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Water Vulnerability in Arctic Households: A Literature-based Analysis

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ABSTRACT. There is an urgent need to understand the contextual factors that influence water vulnerability of households in the Arctic. To evaluate the existing knowledge of Arctic household water vulnerability, this paper presents the results of a narrative review with a systematic search. The review identified 112 documents, including peer-reviewed articles, reviews, book chapters, proceedings papers, and meeting abstracts. The documents were analyzed for the main factors affecting water vulnerability in Arctic households, which fell into two categories: biophysical factors and anthropogenic factors. Within the biophysical category, the majority of documents noted climate change impacts on freshwater supplies and water systems, followed by attention to extreme weather and the seasonality of water supplies. Within the anthropogenic category, the vast majority highlighted infrastructure as the primary issue affecting water access, followed by economic, governance, socio-cultural, and demographic factors. Through these diverse influencing factors, this review situates the discussion of household water vulnerability in the Arctic in a more nuanced light. The categories illuminate patterns between factors, which can worsen, assuage, or mitigate water vulnerability. The complex relationships between these factors influence the degree and nature of water vulnerability in Arctic households. In order to successfully address household water vulnerability in the Arctic, these factors and their dynamic relationships must be considered in freshwater policy and management frameworks.

Key words: vulnerability; Arctic; household

RÉSUMÉ. Il existe un besoin urgent de comprendre les facteurs contextuels qui exercent une influence sur la vulnérabilité de l'eau des ménages de l'Arctique. Afin d'évaluer les connaissances déjà acquises en matière de vulnérabilité de l'eau des ménages de l'Arctique, nous présentons les résultats d'un dépouillement de textes effectué par le biais d'une recherche systématique. Ce dépouillement a permis de repérer 112 documents, comprenant des articles révisés par des pairs, des comptes rendus, des chapitres de livres, des actes de conférences et des résumés de réunions. L'analyse des documents s'est concentrée sur les principaux facteurs touchant la vulnérabilité de l'eau dans les ménages de l'Arctique. Ces facteurs relèvent de deux catégories, soit les facteurs biophysiques et les facteurs anthropiques. Dans la catégorie biophysique, la majorité des documents faisaient mention des incidences du changement climatique sur les approvisionnements en eau douce de même que sur le réseau hydrographique, après quoi l'accent était mis sur les conditions météorologiques exceptionnelles et la saisonnalité des approvisionnements en eau. Pour ce qui est de la catégorie anthropique, la grande majorité des documents mettait l'accent sur l'infrastructure comme principal enjeu influençant l'accès à l'eau, suivie de facteurs économiques, socioculturels, démographiques et de gouvernance. Grâce à ces divers facteurs d'influence, l'analyse permet d'obtenir un portrait plus nuancé de la vulnérabilité de l'eau des ménages de l'Arctique. Les catégories permettent de dégager des tendances entre les facteurs, tendances qui empirent, assouvissent ou atténuent la vulnérabilité de l'eau. Les relations complexes qui existent entre ces facteurs influencent le degré et la nature de la vulnérabilité de l'eau dans les ménages de l'Arctique. Afin de réussir à régler l'enjeu de la vulnérabilité de l'eau dans les ménages de l'Arctique, il y a lieu de tenir compte de ces facteurs et de leurs liens dynamiques en matière de gestion et de formulation de politiques concernant l'eau douce.

Mots clés : vulnérabilité; Arctique; ménage

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INTRODUCTION

In the Arctic, many disparate factors influence household water access and availability. In Alaska, uncertain water supplies and socioeconomic challenges have been described as an "axis of vulnerability" (Penn, 2016:1), and stresses related to water management have been identified as the most critical factor affecting community vulnerability (Alessa et al., 2011). In the Canadian territory of Nunavut, a government-commissioned report found that eight communities are at risk of high water stress because of changing precipitation regimes, climatic threats to their primary water source, and population growth (Jamieson et al., 2017). There have been calls for urgent monitoring of water security and the development of indicators to monitor and quantify changes to water resources across the Arctic (Dudarev et al., 2013b; Nilsson et al., 2013). Despite appeals for further research to understand the impact of climate and environmental changes on water in the Arctic and to find effective approaches to provide water to individuals and communities, analytical gaps remain (AHDR, 2015). The dynamics of Arctic socio-hydrology systems are poorly understood and to date, a comprehensive analysis of Arctic water vulnerability at the household level does not exist. As a result, there is a pressing need to improve understanding of contextual factors that influence water vulnerability within Arctic households, especially with the onset of climate change (Alessa et al., 2008c, 2011; Sarkar et al., 2015; Medeiros et al., 2017).

To address this gap in the literature and deepen understanding of water vulnerability, we conducted a systematic search of literature that identifies and characterizes factors affecting household water vulnerability in the circumpolar North. We synthesized our search in a narrative review that critically reflects on the current state of literature and summarizes it in order to advance theoretical understanding (Greenhalgh et al., 2018).

RESEARCH APPROACH

Conceptual Framing

Vulnerability studies range in topics and circumstances. Vulnerability is understood as a system's susceptibility to harm; it is a function of exposure to external forces (stresses, disturbances), the system's sensitivity to those exposures, and the system's adaptive capacity to respond to changing conditions (Ford and Smit, 2004; Luers, 2005; Plummer et al., 2012; Srinivasan et al., 2013). In a water context, vulnerability has been conceptualized as a community's susceptibility to water-related disasters, water quality, and water insecurity, as well as the vulnerability of water resources to human actions, such as pollution or overuse.

Vulnerability research in the Arctic has focused on present-day threats to water resources from human activities and changes to community water resources due to biophysical and socio-economic processes (Alessa et al., 2008c; Bakaic, 2016). For example, Iqaluit's water resources are under pressure because of a range of accumulating effects and interactions between stressors such as population growth and demand exceeding local water supplies (Bakaic, 2016; Medeiros et al., 2017). Although these vulnerability studies communicate pressing threats to water resources, they do not provide a comprehensive understanding of biophysical and anthropogenic factors affecting household water vulnerability.

This paper investigates the vulnerability of households by examining the degree to which households may be unable to cope with, recover from, or adapt to environmental and socio-economic changes, specifically changes related to water scarcity, water shortages, water variability, and water degradation (Stathatou et al., 2016). To assess household water vulnerability, we look at the factors that affect water access and water availability. We follow the World Health Organization (WHO) to understand water availability as an individual or household's ability to use or obtain a volume of water of sufficient quality and quantity (UNICEF and WHO, 2015; Penn et al., 2017). The United Nations (UN) states that the volume of water required to meet basic needs is approximately 20 L per day (UNICEF and WHO, 2015). Water access is therefore understood as the availability of at least 20 L per person, per day within a convenient distance of the user's dwelling (UNICEF and WHO, 2015). A convenient distance is defined as having an improved water source that is actively protected from outside contamination and within 1 km of a user's dwelling (Cairncross and Valdmanis, 2006). Water access is often calculated as the percentage of a population with access to improved water in a given year and is related to household connections, protected water resources, distribution infrastructure, sustainable use, and affordability (Goldhar et al., 2013; Hanrahan et al., 2014; Penn et al., 2017). Both water access and water availability may be affected by social, political, and economic institutions.

Temporal and spatial scales are critical to consider in order to understand water vulnerability. This research focuses on water vulnerability at the household scale because households are central to managing responses to external stress or perturbations (Eakin and Luers, 2006; Toole et al., 2016). Households are central to understanding water vulnerability in the Arctic and are crucial to perceiving social organization around water resources (Toole et al., 2016). Water use and environmental issues are refracted through social relations within the household, as well as the demands of everyday life (Toole et al., 2016). Research at the household level captures individual decisions influenced by societal values, institutions, macro-scale factors, and individual-level characteristics (Adger, 2000; Toole et al., 2016; Jones and Tanner, 2017). Despite the importance of the household, a significant gap remains in understanding climate impacts on water resources at the household scale (Toole et al., 2016). Studies have revealed that water vulnerability in households is a product of natural water availability and of contextual factors, such as infrastructure, competing sectoral demands for water, and community remoteness (Padowski and Gorelick, 2014; Pandey et al., 2014). Households use their limited assets to adapt to water vulnerability at the expense of education or health, which may reinforce poverty and the economic marginalization of certain communities (Eakin et al., 2016).

Specifically, we ask: "what are the main factors affecting water vulnerability in Arctic households?" To answer this question, the paper examines the dimensions of household water vulnerability through two objectives: 1) a review of how household water vulnerability is conceptualized and characterized in the Arctic; and 2) an identification of the exogenous and endogenous factors affecting water vulnerability in Arctic households. The main goal of this paper is to describe factors affecting water vulnerability that are shared across Arctic households in order to facilitate a regional comparative analysis (Falkenmark, 2001; Sullivan, 2002; Plummer et al., 2012).

METHODS

Search Process and Document Selection

The literature review search was conducted on 1 March 2018 using selected search terms under the broad categories of water, household, and geographic location in Scopus and Web of Science (see Table S1 in the online supplementary material for the identified search terms). We only considered documents that 1) were peer-reviewed articles, reviews, book chapters, proceedings papers, or meeting abstracts; 2) were published on or after 1 January 2000; 3) were written in English; 4) specified a region or area of study in the Arctic (as defined in the Arctic Human Development Report (AHDR), 2015)—the region could cross internationally defined borders and did not need to be within a specific country, such as Lapland in Scandinavia, or the Barents region; 5) had a substantial focus on drinking water and freshwater resources used by Arctic households and communities; and 6) used data or documents from the past or present. We excluded documents if they 1) modeled future scenarios or conceptual frameworks seeking to weigh future options for water management; 2) were a future projection or hypothetical scenario of drinking water and water resources; 3) were classified as "editorial material" or "chronology" in Web of Science; or 4) did not have an identified author.

The search terms used in Web of Science returned 662 results. After only including documents that fit inclusion criteria 1 and 2, this number was restricted to 571. Terms used in Scopus returned 260 papers after being restricted by criteria 1 and 2. After combining results from Scopus and Web of Science (n = 831) and removing duplicate documents (n = 109), a total of 722 documents remained. The abstracts were screened and documents were excluded based on criteria 5 (n = 123). After the full text was screened, 96 documents were left. Documents were excluded if they used modeling and forecasting scenarios or did not use data from the past or present. This was important because the review aimed to capture current, not hypothetical, household water vulnerability. We also excluded papers that only had an abstract in English with the rest of the paper in another language. The third round of screening snowballed references of the 96 included articles, yielding an additional 19 studies, for a total of 115 unique documents. The final selection ensured that all papers were in English, empirical, had explicit methods, and focused on water vulnerability in Arctic households. Overall, 112 studies were reviewed.

Analysis

Qualitative content analysis was used to examine the included documents for underlying key factors that contribute to water vulnerability in Arctic households (Hsieh and Shannon 2005; Zhang and Wildemuth, 2005). Deductive and inductive coding were used to analyze the included case studies. A coding scheme and data extraction table were created to appraise and synthesize the literature. The main categories included descriptive information regarding the article (journal, year, location, and author's country affiliation), thematic content, and theoretical framing. Proximate codes were used to group underlying factors for organizational purposes (see Table S2 in supplementary materials for the code book). The code book was piloted to ensure consistency in the coding process. After deductive coding was completed on the general characteristics of the article, inductive coding was conducted in Atlas TI. The papers were each read to discern factors and themes that contribute to household water vulnerability (Cope, 2010). These codes centred on reoccurring conceptual topics mentioned in the literature, such as poor water governance or lack of infrastructure. Once the coding categories were created, the documents were then re-read in detail and codes were assigned to the papers when explicit reference was made to a coding category. Seven themes were identified: climate change, environment, governance and policy, economics, infrastructure, demographics, and socio-culture. These themes fell into two categories affecting household water vulnerability: biophysical factors and anthropogenic factors. The coded text was analyzed for key relationships that represent central characteristics of the seven themes contributing to water vulnerability and the associated outcomes of water vulnerability in Arctic households. Codes were not assigned in cases where strong inferences had to be made.

RESULTS AND DISCUSSION

Description of Studies

Of the 112 documents analyzed, 48 (43%) were situated in Canada, 34 (30%) in Alaska, 12 (10%) in Russia, two

(2%) in Norway and Denmark, and one (1%) in each of the following countries or regions: Faroe Islands, Greenland, Iceland, Finland, and Sweden (see FIG. S1 in online supplementary materials). Of the studies, 11 (10%) were pan-Arctic, meaning that the documents' focuses spanned the Arctic region, or that they examined multiple regions of the Arctic in their analyses. Similarly, most papers were first-authored by academics and researchers from Canada (46%, n = 52), the United States (34%, n = 39), Russia (7%, n = 8), and Norway (3%, n = 4).

There has been a surge in the publication of studies around household water vulnerability in the Arctic in recent years, with a yearly increase of 11% from 2000 to 2017 (inclusive). The studies were published in 66 different scholarly journals. The most common venue for publication was the *International Journal of Circumpolar Health* (11%, n = 12 papers), followed by *ARCTIC* and *Environmental Science Pollution Research* (5% each, n = 6 papers each).

Not all documents stated the theoretical framing underlying their approach or analysis. Of the 29 (26%) documents that did, 13 (12%) used a vulnerability framing, seven (6%) used social-ecological systems framing, four (4%) cited socio-cultural framing, four (4%) referred to hydrosocial framing, and one paper (1%) used political ecology framing.

Biophysical Factors

Most of the reviewed papers cited biophysical factors as a primary driver of drinking water vulnerability at the household level: 51 papers (45%) referenced climate change impacts on freshwater supplies and water systems; 47 (42%) cited extreme weather events; and seven (6%) noted saltwater intrusion along the coasts due to storm surge. Forty-two papers (38%) referred to the seasonality of water supplies; six (5%) cited water-related diseases due to temporal relationship between weather patterns, water quality, and occurrence of disease; and 29 (26%) cited the impact of topography, geography, and geology on water quantity and water quality.

In the papers reviewed, climate change appears as a leading theme that determines water vulnerability for Arctic households (Daley et al., 2014; Harper et al., 2015b; Sarkar et al., 2015; Penn et al., 2016). On the land, warmer temperatures and variable rainfall are reducing the available water supply in lakes and waterways (Martin et al., 2007; Walvoord and Striegl, 2007; Cunsolo Willox et al., 2012). Communities have reported a gradual drying of lakes and marshes due to higher temperatures (Loring, 2010). In regions of discontinuous permafrost in Alaska, Canada, and Russia, tundra ponds have been reducing in size and disappearing (Chambers et al., 2007; Goldhar et al., 2014).

Thawing permafrost is triggering new interactions between ground and surface water resources. For example, rivers and lakes have been documented draining into the earth and affecting groundwater flow (Chambers et al., 2007; Martin et al., 2007; Thomas et al. 2013). In Nunavik, protective berms containing wastewater lagoons are expected to weaken with the thawing ground and to potentially contaminate drinking water resources with raw sewage (Martin et al., 2007).

These changes have cascading effects that intensify water vulnerability in Arctic households. In Alaska and Labrador, high summer temperatures have additionally resulted in increased algal and biological growth in lakes, compromising water quality and fouling water filters at some water plants (Brubaker et al., 2011a). Such changes expose communities to disturbances in water access and availability (Cunsolo Willox et al., 2012).

The increased magnitude and frequency of climate change-related extreme weather events across the Arctic are influencing household water vulnerability. Extreme weather will contaminate lowland areas' drinking water because of saltwater intrusion from coastal erosion and rising seas (Martin et al., 2007; Evengard et al., 2011; Ford et al., 2014; Harper et al., 2015b). Compromised infrastructure due to extreme weather in Alaska, Nunavut, and Nunatsiavut has diminished water quality and resulted in waterborne disease outbreaks (Daley et al., 2015).

The loss of hydrologic stationarity, which refers to hydrological patterns that are outside of the historical range of observations, is greatly affecting water management and planning processes as it becomes more difficult to predict future events from historical trends (Wilson et al., 2015). Variable rainfall may result in water supplies of uncertain quantity and quality, because of increased turbidity or altered flows, which could compromise mining activities and power generation (Instanes et al., 2016). For example, a period of heavy rainfall forced the Minto mine to release untreated water into the Yukon River in 2008 and 2009 (Pearce et al., 2011). Unpredictable water supply in time and place may exacerbate social inequities (Penn et al., 2016). Climate impacts on water resources have been shown to affect the cultures and resource use patterns of those living in the Arctic (Alessa et al., 2008b; Marino et al., 2009).

In Arctic communities, water quantity and water quality vary dramatically by season because of precipitation patterns, climate, spring runoff, and ice breakup. In Alaska and Canada, in warmer months, many individuals supplement municipal water supply with water resources from surface water and rain (Thomas et al., 2016). In northern Greenland, local hydrology and environmental conditions severely limit water quantity in winter. Individuals are forced to store as much water as possible during summer as possible in order to have sufficient supplies in the cold months (Hendriksen and Hoffmann, 2017). Water quality also varies seasonally. For example, in Yakutia, Russia, the quality of surface water resources is diminished by yearly spring floods, which increase sediment load (Dudarev, 2018).

As a result of seasonal water resources, water-related diseases also fluctuate seasonally because of the temporal relationship between weather patterns, water quality, and disease occurrence. For example, water turbidity increases after periods of heavy rainfall and rapid snowmelt, which can potentially transport pathogens and contaminate drinking water resources in regions with insufficient water infrastructure (Harper et al., 2011; Mutter et al., 2017). Rapid snowmelt can also mobilize arsenic and other pollutants into surface waters. Since communities often consume untreated surface water, this can have dangerous impacts on health (Munk et al., 2011; Sandlos and Keeling, 2016).

Water quality is affected by the topography and geological structure of the land (Sabau and Haghiri, 2008). Lakes can provide high-quality drinking water, depending on their size and depth (Instanes et al., 2016). In the Nenets district of Russia, drinking water quality is influenced by the territory's bogginess and the sea's influence on rivers (Stammler-Gossmann, 2010). Water quantity may be restricted to surface water resources if the presence of permafrost prevents drilling individual water wells (Daley et al., 2014; Lemieux et al., 2016). The quality of groundwater also depends on its residence time in a sub-permafrost aquifer and the composition of minerals in the subsurface environment (Lemieux et al., 2016).

The use of groundwater as drinking water in the Arctic varies considerably. In Alaska, approximately 50% of drinking water is sourced from groundwater, compared to 15% in Norway, 60% in Finland and Sweden, and nearly 100% in Iceland (DEC, 2008; Kløve et al., 2017). In Norway, Sweden, and Finland groundwater is often hydraulically connected to surface water resources (Kløve et al., 2017). The use of poor quality natural water sources can lead to negative health outcomes. The biophysical factors of household water vulnerability exacerbate all of the anthropogenic factors because of the uncertainty regarding the spatial and temporal presence of freshwater resources throughout the year.

Anthropogenic Factors

Under the theme of *governance and policy*, water governance captures the authority, decision-making and accountability, and the prevailing processes, institutions and policies that make decisions and rules regarding water (Simms and de Loë, 2010; Bennett et al., 2016). The presence or absence of water governance is a central factor determining the degree to which households are affected by biophysical factors and experience water vulnerability.

Forty-one documents (37%) highlighted inadequate freshwater policies as central to household water vulnerability. The Government of Nunavut has no specific agency or individual in charge of freshwater resource policy and management (Medeiros et al., 2017). Consequently, in Nunavut and across Arctic Canada, "boil water advisories" (BWA) and poor water quality are commonplace (Jones-Bitton et al., 2016). In the Russian context, there are no federal laws on drinking water and drinking water supply, and regionally targeted programs are insufficient or pending approval (Dudarev et al., 2013b). Across much of the Arctic, groundwater is not well regulated because it is considered safe. It is therefore less adequately chlorinated and monitored for contaminants, even though it may also be a source of waterborne disease (Kuusi et al., 2005).

Poorly designed water policies further exacerbate water vulnerability when there is an inconsistency between household realities and water provisioning. For example, in Nunavut, a baseline water volume per capita per day was established for trucked water supply systems to address the prevalence of gastrointestinal and skin disease (Daley et al., 2014). Yet overcrowded homes and distribution challenges continue to impede households from receiving sufficient quantities of water from municipally delivered sources (Daley et al., 2014). In Alaska, many communities have water systems that are operating past their life span. However, Alaska's state government is less likely to provide financial support to aged systems compared to communities that have no water systems (Loring et al., 2016). This results in a lack of maintenance and operations, and communities suffer from deteriorating and failed water systems.

Additionally, in Alaska and Nunavut there is a lack of compatibility between place-specific and socio-economic variables such as living conditions, public health indicators, and people's use and relationship with water (Daley et al., 2015). Poor source water protection (SWP) of drinking water reservoirs results in their contamination and degradation (Minnes and Vodden, 2017). Even in areas where SWP exists, high costs or lack of institutional capacity may prevent adequate investment in the development and maintenance of infrastructure (Eledi et al., 2017; Hanrahan and Dosu, 2017). As communities in Alaska and Nunavut are growing, upstream and downstream development are often uncoordinated and do not consider where water systems are located or the hydrogeology of the region (Alessa et al., 2008b; Loring et al., 2016). This can increase water vulnerability if upstream development uses greater amounts of water or contaminates the water resources.

Policy coordination can be more complex in transboundary watersheds, such as the Yukon River Basin (Wilson, 2014; Loring et al., 2016). In Canada, differing regulations at the federal level and provincial or territorial level can complicate water policy. For example, there is no national standard that defines a BWA, which can cause confusion or uncertainty when a BWA is issued by a province or territory (Jones-Bitton et al., 2016). Disparate management mechanisms can cause inconsistent or incomplete monitoring and water governance, and data fragmentation (Dube et al., 2013). These governance issues were highlighted in 25 papers (22%) as contributing to household water vulnerability.

Scales of governance from local to national level policies may also lead to centralized control of water resources in top-down governance, which is perceived as monopolistic and a mechanism of limiting social and political control (Eichelberger, 2010). In Alaska, many decisions are made without the input of local village leaders, which perpetuates marginalization and inequalities (Eichelberger, 2014). This also results in unrealistic regulations for drinking water quality at the local level. Since communities are responsible for system maintenance and operations despite lack of funding and support from higher levels of government, if the communities are forced to meet burdensome regulations, the systems will fail (Eledi et al., 2017; Hanrahan and Dosu, 2017; Penn et al., 2017).

Furthermore, current water resource management and policies may be insufficient to address climate change impacts (Instanes et al., 2016). Many issues related to climate change are shared between government agencies, with limited coordination (Stammler-Gossmann, 2010). In Nunavut there has been no policy development regarding climate impacts on freshwater resources. Across the Arctic, policies regulating mining, oil, and gas sectors are often insufficient. In Russia, policies fail to protect water resources from cattle pasture and farmland agricultural runoff (Rasskasova et al., 2017). As a result, contamination and pollutants threaten drinking water resources.

Historical power relations represent the historic geographies of colonialism and the legacy of past decisions, typically made by outsiders, which continue to affect water access within and between regions and result in asymmetrical contemporary power relations between the community and higher layers of governance. Sixteen documents (14%) referred to these relationships and cultural politics as affecting the socio-hydrology cycle and water vulnerability. In Alaska, Wilson (2014) and Loring et al. (2016) highlight how community goals for water resources are often not incorporated into planning and policy processes. Studies from Newfoundland and Labrador and Alaska describe how the exclusion of Indigenous groups in the development of engineered water systems and legal frameworks has led to household water vulnerability (Hanrahan et al., 2014; Wilson, 2014).

The theme of economics shows that while many northern communities do not face a physical scarcity of water year-round, economic barriers make it difficult to ensure adequate water supplies. With declining availability of freshwater resources, households face serious financial burden if they need to use cash to buy drinking water from the store or fuel to gather water from the land (Goldhar et al., 2014). If a household does not have a vehicle or snowmobile, it may be unable to collect water from rivers and lakes during municipal water delivery delays (Daley et al., 2014).

Household water vulnerability is also linked to energy security and determined by the cost of treatment, transportation, and distribution on the supply side (Rodriguez et al., 2013; Sohns et al., 2016). Residents must manage the economic burden of high energy costs and the need for fuel-based transport in order to haul water from distant sources (Eichelberger, 2010; Goldhar et al., 2014; Sarkar et al., 2015; Penn, 2016). Interrelated resource pricing directly affects water's affordability, availability, and use in the Arctic. Therefore, energy insecurity can deepen household water vulnerability (Eichelberger, 2010).

Thirty-five (31%) papers stated that the lack of funding for water systems is a major concern in Arctic countries because of limited economic opportunities, small tax bases, poverty, and the effects of climate change (Eichelberger, 2014; Daley et al., 2015; Penn, 2016). In Black Tickle Labrador, in a year without funding, there were mechanical failures and chlorine supplies ran out (Hanrahan et al., 2016). Governments around the Arctic often fail to provide essential funding for operations and maintenance of the system after paying for infrastructure development (Hanrahan and Dosu, 2017). Hanrahan et al. (2017) found that government off-loading of the water system to communities in Newfoundland and Labrador was the root of identified water crises since funding requirements far exceed local capacity. Lack of funds makes it difficult to recruit and train enough operators and administrators to run water systems sustainably, and retaining operators is difficult in small towns because of non-existent or small salaries, unattractive benefit plans, and low morale (Minnes and Vodden, 2017).

Forty-five documents (40%) described maintenance and operation issues as contributing to household water vulnerability. These challenges are driven by the geography of Arctic communities, lack of funding, and outdated systems. Nineteen documents (17%) referred to the challenges of providing water access to communities because they are often remote and isolated from one another. These characteristics make it difficult to have economies of scale, and increases shipping and construction costs and shipping times (Martin et al., 2007; Hendriksen and Hoffmann, 2017; Daley et al., 2018b). In communities across Greenland and elsewhere in the Arctic, the location of the local water supplies in relation to the settlements was not a pressing issue when the communities were first established (Hendriksen and Hoffmann, 2017). However, as these communities grew over time, this lack of consideration for available water supplies became a critical water security concern. In Nunavut, many communities cannot meet federal regulations for microbial and chemical contaminants because their remote geography limits financial and technical capacity (Lane et al., 2018). The engineering of water systems is challenged by the cold climate where underground piping is not viable in many communities and operating costs are high (Brubaker et al., 2011a; Daley et al., 2014). Due to the seasonal darkness and extreme cold, repairing failed infrastructure can be difficult or impossible (Penn, 2016).

Operation and maintenance of water systems are further challenged by limited expertise (Martin et al., 2007). In Newfoundland and Labrador, nearly 25% of administrators from communities with 1000 or fewer people did not have a certification or formal training to operate water systems (Minnes and Vodden, 2017). Limited expertise may result in operational problems in the distribution system or a mistake by an operator, such as turning off the disinfection system (Jones-Bitton et al., 2016). In some cases, operational failures of water systems have led to lengthy service disruptions and raw sewage spills near homes (Daley et al., 2018b). Further, a pressure loss in water systems increases the risk of gastrointestinal illness (Gunnarsdóttir et al., 2013).

Twenty-six (23%) papers described how resource development might become an increasing cause of Arctic household water vulnerability due to inadequate governance and management (Wesche and Armitage, 2010; Medeiros et al., 2017). Documents highlighted how adverse effects of industrial development activities, such as mining, accumulate downstream and may contaminate food and water resources (Alessa et al., 2008b; Sarkar et al., 2015; Sandlos and Keeling, 2016). In the Nenets district, poor water quality has been related to industrial and agricultural work (Stammler-Gossmann, 2010). In some areas of Alaska, water scarcity has coincided with mineral and petroleum development (Alessa et al., 2011). In the Murmansk region, energy and mining industries are the highest water consumers (Kashulin et al., 2017).

In the Arctic, *infrastructure* can be a contributor to water vulnerability. Poor water infrastructure adversely affects water availability, quality, and distribution (Penn, 2016). Inadequate infrastructure on the supply side was cited by 78 papers (70%) and describes challenges water system operators face, such as maintaining the chlorine level from the distribution centre to households, coordinating between water and sanitation systems, and integrating information across disciplines. Circumpolar communities are afflicted with aging water infrastructure, unreliable water supply and sewage systems, BWAs, and a range of raw freshwater quality (Brubaker et al., 2011a; Dudarev et al., 2013a; Daley et al., 2015; Penn, 2016). These supply-side challenges leave communities underserved due to limited financial and human capital (Bakaic and Medeiros, 2017). Many Arctic communities are wholly or partially dependent on water supplied from municipalities. As a result, households face water vulnerability due to insufficient water quantity and poor water quality.

Despite variable raw water quality, water supplied to communities such as Coral Harbour in Nunavut, is treated only with chlorine (Daley et al., 2014). By not using additional chemical or physical filtration, harmful contaminants may be left in the source water. Lack of adequate treatment was also documented in Alaska where additional chemicals or physical filtrations would help remove further contaminants from source water (Brubaker et al., 2011a). In Russia, more than 27% of water pipelines from surface reservoirs do not have water purification facilities and 16% lack disinfection systems (Dudarev et al., 2013b). In Newfoundland and Labrador, communities are issued BWAs if their water is unsafe to consume due to residual chlorine issues, an absent disinfection system, operational problems in the distribution system, presence of microbes, or human fallibility (Jones-Bitton et al., 2016; Minnes and Vodden, 2017).

A growing issue for Arctic water treatment facilities is removing pharmaceutical residues and additives found in personal care products, which remain in wastewater and sludge. Pharmaceuticals degrade much slower at high latitudes than at lower latitudes (Huber et al., 2016). Yet, there is insufficient information on how persisting pharmaceuticals in sewage lagoons impact local water supplies (Mutter et al., 2017). Water system failures and cultural preference have caused many people to continue collecting water from rivers, lakes, or melt ice. These sources, however, can increase the risk of gastrointestinal diseases from natural pathogens (Martin et al., 2007; Hanrahan et al., 2014; Daley et al., 2018a). The lack of water infrastructure and limited access to safe drinking water results in diminished health (Hennessy and Bressler, 2016).

On the user side, at-home storage tanks and their associated dippers are often contaminated with bacteria from poor sanitation practices between fillings (Chambers et al., 2007; Martin et al., 2007; Wright et al., 2018a). Eighteen documents (16%) cited inadequate infrastructure at the user end, such as insufficient storage tanks, which have been found to be more contaminated than water at traditional collection sites (e.g., brooks, rivers, lakes) because of lack of information regarding storage tank care (Martin et al., 2007). After public officials suggested storage containers should be cleaned, a study of a community in coastal Labrador found that 67% of containers were cleaned less than once a month, and 43% of containers had never been cleaned (Wright et al., 2018a). Contamination can also occur in the water tank biofilms due to lack of secondary disinfection to remove microbial growth, which may contribute to gastrointestinal illness (Daley et al., 2018b; Lane et al., 2018). In-home water supply shortages may also occur due to lack of infrastructure or overcrowding in homes (Daley et al., 2014; Hennessy and Bressler, 2016).

Studies emphasized that limited data on water systems and poor site-specific household data hinder efforts to evaluate the risks associated with drinking water from traditional sources (Hennessy and Bressler, 2016; Daley et al., 2018a). In the Arctic, there are no baseline data to understand the impact of climate change and external forces on water supplies (Bakaic and Medeiros, 2017). There is a lack of data regarding not only the physical condition of water systems, but also the indicators of good management and operation, and effectiveness of oversight and regulation (VanDerslice, 2011). As well, there is no full assessment of the risks of using groundwater supply for drinking water in Nordic regions (Kløve et al., 2017). In Greenland, there are no data on how many households have piped water (Hendriksen and Hoffmann, 2017). While in the Murmansk region of Russia, there are no central data registers on qualitative and quantitative indicators for water and water management (Kashulin et al., 2017).

Limited data were referenced by 39 documents (35%). Insufficient data hamper the ability to deepen an understanding of the relationship between freshwater and Arctic peoples (Marino et al., 2009). There is little information on water-related costs that individuals incur to provide sufficient water quantity and quality to their homes, such as snowmobile maintenance, and energy costs to boil water or to purchase and maintain filters (Hanrahan et al., 2014). Loring et al. (2016) document the lack of regional hydrology data in Alaska as contributing to reduced community planning of water systems. Without detailed local data and monitoring, there can be little integration across sectors, which may intensify water management challenges or result in system failures (Alessa et al., 2008b).

Additionally, there is insufficient information on the incidence of waterborne and water-washed diseases because they are not typically reported and tracked; this is especially true in Inuit and Indigenous communities (Hennessy and Bressler, 2016; Lam et al., 2017). In Canada, the impact of acute gastrointestinal illness is not well understood because of the limited availability and quality of surveillance data (Harper et al., 2015a). In Greenland, there is no systematic overview of the health consequences that households are afflicted with as a consequence of an absence of piped water and water tanks (Hendriksen and Hoffmann, 2017).

Twenty-eight documents (25%) referred to the relationship between water and sanitation services as contributing to household water vulnerability; they noted potential health risks from hydrological connectivity between wastewater treatment areas and drinking water resources (Healey et al., 2011; Daley et al., 2015). The infrastructure issue for wastewater and drinking water interactions is threefold. First, in Arctic countries, treatment of drinking water often only removes a low level of pathogens (Daley et al., 2018a). Second, wastewater is often mishandled and inadequately treated (Sarkar et al., 2015). In Nunavik, for example, water supplies may be threatened by migrating pathogens from nearby wastewater lagoons (Martin et al., 2007). In Anadyr City, approximately 1.8 million cubic meters of untreated sewage are released into the Kazachka River annually, which flows into the Bering Sea (Dudarev, 2018). And third, households often use the same vehicle to transport wastewater and to collect drinking water, creating a contamination risk. For example, in Black Tickle, Labrador, households use the same *komatiks* to dump wastewater at the landfill site as they do to retrieve water (Sarkar et al., 2015).

The legacy of old infrastructure, such as old pipes or buried military waste, was discussed by 15 documents (13%) as affecting household water vulnerability. In the Arctic, many water systems are operating past their planned end of life and are therefore expensive and difficult to maintain and operate (Penn et al., 2017). Degrading infrastructure is a concern for rural Newfoundland and Labrador and many other regions of the Arctic, and the lack of funds make necessary repairs and upgrades difficult (Minnes and Vodden, 2017). In Yakutia, Russia, for example, approximately 75% of the water systems need to be replaced because they have had no major improvements to their technology or the facilities since they were installed in the 1960s and 1970s (Dudarev, 2018). In Chukotka, Russia, 40%–80% of the centralized water systems need to be replaced (Dudarev, 2018).

When there is degraded water infrastructure, communities are exposed to increased health risks. Some communities are faced with BWAs for one-third of the year (Hanrahan and Dosu, 2017). In Chukotka, Russia, the use of old technology and lack of water treatment facilities exposes the population to waterborne diseases. These threats are compounded by deteriorating and corroded pipelines and distribution networks (Dudarev, 2018). Corroded drinking water systems can release heavy metals such as lead, copper, and zinc into the water supply and diminish household water resources (Daley et al., 2018b).

Local water resources can also be stressed by the legacy contamination of past projects, population growth, and land development for resources (Medeiros et al., 2017). Past mining disposal sites across the Arctic have enduring effects that acutely impact local community health for generations (Hossain, 2016; Sandlos and Keeling, 2016). In east-central Alaska, for example, household freshwater wells contain some of the highest levels of arsenic in the U.S., which has been directly linked to historic gold mines (Alessa et al., 2011). As Arctic communities continue to grow and evolve, they are concerned with not only maintaining the capacity of their water systems and addressing existing water threats, but also responding to climate change and emerging threats (Loring et al., 2016).

Demographic factors were highlighted as an important theme for their contribution to water vulnerability in rural Arctic households. Certain populations, such as the elderly, children, people with disabilities, and those without a vehicle struggle to collect water throughout the year (Eichelberger, 2010; Goldhar et al., 2013). Age dynamics were noted by 14 papers (13%) as affecting household water vulnerability due to Elders' knowledge of freshwater resources compared to younger generations (Alessa et al., 2010). In remote Alaskan communities, studies reveal that as age increases, there is a greater perception of change in hydrological resources (Alessa et al., 2007). Some studies attribute this relationship to the generational connectedness to land and water from subsistence activities (Alessa et al., 2010; Wilson et al., 2015). The shift away from land-use activities has impacted the intergenerational transfer of knowledge about the land and people's connection to place (Wesche and Armitage, 2010). These age dynamics and connectedness to the environment also play a role in how people perceive drinking water quality (Ochoo et al., 2017). Older generations prefer traditional water sources, whereas younger generations use the municipal water supply if it is available (Altaweel et al., 2009; Ritter et al., 2014).

Population flux described in 15 documents (13%) is a growing concern; for example, rural outmigration exacerbates water vulnerability because municipal water service jobs do not always retain employees (Loring et al., 2016). Youth outmigration and aging populations intensify the problem of local government lacking resources because of a smaller tax base (Loring et al., 2016; Hanrahan and Dosu, 2017). Yet some Arctic regions are growing quickly. Between 2000 and 2010, some communities in Alaska, Iceland, and the Canadian Arctic grew faster than the global growth rate. Nunavut was the fastest-growing region in the Arctic, increasing 20% since 2000 (Larsen and Fondahl, 2015). Migration from other regions to the Arctic contributed to some of the increase, but most of the increase was the result of natural population growth due to young populations and high fertility rates (Larsen and Fondahl, 2015).

Population flux challenges the capacity of water infrastructure and coordinated water systems planning (Warren et al., 2005; Loring et al., 2016; Instanes et al., 2016). The population influxes to the North may be seasonal as well, further stressing water systems and affecting water quantity and quality (Instanes et al., 2016; Medeiros et al., 2017). Thirteen papers (12%) noted the lack of multiple water sources as contributing to water vulnerability. This is particularly a concern where expanding populations in the North are reducing water levels, lowering municipal water supplies (Medeiros et al., 2017). The city of Iqaluit, Nunavut, for example, secured an alternate freshwater source to its primary freshwater source due to rapid urban growth and pressure on its sole water supply (Bakaic and Medeiros, 2017). The migration of people to urban areas was noted by nine papers (8%) as contributing to water vulnerability across the Arctic, because of the additional stress on water infrastructure due to additional users and decreased payers in rural areas, resulting in new challenges around water abstraction and supply (Kløve et al., 2017).

Another important factor in determining water vulnerability in remote Arctic households is individual levels of education within the home and community, which was highlighted in 24 documents (21%). Communities without water access in Alaska are concentrated in Alaska's western and northern regions, where there are higher mean percentages of residents who are Alaska Native, live in poverty, and have a lower than Grade 12 education (Gessner, 2008). In Newfoundland and Labrador, a household with a higher level of education was more likely to engage in municipal water quality projects (Sabau and Haghiri, 2008). In Alaska, communities have a greater chance of receiving funding for their water systems if they have educated residents who can complete grant applications and apply for money to support their water systems (Marino et al., 2009). Education also results in better cleaning and maintenance of water infrastructure at home. Higher levels of awareness of waterborne and water-washed diseases resulted in improved water quality monitoring at home and promoted hygiene practices (Roche et al., 2012; Hennessy and Bressler, 2016).

Sociocultural factors were highlighted as important aspects contributing to household water vulnerability. In many Arctic regions, untreated water is believed to be healthier and less contaminated than water from household tanks because there are fewer bacteria present and water has not been sitting in a truck or storage container (Martin et al., 2007; Marino et al., 2009). In Labrador, Nunatsiavut, Alaska, and Nunavut there is cultural attachment to raw, non-chlorinated drinking water, such as from melted ice and rivers, as individuals believe that raw water is of superior quality in terms of taste, health, and safety (Martin et al., 2007; Wilson, 2014; Daley et al., 2015). In Shishmaref, Alaska, residents perceive water from the centralized water system to be substandard due to taste, odor, color, and past experience, causing them to continue collecting drinking water from local surface waters (Marino et al., 2009). Additionally, many Arctic communities dislike the taste of chlorine. In Alaska's northwest Arctic region, residents associate the taste of chlorine with cancer (Ritter et al., 2014).

Due to frequent BWAs in Arctic Canada, residents lose trust in and develop negative perceptions of the drinking water system, which leads them to consume alternative beverages (e.g., soda) or water from other local sources (Sabau and Haghiri, 2008; Wright et al., 2018b). In 2006, Statistics Canada found that close to 40% of Canadian Inuit adults felt that their drinking water was contaminated at times throughout the year, and 15% felt it was not safe to consume (Wright et al., 2018a). Many communities do not trust the water utilities because of the high cost of purchasing water and frequent breakdowns (Sarkar et al., 2015). The majority of residents in Newfoundland and Labrador stated that they were very concerned with the overall safety of their water quality (Roche et al., 2013).

The cultural preference and practice of gathering drinking water from the land has contributed to household knowledge of seasonal water attributes, such as water levels and long-term changes in freshwater (Goldhar et al., 2014). The rate of change and the kinds of change experienced by individuals are constantly in flux (Fazey et al., 2011). As perceptions of the environment change, so too do concerns regarding water quality and the way that residents use water resources (Medeiros et al., 2017). The interpretation of environmental changes varies across communities and is central to understanding the willingness and ability of individuals to respond to change (Alessa et al., 2008b). The importance of people's perceptions of water was referred to by 44 documents (39%) as contributing to household water vulnerability.

Changing socio-hydrology represents the shift in residents' relationships with water sources and how those changed relationships influence household water vulnerability. Socio-hydrology captures the generational differences in familiarity with water resources in time and place. With the installation of a municipal water supply, a community's connection to local water resources changes (Alessa et al., 2007). A study showed how users that do not know the source of their water supply, or rely on institutions to obtain and treat it, largely view water as a commodity (Alessa et al., 2010). Additionally, in many Arctic communities, collecting water is a group activity that is a part of the local economy of exchanges and sharing (Eichelberger, 2012). If collecting water from traditional sources ends, individuals in the community may not sense changes in the social-ecological system or they may become less familiar with the location and reliability of traditional water sources (Alessa et al., 2010). Twenty-nine (26%) documents describe how changing socio-hydrology may worsen the impact of biophysical exposures on households or leave them more vulnerable to municipal water system disruptions (Altaweel et al., 2009; Wesche and Armitage, 2010; Eichelberger, 2014; Hanrahan et al., 2014). It may also affect their spiritual and physical well-being (Wright et al., 2018b).

A household's water vulnerability may also be reduced or increased depending on its kinship network, according to 15 papers (13%). A household's kinship network may be affected by the length of the relationship with the friend or kin, employment outside of the town, and other factors. Households without running water rely on kin or close friends for showers, laundry facilities, and drinking water (Eichelberger, 2010). If a household does not have family members, it can be challenging to secure enough drinking water supplies. In Canada, when someone like an Elder, a lone parent, or a widow does not have kin to help them, they may be unable to get sufficient water for their needs (Daley et al., 2014). When water is scarce, households with large kinship networks benefit from the valued sharing practices that allow households to access additional water supplies (Eichelberger, 2012). As a result of depending on a network of family and friends, individuals can feel that they need to use water given by others sparingly in order to not be too burdensome (Hanrahan et al., 2016). While some households share expenses of water retrieval, others do not have the means to compensate their family and friends who were spending more of their own income on fuel to make more trips to haul water.

Four papers (4%) stated that human fallibility can also increase the risk of household water vulnerability due to disruption of the water system and water distribution. In Canada, municipal tanker trucks are relied upon for drinking water delivery and wastewater removal; however, those services are delayed when vehicles break down, Arctic weather conditions prevent delivery, or operators are ill or unavailable (Daley et al., 2015). To cope with system failure, individuals and households depend on kinship networks to supplement their water supply (Daley et al., 2014). Individuals may also haul available iceberg water, which can threaten their safety because of uncertain ice conditions (Hanrahan et al., 2014).

Outcomes of Household Water Vulnerability

The most widely discussed outcome associated with household water vulnerability in the articles was health, with 57 papers (51%) describing a connection between poor access to safe water and poor health, such as respiratory illness and bacterial skin infections. In Alaska, villages that do not have in-home water services experience high rates of lower respiratory disease and skin infections (Eichelberger, 2012; Daley et al., 2014). These transmission pathways can be interrupted by increasing the quantity of water available to households (Thomas et al., 2013; Hennessy and Bressler, 2016). Poor health outcomes also include mental health impacts. When extreme weather and environmental changes reduce the accessibility of water resources, individuals have increased anxiety, depression, and fear as they are unable to secure sufficient water for themselves and their households (Brubaker et al., 2011c; Sarkar et al., 2015).

Within the documents that discussed outcomes of water vulnerability, 19 (17%) found water insecurity was associated with the lack of drinking water access and availability. Some of the documents described how water insecurity is the result of poor source water protection, climate change, or historical power relations (Eichelberger, 2014; Hanrahan and Dosu, 2017; Daley et al., 2018a), while others detailed factors described in the sections above. Eighteen papers (16%) discussed how water vulnerability affected household income. Residents reported needing to purchase water from the store or buy fuel to travel to find drinking water on the land (Goldhar et al., 2014). With widespread poverty in Arctic communities, many households cannot spend extra money on the fuel required to boil water in their home to improve water quality, and purchasing bottled water to increase water quantity is often cost prohibitive (Hanrahan et al., 2014; Sarkar et al., 2015). Households that cannot pay high water bills may be disconnected, which increases both their water insecurity and the user fees across the network because of a smaller customer base (Eichelberger, 2014).

The cost of water supply is a main determinant of the amount of water people use, and studies show that drinking untreated water is a result of not being able to pay for treated water (Ritter, 2007; Penn et al., 2017). Depending on water quality and quantity, income may be additionally affected due to medical bills to treat gastrointestinal illness and other waterborne or water-washed illnesses. Further, residents of rural communities with inadequate water infrastructure may be required to spend more on snowmobile and ATV maintenance if they are required to haul water from distant local water sources (Sarkar et al., 2015).

Water conservation was associated with household water vulnerability in 16 documents (14%). These articles detailed how households with limited water supply recycle or ration water to increase the quantity available for their needs. When households reuse water in washbasins it can spread pathogens (Chambers et al., 2008). Daley et al. (2014) found that residents of Coral Harbour use one-third the amount of water compared to average Canadians. People who depend on others to haul water for them consciously conserve water resources. Restricted water use can lead to significant health impacts, such as poor hygiene practices, and increased transmission of respiratory pathogens among other water-washed diseases (Wenger et al., 2010).

Food security was closely tied to household water vulnerability, with 11 papers (10%) noting a relationship between food and water security. Studies have documented that chronic water insecurity is associated with poor food security (Goldhar et al., 2014; Hanrahan et al., 2014). Changes to local hydrology, such as reduced snowfall or warming waters, impact the water bodies that provide spawning grounds, habitat, or migratory routes for wildlife (Vlassova, 2006; Wilson et al., 2015). Low water levels in Alaska threaten salmon runs and their spawning success (White et al., 2007). In Tuktoyaktuk, Canada, the municipal water system has caused lake levels to drop significantly and the whitefish populations to plummet (Goldhar et al., 2013). As a result of hydrological changes, wildlife is adversely affected and food security decreases.

Household water vulnerability was associated with mental stress in eight papers (7%). Mental well-being was affected as men and women struggle to secure sufficient water supplies and manage the burden on family members to haul water (Hanrahan et al., 2014). Mental health is also impacted by fear, anxiety, and depression as extreme weather (e.g., flooding and storm surges) threatens property, communities, cultural places, and human life (Brubaker et al. 2011c). Climate change is worsening mental stress due to damage to infrastructure and threatening communities' economies and viabilities (Brubaker et al., 2011b).

Two papers (2%) associated poor water quality or insufficient water quantity with missed school or work-related activities due to illness. Missing school and work has the additional impact of diminishing household income due to lost productivity. Chronic pain, such as back pain and shoulder injuries, was noted in one paper (1%) (Hanrahan et al., 2014). Likewise, one paper (1%) discussed how municipal water supply affects exercise, because when residents haul water from traditional water sources it is a very physical activity (Eichelberger, 2014).

CONCLUSION

This paper systematically reviewed the current state of the literature on water vulnerability at the household level in the Arctic. This analysis of 112 documents is a first step at synthesizing the multi-dimensional and interlinked biophysical and anthropogenic factors that influence household water vulnerability. The paper develops a deeper understanding of the cross-scalar dynamics between place-based vulnerabilities and larger trends such as urbanization and climate change.

The paper emphasizes that climate change and its associated impacts dominate the biophysical category. Climate change impacts will be insidious and must be urgently addressed in order to help communities adapt to heightened water vulnerability. This will require governments to improve supply-side infrastructure as highlighted in the papers.

The categories reveal the important interactions and unpredictability of the coupled socio-hydrology system and the relationship that people and water have with one another. They illuminate underlying factors that can worsen, assuage, or mitigate household water vulnerability. For example, the slowly shifting socio-hydrology may significantly increase the degree to which an individual or a community is affected by an extreme weather event as their temporal and seasonal familiarity with water resources diminishes over time. Yet kinship networks may mitigate water vulnerability due to individual and generational distancing from freshwater resources or when there are distribution failures. However, robust kinship networks are not universal and complete dependence on them to resolve household water vulnerability may exacerbate inequities and health concerns in the Arctic.

The categories also reveal that it is important to account for the spatial and temporal factors that affect household water vulnerability. Such a water management framework would account for multiple exposures existing in a watershed, such as downstream impacts of mining and resource development (Alessa et al., 2008a; Champalle et al., 2013). This framework would improve the Arctic community's ability to mitigate threats to water resources and assuage household water vulnerability.

This review was limited by the lack of available articles on household water vulnerability from Russia, Scandinavia, and Greenland. The review may have captured fewer documents from these regions because the inclusion criteria required articles to be written in English. While this limitation is important to note, the review does include key articles from leading researchers from those nations written in English journals and for international bodies such as the Arctic Council. Future research should continue to assess water vulnerability at the household level by addressing the many data gaps that exist, such as tradeoffs households make among food, energy, and water security. More studies are needed regarding how human and natural factors are connected to household water vulnerability, and how policy and water systems management can better mitigate water vulnerability. Additionally, more attention should be paid to the outcomes associated with household water vulnerability in addition to the factors that lead to a lack of drinking water access.

The biophysical and anthropogenic categories will continue to evolve and challenge Arctic communities' management of water resources. Water vulnerability would be better mitigated with consideration of tradeoffs across sectors, such as among energy, food, and water resources. Several papers overlooked the impact of pollutants on water and instead focused on the potential contamination of country food due to climate change, which highlights how water remains a tangential issue to food and energy (Healey et al., 2011). In order to reduce the vulnerability of communities that depend on a sole water supply and that will face increasing future pressures on water resources, future research should focus on collecting more data on regional hydrology and identifying and monitoring local surface water and ground water resources (Simms and de Loë, 2010; Hossain et al., 2016).

Cumulative factors determine household water vulnerability in and between Arctic communities and regions. Those factors are dynamic. The changing biophysical conditions and evolving contextual characteristics, such as technological and institutional capacity, influence how climate change is experienced and managed, and influence the impact of fast and slow drivers of change (O'Brien et al., 2007; Goldhar et al., 2014). Going forward, there is a continuing need to consider climate impacts on freshwater resources at a local level and identify the best policy and management strategies to support communities that are affected by these changes. Broader regional and pan-Arctic analyses would also allow for further comparison of factors affecting household water vulnerability, and share valuable lessons learned.

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APPENDIX 1

The following supplementary materials are available online:

FIG. S1. Regional distribution of reviewed documents.
TABLE S1. Search terms of the narrative review.
TABLE S2. Code book for the narrative review.

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