implementation? a. How available are these individuals? 3. In your own words, can you describe the role of the focal teachers in your school? a. How do you think other teachers and students perceive focal teachers? b. To what extent do you respect the opinions and actions of the focal teacher? 4. What have the focal teachers taught you about handwashing with soap? 5. In your own words, can you describe the role of the hygiene club in your school? a. How do you think other teachers and students perceive the hygiene club?
Perceptions of how the program influenced students' handwashing behavior	8. How would you describe students' handwashing behavior in general a. **Before** Splash's intervention ? a. A**fter** Splash's intervention ?

	1. How do you feel you've helped change students' handwashing behavior at school?
Perceptions of the program's **reach** in their school	7. Please tell me how handwashing lessons are delivered to students outside of the hygiene club.

Table A4. In-depth Interviews (IDIs) guide for Non-hygiene-club students

Data variables (information want to obtain)	**Interview guiding questions**
Practices on HW	1. Tell me about the last time you washed your hands at school. a. What did you use? b. What were you doing immediately before washing your hands? c. What did you do after you washed your hands? 2. Are there other times during the day you usually wash your hands? a. Why is it important to wash hands then? 3. Pretend like you're about to wash your hands, can you show me how you do it?
Knowledge on HW	4. What is the difference between washing your hands with soap and washing your hands with only water? (For the following questions 5-8, UW researchers recommend DeepDive create two sets of cards with the answers "before," "after," "both," and "not at all" that each child in the friendship pair can hold up to the interviewer after the question has been asked. This method of answering may help mitigate the influence of peer pressure.) 5. A mother changes her baby's diaper. When should she wash her hands, before, after, both, or not at all? 6. A doctor sees a patient. When should they wash their hands, before, after, both, or not at all? 7. A parent prepares lunch at home. When should they wash their hands, before, after, both, or not at all? 8. A student is eating lunch in the school cafeteria. When should they wash their hands, before, after, both, or not at all?
Barriers/enablers & motivation surrounding handwashing	9. What are the most important reasons someone might want to wash their hands with soap? (Let the students think of their own reasons first.) a. Then show and read off the list. Ask each student to choose one from the list that they think is also important.

	i. Hands are dirty ii. To make hands smell good iii. Don't make others sick iv. Protect my friends and family v. Be a good role model vi. Be like everyone else around me vii. Show off to everyone viii. Fun to do ix. Because it's the 'right thing to do' 10. What do feel when you don't WASH your hands? 11. When your peers don't wash their hands, what do you think prevents them?
Knowledge on Splash's program at school	12. In your own words, can you describe the role of the hygiene club in your school? a. What activities has the hygiene club done in your school?
HW related lesson or activity learned from the project and bringing home what they've learn to families	13. Please tell me about your favorite lesson you've had in class about handwashing. a. Who led the lesson? b. If they mention a video lesson, then probe about their other favorite non-video lesson and how they learned it and who led it. 14. Please tell me about your favorite lesson or activity you've had outside the classroom about handwashing. a. Who led the lesson or activity? 15. Have you shared anything you've learned about handwashing with your family? a. If so, what did you share? b. After you shared, were there any changes in handwashing in your home? c. If not, why not?

Table A5. Code dictionary for interviews

BCD Factors	Subfactors	Definition
Executive	Clean hands, dirty hands	Related to Splash's lesson involving the use of soap to remove germs
	General Germ	Related to general germ knowledge learned outside of clean hands, dirty hands
Motivated	Disgust	Related to handwashing because of general feelings of disgust or being perceived as dirty
Physical	Handwashing station	Mention of handwashing stations
	Soap drive	Mention of soap drives or access or soap
	Water tanks	Mention of water tanks, or storage

	Other	Related to physical infrastructure but not related to handwashing stations, soap drives, or water tanks
Reactive	Mirrors	Related to mirrors
	Handwashing monitors	Related to the students and teachers monitoring handwashing
	Posters	Related to posters
Social	Friday cleaning	Mention of school clean ups
	Handwashing pledge	Mention of Splash's handwashing pledge
	Hygiene club	Mention of the hygiene club
	Soap drive	Mention of soap drives or access or soap
	Handwashing monitors	Related to the students and teachers monitoring handwashing
	Teacher training	Mention of trainings done for teachers

APPENDIX B: SUPPORTING INFORMATION FOR CHAPTER 3

Table B1. Occupation information for respondents

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

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

Table B2. Demographic information for respondents

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

Table B3. Coding dictionary for interviews

Factors	**Definition**
Availability	Related to the whether the water source is available to be used for drinking water systems
Chemical content	Related to the chemical content of the water source

Financial considerations	Related to the costs of constructing, operating, maintaining, distributing, and energy and price of water
Geographic location	Related to how the geography impacts the success or failures of water treatment systems
Groundwater under the influence of surface water	Related to instances in which groundwater is directly under the influence of surface water
Health	Related to how the drinking water systems impact community health
Preference	Related to water official and community member preference between water sources
Quality	Related to the quality of water sources
Regulations	Related to the regulations of treating each water source and how they impact the success and failure of drinking water projects
Seasonal influences	Related to how the water source is impacted by seasons
Taste	Related to the community taste preference between water sources
Technical system considerations	Related to the successes or failures of different drinking water treatment and infrastructure

APPENDIX C: SUPPORTING INFORMATION FOR CHAPTER 4

Code C1. Hourly Load Python Code

```
import pandas as pd
import os

# Folder containing the CSV files
folder_path = '/Users/rachelpearson/Documents/Python_folder/'

# List of cities (assuming your CSV files are named data1.csv, data2.csv, ..., data15.csv)
cities = [f"data{i}.csv" for i in range(1, 16)]

# Dictionary to hold the results for each city
average_monthly_load = {}

# Iterate through each city's data file
for city in cities:
    file_path = os.path.join(folder_path, city)

    # Load the data (assuming there's a datetime column and a 'Load (kW)' column)
    df = pd.read_csv(file_path)

    # Check if 'Date-time' and 'Load (kW)' columns exist
    if 'Date-time' not in df.columns or 'Load (kW)' not in df.columns:
        print(f"Skipping {city}, missing required columns.")
        continue

    # Convert 'Date-time' to datetime, handling errors
    df['Date-time'] = pd.to_datetime(df['Date-time'], errors='coerce')  # Convert to datetime,
handle errors

    # Drop rows with invalid datetime
    df = df.dropna(subset=['Date-time'])

    # Set 'Date-time' as index
    df.set_index('Date-time', inplace=True)

    # Convert 'Load (kW)' column to numeric, coercing errors to NaN
    df['Load (kW)'] = pd.to_numeric(df['Load (kW)'], errors='coerce')

    # Drop rows with NaN in 'Load (kW)' column
    df = df.dropna(subset=['Load (kW)'])

    # Resample the data by month and calculate the average load for each month
    monthly_avg = df.resample('M')['Load (kW)'].mean()  # Use monthly resampling
```

```
    # Check if monthly averages are calculated
    if monthly_avg.empty:
        print(f"No data for months in {city}. Skipping this city.")
        continue

    # Create a list with averages for each month (1 through 12), fill missing months with NaN
    avg_by_month = [monthly_avg.get(pd.Timestamp(f"2024-{month:02d}-01"), None) for
month in range(1, 13)]

    # Save the results in the dictionary
    average_monthly_load[city] = avg_by_month

# Output the results into an Excel file
output_file = '/Users/rachelpearson/Documents/Python_folder/average_monthly_loads.xlsx'

with pd.ExcelWriter(output_file) as writer:
    # Iterate through each city and write the results to a new sheet in the Excel file
    for city, avg_load in average_monthly_load.items():
        # Prepare a DataFrame with the average monthly load for each city
        months = ['January', 'February', 'March', 'April', 'May', 'June', 'July', 'August', 'September',
'October', 'November', 'December']
        df_avg = pd.DataFrame(avg_load, index=months, columns=['Average Load (kW)'])

        # Write the data to the Excel sheet, with the city name as the sheet name
        df_avg.to_excel(writer, sheet_name=city, index_label='Month')

print(f"Results have been saved to {output_file}")
```

Code C2. Daily load code

```
import pandas as pd
import os

# Folder containing the CSV files
folder_path = '/Users/rachelpearson/Documents/Python_folder/'

# List of cities (assuming your CSV files are named data1.csv, data2.csv, ..., data15.csv)
cities = [f"data{i}.csv" for i in range(1, 16)]

# Dictionary to hold the results for each city
total_daily_load = {}

# Iterate through each city's data file
for city in cities:
    file_path = os.path.join(folder_path, city)
```

```
    # Load the data (assuming there's a datetime column and a 'Load (kW)' column)
    df = pd.read_csv(file_path)

    # Convert 'Date-time' to datetime, handling errors
    df['Date-time'] = pd.to_datetime(df['Date-time'], errors='coerce')  # Convert to datetime,
handle errors

    # Drop rows with invalid datetime
    df = df.dropna(subset=['Date-time'])

    # Set 'Date-time' as index
    df.set_index('Date-time', inplace=True)

    # Convert 'Load (kW)' column to numeric, coercing errors to NaN
    df['Load (kW)'] = pd.to_numeric(df['Load (kW)'], errors='coerce')

    # Drop rows with NaN in 'Load (kW)' column
    df = df.dropna(subset=['Load (kW)'])

    # Resample the data by day and calculate the total load for each day
    daily_total = df.resample('D')['Load (kW)'].sum()  # Sum the load for each day

    # Group by month (January through December) and calculate the total daily load for each
month
    total_daily_load_by_month = daily_total.groupby(daily_total.index.month).sum()  # Sum the
daily loads for each month

    # Ensure every month from January to December is represented
    total_daily_load_by_month = total_daily_load_by_month.reindex(range(1, 13), fill_value=0)

    # Save the results
    total_daily_load[city] = total_daily_load_by_month.tolist()

# Output the results into an Excel file
output_file = '/Users/rachelpearson/Documents/Python_folder/total_daily_loads.xlsx'

with pd.ExcelWriter(output_file) as writer:
    # Iterate through each city and write the results to a new sheet in the Excel file
    for city, total_load in total_daily_load.items():
        # Prepare a DataFrame with the total daily load for each month
        months = ['January', 'February', 'March', 'April', 'May', 'June', 'July', 'August', 'September',
'October', 'November', 'December']
        df_total = pd.DataFrame(total_load, index=months, columns=['Total Daily Load (kW)'])

        # Write the data to the Excel sheet, with the city name as the sheet name
```

```
        df_total.to_excel(writer, sheet_name=city, index_label='Month')

print(f"Results have been saved to {output_file}")
```

Code C3. Hourly load code

```
# Folder containing the CSV files
folder_path = '/Users/rachelpearson/Documents/Python_folder/'

# List of cities (assuming your CSV files are named data1.csv, data2.csv, ..., data15.csv)
cities = [f"data{i}.csv" for i in range(1, 16)]

# Dictionary to hold the results for each city
average_hourly_load = {}

# Iterate through each city's data file
for city in cities:
    file_path = os.path.join(folder_path, city)

    # Load the data (assuming there's a datetime column and a 'Load (kW)' column)
    df = pd.read_csv(file_path)

    # Ensure 'Date-time' is parsed correctly
    df['Date-time'] = pd.to_datetime(df['Date-time'], errors='coerce')  # Convert to datetime,
handling errors

    # Drop rows with invalid datetime
    df = df.dropna(subset=['Date-time'])

    # Set 'Date-time' as index
    df.set_index('Date-time', inplace=True)

    # Convert 'Load (kW)' column to numeric, coercing errors to NaN
    df['Load (kW)'] = pd.to_numeric(df['Load (kW)'], errors='coerce')

    # Drop rows with NaN in 'Load (kW)' column
    df = df.dropna(subset=['Load (kW)'])

    # Resample the data by hour and calculate the average load for each hour
    hourly_avg = df.resample('H')['Load (kW)'].mean()  # Resample by hour ('H' stands for hour)

    # Save the results in the dictionary (store average hourly load for each city)
    average_hourly_load[city] = hourly_avg.tolist()

# Output the results into an Excel file
```

```
output_file = '/Users/rachelpearson/Documents/Python_folder/average_hourly_loads.xlsx'

with pd.ExcelWriter(output_file) as writer:
    # Iterate through each city and write the results to a new sheet in the Excel file
    for city, hourly_load in average_hourly_load.items():
        # Create a DataFrame for each city with the average hourly load
        hourly_df = pd.DataFrame(hourly_load, columns=['Average Load (kW)'],
index=pd.date_range(start='2024-01-01', periods=len(hourly_load), freq='H'))

        # Write the data to the Excel sheet, with the city name as the sheet name
        hourly_df.to_excel(writer, sheet_name=city, index_label='Date-Time')

print(f"Results have been saved to {output_file}")
```

Code C4. Solar load code

```
# File paths
input_file = '/Users/rachelpearson/Documents/Python_folder/solar_holycross.xlsx'  # Replace
with your file path
output_file =
'/Users/rachelpearson/Documents/Python_folder/solar_radiation_summary_holycross.xlsx'  #
Output Excel file

# Read the Excel file
df = pd.read_excel(input_file)

# Ensure column names are correct
df.columns = ['YEAR', 'MO', 'DY', 'HR', 'ALLSKY_SFC_SW_DWN']

# Validate if the necessary columns are present
required_columns = ['YEAR', 'MO', 'DY', 'HR', 'ALLSKY_SFC_SW_DWN']
if not all(col in df.columns for col in required_columns):
    raise ValueError("Input file does not contain the required columns.")

# -----------------
# Hourly Solar Radiation
# -----------------
# Group by hour and calculate the average solar radiation
hourly_avg_radiation = df.groupby('HR')['ALLSKY_SFC_SW_DWN'].mean().reset_index()
hourly_avg_radiation.rename(columns={'ALLSKY_SFC_SW_DWN': 'Average Hourly
Radiation'}, inplace=True)

# -----------------
# Daily Solar Radiation
# -----------------
# Group by year, month, and day, and calculate the total daily radiation
```

```
daily_total_radiation = df.groupby(['YEAR', 'MO',
'DY'])['ALLSKY_SFC_SW_DWN'].sum().reset_index()
daily_total_radiation.rename(columns={'ALLSKY_SFC_SW_DWN': 'Total Daily Radiation'},
inplace=True)

# Map numeric months to month names
month_mapping = {
    1: 'January', 2: 'February', 3: 'March', 4: 'April', 5: 'May', 6: 'June',
    7: 'July', 8: 'August', 9: 'September', 10: 'October', 11: 'November', 12: 'December'
}
daily_total_radiation['Month'] = daily_total_radiation['MO'].map(month_mapping)

# Reorder columns for clarity
daily_total_radiation = daily_total_radiation[['YEAR', 'Month', 'DY', 'Total Daily Radiation']]

# -----------------
# Monthly Solar Radiation
# -----------------
# Group by year and month, and calculate the total monthly radiation
monthly_total_radiation = df.groupby(['YEAR',
'MO'])['ALLSKY_SFC_SW_DWN'].sum().reset_index()
monthly_total_radiation.rename(columns={'ALLSKY_SFC_SW_DWN': 'Total Monthly
Radiation'}, inplace=True)
monthly_total_radiation['Month'] = monthly_total_radiation['MO'].map(month_mapping)

# Reorder columns for clarity
monthly_total_radiation = monthly_total_radiation[['YEAR', 'Month', 'Total Monthly
Radiation']]

# -----------------
# Save results to an Excel file
# -----------------
with pd.ExcelWriter(output_file) as writer:
    hourly_avg_radiation.to_excel(writer, index=False, sheet_name='Hourly Radiation')
    daily_total_radiation.to_excel(writer, index=False, sheet_name='Daily Radiation')
    monthly_total_radiation.to_excel(writer, index=False, sheet_name='Monthly Radiation')

print(f"Solar radiation summary has been saved to: {output_file}")
```

Code C5. Linear fill code

```
# Define the folder path
folder_path = '/Users/rachelpearson/Documents/Python_folder/'

# Load the dataset
file_name = 'load_data.csv'  # Replace with your file name
```

```
data_path = folder_path + file_name
data = pd.read_csv(data_path)

# Ensure the date-time column is in datetime format
data['date-time'] = pd.to_datetime(data['date-time'])

# Sort by date-time to ensure proper order
data = data.sort_values(by='date-time')

# Interpolate missing load data
if 'load(kW)' in data.columns:
    data['load(kW)'] = data['load(kW)'].interpolate(method='linear', limit_direction='forward')

# Save the updated dataset
output_file = 'filled_load_data.csv'
output_path = folder_path + output_file
data.to_csv(output_path, index=False)

print(f"Missing load data filled and saved to {output_path}")
```

APPENDIX D: CIRRICULUM VITAE

RACHEL PEARSON (703) 618-1176 | pearson5@UW.edu
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EDUCATIONAL HISTORY

University of Washington, College of Engineering Seattle, WA
Ph.D. Major: Civil and Environmental Engineering (Construction, Energy, and Sustainable Infrastructure) Dec, 2024
Qualifying Exam passed Summer 2022
Advised by Dr. Jessica Kaminsky

University of Washington, College of Engineering Seattle, WA
M.S. Major: Civil and Environmental Engineering (Construction, Energy, and Sustainable Infrastructure) May 2024
Advised by Dr. Jessica Kaminsky

University of Virginia, School of Engineering and Applied Science Charlottesville, VA
B.S. Major: Civil and Environmental Engineering *Minor: Environmental Planning and Policy* May 2019

PUBLICATIONS

1. Thelemaque, N., Cotherman, A., Pearson, R., Eichelberger, L., Neumann, R., Kaminsky, J. (in press). "Identifying the Built, Natural, and Social Factors of Successful and Failed Rural Alaskan Water Projects: Perspectives from State and Regional Professionals." ACS ES& T Water. American Chemical Society. https://pubs.acs.org/doi/abs/10.1021/acsestwater.2c00201
2. Pearson, R., Williams, M., Kaminsky, J. (in press). "Analysis of Factors Influencing Teacher and Student Water, Sanitation, and Hygiene Knowledge and Behaviors in Addis, Ababa Ethiopia." ACS ES& T Water. American Chemical Society.
3. Pearson, R., Hamlet, L., Kaminsky, J. (pending acceptance). "Influence of hygiene education in schools on household hygiene knowledge and behaviors in Addis Ababa, Ethiopia." Evaluation and Program Planning.
4. Pearson, R., Thelemaque, Eichelberger, L., Neumann, R., Kaminsky, J. (in progress). "Identifying the Factors Leading to Water Source and System Choice in Rural Alaskan Communities: Perspectives from State- and Regional Professionals".
5. Pearson, R., Lukuyu, J., Kaminsky, J. (in progress). "The Potential of Renewables for Meeting the Electrical Demands of Water Treatment and Delivery in Rural Alaska."

CONFERENCE PROCEEDINGS

1. Pearson, R., Lukuyu, J., Kaminsky, J. "Techno-economic analysis of integrating renewable energy and water treatment infrastructure." *Engineering Project Organization Conference*, Bar Harbor, ME, 2024.
2. Pearson, R., Kaminsky, J. "Biology Shaping Civil and Environmental Infrastructure: A Review of Biologically Inspired Infrastructure." *Construction Research Congress*, Des Moines, IA, 2024.
3. Pearson, R., Kaminsky, J. "Water Source and System Choice in Rural Alaskan Communities: Perspectives from State- and Regional Professionals." *Engineering Project Organization Conference*, Germany, 2023.

SERVICE

Graduate Student Advisory Board, *Co-chair*

- Leader of the Graduate Student Advisory Board running meetings, events, organizing committees, and quarterly updates with the department chair
- Represents the voices of all graduate students in Civil and Environmental Engineering at UW to serve as the main point of contact between CEE graduate students, undergraduate students, and our administration.
- Serves on the diversity, equity, and inclusion (DEI) committee by attending departmental DEI meetings and improving DEI within the department

CEE Department Strategic Planning Committee, *Member*

- Serve on a 12-member team of faculty, staff, students, and alumni for the CEE strategic planning efforts to establish values and mission for the CEE Department, articulate four to six grand challenge research and teaching themes that we will pursue in the coming years, and establish an organizational structure that will help us to achieve this goal

CESI Research Group, *Leader*

- Organize biweekly research group meetings for the Construction, Energy, and Sustainable Infrastructure Group
- Lead up to twelve graduate students and professors in meetings to discuss research projects

Paper Review for Journal of Water, Sanitation, and Hygiene for Development

- Reviewed paper: Access to Handwashing with Soap Facility: A Post-sensitization Investigation of Drivers
- Reviewed paper: An evidence-based approach towards identifying household emerging pollutants in rural areas in Southern Karnataka
- Reviewed paper: The condition of water, sanitation, and hygiene (WASH) in Ghana's basic schools: Empirical evidence from Wa Municipality

Engineers without Borders- UW Student Group, *Graduate Student Advisor*

- Working with student groups to plan and complete projects with Engineers without Borders

INVITED LECTURES

1. Panel Member of Civil Engineering Career Fair Preparation Information Session - Fall 2022
2. Graduate School Representative at CEE Networking Night - Fall 2021
3. Keynote Speaker at American Public Works Association Resume Night - Fall 2021
4. Panel Member of Civil Engineering Career Fair Preparation Information Session - Fall 2021
5. Construction Engineering Course Lecturer – Career fair preparation, justice, equity, diversity and inclusion, engineering economics, earthwork calculations, and productivity calculations – Fall 2021 and Winter 2022

AWARDS AND HONORS

Virginia Tech Future Faculty Diversity Program Fellow

- Selected for the 2023 cohort of scholars and future faculty

Engineering Project Organization Conference Compass Award, *Recipient*

- Presented to a distinguished Ph.D. student at the 2023 conference

Clean Energy Institute Graduate Fellowship, *Recipient*

- Received three quarters of funding to conduct research involving clean energy and participate in Clean Energy Institute lectures, events, and outreach

Valle Scholarship and Scandinavian Exchange Program, *Recipient*

- Received two quarters of funding to conduct research at the Norwegian University of Science and Technology.

Charles V. "Tom" and Jean C. Gibbs Endowed Presidential Fellowship, *Recipient*

- Received one year of funding to do research to develop better water and sanitation systems for populations in developing countries.

TEACHING EXPERIENCE

Co-Instructor, Engineering for Developing Communities Spring 2023

- Responsible for developing course content, delivering lectures, grading, creating the course Canvas website, and interacting with 50+ students
- Received a 4.3/5.0 rating from course evaluations filled out by 73% of the class

Teaching Assistant, Engineering for Developing Communities Spring 2022

- Held office hours 3 hours per week, answering questions on homework, quizzes, and lectures
- Graded homework, quizzes, reflections, and projects in a timely manner for 80+ students

Teaching Assistant, Construction Engineering Fall 2021-Spring 2022

- Conducted class sessions with 60+ students doing practice problem-solving in earthwork and productivity and engineering economics
- Held office hours 3 hours per week, answering questions on homework, quizzes, and lectures
- Collaborated with students using my experience interviewing engineers at my prior job to help train undergraduate students for career fairs and interviews
- Graded homework, quizzes, reflections, and projects in a timely manner for 60+ students

INDUSTRY EXPERIENCE

Bohler Engineering Herndon, VA

Design Engineer Summer 2019-Summer 2021

- Designed stormwater management systems, including storm computations for both quality and quantity
- Completed complex site plans, vertical and horizontal utility layouts and profiles, storm drain computations, and site grading
- Coordinated with clients, jurisdictional county staff, design firms, architects, and surveyors
- Worked with teams to organize and design site plan sets with strict deadlines and high-profile clients
- Founded and lead my office’s first philanthropy committee, which holds one large fundraiser per year and many other smaller events
- Member of a committee that interviewed prospective new hires and interns and spoke about Bohler at college career fairs and information sessions

Virginia Transportation Research Council Charlottesville, VA

VDOT Research Assistant Intern Summer 2018 – Spring 2019

- Conducted literature reviews on stormwater management, reverse osmosis, solar roadways, and sound barrier walls
- Collaborated with research scientists on VDOT’s climate change report and a study on vehicle wildlife collisions

CBG Building Group Arlington, VA

Intern Project Engineer Summer 2017

- Responsible for heading up composite cleans and window deliveries, scheduling inspections, dumpster pulls, and deliveries, logged daily reports and rough openings, worked on MEP and steel coordination and other varied tasks

TECHNICAL SKILLS

Programs

- Nvivo, R, AutoCAD, Civil 3d, Python, Excel

Languages

- Beginner French