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Title Page:

What conditions are associated with household water vulnerability in the Arctic?

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Highlights:

- Biophysical variability and socio-political changes contribute to household water vulnerability in the Arctic
- Age dynamics and demographic shifts in Arctic regions are influencing household water vulnerability
- Societal changes must be considered in present and future Arctic freshwater policy

Abstract
Increasing pressure on water resources from demographic shifts, climate change, and development patterns are affecting water access and water availability in Arctic households. There is an urgent need to improve understanding of the factors that contribute to Arctic household water vulnerability. This paper examines the key conditions or combinations of conditions associated with water access and water availability that collectively impact household water vulnerability in the Arctic, based on an analysis of 28 case studies. Five conditions were identified through a literature review as contributing to household water vulnerability: inadequate freshwater policies, inadequate funding, inadequate infrastructure, biophysical variability, and societal changes. We used qualitative comparative analysis (QCA) to explore the configurations of these conditions along causal pathways that lead to household water vulnerability. The case studies were grouped into one of three typologies of household water vulnerability: political ecology, water security, or socio-hydrology. Through the analysis, absence of societal change in the Arctic was found to be a necessary condition for the political ecology typology, and the presence of freshwater policies and societal change in the Arctic were observed to be necessary conditions for the socio-hydrology typology. The research reveals how societal changes and anthropogenic factors contribute to household water vulnerability and must be considered in present and future Arctic freshwater policy.

Keywords:

- Drinking water, vulnerability, Arctic, socio-hydrology

1. Introduction

Household water vulnerability varies widely around the Arctic due to local hydrogeological factors, prioritization of water use, human activities, and government decisions, among other factors (Kløve et al. 2017). An Arctic Council survey conducted in 2016 documented the disparity in access to water services across the Arctic. It found that 25% of communities in rural Greenland have no access to improved water, compared to communities in Yukon, Northwest Territories and Nunavut that have more than 99% access to improved water sources (Poppel and Kruse 2006; SDWG 2016). In rural Alaska, only 85% of housing units have water and sewer services (HSS and ANTHC 2017). Even when water access is high, as it is in Northern Canada, water is not always safe to drink due to high levels of total coliform bacteria, high turbidity, and the presence of parasites, among other issues (Hennessy and Bressler 2016). Limited water availability due to the physical scarcity of local water supplies also challenges Arctic communities. For example, communities in Greenland must store sufficient quantities of water for four months a year in winter when no water is locally available (Hendriksen and Hoffmann 2017).

Household water vulnerability may be caused by insufficient water availability or lack of water access. Water availability is an individual's or household's ability to use or obtain a volume of water of sufficient quality and quantity (WHO/UNICEF 2015; Penn et al. 2017). According to the UN, 20 liters (L) of water are required to meet an individual's basic daily needs (WHO/UNICEF 2015). Water access is the availability of at least 20 L per person per day within a 'convenient distance' of the user's dwelling (WHO/UNICEF 2015), where convenient distance is defined as having an improved water source that is actively protected from outside contamination within one kilometer of a user's house (Cairncross and Valdmanis 2006).Water access is calculated as the percentage of a population with access to improved water in a given year, and it is related to the presence of household connections, protected water resources, and distribution infrastructure (Goldhar et al. 2013; Hanrahan et al. 2014; Penn et al. 2017).

International and regional governments recognize the challenge household water vulnerability poses in the face of climate change and have called for the development of Arctic water indicators in order to measure impacts on water systems over time (Nilsson et al. 2013a, b). These indicators would seek to document drinking water contaminants, waterborne diseases, per capita renewable water, accessibility of running water, and water safety plans that measure security of the entire distribution chain from raw water supply throughout the piping infrastructure (Nilsson et al. 2013b; Larsen and Fondahl 2015). The past Swedish and U.S. chairmanships of the Arctic Council championed the development of water indicators and a water resources vulnerability index that focus on human health (Kliskey et al. 2018; Williams et al. 2018). Contributing to this work, the arctic water resources vulnerability index (AWRVI) helps communities assess risks to their water resources due to biophysical conditions and their socio-economic capacities to respond to those risks (Kliskey et al. 2018).

Recent studies in Northern Alaska reveal how limited water supply and local development can result in greater community vulnerability (Williams et al. 2018). Exacerbating existing water challenges, climate change will threaten many communities' water resources due to thawing permafrost and changes to the Arctic's water cycle (AMAP 2017a, b). In 2016, the Government of Nunavut released a report stating that eight communities are at risk of high water stress due to changing precipitation regimes, climatic threats to their primary water source, and population growth (Jamieson et al. 2017).

Research has highlighted disparate factors that influence water vulnerability at the household scale in different regions of the Arctic, including climate change, water contamination, mining, and wastewater management (Alessa et al. 2011; Brubaker et al. 2011). Studies have focused on analyzing the health impacts of inadequate water access in the Arctic, which leads to higher incidence of water-washed diseases, such as trachoma, bacterial skin infections, and respiratory infections (Hueffer et al. 2013; Hennessy and Bressler 2016). In Alaska, infant hospitalization rates for lower respiratory tract infections and documented pneumonia are five times and eleven times the general U.S. infant population, respectively (Hennessy and Bressler 2016). To reduce the prevalence of these diseases, studies reveal a significant association between the interruption of disease transmission and higher water volumes through in-home water service due to improved hygiene practices (Harper et al. 2011; Brubaker et al. 2011; Dudarev et al. 2013b; Daley et al. 2015; Hennessy and Bressler 2016).

Water vulnerability due to poor water access or availability has been shown to diminish human health because households are forced to make do with limited water resources, which may be of poor quality. In Labrador, acute gastrointestinal illness is associated with household practices of drinking water storage and challenges related to the quality of municipal drinking water (Wright et al. 2017). In Finland, 76% of waterborne outbreaks in drinking water occurred in small and remote groundwater systems with inadequate disinfection treatment (Kløve et al. 2017). In North-western Arctic Russia, 51% of the population is exposed to high levels of chemical contamination due to unstandardized water protocols, unregulated water quality, and poor water supply systems (BEAC 2012; Dudarev et al. 2013a; Emelyanova and Rautio 2016).

Although these studies have made important strides towards improving contextual insights around water access and availability, analytical gaps remain regarding the possible combinations of factors that are associated with household water vulnerability. To address this need and improve conceptual understanding of the how social and biophysical factors interact with one another, and how they influence household water vulnerability, the article asks: what are the key conditions or combinations of conditions associated with water access and water availability that collectively impact household water vulnerability in the Arctic? To answer this question, we use qualitative comparative analysis (QCA) to examine household water vulnerability. This article identifies conditions and the combination of conditions that contribute to household water vulnerability.

We use a social-ecological systems (SES) framing to examine the interacting social and hydrological systems, and the network of dynamic variables that operate within and across these complex systems (Berkes and Folke 1998; Ostrom 2009). Drawing on SES principles, this paper's theoretical framing explores how household water vulnerability is affected by a range of context-specific conditions, such as history and politics at different scales, and by longer-term phenomena, such as climate change. We take a multidimensional view of interactions between people and the environment in order to assess the complex social and biophysical processes that create and mediate water vulnerability (Bohle et al. 1994; O'Brien et al. 2007).

This research examines water vulnerability at the household scale because households are central to managing and responding to water vulnerability (Eakin and Luers 2006; Toole et al. 2016). A household is defined as a social unit that pools and shares its resources (Netting et al. 1984; Wutich et al. 2017). In the Arctic, households are commonly multi-generational, and resources like food and water are shared among extended family members (Wright et al. 2017). While a household may experience water vulnerability as a social unit, the lack of water may be felt more by certain members of the household, such as those who experience greater mental distress or who choose to sacrifice water consumption for other family members.

2. Methodology

2.1 Qualitative Comparative Analysis (QCA)

QCA was developed as a comparative approach to research macro-level questions about society, economy, and cultural dynamics in political science and welfare state studies (Rihoux and Ragin 2009; Cairns et al. 2017). It is a context-specific method that uses a set-theoretic approach to compare across cases systematically (Amenta and Poulsen 1994; Rihoux and Ragin 2009). A case is the unit of analysis. QCA analyzes social reality by designating data set membership scores; modeling social phenomena in terms of set relations; and identifying necessary and sufficient conditions that produce an outcome (Schneider and Wagemann 2012).

QCA employs Boolean logic to establish which conditions are related to a specific outcome (Ragin 1999). The Boolean algorithm organizes cases to find common pathways that connect those conditions to an outcome. A condition is defined as an explanatory variable that is necessary and/or sufficient for an outcome to occur, in comparison to probabilistic methods that seek to understand the independent, additive influence of variables on an outcome. A condition is necessary to produce an outcome if it is always present when an outcome occurs. A condition is sufficient to produce an outcome if the outcome always occurs when the condition is present. An outcome is the variable that is explained by the conditions. It is the main focus of the study.

Through QCA's systematic cross-case comparison, the research may examine the different combinations of conditions associated with an outcome and develop set-theoretic knowledge that may help examine the plausibility of 'causal' relationships (Fiss 2011; Srinivasan et al. 2012; Pahl-Wostl and Knieper 2014). While QCA explores these pathways, it does not seek to determine correlation or causality; it is a method of comparison (Rihoux and Ragin 2009). QCA uses 'causal' to describe the relationship between conditions and an outcome, and to highlight possible associations between them. QCA maintains that causation is not additive, but instead a condition works in conjunction with other conditions to produce an outcome, and different combinations of conditions may lead to the same outcome (Amenta and Poulsen 1994). The method therefore implicitly rejects the idea that there is one pathway between 'cause' and 'effect' that leads from a condition to an outcome (Cairns et al. 2017).

QCA embraces complexity theory's principle that the relationship between conditions and the outcome is non-linear (Cairns et al. 2017). Through QCA's set relations and its use of 'truth tables,' the method explores causal complexity using equifinality, conjunctural causation, and asymmetrical causation. Equifinality assumes that multiple pathways to an outcome coexist. Conjunctural causation states that a condition does not necessarily influence the outcome in isolation from the other conditions (Schneider and Wagemann 2012). Asymmetrical causation highlights that both the occurrence and the non-occurrence of causal conditions require analysis in order to understand how the presence or absence of conditions may affect the outcome differently (Schneider and Wagemann 2012). By considering these three components of causal complexity it is possible to fully explore connections between conditions and the outcome (Watts et al. 1993). The following sections detail the application of QCA in this article through case study selection and analytical design.

2.2. Implementation of QCA

In this article, QCA is implemented in four steps to systematically analyze heterogeneous cases of household water vulnerability in the Arctic (Schneider and Wagemann 2012; Cairns et al. 2017). First, studies of household water vulnerability in the Arctic are identified and selected as described in Section 2.3. Second, the studies fitting the inclusion criteria (Table 1) are analyzed to identify 'typology indicator variables' that lead to household water vulnerability. These variables are then classified in typologies of household water vulnerability.

Third, the conditions that influence the typologies of household water vulnerability are coded. The conditions represent fundamental social and biophysical processes, such as climate change, demographic shifts, and infrastructure. Within QCA there exist two main variants: crisp-set QCA (csQCA) and fuzzy-set QCA (fsQCA). Crisp-set QCA assigns cases a score of 1 or 0, whereas fuzzy-set scores cases on a gradation of membership which allows for nuance in understanding why cases may or may not be fully 1 or 0, i.e. fully in or out of a set. This article uses csQCA to analyze the data because it was apparent in case studies whether the condition, such as "inadequate funding" or "inadequate infrastructure" was present or absent. For example, Sarkar et al (2015) state "the community did not have any piped water supply. Their regular sources of water consisted of several unmonitored local streams, brooks, and ponds." This would be scored "1" for the presence of inadequate infrastructure.

Fourth, we use 'truth tables' to assess contextual characteristics associated with the different typologies of household water vulnerability. The rows of the truth table represent a configuration of conditions that produce a particular outcome (Roig-Tierno et al. 2017). The Boolean approach models household water vulnerability as a function of these independent conditions. The result of QCA is a list of terms that represents a possible causal pathway determined by a set of conditions that must occur simultaneously to generate the outcome (Srinivasan et al. 2012). The results returned by csQCA allow the researcher to ask focused questions about the mechanisms that produce the outcome.

2.3 Search Process and Case Study Selection

To identify case studies for QCA, a literature review was conducted using selected search terms under the broad categories of water (e.g. water management, drinking water), household (e.g. home, house), and geographic location (e.g. Arctic, circumpolar) in SCOPUS and Web of Science (see Table S1 in supporting information for search terms, and more details on literature in the forthcoming article (Sohns et al.)).

From the 112 documents identified in the (Sohns et al.) literature review, we retained documents that fit the inclusion/exclusion criteria of Table 1. After eliminating documents that were not peer-reviewed or did not state a specific study period in their methods (criteria 1 and 7), we were left with 31 case studies for QCA analysis (see Figure S1 in supporting information for flow-chart of inclusion/exclusion process).

A case study is defined as a spatially delineated research study at the regional or local scale conducted over a defined period of time that focused on water availability and water access issues in the Arctic (see Table S2 in supporting information for geographical scope of article). The case study could describe either causes or consequences of water access and water availability issues, such as water quantity shortages or poor water quality. The case studies all had to fit into the specific inclusion parameters, but additionally were selected due to their diversity on relevant dimensions of analysis. The selection of diverse cases has the additional advantage of introducing variation on the key conditions of interest.

Table 1: Inclusion/Exclusion Criteria (based on (Sohns et al.))

Included if the document was:	(1) a peer-reviewed article; (2) published on or after January 1, 2000; (3) written in English; (4) specify a region or area of study in the Arctic (as defined by AHDR). That region can cross internationally defined borders and does not need to be within a specific country, such as Lapland in Scandinavia or the Barents region; (5) has a substantial focus on drinking water access and freshwater resources used by Arctic households and communities; (6) uses data or documents from the past or present; (7) states a specific study period, or the fact that the study had been conducted in the past needs to be implicit in the paper's methods. This is critical as water systems are dynamic with constantly changing exposures, variables, and responses.
Excluded if the document was:	(8) modeled future scenarios or conceptual frameworks that seek to weigh future options for water management; (9) is a future projection/hypothetical scenario of drinking water and water resources. This was important because we want to capture current, not hypothetical, household water vulnerability. (10) was classified as 'editorial material' or 'chronology' in Web of Science (11) does not have an identified author

2.4 Analysis

2.4.1 Coding for conditions of household water vulnerability

We used deductive and inductive coding to identify conditions that explain household water vulnerability within the case studies. A coding scheme and data extraction table were created to analyze and synthesize the literature. The main categories included: descriptive information (i.e., journal title, year of publication, location, and author's country affiliation); thematic content; and theoretical framing. Proximate codes were used to group underlying factors for organizational purposes (see Table 2 for the detailed code book). By combining underlying factors, our underpinning theory is that conditions are chain-logical. That is, one or several underlying factors may drive one or more proximate conditions that result in the observed outcome. Emerging from the cases, five ‘proximate’ conditions were generated, which fall into one of the four subsystems of SES: social system, governance system, infrastructure system, and resource system (Ostrom 2009).

After deductive coding was completed on the general characteristics of the article, inductive coding was conducted using Atlas TI software (Friese 2012). The documents were each read to discern conditions and themes that contribute to household water vulnerability (Cope 2010). These codes centered on reoccurring conceptual topics mentioned in the case studies, such as poor water policies, lack of infrastructure. Once the coding categories were created, the documents were then re-read in detail and codes were assigned to conditions when authors made explicit reference to a coding category. Codes were not assigned in cases where strong inferences had to be made.

In QCA, it is recommended that there are more case studies than the number of conditions, such as at least four cases for every one condition (Amenta and Poulsen 1994; Marx and Dusa 2011). In complex, non-linear systems, researchers have successfully reduced the number of coded independent conditions using chain-logical causation and concomitant occurrence. We selected conditions using a conjunctural theory approach that predicts that there are multiple causal combinations that lead to household water vulnerability (Srinivasan et al. 2012). This strategy exploits QCA’s ability to produce causal pathways that reflect the heterogeneity of the conditions (Amenta and Poulsen 1994). The causal pathways show how sets of conditions derived from the case studies may be associated with a particular outcome (Blackman et al. 2013). The identified conditions were dichotomized according to Boolean algebra, which seeks to simplify complex data sets into binary values of 1 or 0 if a condition is present or absent, respectively.

These ideas are depicted in Figure 1, which shows how the condition “inadequate infrastructure” can be produced by inadequate infrastructure on the supply side and on the user side. There may be many concomitant conditions that lead to inadequate infrastructure. The pathways in Figure 1 reveal that inadequate infrastructure could be attributed to several underlying factors on either the supply, distribution side or on the user, consumer side. For example, inadequate infrastructure on the supply side may be the result of “poor monitoring and data collection” due to a lack of trained operators or limited recordkeeping. Using this approach in QCA, the condition of inadequate infrastructure will be coded as being present if any one of the underlying factors is present. This coding process across the 31 case studies resulted in five conditions: inadequate freshwater policies, inadequate funding, inadequate infrastructure, biophysical variability, and societal changes (see Table 2).

Figure 1: Example showing how inadequate infrastructure (the proximate condition) may be produced by underlying factors (Figure created by first author, format inspired by (Srinivasan et al. 2012)).

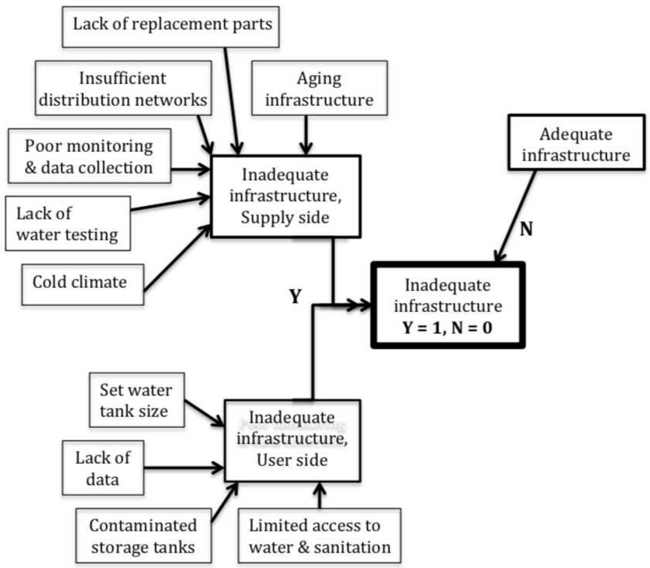

Table 2: Proximate conditions and underlying factors influencing household water vulnerability

Condition Type	**Proximate Condition (abbreviated name)**	**Underlying Factors**
Governance system	Inadequate freshwater policies (NOPOL)	• Lack of drinking water guidelines; • An absence of rigorous freshwater monitoring; • Absence of freshwater policies; • Standard volume of water supplied to household despite its particular circumstances; • Incomplete consideration of socio-political aspects of water, compared to technological; • Lack of preparedness for waterborne disease outbreak; • Lack of compatibility between place-specific, cultural, and economic variables such as public health trends, living conditions, and water related behaviors of system users and policies; • Layers of governance (local to national to international); • Transnational populations; • Overcrowding of homes leading to insufficient water supply • Ownership of water supply system;

		• Alignment of goals
Governance system	Inadequate funding for water systems (FUNDIN)	• Residents cannot pay fees due to poverty and the high cost of treatment and distribution; • Limited household income; • Limited government funding; • Access to transportation by ownership of vehicle; • Transportation costs are too high, such as snowmobile purchases, ATV purchases, snowmobile maintenance, gasoline; • Residents dependent on government transfers • Shortage of qualified operators; • Cold/harsh climate increases construction challenges, operational costs; • Interrelated resource pricing, increasing energy costs affect water access and rates of consumption, energy price increases price of water, thus affecting affordability, availability, and usage of water; • Remote, rural communities challenge low construction costs • Lack of resident tax base
Infrastructure system	Inadequate infrastructure (NOINFRA)	• Lack of water testing for metals, chemicals; • Challenges with maintaining chlorine levels from distribution center to household; • Lack of access to water; • Lack of access to washeteria; • Storage in tanks that may become contaminated; • Cold War and nuclear disposal sites, managing abandoned mines and mine waste; • Levels of education; • Deteriorating infrastructure; • Wastewater management and sewage runoff compromising drinking water quality • Lack of water data on consumption/access and regional hydrology; • Little integration of data across disciplines/knowledge; • Little sharing of information about water resources; • Inadequate monitoring and record keeping
Resource system	Biophysical variability (CC)	• Climate change impacting water resources availability, quality and quantity; • Extreme weather threatening water systems;

		• Water and sanitation infrastructure at risk due to eroding beach and storm surge; • Infrastructure damage due to thawing/melting permafrost • Rising temperatures and flooding threatening water sources and water systems • Climate change damaging existing clean water and wastewater infrastructure • Quality and quantity of water supply changes over a year due to climate and hydrologic cycle; • With presence of multiple sources of water, communities and individuals were able to employ a coping mechanism of retrieving their own water when there were system failures; • Topography and geography of land
Social system	Societal changes (CULTUR)	• Framings of water security; • Perception of freshwater as a finite resource with multiple values; • Piped water is considered to be substandard quality and community members continue to rely on traditional water sources; • Loss of sensitivity to hydrological changes; • Generational differences in familiarity with water resources in time and place; • Levels of education; • Pollution/changing land = dispossession and loss of health tied to the inability to safely and confidently use water resources; • System disruption due to human error, such as truck distribution network, illness • Arctic populations are growing in the warmer climate; • Shifting size of communities; • Changes in age composition; • Rural to urban migration; • Rural outmigration; • Increasing demand on and threats to freshwater resources due to heightened resource development and industrial activities; • Importance of having able bodied kin to gather water;

	• Kin network affected by length of relationship, employment outside the town, illness; • Dependence on fuel-based transportation to gather/access water

2.4.2 Coding for the typologies of household water vulnerability

In defining the outcome of household water vulnerability this paper develops typologies that account for the outcome's complexity, employing an approach developed by Srinivasan et al (2012). Instead of focusing on a single condition that defines household water vulnerability, typologies look broadly across the case studies to describe how household water vulnerability is produced by simultaneously occurring or associated conditions (Srinivasan et al. 2012). The typologies characterize clusters of conditions instead of isolated conditions (Manuel-Navarrete et al. 2007). Each typology therefore represents a set of conditions connected to the case studies that details household water vulnerability in the Arctic.

To identify central characteristics of household water vulnerability, the same coding procedure described in Section 2.4.1 was used. In order to develop typologies of household water vulnerability, eleven binary variables were identified as describing average household water vulnerability, variance in household water vulnerability, and future variance in household water vulnerability (Table 3) (Srinivasan et al. 2012). For each typology, an outcome vector was created, and then each case study's coded vector was compared to the typology's vector to determine its proximity to it. For example, a typology could have the vector [1, 1, 1, 0, 0, 0, 1, 0, 1, 0, 0] using binary coding along the eleven typology indicator variables (Srinivasan et al. 2012). If the Euclidean distance between the case study's vector and the typology's vector was less than a determined cutoff value, the case study was classified as that typology (Srinivasan et al. 2012). The development of typologies was an iterative process that resulted in each case study belonging to only one of the three typologies: political ecology, water security, or socio-hydrology.

Table 3: Indicator variables for the three typologies of household water vulnerability

Typology Variable Category	Typology Indicator Variable
Average household water vulnerability due to water availability and access	Persistent lack of access to sufficient quantity and quality of water for livelihood and household needs
	Enduring lack of sufficient quantity and quality of water for drinking and hygiene needs
	Critically unequal access and availability of water supplies resulting in diminished health
Variance in household water vulnerability due to water availability and access	Changing access and availability of water due to interaction with other resources, energy prices and food security tradeoffs

	Changing access to and availability of water leading to income, health, and education declines
	Changing quantity and quality of water due to biophysical factors
	Changing quantity and quality of water due to anthropogenic factors
Future variance in household water vulnerability due to water availability and access	Long-term impacts of climate change on water resources
	Long-term changes in population size
	Long-term impacts of resource development and industrial impacts on watersheds, such as downstream aggregation of mining activities
	Long-term consequence of changing socio-hydrology, loss of freshwater knowledge, and changing perceptions of water

2.4.3 Conducting QCA

Once the typologies and conditions were identified, QCA was applied to trace the relationships between the conditions and each possible typology. These identified relationships are referred to as causal pathways in QCA, as they represent the association between conditions and the produced typology of household water vulnerability. Each data set was dichotomized using 1s and 0s and organized into a truth table using TOSMANA software version 1.54 (Cronqvist 2016). Results were compared with the truth table and configuration of conditions produced by fs/QCA software (Ragin and Davey 2016). While the computer program is called fs/QCA, the software allows for crisp-set analysis, which is what was used in this article. TOSMANA and fs/QCA software were used because they are the two most commonly used software to conduct QCA analysis, and by using different software, it was possible to compare their respective results (Thiem and Du 2013).

Truth tables provide a succinct and parsimonious understanding of how conditions are linked to the outcome. In a truth table, there may be 2^k rows, where k represents the number of conditions and 2 indicates that the condition may be present or absent (Schneider and Wagemann 2012). Each row shows the logical combinations between the conditions and is a statement of sufficiency (Rihoux and Ragin 2009). In generating the truth table, each case can only belong to one row.

In the transformation of the data matrix of coded conditions to a truth table, contradictions in logic are highlighted by the computer program. Contradictions flag potential problems with theoretical specification of the conditions and indicate that some cases may not be explained by the model (Marx and Dusa 2011). Contradictions require the researcher to return to the case studies and resolve the problems before further analysis. To address contradictions, the three typologies representing the outcome of household water vulnerability were reassessed to ensure that they were clear and do not result in confusion among cases. Next, to resolve the identified contradictions highlighted in the truth tables, seven case studies were reconsidered to determine whether they were indeed part of the same typology (Rihoux and Ragin 2009). As a result, three case studies were excluded from analysis because it was unclear whether other factors affected their membership in the typology (Schneider and Wagemann 2012). This left 28 case studies for QCA (see Table 4 for concise inclusion details of the case studies).

Table 4: Concise inclusion details of the case studies – Location, Period of Study, Sample Size, Methods

Case Number	Region	Study period (indicating that the research took place in the past)	Sample Size	Research methods
1	Alaska	July 2004, August 2005, 2006	5 villages on the Seward Peninsula	Semi-structured interviews
2	Finland	August 1998	10% random sample of northern Finnish town (218 people)	Water sampling; stool specimen sampling
3	Northern and Western Alaska	Fall 2001	5 communities' water utilities	Water sampling
4	Nunavik	2003	4 communities	Semi-structured interviews; Water sampling
5	Alaska	2005, 2006	Seward Peninsula	Water sampling; Vulnerability assessment
6	Shishmaref and White Mountain, Alaska	2003-2006	2 communities	Semi-structured interviews; participant observation
7	Northwest Arctic Borough	March 2008-June 2009	101 residents in 5 communities	Open-ended, semi-structured interviews; Participant observation
8	Nunatsiavut	2005-2008	2 communities	Weather data; clinic visits
9	Russian Arctic	2000-2011	18 regions of Russian Arctic	Water consumption data; water sampling of biological and chemical contamination of

				water reservoirs and of drinking water
10	Nunatsiavut	2009	89 households	Household interviews; open-ended and fix-choice questions; literature review
11	Newfoundland and Labrador	March-April 2007	618 surveys	Cross-sectional telephone survey; Questionnaire
12	Coral Harbour, Nunavut	Implicit in study	37 people	Semi-structured interviews; Review of documents
13	Black Tickle, Newfoundland and Labrador	April 2013	37 people	Open-ended interviews; Water sampling; Focus group
14	Northwest Alaska	Implicit in study	101 people	Semi-structured interviews; Archival research
15	Newfoundland and Labrador	2010-2011	25 municipal water systems	Water sampling
16	Ruby Village, Alaska	2010-2011	20 people	Semi-structured interviews; literature review
17	Western Alaska	Implicit in study	4 communities (1,403 people)	Medical records
18	Newfoundland and Labrador	Implicit in study	283 people	Literature review; Media scans; Policy workshops; Community surveys; Interviews
19	Bristol Bay and Kotzebue Sound regions, Alaska	Implicit in study	Communities across 2 regions of Alaska	Semi-structured interviews
20	Newfoundland	2012	100 households	Telephone survey; Water sampling
21	Chukotka and Yakutia, Russian Arctic	2013-2015	18 selected regions in Arctic Russia	Analyzing official statistical sources

22	Labrador	June 2014	246 people	Survey; Questionnaires; Water sampling
23	Rigolet, Labrador	2012-2014	~235 people	Questionnaires
24	Seward Peninsula	2004	134 people	Surveys; Interviews
25	Bristol Bay, Alaska	Implicit in study	6 communities	Participant observation; Interviews
26	Alaska	2000-2004	128 villages (12,480 homes) in 6 regions	Medical record review
27	Greenland	Implicit in study	6 towns; 11 villages	Review
28	Rigolet, Nain, Labrador	2009, 2010	134 people	Interviews; Participant observation; Review of city records

3. Results

QCA revealed the combinations of the five conditions: inadequate freshwater policies, inadequate funding, inadequate infrastructure, biophysical variability, and societal changes that produce the three typologies of household water vulnerability. The typologies: political ecology, water security, and socio-hydrology describe household water vulnerability under those theoretical framings. All typologies were associated with the five conditions, and revealed problematic social-hydrological water systems, such as chronic unmet water needs, or poor governance of human-water systems.

In analyzing the results, the consistency and coverage were examined for each solution, condition, and truth table row in the typologies (supporting information Figures S2-S4). Consistency is the degree to which empirical evidence supports the claim that a set-theoretic relation exists between the condition or configuration of conditions, and the outcome (Rihoux and Ragin 2009). Coverage reveals how much of the outcome is covered by the sufficient condition under analysis and assesses the relation in size between the condition set and the outcome set (Schneider and Wagemann 2012). Consistent with QCA studies, for a condition to be considered necessary in this article, the consistency had to be threshold of 0.9 or greater, and coverage had to be 0.6 or greater (Rihoux 2017).

The results reported in the following sections reflect the intermediate solutions generated by the fs/QCA software. The intermediate solution is a subset of the most parsimonious solution, and a superset of the conservative solution (Schneider and Wagemann 2012). The intermediate solutions were chosen because they incorporate theoretical notions that balance complexity and parsimony, but do not rest on difficult or untenable assumptions of logical remainders. Logical remainders are logically possible combinations of conditions, but they do not have any empirical evidence among the case studies to determine whether the combination produces the outcome or not (Schneider and Wagemann 2012). In the analysis of the results, it is important not to interpret relations between singular conditions and the outcome of household water vulnerability. The causal pathways highlight the importance of considering the relationship between the conditions and how they influence one another.

3.1 Political-Ecology

This typology of household water vulnerability is characterized by case studies that describe limited water access due to factors like poor water policy and water management frameworks. The case studies in this typology are represented by the political ecology theoretical framework, which looks at the broader political, social and economic contexts that influence human-water relationships (Robbins 2004). The typology is associated with a lack of water infrastructure, such as pipes to deliver water to homes, chlorine supplies, or monitoring equipment. Poor infrastructure adversely affects households' access to water supplies. For instance, a case study describes how a Finnish municipality's inadequate treatment of the tap water supply resulted in a large outbreak of acute gastroenteritis (Kuusi et al. 2005).

Poor infrastructure may correspond to a household's or community's lack of power, resource access, and resource control. The political ecology typology includes case studies that describe these power asymmetries and how they contribute to household water vulnerability. The typology captures the importance of historical development patterns, and asymmetrical power relationships between communities and higher layers of government that are associated with chronic household water vulnerability. Past decisions regarding water infrastructure were often made in a top-down manner that are now obstacles to household water access communities must overcome to increase water access (Loring et al. 2016). For example, one case study describes how a third of Native Alaskan households do not have running water and sewer services due to lack of investment as a result of limited community inclusion in decision making processes (Eichelberger 2014). The case studies in this typology directly highlight the role of the state in creating water vulnerability.

The absence of societal change was identified as a necessary condition for this typology. This suggests that without societal change, the existing power and information asymmetries governing human-water systems will continue. If the power structure endures then water resources will continue to follow the same distribution pattern and reinforce development pathways. For example, in Alaska, as elsewhere in the Arctic, indigenous water governance principles have historically not been integrated into the prevailing Western water governance framework managing local water systems (Wilson 2014). Without explicitly integrating indigenous ideas into water governance, indigenous peoples' rights, traditions and resource management preferences continue to be marginalized (Wilson 2014).

This typology is produced along two causal pathways (see Figure S2 in supporting information for solution terms). The first pathway is associated with the presence of inadequate infrastructure combined with the absence of biophysical variability and absence of societal changes. This pathway describes the status quo where many households lack adequate infrastructure to provide sufficient water access to meet their basic needs. The pathway highlights how household water vulnerability can result from government actions if there are no changes occurring climatically or in society that would mitigate household water vulnerability. The second pathway describes the presence of inadequate freshwater policies combined with inadequate funding and inadequate infrastructure, and the absence of societal changes. This pathway describes many case studies that experience household water vulnerability as a result of institutional decisions regarding freshwater policy, funding, and infrastructure. A lack of comprehensive freshwater policy that accounts for the many competing demands on water, or deficient funding of water systems influence household water vulnerability as people lose access to much needed water supplies.

Household water vulnerability is therefore a product of political processes and of historical development across scales, and of contextual factors, such as infrastructure, competing sectoral demands for water, and community remoteness (Padowski and Gorelick 2014; Pandey et al. 2014). The first pathway may provide a more relevant explanation of the outcome since it has a unique coverage of 0.5 compared to the second pathway's unique coverage value of 0.375. Unique coverage is the percentage of all cases' set membership in the outcome uniquely covered by a single path of an equifinal solution term (Schneider and Wagemann 2012).

3.2 Water Security

Case studies in this typology reflect the water security theoretical framework, as the cases highlight issues of water access, availability, affordability and chronic scarcity. The case studies emphasize the important relationship between household access to sufficient water supplies and a healthy and productive life (O'Brien and Leichenko 2008; Wheater 2014; Hossain et al. 2016; Srinivasan et al. 2017). Due to chronic water vulnerability, case studies are characterized by poor health outcomes, including skin and lung disease, and mental health issues resulting from household water vulnerability. For example, a case in Russia documents how people were consuming drinking water that was highly contaminated by chemical and biological agents, which resulted in high rates of waterborne diseases (Dudarev et al. 2013c, b).

The case studies in this typology highlight the connection between poor drinking water quality and insufficient water quantity and waterborne and water-related diseases. A case study in Alaska documents how homes with piped water supplies have significantly lower rates of respiratory, skin and gastrointestinal infections (Thomas et al. 2013). The case studies reveal that worse health outcomes may reinforce household water vulnerability as people struggle to access water. For example, if a household is burdened with high medical costs due to water related diseases, the household may not be able to afford water because it is forced to make tradeoffs between necessities such as medicine, water and energy. Case studies also emphasize how health is diminished by unmonitored water supplies and lack of information, such as poor understanding of how to clean water storage tanks.

For cases in this typology, household water vulnerability can occur along three causal pathways (see Figure S3 in supporting information for solution terms). The first pathway involves the absence of societal changes, inadequate freshwater policies, biophysical variability and inadequate infrastructure, combined with the presence of inadequate funding. This pathway highlights the role that inadequate funding of water systems, water treatment, and operations and management programs have in contributing to household water vulnerability. The second pathway is associated with the presence of inadequate funding, inadequate infrastructure and biophysical variability, combined with the absence of inadequate freshwater policies and societal changes. Case studies described how lack of infrastructure, poor funding, and the impacts of climate change would result in household water vulnerability if freshwater policies or societal changes did not mitigate these challenges, such as improved water policies to enhance the use of alternate water sources.

The third causal pathway that produces this typology is the combination of the presence of inadequate infrastructure, biophysical variability, societal changes, inadequate funding, and inadequate freshwater policies. This pathway shows that when all conditions are present household water vulnerability occurs because there are anthropogenic and biophysical changes on top of existing structural issues, such as inadequate infrastructure, weak freshwater policies, and poor funding of water systems. Of these pathways, the third pathway may provide the most relevant explanation since it has a unique coverage of 0.5, compared to the first and second causal pathways' unique coverage values of 0.33 and 0.17, respectively.

These three pathways emphasize the important role that inadequate funding has in contributing to household water vulnerability, such as existing poverty, lack of a resident tax base, or limited government support. Yet, in analyzing the conditions in the fs/QCA software, no conditions met the threshold for necessary conditions of 0.9 consistency or greater, or 0.6 coverage or greater. Therefore, the conditions determining the outcome are sufficient conditions, but are not necessary.

3.3 Socio-Hydrology

The case studies in this typology are represented by the socio-hydrology theoretical framing, 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). This typology is characterized by case studies that describe perceptions of water resources and local values regarding water, and how they affect household water use. The typology identifies biophysical features and attributes of institutions that influence short and long-term household water vulnerability (Srinivasan et al. 2012; Padowski et al. 2015).

Case studies describe the importance of long-term changes, such as demographics, scale and population growth. For example, a case in Alaska documents how community knowledge passed on from elders helps households respond to changes in their environment (Alessa et al. 2008a). A household's ability to respond to water vulnerability is influenced by changing age dynamics, societal change and shifting community values. Additionally, climate impacts and cultural shifts change people's perspective of water resources and their respective quality. A case study in Northwestern Alaska details how culturally specific ideas regarding health and water quality influence how communities use centralized water systems (Marino et al. 2009). Cases in this typology underscore how household water vulnerability is both the result of chronic and current factors that affect household income, education, and social structure.

Through analysis of necessary conditions in the fs/QCA software, it was revealed that freshwater policies (i.e. the absence of inadequate freshwater policies) and societal changes were necessary conditions for this typology. In this typology, household water vulnerability can be produced along four causal pathways (see Figure S4 in supporting information for solution terms). The first pathway occurred when there was an absence of inadequate freshwater policies and inadequate funding combined with the presence of societal changes. This pathway suggests that even with freshwater policies and funding, household water vulnerability can be produced due to societal changes, such as loss of water knowledge over generations (Wilson 2014).

The second pathway that produces the typology is an absence of deficient freshwater policies combined with the presence of biophysical variability and societal changes. Again, this pathway reveals that even with freshwater policies, biophysical changes and societal changes can lead to household water vulnerability. For example, case studies highlighted how household water vulnerability is affected by the seasonality of water resources since water will not be available in the time and place that they need it (Martin et al. 2006; Marino et al. 2009).

Third, this typology may be caused by an absence of inadequate freshwater policies, inadequate funding, and inadequate infrastructure, combined with the presence of biophysical variability. This pathway documents the importance of biophysical changes, such as thawing permafrost and increased extreme weather. Fourth, the typology may be produced by the presence of inadequate funding, inadequate infrastructure, and societal changes, combined with the absence of biophysical variability. The second pathway may provide a more relevant explanation of the outcome since it has a unique coverage of 0.42 compared to the first, third and fourth pathways' unique coverage values of 0.14, 0.07, and 0.07, respectively.

4. Discussion

This article advances understanding of household water vulnerability in the Arctic by assessing the key conditions and combinations of conditions that contribute to whether a household has water access. QCA was used to examine 28 Arctic case studies. The findings trace five conditions: inadequate freshwater policies, inadequate funding, inadequate infrastructure, biophysical variability, and societal changes to three typologies of household water vulnerability.

Through the identified typologies, it is possible to compare configurations and examine the relationship between the underlying factors and proximate conditions and the pathways that generate household water vulnerability. Results revealed a limited number of pathways describing the articulation of causes of household water vulnerability in the Arctic under different contexts. The findings emphasize that household water vulnerability is influenced by anthropogenic factors, such as social dynamics in a community and the age of people in the households. While the cases each fit into a unique typology, the typologies are interconnected, as they all exist as types of household water vulnerability.

In the political ecology typology of household water vulnerability, the absence of societal change was identified as a necessary condition with a coverage of 0.6. Without societal change, household water vulnerability is perpetuated by the legacy of past decisions and power asymmetries between government and communities. Case studies discussed how colonial history influences how households are able to respond to changing water access and water availability due to continuing lack of power in decision-making processes (Sarkar et al. 2015). This typology highlights how a household's ability to mitigate water vulnerability is associated with chronic vulnerability, such as the enduring influence of past water policies, and current vulnerability, like existing infrastructure and water management strategies.

Both of the causal pathways in the political ecology typology underscore how deficiencies of the state, such as lack of freshwater policies or inadequate infrastructure can lead to household water vulnerability without societal changes that could mitigate poor water access and water availability. These findings are significant because many Arctic freshwater management strategies neglect to consider cultural factors and societal changes, such as age dynamics and shifting demographics.

The case studies in this typology emphasize how social bonds critically affect whether households have water access. In Alaska, when a household loses access to water, the members often rely on kin for drinking water (Eichelberger 2010). If a household does not have a strong kinship network, then it may be more susceptible to water vulnerability. The typology also illuminates how framings of water security influence how people use water. Many people, especially older generations have cultural attachment to specific water sources or perceive traditional waters to be more desirable than chlorinated, municipally-supplied water (Goldhar et al. 2014; Daley et al. 2015). Therefore, as traditional water supplies from rivers and ice become more difficult to obtain due to climate change or human activities, the water vulnerability of households that are culturally attached to those waters is increased. These social, cultural, and economic factors that affect household water vulnerability must be incorporated into water systems planning.

The water security typology reveals the importance of chronic factors that contribute to household water vulnerability. The typology explores how persistent lack of access to sufficient water quantity and quality may affect livelihood and household needs. The water security typology highlights how enduring unequal access and availability of water supplies for drinking water and hygiene needs can result in diminished health due to waterborne and water-related illness. The lack of necessary conditions in this typology suggests that no certain conclusions can be drawn regarding the typology's causal pathways, yet the combinations of conditions do show that there are many factors that contribute to household water vulnerability. Indeed, the presence of all five conditions had the greatest coverage of the three causal pathways, at 0.5 in producing the outcome. This implies that the combination of all factors: inadequate freshwater policies, inadequate funding, inadequate infrastructure, biophysical variability, and societal changes led to household water vulnerability across majority of the cases in the typology. It is worth noting that the presence of inadequate funding is common across the three causal pathways. This may indicate that funding for water systems from government support and a strong user base are vital in order to prevent poor health outcomes due to household water vulnerability.

In the socio-hydrology typology of household water vulnerability, freshwater policies and societal change were independent, necessary conditions. The coverage for societal change was 0.8 compared to freshwater policies' coverage of 0.6, which may suggest that societal change is a more relevant outcome-producing condition. This again stresses the importance that societal change has on household water vulnerability across the Arctic. For example, rural outmigration is affecting water access because the tax base is weakened with fewer people to fund water systems (Loring et al. 2016). Migration from rural to urban areas also makes it difficult to retain qualified water systems operators which increases the risk of water system failure. Additionally, as populations grow, there are siting concerns for water systems. Due to the lack of available hydrological data, there is uncertainty of where to safely locate wells and septic systems (Loring et al. 2016).

The socio-hydrology typology of household water vulnerability explicitly distinguishes between current and long-term changes. It highlights the importance of considering the existing variability that influences household water vulnerability, such as social perception of the safety and value of different water resources and whether members of the household know where multiple water supplies are located. The typology also stresses the importance of development patterns on water vulnerability. Mining and petroleum industries are affecting land use in the Arctic (Alessa et al. 2008b). Intensive resource development can compromise nearby freshwater resources and leave communities exposed to water scarcity due to water contamination.

A number of case studies highlighted the slow progress of Arctic freshwater policy and expressed that new policies are urgently needed to address climate change, extreme weather, and changing environmental conditions. Freshwater policies across the Arctic fall short of protecting drinking water supplies and watersheds. In Russia, there is a serious need to reform the Russian water industry and to improve federal laws regulating drinking water supplies (Dudarev et al. 2013c). In Nunavut there is no rigorous monitoring of drinking water quality nor reporting protocol (Daley et al. 2014). These problems are common across Arctic nations and were highlighted in a recent report, which declared that water resources management strategies are necessary to maintain Arctic freshwater supplies and mitigate water-related hazards, such as flooding (AMAP 2017b).

Through this typology's causal pathways, it is revealed that even when there are existing freshwater policies, if both biophysical variability and societal changes are present, household water vulnerability may be produced. Governments should support household and community efforts to respond and adapt to household water vulnerability due to the dramatic changes occurring in the Arctic as a result of longer-term climatic and demographic shifts. The case studies emphasize that cultural and social characteristics specific to each community must be considered in the design of water systems and the policies that govern them (Daley et al. 2015; Loring et al. 2016).

For example, in northern Canada, as around the Arctic, there is a housing shortage which forces people to share their homes and leads to overcrowding. In Nunavut, this 'hidden homelessness' describes how people who do not have a home live temporarily in another's dwelling (Daley et al. 2014). This increases household water vulnerability because each home has a set volume of water that is delivered to their water tank, which therefore determines how much water a household has to use and share among household members (Daley et al. 2014). Such social realities should be accounted for in the design and implementation of water systems.

The conditions and causal pathways identified by QCA reveal the similarities between Arctic contexts, including colonial legacy, power asymmetries, and demographic shifts. However, it is important to consider the contextual differences between nations that affect government mechanisms and policy design. While QCA enhances comparative knowledge of the case studies in each of the typologies and identifies common themes with the typologies of household water vulnerability, QCA is not without its limitations. A potential weakness of QCA is that its determinism may omit potential causal conditions and therefore produce misleading results.

Another possible limitation of QCA stems from the conversion of continuous variables into dichotomous conditions. The researcher must assume that the nature of the relationship between the independent condition and the outcome is a threshold, and therefore that expressing the condition as present or absent is sufficient without using degrees of presence to express the conditions (Blake and Adolino 2001). Additionally, in csQCA, since each condition has one of two values it is not possible to examine their relative strengths or proportional relationships (Blake and Adolino 2001). Therefore, it is difficult to determine which condition has more impact on the outcome compared to another condition. QCA may also be undermined by its expectation that explanations are conjunctural and deterministic (Amenta and Poulsen 1994). There has also been recent criticism of complex and intermediate solutions generated by QCA because they may conclude more than is warranted from causal inference (Baumgartner and Thiem 2017).

5. Conclusion

This article reviewed 28 cases in the Arctic using QCA in order to improve conceptual understanding of the conditions and causal pathways that produce household water vulnerability. Through the analysis of the configurations of the five conditions (inadequate freshwater policies, inadequate funding, inadequate infrastructure, biophysical variability, and societal changes), this article contributed new insight regarding the conditions' association and influence on the three typologies of household water vulnerability: political ecology, water security, and socio-hydrology. The QCA results underscore the similarities across the heterogeneous case studies while maintaining the complexity of the individual cases.

The findings of QCA highlight the importance of the multiple conditions and their underlying factors which act on household water vulnerability. The results emphasize how aspects of the socio-hydrological cycle, such as societal change interact with freshwater policies and biophysical variability to influence household water vulnerability. Water policymakers must engage with community organizations, Tribal Councils, and others that have intimate knowledge of the household realities which result in water vulnerability, and of the community characteristics in which the household is embedded. This engagement may take many forms, such as direct avenues for feedback or adaptive management, but should result in these groups' perspectives being included in final policies, water systems design, and governance.

These groups will provide necessary insight regarding how social and cultural conditions, and political structures affect household traits, decision-making and daily economic tradeoffs. In turn, this information can be incorporated in government policies at all levels to ensure they respond to household needs and reflect household capacity to afford and maintain a specific water system. The article's findings have broad implications for the Arctic, as regions should promptly implement freshwater policies that respond to climate impacts and societal shifts, increase funding of water systems, and consider the complex interactions between the dynamic conditions contributing to household water vulnerability in future water management strategies.

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