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Title Page:

Participatory Modeling of Water Vulnerability in Remote Alaskan Households Using Causal Loop Diagrams

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Abstract

Despite perceptions of high water availability, adequate access to sufficient water resources remains a major challenge in Alaska. This paper uses a participatory modeling approach to investigate household water vulnerability in remote Alaska and examine factors that affect water availability and water access. Specifically, the work asks: how do water policy stakeholders conceptualize the key processes that affect household water vulnerability in the context of rural Alaska? Fourteen water policy stakeholders participated in the modeling process, which included defining the problem of household water vulnerability and constructing individual causal loop diagrams (CLDs) that represent their conceptualization of household water vulnerability. Individual CLDs were subsequently combined and five sub-models emerged: environmental, economic, infrastructure, social, and health. The environmental and economic sub-models of the CLD are explored in depth. In the environmental sub-model, climate change and environmental barriers due to geography influence household water vulnerability. In the economic sub-model, four processes and one feedback loop affect household water vulnerability, including operations and maintenance funding, the strength of the rural Alaskan economy, and the impact of regulations. To overcome household water vulnerability and make households more resilient, stakeholders highlighted policy solutions under five themes: economics, social, regulatory, technological, and environmental.

Keywords: water vulnerability; Alaska; participatory modeling; causal loop diagrams; Arctic; climate change

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1. Introduction

Water vulnerability affects many regions and communities globally as households struggle to secure adequate water due to water availability and access constraints. Water vulnerability is defined as a lack of water availability and water access in the time and place that households require it. Water availability is understood as a household's ability to use or obtain a volume of water of sufficient quality and quantity (WHO/UNICEF, 2015). To meet basic personal hygiene needs and food hygiene, a person requires 20 liters of water per day (WHO/UNICEF, 2015). The Joint Monitoring Programme (JMP) led by the WHO and UNICEF now details that safely managed drinking water must be available on the premises, available when needed, and free from contamination (WHO/UNICEF, 2017). Water access is often measured as the percentage of a population that has sufficient water to meet domestic needs, and it is related to household connections, protected water resources, distribution infrastructure, sustainable use, and affordability (Christina Goldhar, Bell, & Wolf, 2013; Maura Hanrahan et al., 2014; H. Penn, Loring, & Schnabel, 2017).

Past studies have largely focused on the lack of water services in low- and middle-income countries. Yet, in high-income countries, such as in the Arctic, households also suffer from a lack of water access and availability. Household water access is influenced by factors such as household income, existing water infrastructure, and seasonal and climatic factors. The cold Arctic climate may rupture pipes, result in broken infrastructure, or long delivery times for replacement parts. Additionally, water availability varies widely due to local hydrogeological factors and climate change, and due to human activities, such as specific land uses, or government decisions (Kløve et al., 2017). To cope with insufficient water access to their homes, households depend on local water sources that are culturally significant, such as rivers, ice, snowmelt and lakes (Harper et al., 2015; Wright et al., 2018). These water resources can adversely impact health due to poor water quality or contamination in some instances (Daley, Jamieson, Rainham, & Hansen, 2018; Harper et al., 2015; Martin et al., 2007).

Water vulnerability remains a problem in Alaska, where water management challenges have been identified as the most critical factor affecting community vulnerability (Alessa et al., 2011). Indeed, uncertain water supplies and socioeconomic stressors in Alaska have been described as an "axis of vulnerability" (Penn 2016; 1). Over the years, the Alaska state and federal government has initiated several projects to improve drinking water access. These efforts have reduced waterborne diseases, improved the health of communities, and raised awareness of water access problems. However, even with the development of innovative strategies to address remote household water vulnerability, there remains a pressing need to improve understanding of the contextual factors that influence water vulnerability within Alaskan households and its consequences (Alessa et al., 2011, 2008; Medeiros, Wood, Wesche, Bakaic, & Peters, 2017; Sarkar, Hanrahan, & Hudson, 2015). In particular, research highlights how household water vulnerability is influenced by climate change, mining, and wastewater treatment, while emphasizing an analytical gap regarding the relationship between social and biophysical factors and how policy can better mitigate water vulnerability (Alessa et al., 2011; AMAP, 2017; Nilsson et al., 2013).

Studies have highlighted how stakeholders' understanding of the complexity of water systems and nuances of policy options can be critical in developing useful modeling exercises (Halbe, Pahl-Wostl, Sendzimir, & Adamowski, 2013; Inam, Adamowski, Halbe, & Prasher, 2015; Malard et al., 2015). In Alaska, however, efforts to incorporate stakeholders in modeling have been limited (N.J. Wilson, Mutter, Inkster, & Satterfield, 2018). To address this research need, this article asks: how do water policy stakeholders conceptualize the key processes and dynamic factors that affect household water vulnerability in the context of rural Alaska? Following the participatory modeling approach developed by Inam et al (2015) and Malard et al (2015), we explicitly engages with water policy stakeholders in order to deepen awareness of how they conceptualize water vulnerability, and to illuminate the complex institutional environment that affects households' water access.

Participatory modeling is the process of engaging with key stakeholders to incorporate their knowledge into a formalized and shared representation of reality (Inam et al. 2015). The participatory modeling approach serves as a tool to deepen understanding of the macro-scale factors and individual level characteristics of water vulnerability in remote Alaskan households, to explore the feedbacks between variables, and to capture the diversity of perspectives held by water policy stakeholders regarding water vulnerability's causes and consequences. Through the modeling approach, we worked with the identified key stakeholders and had each stakeholder develop a personal causal loop diagram (CLD) that mapped their view of the causes and consequences of household water vulnerability, and feedback loops between variables. The individual CLDs were then integrated to develop a model that provides insight on household water vulnerability in Alaska. The final merged CLD cannot be used to simulate quantitative changes as with a systems dynamics model, but can serve as a valuable tool to visualize the system, allow for qualitative analysis, identify knowledge gaps, increase stakeholder's awareness of the interlinked social and hydrological systems, and encourage short- and long-term policy development. The final merged CLD model developed from this study serves as a first step and may be later quantified and calibrated in a systems dynamic model.

In the following sections, we describe the research's study area in Alaska, outline the methodology underpinning participatory modeling, and discuss the merged CLD model results.

2. Study area

Alaska is the largest U.S. state by area, with an estimated population of 739,795 people in 2017, 239,204 of whom live in rural Alaska (USDA-ERS, 2018). Communities are distributed unequally across the state, with most people living in southern Alaska. Anchorage contains nearly 40% of the state's population (DCCED-DCRA, 2017). Nearly 14.8% of the state's population is Alaska Native (DCCED-DCRA, 2017). The poverty rate in rural Alaska is 14.4% and the unemployment rate is 8.5%, compared to the respective rates of 7.7% and 6.5% in the urban areas of the state (USDA-ERS, 2018). Seventy-nine percent of Alaskan municipalities, which represent communities at the local and regional level, are considered rural with fewer than 1,500 residents (DCCED-DCRA, 2017). Due to the state's size and topography, 86% of Alaskan municipalities are not connected to the road system (DCCED-DCRA, 2017).

Infrastructure challenges affect Alaska's water systems for more than 45 years despite government and community led initiatives (L. Eichelberger, 2017). Inadequate water access has been a persistent issue in more than 200 rural Alaskan communities, whose residents are primarily Alaska Native people. Sixteen percent of rural Alaskan households have access to unimproved surface water, whereas 84% have access to improved water sources (USDA-ERS, 2018). As of 2015, 6.1% of communities in rural Alaska hauled water to their homes, 7.2% had mixed service, 11.1% had individual wells and septic tanks, 17.2% were unserved and 58.3% of communities had piped water supply (AK DEC, 2019).

Household water access is affected by affordability. Between rural and urban areas there is a dramatic difference for the price of water. In the Highlands subdivision of Anchorage, the metered rate per 1000 gallons of water was $4.98 in 2017 for a household, whereas in Eek, Alaska, residents haul treated water from a community watering point and pay $0.25 for every five gallons of water (i.e. $50.00 for 1000 gallons) (RCA, 2017). The Alaska Department of Environmental Conservation is developing an index to reveal the affordability of rural Alaska's water and sewer household rates (AK DEC, 2019). Many remote communities have a service rate for water that is considered a "high burden" due to their household income quintile value and other socioeconomic indicators. For example, the annual rates for water service in Ambler in the Northwest Arctic Bureau, in Pitkas Point in the Kusilvak Census Area, and in Goodnews in the Bethel Census Area are: $42.84, $70.00, and $50.00, respectively. All of these communities' rates are considered a high burden due to the household characteristics, such as annual income.

Due to the costliness of water and challenges accessing it, rural Alaskan homes without piped water were found to use 5.7 L of water per person per day on average (Hennessy & Bressler, 2016), which is far below the WHO standard of 20 L of water per person per day, and the average 302 to 379 L of water per person per day in the U.S. (L. P. Eichelberger, 2010; Thomas et al., 2016; USGS, 2016). Thomas et al. (2016) document that before in-home water service was installed in Alaskan homes, mean household water use was between 3.4 L and 5.7 L per person per day, compared to 34.8 L to 143.3 L per person per day after in-home water installation (Thomas et al., 2016). There is great variation between individual households' water use. In Newtok, Alaska, a recent study found that household consumption patterns range from 1.1 to 16.2 L per person per day (L. Eichelberger, 2019).

Alaska has remarkably low water access compared to other Arctic nations. In Nunavut, water use in 2014 was reported to be 110 L per person per day, with a Canadian mandate provide 90 L per person per day (Bressler & Hennessy, 2018; Daley, Castleden, Jamieson, Furgal, & Ell, 2014) in Nunavut. In the Northwest Territories, the Canadian mandate requires 90 L of water per person per day if it is trucked, and 225 L of water per person per day if it is piped (Bressler & Hennessy, 2018). In Lapland, the Finnish mandate requires 120 L of water per person per day, and in Norway, the mandate ensures 200 L of water per person per day.

Similar to Alaska, Greenland and the Russian Arctic have comparatively low water access. In Greenland's northern towns of Upernavik and Qaanaaq, water use is approximately 35 L per person per day, and in the nine settlements surrounding those two towns, water use is about 10 to 17 L per person per day (Hendriksen, 2019). While two settlements have zero L per person per day (Hendriksen, 2019). In the Russian Arctic, Siberia and Far East, water use is approximately 125 to 340 L per person per day, but where water may be accessible, it may not be available due to high rates of contamination and poor water quality (Dudarev et al., 2013).

Low water use is considered a health concern because insufficient water quantity and water quality contribute to higher rates of waterborne diseases, such as gastrointestinal infections, and water-washed diseases, such as skin and respiratory infections (Hennessy & Bressler, 2016; Hennessy et al., 2008). In rural Alaskan communities where fewer than 10% of homes have piped water supply, infants are hospitalized at a significantly higher rate for pneumonia and respiratory infection (Thomas et al., 2016). Among Alaska Native children under the age of 5, the rate of hospitalization and outpatient visits for diarrhea was twice the US rate in 2004 (Thomas et al., 2016).

Due to the disparity in water access between urban and rural Alaskan households and the resulting health consequences that households face, this research investigates water vulnerability at the household scale in rural communities. Households are central to responding to external stress, and are crucial to understanding social organization around water resources (Toole, Klocker, & Head, 2016). Water use and environmental issues are refracted through social relations within the household, and the demands of everyday life (Toole et al., 2016).

3. Methodology

The participatory modeling approach used in this article is guided by a socio-hydrology framework, which studies the cascading effects of hydrologic changes on communities and the complex interactions between society, institutions, and the natural environment (Sivapalan et al., 2014; Wheater, 2014). The framework analyzes aspects of political ecology by understanding that water systems are shaped by power imbalances and cultural politics. Indeed, emerging water problems globally, such as pollution or scarcity are frequently due to a crisis of governance rather than a problem of water resources (Falkenmark, 2001; Gupta, Pahl-Wostl, & Zondervan, 2013; Linton, 2014; Vörösmarty, Pahl-Wostl, Bunn, & Lawford, 2013). These water problems may stem from the fact that historically water governance strategies neglected the human dimension and complexity of systems (Pahl-Wostl, Holtz, Kastens, & Knieper, 2010).

Since policy and law influence the context in which households make decisions, this research engages with stakeholders at the policy level to improve understanding of how they conceptualize the variables that affect water vulnerability, its consequences and feedback loops. These stakeholders are referred to as water policy stakeholders in this article. In capturing these stakeholders' perceptions through participatory modeling, it is possible to examine the characteristics of institutional politics, society, scale, power, and history that inform local water vulnerability (H. J. F. Penn, 2016). These water policy stakeholders impact household water vulnerability as they are involved in rural water policy and management; implement regulations; provide guidance to federal and state agencies; and contribute to the development of future water policy. By focusing on policy stakeholders, this research acknowledges that households make choices on how to adapt to water vulnerability in circumstances that are not only of their own choosing (Healey, Magner, Issaluk, & Mackenzie, 2011).

In the participatory modeling approach (Inam et al. 2015, Malard et al. 2015), the facilitator works with the stakeholders to construct CLDs through a four-stage process: 1) problem definition and boundary setting, 2) stakeholder analysis and selection, 3) individual stakeholder interviews to develop CLDs and subsequent digitization of CLDs, 4) construction of a collective CLD (Inam et al., 2015). Each of these stages is detailed in the following sections. The participatory modeling process was conducted over a 5-month period from April to August 2018.

3.1 Problem definition

To start the modeling process, the lead author facilitated a discussion to define the problem both physically and conceptually with individual stakeholders. In the context of this study, we define stakeholders as practitioners who can affect household water vulnerability through their profession and work (Achterkamp & Vos, 2007). Stakeholders to be involved in participatory modeling were identified through knowledge of the literature, purposeful and snowball sampling, and semi-structured interviews (Chevalier & Buckles, 2013). During the problem-framing process with the stakeholders, the boundaries of the problem were iteratively narrowed through: (i) selection of problem theme and key factors (ii) definition of time horizon, (iii) definition of the boundaries of the model, (iv) the key consideration of the variables and relationships between concepts, and (v) identification of stakeholder groups. These steps took place with and were guided by the stakeholders.

In the discussions with stakeholders, household water vulnerability in rural Alaska was identified as an enduring problem that would benefit from stakeholder engagement and participatory modeling. During the CLD development with each stakeholder, problems of water access and water availability due to biophysical and anthropogenic factors were considered. Problem themes that arose centered on climate change, environmental conditions, health, social impacts, economics, governance and infrastructure. Household water vulnerability was confirmed by the stakeholders to be a critical problem. Stakeholders generally defined household water vulnerability as a household's access to a sufficient quantity of safe quality water at the household level, and the availability of water in remote Alaskan households.

Stakeholders emphasized that when water is available, there is an issue of access because often water collection points are located far from households. In the stakeholders' framing of the problem, household water access and water availability include problems of quantity and quality. Stakeholders discussed how government regulations defining clean drinking water may differ from household perceptions of what is safe. The stakeholders articulated that both the causes and consequences of water access in rural Alaska were important to consider. The time horizon for the problem was established to be the last thirty years. The stakeholders defined the households as rural or remote, meaning that they are in communities that are difficult to access, and may be off the road system. The households are not in cities or in the developed areas directly surrounding cities. The problem definition continued to be iteratively refined throughout stakeholder identification and selection, and the participatory modeling process.

3.2 Stakeholder identification and analysis

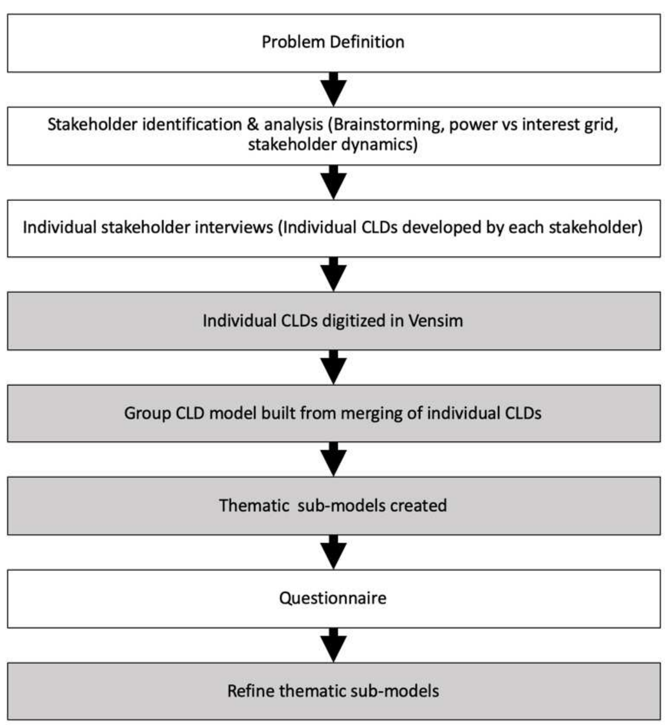
After problem framing, those stakeholders were included in the participatory modeling process, as well as additional stakeholders that were identified as individuals that can influence the situation or proposed action, or may be affected by it (Chevalier & Buckles, 2013). Therefore, stakeholder identification and problem framing were an iterative process conducted with the stakeholders. Based on the discussion with stakeholders and the literature review (Sohns, Ford, Riva, Robinson, & Adamowski, 2019), several groups involved in addressing water vulnerability in remote Alaskan households were identified as important to include in the modeling process. The different groups address water vulnerability in a variety of mechanisms. For example, the U.S. Arctic Research Commission (USARC) hosts a water and sanitation working group that promotes research, development, and funding of innovative strategies. The USARC improves village level capacity and enhances technical assistance for water and wastewater services. Members of the working group include individuals from the Alaska Department of Conservation (DEC), Alaska Native Tribal Health Consortium (ANTHC), Alaska Pacific University, Alaska Public Health Association, Centers for Disease Control and Prevention (CDC), Denali Commission, Environmental Protection Agency (EPA), Indian Health Service (IHS), USARC, University of Alaska Anchorage, University of Alaska Fairbanks, Village Safe Water, U.S. Department of Agriculture (USDA), and Yukon-Kuskokwim Health Corporation.

The USDA Rural Development program helps remote Alaskan villages provide safe, reliable drinking water and waste disposal systems for households and businesses. The Alaska DEC's Village Safe Water program seeks to improve public health and compliance with environmental laws by upgrading the level of sanitation facilities in rural communities through financial and technical assistance. ANTHC partners with communities to support water and sewer systems through the Alaska Rural Utility Collaborative (ARUC).

Stakeholders within these organizations were contacted by email and phone to identify other people to include in the participatory modeling process (Achterkamp & Vos, 2007). This kind of purposeful and snowball sampling use connections between people to find individuals that are especially knowledgeable of and central to the phenomenon of interest (Palinkas et al., 2015). Semi-structured interviews from February to August 2017 with people in Alaska over the phone and in person identified additional stakeholders to include in the participatory modeling process. Therefore, the stakeholder list was iteratively updated.

Once key stakeholders were identified, stakeholder analysis was conducted to describe the characteristics and relationships of stakeholders and explore their relationship to the problem variable (see Figure 1). Stakeholder analysis categorizes people based on their role, interest, power, legitimacy and urgency (Inam et al., 2015; Mitchell, Agle, & Wood, 1997). We selected stakeholders based on their level of interest and sense of urgency regarding household water vulnerability, and their legitimacy and power in the decision-making process and management of household water vulnerability (Butler & Adamowski, 2015).

Figure 1: Participatory modeling process. Blue rectangles indicate that the step included the 14 stakeholders (engaging them individually), while the orange rectangles indicate the step was done without stakeholder involvement.



Legitimacy is defined as the social or legal rights and responsibilities of a stakeholder regarding the issue, and that those rights are recognized through law or customs, and the stakeholder exercises those rights. Power is the ability of a stakeholder to influence others and use resources to achieve their goals, some sources of power may be economic wealth, political authority, access to information, and social ties (Chevalier & Buckles, 2013). Urgency implies that the issue is time-sensitive and critically important to the stakeholder (Butler & Adamowski, 2015). A power versus interest grid (see Figure S1 in supporting materials) was also used in the stakeholder analysis process in order to prioritize stakeholders for interviews (Bryson & Crosby, 2006).

To ensure critical stakeholders were not missing, the individuals were organized in a stakeholder typology diagram that reflects their dynamics. These stakeholder typologies are: experts, decision-makers, implementers, and users (Inam et al., 2015). Many interviewees had multiple stakeholder roles through their employment and personal experience, which influenced their conceptualization of household water vulnerability in the modeling process from the perspective of expert, decision-maker, implementer, or user.

Overall, 14 stakeholders were recruited to participate. The stakeholders were located primarily in the Anchorage, with one stakeholder in Fairbanks (see Text S1 in supporting materials). The number of stakeholders selected is consistent with other studies using the participatory modeling approach (Inam et al., 2015; Malard et al., 2015). The main expertise of the stakeholders was health (2), science policy (2), economics (3), environment (1), and engineering (6). The stakeholders represented federal agencies (5), state agencies (3), non-governmental organizations (4), and academia (2). The stakeholders worked on issues affecting water and sanitation systems in remote Alaska, including tribal lands. Although the majority of the stakeholders lived in urban areas of Alaska, most had extensive experience working and/or living in rural Alaska. The final list of stakeholders to take part in the modeling process sought to represent all categories, and include diverse perspectives of the defined problem (Butler & Adamowski, 2015). After the list of stakeholders was generated, stakeholders were asked if there were any others that should be added. Those people were contacted, and interviews were arranged when possible.

3.3 Constructing causal loop diagrams (CLDs) through stakeholder interviews

Once stakeholder analysis was completed, the identified individuals were independently contacted to set up interviews. One individual interview was conducted with each stakeholder to facilitate the development of a CLD on the defined problem, household water vulnerability. On average, an interview was approximately 85 minutes. Interviews took place in Alaska over five weeks in April and May 2018.

Participatory modeling has been used successfully in natural resources management and watershed planning (Butler & Adamowski, 2015; Medema, Wals, & Adamowski, 2014; Voinov & Bousquet, 2010). System conceptualization begins with the development of CLDs (Blair & Buytaert, 2016). These models identify individual relationships and interactions in the system as root causes of feedbacks, time-lags, and other non-linear effects (Blair & Buytaert, 2016). A CLD is a visual tool that identifies central concepts in a complex system that may be affecting water vulnerability (Voinov

& Bousquet, 2010). Each CLD represents a stakeholder's personal conceptualization of the system (see Figure 2).

Figure 2: An example of a stakeholder's CLD. Pink post-it notes represent the causes of the problem variable; the blue post-it note represents the problem variable; the yellow post-it notes represent the consequences of the problem variable.

To create their individual CLD, the stakeholders followed a four-step process, described by Vennix (Vennix, Akkermans, & Rouwette, 1996). First, each stakeholder was presented with the objective of the method and provided instructions on how to develop a CLD through a simple example. The same example that described variables affecting traffic congestion was presented to all stakeholders. Each stakeholder found this sufficient to creating their own model. Second, a large piece of white paper and sticky notes of three different colors were provided to the stakeholder to generate the CLD (Figure 2). A different color sticky note was used for the problem variable (blue), the causes (pink), and consequences (yellow). Each stakeholder would place the problem variable in the center of the sheet, and then add first order (direct) causes and then second order (indirect) causes to the sheet of paper in columns to the left of the problem variable. The most direct causes occupied the columns closest to the problem variable.

The stakeholder identifies which variables are connected to one another by drawing arrows between them. The arrow represents a causal link. By following the arrows, it is possible to explore causal pathways and feedback loops between the connected variables. The stakeholder also assigns each arrow with a polarity (+/-). The negative (-) polarity indicates an inverse relationship between the causative and effect variables, whereas a positive (+) polarity signals that if the causative variable increases or decreases, the effect variable will also increase or decrease in the same direction. The causes are the variables that are salient in the stakeholder's perception of the system and do not assess the relative importance of the variables. The first and second order consequences are then added to the piece of paper in columns to the right of the problem variable. The stakeholder also assigns arrows and polarities to the consequences.

In the final stage of developing the model, the stakeholder draws relationships between the consequences and the causes, which create feedback loops. In CLDs, it is important to identify closed loops in order to determine if they are reinforcing or balancing in nature. A reinforcing loop self-reinforces in a positive feedback and represents an exponential increase or decrease in a process. Whereas a balancing loop equilibrates the system because an increase in the value of the problem variable generates a change across the feedback loop that reduces its magnitude.

To aid in the creation of the CLDs, the facilitator guided stakeholders with the following series of questions (Halbe et al., 2013):

1. How has the problem developed over time?
2. What are the most important direct causes contributing to the problem's development?
    a. What are the indirect causes?
    b. What are the polarities of those relationships?
3. What are the direct consequences of the problem?
    a. What are the indirect consequences?
    b. What are the polarities of those relationships?
4. What are the feedback processes?
5. What kind of policies can be adopted to solve this problem in the short term?
    a. In the long term?
6. What are the main obstacles to those policies succeeding?

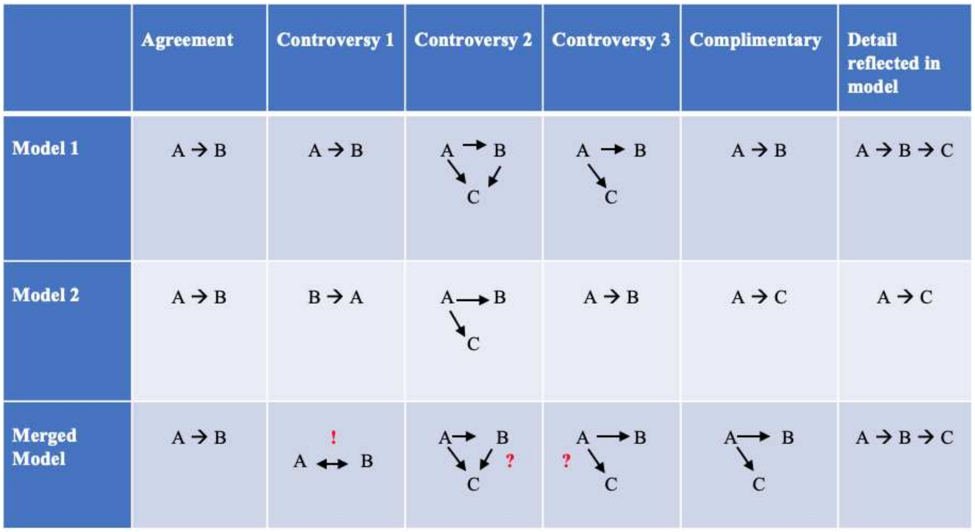
Other than asking the guiding questions or helping to clarify questions from a stakeholder, the facilitator remained quiet in order to let the stakeholders independently develop a CLD without bias or interruption. CLD generation was completed on a one-on-one basis with the facilitator so that stakeholders could freely express their opinions.

3.4 Developing the merged CLD

After all 14 stakeholders developed their individual CLDs in separate interviews in April and May 2018, the facilitator generated a merged CLD using VENSIM software in June 2018 (Inc., 2015). This process aggregated the individual CLDs by starting with the most complex individual CLD and then added insights from the other models one by one. If there was agreement between the individual models regarding the variables and relationship between those variables, then there was no controversy and variables continued to be added to the model. If one of the models shows an additional variable between two variables in the cause-effect relationship, then the middle variable was added so that the merged model reflected that detail (Inam et al., 2015; Malard et al., 2015).

If there was disagreement between models, the difference was noted as being one of three types using the method described in Figure 3. First, if there was disagreement in the direction of the arrows between variables, the group CLD reflected those divergent opinions with an arrow in both directions and an exclamation point between variables. Second, if the first model depicted variables as consequences or causes of a variable that another model show is independent or not related, then the merged model reflected the connection between the variables but flagged it with a question mark. Third, if the first model showed a variable affecting two other variables, but another model showed that same variable only affecting one variable, then the first model’s additional cause-effect relationship is flagged with a question mark.

Figure 3: Main Types of Controversy



The merged model included all diverging perspectives of the 14 stakeholders. (See Figure S2 in supporting materials for final merged model). The final CLD captured the complete system and allowed the macro-scale outcomes, such as emergence and cross-scale interactions to be assessed (Blair & Buytaert, 2016). Due to the rich detail of the merged model, five sub-models were identified: economic, environmental, infrastructure, social, and health (Figure 4). Figure 4 highlights the major components of each sub-model that were described by stakeholders during CLD development. The participatory modeling process deepened understanding of the many factors that influence household water vulnerability, of future research needs, and insight into the complex system to inform future policy.

To address the points of disagreement in the merged sub-models, we sent a questionnaire to the 14 stakeholders. The questionnaire asked detailed questions about the cycles and processes identified in the thematic sub-models (Figure 4). Eleven of the 14 interviewed stakeholders provided detailed comments and feedback on the questionnaire. The responses to the questionnaire and subsequent discussions with stakeholders elucidated differences in ideas regarding causation and perspectives around household water vulnerability. The questionnaire reconciled diverging opinions on relationships between variables and improved the thematic sub-models. It is important to note that while the sub-models were analyzed independently, they are all related and together create the merged CLD.

Figure 4: Thematic sub-models derived from the merged CLD

Sub-Model		Major Themes
1	**Economic**	Financial burden
		Operation and maintenance capacity
		Household income constraints
		Economy in rural Alaska
2	**Environmental**	Locally available source water
		Water security
		Climate change
3	**Infrastructure**	Piped or haul water system
		Village level capacity
4	**Social**	Population changes
		Community resilience
		Hydrosocial
5	**Health**	Lung/skin disease
		Gastrointenstinal illness
		Mental health
		Quantity of water consumed

3.5 Limitations

There are various limitations associated with CLDs and their application, including that since CLDs are models, they are a representation of reality and may not reflect the true nature of the system (Inam et al., 2015). To address this, we engaged with stakeholders from varied backgrounds and with diverse perspectives to ensure that many representations were captured in the final CLD. Critics of participatory modeling argue that there may be little correspondence between the stakeholder's mental model and the loop structure that is generated by the modeling process (Bureš, 2017). To address this, we discussed the results with stakeholders and incorporated stakeholder feedback through the questionnaire. Critics also argue that top-down models, such as CLD, only produce deterministic results. This article followed the simplification process developed by Bureš (2017) and lists the exogenous variables that were removed in Table S1 in supporting materials. The approach to consider parts of the model separately is sometimes criticized since the value of the gathered complexity in the merged CLD is reduced through the process of thematic model development (Bureš, 2017). While we developed sub-models, they are linked within the larger, merged CLD so the system's complexity is intact.

4. Results

The following results detail the findings from the participatory modeling process and represent the stakeholder's perceptions of household water vulnerability.

4.1. Discussion of thematic sub-models from the merged CLD

4.1.1 Environmental sub-model

The environmental sub-model consists of several main factor groupings: locally available source water, water security and climate change. Stakeholders highlighted that local environmental features and climate change are central to whether there is water available to households. Local source water availability determines whether a household has sufficient quantity of good quality water. Local water availability is affected by water's seasonality and risk of pollution from both natural sources such as excess minerals, and man-made sources from resource or industrial development. In the interviews, stakeholders were forward looking, and discussed future impacts on water resources, such as increasing climate change impacts that may make the hydrological cycle more variable and households will be less certain whether historic water supplies will exist in the same time and place.

Stakeholders highlighted the importance of different perceptions of water due to cultural preference. Many households continue to gather drinking water from rivers, lakes, or melt ice. Collecting water from these resources has contributed to household knowledge of seasonal water attributes, such as water levels and long-term changes in freshwater (C. Goldhar, Bell, & Wolf, 2014). Stakeholders described how climate change has also been affecting local hydrological systems and landscapes due to permafrost thaw, silting of river sources, and changing local soil conditions. Stakeholders detailed how intensifying climate change impacts, such as coastal erosion and storm surge may compromise water sources that communities depend on due to damaged water infrastructure or saltwater intrusion into drinking water sources. All of these changes will profoundly impact water quality and quantity, and therefore influence the level of water treatment necessary to meet state and federal regulatory standards. Such changes to water quality affect local source water availability because communities may not be able to afford the new level of treatment required or have adequate training.

Stakeholders additionally described how environmental and physical barriers influence local source water availability because difficult topography may make certain water systems or infrastructure too costly to construct. Stakeholders highlighted how availability and access to a safe local water supply affects human health. With increased access and availability of water to remote Alaskan households, there is an immediate health benefit because households no longer need to practice extreme water conservation or limit hygiene practices due to prioritized water use (Thomas et al. 2016). Stakeholders detailed how with improved water quality and quantity, people use water for personal hygiene and cooking which reduces the incidence of lung and skin disease and gastrointestinal illness. They also discussed how more available water alleviates stress and therefore improves mental health. Stakeholders also emphasized how better hygiene improves dental care through tooth brushing.

In discussions with stakeholders after the merged CLD was developed, two processes linking variables to household water vulnerability were identified. First, more environmental and physical barriers, such as geography or cold climate can restrict the economy in rural Alaska. A constricted economy impacts access to water due to household income constraints and therefore decreases household water access. Stakeholders described how more environmental and physical barriers can increase the capital costs of constructing water systems, which may make a community less likely to build water infrastructure and then decrease water access. Second, an increase in climate change impacts, such as permafrost thaw or siltation of rivers may make some water resources no longer available or usable. However, climate change may also increase rainfall in certain areas, making more water available, but not necessarily in the required time and place (AMAP 2017). Stakeholders discussed how climate impacts may increase capital costs to construct or to maintain systems in some areas, which may make communities less inclined or able to build water infrastructure. Capital costs may increase due to more conservative designs targeting greater resiliency in the face of uncertain climatic changes. Therefore, due to increased costs, water access may not improve beyond the existing system.

4.1.2 Economic sub-model

The economic sub-model consists of several main factor groupings: operations and maintenance capacity, household income constraints, economy in rural Alaska, financial burden of water, and funding. Operations and maintenance capacity are affected by the village's size, the level of training of operators, and the community's ability to retain trained operators. Stakeholders described how a community's ability to retain operators is shaped by the presence of available and interested personnel, the hours and pay for operators, the difficulty of exams, and potential cultural bias against full time employment in remote communities. Stakeholders also emphasized how operations and maintenance capacity is influenced by existing software and hardware and the type of water system in the community, such as piped or haul. It is also influenced by state revenue sharing and the community's access to funding for operations and maintenance using the competitive procurement process.

During the participatory mapping process, stakeholders emphasized that household income is a dominant factor affecting water vulnerability. Stakeholders described how household income influences water vulnerability because some people may not be able to afford water if the cost of equipment, such as a snowmobile or ATV and the associated fuel prices increases suddenly. If available water sources are far from their home, households may be forced to spend more on fuel to haul water. These tradeoffs are a direct tension between water and energy security and determine whether a household can afford sufficient water supply.

Additionally, household income may be constrained by the number of people occupying a home. Stakeholders described how some families share income among members in order to provide for children, elderly or unemployed members. Household incomes may also be inhibited if there is a reduction to the permanent fund division (PFD) which provides Alaskans with an annual dividend. These challenges to water vulnerability, and constraints on household income are increasing due to climate change impacts, such as storm surge and coastal flooding. Households may be forced to adapt to these impacts at the expense of other aspects of their welfare, therefore reinforcing poverty traps and economic marginalization (Eakin et al., 2016).

The character of the water system's economics also affects household income. For example, if water bills are charged on a flat monthly rate, if users pay per volume at a central watering point, or if there are few users on a water system it may be more difficult for households to afford water access. Stakeholders also emphasized that household water vulnerability is affected by the economy in rural Alaska. They described how the economy in rural Alaska is influenced by how robust the local job market is, the time that people have available for subsistence work and other activities, and environmental and physical barriers to certain jobs and industries.

Through discussion with stakeholders after the merged CLD was developed, four processes and one reinforcing loop were identified in the sub-model. These processes and loop illuminate connections between factors and their impact on water access. First, if there is more access to operations and maintenance funding, there will be more village level capacity to operate and maintain systems, if skilled operators are available. Good operations and maintenance in a village will likely decrease necessary capital expenditures required to repair systems, as a result there may be more funding available to construct new water systems in underserved areas. Stakeholders said this would positively impact water access and availability because it would reduce the number of days that a system is non-functional.

Second, stakeholders revealed that there is no direct causal relationship between health care costs and funding for water infrastructure, such as for construction or for operations and maintenance. Stakeholders described the process of how medical care costs have been increasing and while the health care budget is separate from funding for water infrastructure, if the overall state budget is too high there may be greater hesitation to fund water and sewer capital projects. As a result, water security may be affected since funding for construction, or operation and maintenance of water systems would be reduced. Therefore, the prevalence of water-related illness may increase or stay at the same rate. This will increase hospitalizations, doctor visits, and medical costs.

Third, a process identified in the sub-model is: with more available jobs, and a stronger economy in rural Alaska, there are fewer household income constraints, which reduces household water vulnerability because water is more affordable. This would mean households would have more water available for personal hygiene and make them more available to work and accept potential jobs due to reduced illness and improved mental health.

Fourth, the impact of regulations on the economics of water infrastructure was highlighted. As regulations regarding water quality increase, the capital cost of building infrastructure increases, which may reduce funding agencies' interest in providing the capital necessary to construct infrastructure. This would result in no new water infrastructure being constructed, or improvements of existing infrastructure. Stakeholders described how more regulations regarding the operations and maintenance of water systems, increases the capital cost of the systems. Since communities carry this expense, it may decrease their interest in building water infrastructure.

Fifth, the merged CLD revealed a reinforcing loop. Although the economy in rural Alaska is not strong at the moment, stakeholders emphasized that if the economy in rural Alaska were to improve, extreme water conservation in households could decrease because water usage would become more affordable. As people can afford to be less conservative with water use, water access and availability in the home could be increased, which may increase school attendance since people are not afflicted with as many water-borne or water-related diseases (Cooper-Vince et al., 2017). The graduate rate would then increase. Stakeholders said that as graduation rates go up, those individuals are qualified for more jobs, and the economy in rural Alaska would continue to strengthen.

4.1.3 Health sub-model

The health sub-model consists of several main factor groupings: lung and skin disease, gastrointestinal illness, mental health, and quantity of water consumed. In the health sub-model, stakeholders identified additional processes linking variables of household water vulnerability. First, stakeholders described how an increase in access and availability of water improves sanitation infrastructure and decreases use of honey buckets and outhouses. This decreases personal discomfort and inconvenience, and therefore increases mental health by reducing stress. Stakeholders described how improved mental wellbeing may also increase village level capacity to operate and maintain water systems, or to apply for funding. With increased operations and maintenance funding, the community's water access will be maintained or improve, further benefitting mental health. One stakeholder emphasized that mental health is a result of the improved water and sanitation improvements, not a cause of improved capacity that leads to increased water and sanitation access.

This finding supports water security research that has been conducted in other rural, remote and marginalized households other Arctic regions, such as Labrador, and in distant geographies, like Nepal, Bolivia, and Uganda (Biggs, Duncan, Atkinson, & Dash, 2013; M. Hanrahan, Sarkar, & Hudson, 2016; Mushavi et al., 2019; Sarkar et al., 2015; Wutich & Ragsdale, 2008). The findings of this participatory modeling process support recent literature that identifies a connection between a sense of choiceless-ness, depression, and emotional distress tied to water insecurity (Brewis, Choudhary, & Wutich, 2019; Cooper-Vince et al., 2017; Mushavi et al., 2019; Wutich & Ragsdale, 2008). For example, Mushavi et al. (2019) describe the statistically significant association between water insecurity and depression symptom severity among men and women in rural Uganda. In Haiti, Brewis et al. (2019) documented how water insecurity has a direct and independent impact on depression and anxiety levels in households. These studies emphasize the impact of household water insecurity on health and reveal that the lived experience of water insecurity differs with age and gender (Cooper-Vince et al., 2017; Mushavi et al., 2019).

Households in the Arctic and in the non-Arctic contexts suffer from stress and anxiety due to lack of sufficient water supplies. The relationship between water insecurity and emotional distress, and its mechanisms are critical to consider as household water insecurity is addressed through health and policy interventions (Brewis, Choudhary, et al., 2019; Mushavi et al., 2019). In order to address the impacts of water shortages on mental health and manage water resources effectively, the dialogue between governments, utility operators, and community leaders must be informed by how households use water supplies, perceive drinking water quality, and cope with water shortages.

In the health sub-model, stakeholders also identified how as access and availability of water increase, funding goes up, which increases water quantity and quality. As a result, stakeholders explained how this diminishes the replacement of water with sugary beverages, such as soda. Stakeholders described how increased water access therefore decreases the incidence of dental and medical complications, such as insulin resistance, diabetes, and obesity from sugary drinks. A recent study found that not having access to in-home piped water has a borderline significant effect on behaviors surrounding sugar-sweetened beverage consumption and general perception of health in rural Alaska (Mosites et al., 2020).

4.1.4 Social sub-model

The social sub-model consists of several main factor groupings: population changes, community resilience, and hydrosocial impacts. In the sub-model, stakeholders described several factors that influence household water vulnerability including the inability to repair systems due to missing parts. Stakeholders also described difficulty in securing funding for water systems, which are exacerbated by language barriers and the challenges of grant writing. Stakeholders emphasized the hydrosocial impacts of water vulnerability, such as lifestyle changes, convenience, and social stigmas.

Stakeholders also discussed the connection between water and food security. The process they described occurs when people have increased access to piped water supply, which leads to more time for subsistence work, such as gathering food. As a result, food security increases. In turn, this increases household income because less money has to be spent on store-bought food. This may mean that there is more money available to purchase water, which may further reduce household water vulnerability.

These findings support research in other contexts that have demonstrated how water and food insecurity are acute and chronic stressors that undermine human health. Brewis et al. (2019) revealed that water insecurity chronically coexists with household food insecurity. In their examination of cash expenditures and food and water insecurity, Stoler et al. (2019) found that water infrastructure interventions that increase households' water costs may exacerbate water insecurity, especially for the lowest-income households. Along the Texas-Mexico border, Jepson (2014) revealed that factors such as service reliability or physical capacity to access water reduced household water security among the economically disadvantaged. In her work, Jepson (2014) further documented the significance of water quality acceptability to households and whether they were water insecure.

Similar to food sharing practices documented in the Arctic, water is shared within a household and between kin. Water sharing practices have been documented in other regions, such as sub-Saharan Africa and Bangladesh, where water is shared between neighbors and families as a coping strategy against water shortages, lack of access, and unaffordable water supplies (Brewis, Rosinger, et al., 2019; Stoler et al., 2019; Wutich et al., 2018). In sub-Saharan Africa, these practices were a form of general reciprocity with no expectation of direct payback between households (Brewis, Rosinger, et al., 2019). These water sharing practices can buffer households from the negative health impacts of water shortages (Stoler et al., 2019). Stakeholders stressed that funding is an issue of political will, advocacy, and problem awareness. With increased statewide knowledge of the water challenges that rural Alaska faces, stakeholders believe funding for rural water systems will increase.

4.1.5. Infrastructure sub-model

The infrastructure sub-model consists of several main factor groupings: piped or haul system, and village level capacity. In the sub-model stakeholders discussed the relationship between a lack of funding for water systems, the Arctic's difficult topography, and inadequate infrastructure. Due to the environmental conditions and remote geography of Alaska, stakeholders described the difficulty in providing sufficient infrastructure. Stakeholders also emphasized that future infrastructure should consider community capacity, belief structure, and local preferences. In considering such factors, infrastructure will be more long-lasting and resilient.

4.2 Policy Implications

The 14 stakeholders described policy solutions that could help alleviate household water vulnerability. The solutions are presented under the following five main themes: economics, social, regulatory, technological, and environmental, which were developed around the policy tool that could be used to produce a new outcome under the respective theme. It is important to note that many of the policy recommendations described below are cross-cutting. For example, although one policy may predominantly impact an economic issue and therefore be labeled an 'economic policy solution,' the policy may also influence social aspects of remote Alaskan households.

4.2.1 Economic policy solutions

Economic solutions proposed by stakeholders emphasized a need for increased operations and maintenance support from federal and state governments for water systems. Another stakeholder suggested that it would be best to promote for-profit native corporations to fund water and sewer systems in villages. This funding could add jobs, improve access to water, and decrease long term capital expenditures. Some stakeholders proposed creating a government-run fund to support operation and maintenance of existing systems. This would help marginally financially feasible communities get support for their water systems regarding basic elements, such as billing collection, maintenance and procedures, and emergency plans. Stakeholders agreed that current financial mechanisms in Alaska are outdated and that more communities need to become qualified to apply for loans and build water infrastructure and to support operations and maintenance. Increased construction funding would allow for improved water monitoring and treatment. A stakeholder said that regionalized funding would be ideal because each region has different challenges.

Better funding for operations and maintenance would allow for improved institutional and community capacity to operate and maintain water systems. It would also create more positive outcomes in operation and increase the longevity of capital funding investments, which may lead to more built infrastructure. One means of increasing community capacity is through operator training and certification, which stakeholders said is a necessary policy. For example, people could be certified to operate their village's specific water system. This would overhaul training requirements for rural water systems and better consider operators' language and education background. A stakeholder encouraged the implementation of a best practices scoring system so that operations and maintenance may be better funded from an outside entity. Through a scoring system, the likelihood of utility success would increase.

Several stakeholders said that subsidizing user fees has helped people access water. These stakeholders emphasized that the federal or state subsidy would assist small villages with operation and maintenance expenses so that systems do not degrade due to deferred maintenance. Yet, these stakeholders emphasized the need for direct research to support this claim. Future research must demonstrate that subsidies for water are effective at a local level. A different stakeholder believed the opposite, stating that subsidies to help finance water are not a good option because water is not cheap to collect or treat. If subsidies were implemented, there is concern that they may lead to water waste or a lack of conservation since water would become more affordable.

4.2.2 Social policy solutions

Social policy solutions focused on improving the quality of life and public health in rural Alaska in both the short and long term. Stakeholders said there should be policy initiatives to build up the local economy in these remote villages. By alleviating poverty and the depressed economy, communities' health would improve due to less water conservation as water becomes more affordable. Long-term policies should affect the wellbeing of rural communities, such as ensuring that there is sufficient housing so that overcrowding does not occur. Policies should also support mental health initiatives in a comprehensive manner. Another social policy proposed by stakeholders is for Alaska to implement a soda-tax in order to pay for preventive services such as dental screenings, tooth brushing education, and exercise programs or outdoor trails in order to offset adverse health impacts from soda consumption.

Additionally, stakeholders emphasized that schools should continue to recognize the value of Native culture with culturally specific curriculums that focus on the traditional lifestyle. Policies should recognize the differences between life in rural Native Alaska and urban areas, specifically reducing the technical complexity of infrastructure, capital costs, and operations and maintenance costs. Policies should help tribes apply for water rights such as intake and outtake permits in order to secure water access. It is also important that all of Alaska commit to providing higher education that incorporates information on rural Alaska, such as the disparity between urban and rural water and sanitation systems.

4.2.3 Regulatory policy solutions

Regulatory solutions recommended by stakeholders included revising or tailoring regulations to reduce burdensome requirements in specific circumstances in order to allow construction of less costly systems on the way to a fully compliant system. These systems would be supported by system specific testing and modeling based on local source water contaminants and would be overseen by trained and certified operators. Changes to regulations would improve water access in rural households. Stakeholders emphasized that regulatory reform is necessary so that there is not a water system policy that is "one size fits all" across diverse communities and topographies. A stakeholder said that some public health improvements are burdensome and that new regulations would help communities find good water systems that meet their needs and capacity.

Currently, there are no water quantity standards, but there are water quality standards. Stakeholders emphasized the importance of water quantity in alleviating poor health. Many stakeholders said that if the quantity of water being delivered to households can be increased, it should be, even if that water is of less good quality. These stakeholders emphasized that there should be ways to provide more water to households through diverse or untreated water sources, even if they are not up to EPA standards. For example, policies could also provide funding for alternative systems, such as rainwater catchment systems or grey water recycling and reuse, which may not meet potable water standards at the state or federal level but could improve quality of life in households and communities.

In order to improve management of water systems, a stakeholder proposed that the state government assume ownership of the water system. While this would be good for the operations and maintenance of the water system, it would be difficult to finance.

Several stakeholders emphasized that remote maintenance initiatives, such as ARUC should be replicated for communities across Alaska. One stakeholder said that a regionalized collaborative should be created with local buy-in and support.

4.2.4 Technological policy solutions

Many stakeholders proposed that technological innovation and solutions are needed to address the challenging topography in villages, which makes infrastructure difficult to construct and maintain. In particular, stakeholders said there should be a long-term policy to change how water is provided from conventional pipes to non-conventional systems, and to promote household-level solutions. There need to be new designs and construction of water delivery infrastructure from source water to the household or central watering point.

4.2.5 Environmental policy solutions

Environmental solutions were proposed by stakeholders due to the onset of climate change. They stated that there is a need for new design criteria to drive a consistent approach for resilient water systems. Other stakeholders argued that there should be policies in place to help communities relocate as their infrastructure is challenged by storms or rising sea levels. These policies could include funding assistance for community relocation and promoting access to new sites. Stakeholders suggested that funding be made available to address climate change impacts to water systems and support adaptation strategies adopted by communities. There should additionally be policies to fund studies of climate change projections, the magnitude of its impacts, and the pace of change so that communities can make informed decisions and adapt to and mitigate climate change impacts. Stakeholders also emphasized that policies address environmental concerns, such as pollution from natural and man-made sources.

4.2.6 Obstacles to policy solutions

Major hurdles to these policies include climate change, funding, education, and the value that the public places on unique Native cultures. Climate change is a pressing concern for household water vulnerability. A stakeholder described how the lack of ingenuity regarding water sources from regulators has limited governments' use of diverse water sources and has left households with poor water access. Climate change will continue to challenge water policy and management due to uncertainty regarding specific impacts and lack of data.

Funding is another central obstacle to addressing water vulnerability because water systems are costly. Water systems in remote Alaska are highly decentralized and require a significant level of technology to operate, yet there is a limitation on the community's ability to maintain them. As populations continue to change, or decrease due to outmigration, it becomes more difficult to fund water systems. Stakeholders were additionally frustrated that there is little state and federal funding support for operations and maintenance of water systems. Scales of government also complicate funding and make it difficult to plan and coordinate strategies across groups. Alaska only receives 1% of the State Revolving Fund (SRF), and those funds are competed for by the many communities across the state.

Another hurdle that was mentioned by stakeholders is the public's valuing of unique native cultures. Currently there is not much external awareness and understanding of the water issue in rural Alaskan households throughout the state, in urban areas, or in the rest of the U.S. For sustainable water access, stakeholders stated that local community values and perceptions of water must be integrated into water management and technology. Stakeholders emphasized that the lack of school resources in remote communities can result in lower education levels that hinder efforts to address household water vulnerability, discourage water use for hygiene, and increase extreme water conservation. Stakeholders also mentioned that the lack of economic opportunities and institutional capacity in remote Alaska are hurdles to decreasing household water vulnerability.

4.3 Future areas of research

Through the participatory modeling process, several areas for future research were identified. To date, there has not been a large-scale effort to identify economic opportunities around subsistence activities or declare areas of Alaska "subsistence only" in order to recognize that Western economic development is not viable. Future research could include a more diverse array of stakeholders in the modeling process, such as community members and leaders of Alaskan Tribal Organizations. Future research must show where operations and maintenance funding fall short. Those findings may stimulate political will to change funding policies. There should also be more research on the impacts of newly gained water access on communities, and how piped water supply impacts traditional water use habits and local water knowledge.

This research contributes to our understanding of how water vulnerability is considered by stakeholders who implement water policy in Alaska. Future research could build on this work by conducting participatory modeling with rural communities instead of water policy stakeholders. Currently, the participatory modeling results highlight consequences of household water vulnerability that may be perceived as negative pathways resulting from not having water access or locally available water sources. In order to improve comparison of water challenges around the Arctic, there needs to be more research on water access and water availability issues in all Arctic regions, especially in Russia and Greenland. Future research could also quantify the CLDs developed in this article and couple the quantified CLDs with hydrological models.

5. Conclusion

This article examined household water vulnerability in Alaska through stakeholder engagement and the development of CLDs, by looking at how water policy stakeholders conceptualize the key processes and dynamic factors that affect household water vulnerability. From the individual and merged CLD models generated during the research, five thematic models emerged: economic, environmental, infrastructure, social, and health. This article explored the processes and feedback loops illuminated in the environmental and economic sub-models in depth. The environmental sub-model revealed that environmental and physical barriers, and climate change impacts affect household water vulnerability. The economic sub-model illuminated how household income constraints, operations and maintenance funding, medical care costs, available jobs in remote Alaska, regulations, a strong economy, and time for subsistence work impact household water vulnerability.

This research highlights how capturing the perspectives of stakeholders who implement water policies, and incorporating interdisciplinary ideas from physical, social, economic, and political sectors into a model can lead to innovative solution strategies that better reflect the human-hydrological cycle and account for the system's many diverse and complex relationships. The findings from this research provide knowledge into the unique experience of household water vulnerability in Alaska and the Arctic contexts. Through participatory modeling, this research provided new insights into the formal and informal institutions that influence household water vulnerability in the Arctic. Research in other contexts emphasizes the importance of historical, socio-cultural, and legal factors in determining how water is allocated, distributed, and regulated. Wilson et al. (2019) describe how governance in the context of indigenous households and communities must account for the informal decision-making processes around water, and how water systems have been shaped by historical and ongoing colonialism. The findings from participatory modeling in Alaska therefore deepen understanding of how water governance is linked to political and economic interests that exist within institutional arrangements and social relations (Nicole J. Wilson, Harris, Nelson, & Shah, 2019).

The results reveal that CLDs can help represent the socially relevant complexity of a system. Not only do CLDs identify the complex factors, but they also include the feedback dynamics. Through the simplification process used in this article, it was possible to see connections between factors and highlight policy solutions by visualizing the system as interconnected, versus a cause-and-effect relationship based on linear principles (Bureš, 2017). Participatory modeling allowed for a rigorous assessment of the role social institutions have in affecting household water vulnerability in remote Alaska, which to date has been largely lacking in water vulnerability analyses (Padowski, Gorelick, Thompson, Rozelle, & Fendorf, 2015). The analysis provides insight into the unique factors that challenge households in Alaska from achieving water security.

The models improve understanding of the Alaskan water system, thus providing a conceptualization of a path towards water systems management that is coordinated and effective in the long-term (Halbe et al., 2013). The visualized system dynamics may also allow stakeholders to envision different pathways that can build capacity in water governance, institutions, and individuals, thereby reducing household water vulnerability (Halbe et al., 2013). Future water policies should explore the feedback loops between variables and consider the dynamic tradeoffs households must balance in their effort to mitigate water vulnerability.

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