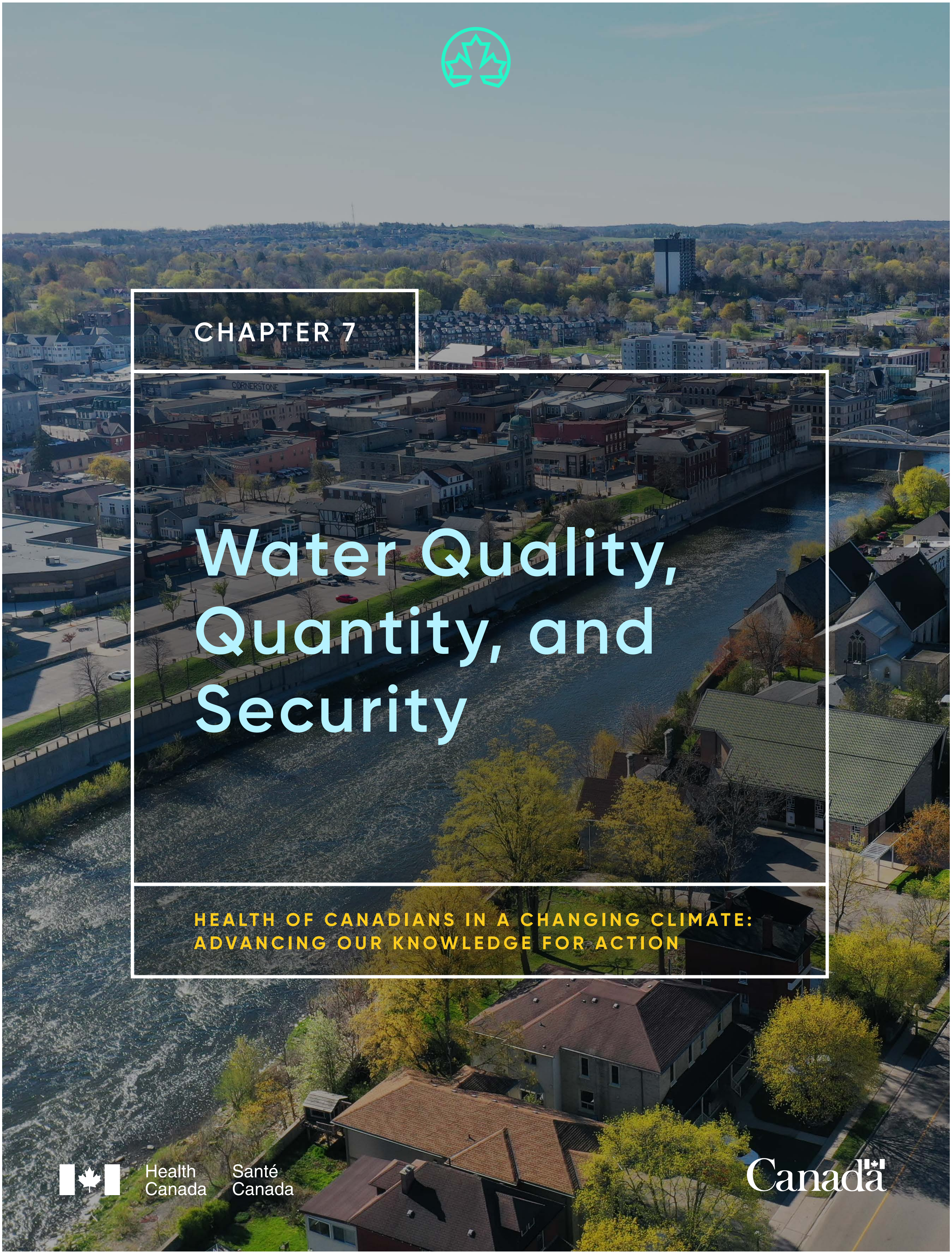

CHAPTER 7

Water Quality, Quantity, and Security

HEALTH OF CANADIANS IN A CHANGING CLIMATE: ADVANCING OUR KNOWLEDGE FOR ACTION

Health Canada Santé Canada

Canada

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Table of Contents

Summary

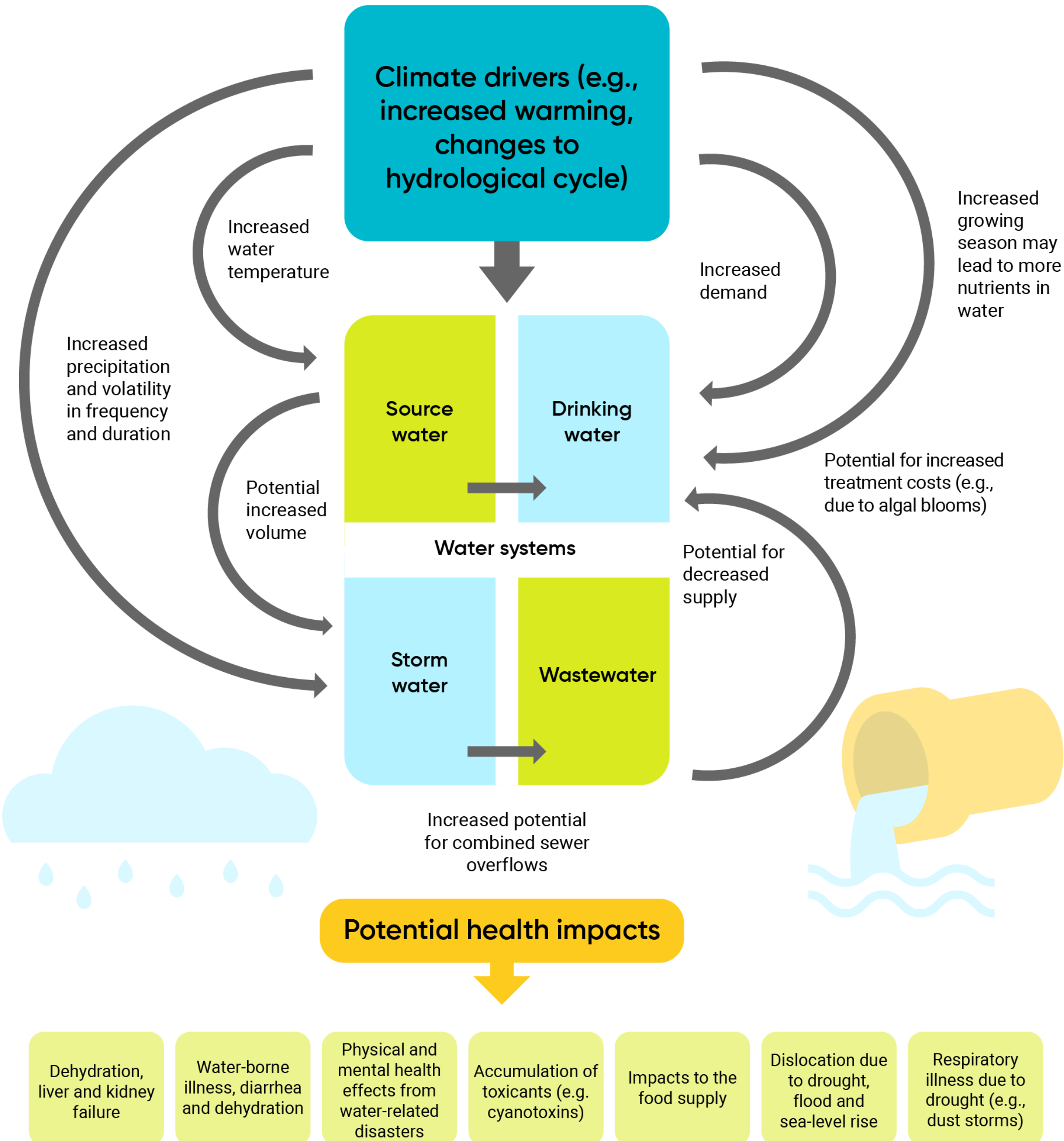
Climate change is expected to result in fluctuations in water quantity, degraded water quality, increased flood and drought risks, as well as a greater burden of climate-related water-borne disease. The impacts of sea-level rise and loss of ice in Canada are likely to be significant. Not all Canadians will experience these impacts equally. First Nations, Métis, and Inuit communities, many of which already face water insecurity, are expected to be disproportionately affected, as are rural and remote communities that have only basic water and sewage infrastructure.

The health impacts associated with climate change effects on water quality and quantity are not inevitable. Through effective mitigation and adaptation, they can be reduced. Canadians can better adapt to these anticipated impacts and protect health by assessing local climate risks and vulnerabilities, developing adaptation plans, improving surveillance systems, building climate-resilient water systems, and promoting intersectoral collaboration to protect water resources and address climate-related risks.

Key Messages

- Changes in precipitation and temperature due to climate change will result in impacts on water quality and quantity and disrupt both natural water systems (rivers, lakes, oceans) and human drinking water and wastewater systems, thereby increasing risks to the health of Canadians. The extent and intensity of these changes will vary by region and season.
- Water-related health risks associated with climate change include threats to drinking water and irrigation supplies; increases in water-borne diseases (e.g., cryptosporidiosis, giardiasis, campylobacteriosis); physical injuries and mental health impacts from extreme weather events such as floods and droughts; and threats to health and well-being due to the socio-economic and environmental consequences of water insecurity.
- Climate change-related water and food shortages, coupled with increasing population growth in climate vulnerable regions of the world with fewer resources, could affect Canada through regional and international migration.
- Adaptation to the anticipated impacts of climate change on water resources and human health can help protect Canadians from future risks. Adaptation will require broad multi-sectoral action and coordination among, for example, public health practitioners and service providers, and water and wastewater managers.
- Indigenous Peoples are among those most affected by the degradation of water resources, but they also possess countless generations of accumulated knowledge, which can be applied to protect health. Partnerships among Indigenous communities, health authorities, and water managers are needed to identify the population-specific health impacts of climate change impacts on water resources and to implement effective adaptation options informed by traditional knowledges and cultural needs.

- More information is required on the current burden of disease in Canada related to climate change impacts on water resources and related hazards, and on the projected health risks from further warming. Research is also needed on the most effective ways to adapt to increasing stresses on drinking water systems and on needed public health interventions, including the communication of risks to the public. Better models for regional drought and flood prediction are needed.
- Health authorities can increase understanding of climate change impacts on water resources and health, as well as potential adaptation options, by conducting local and regional vulnerability and adaptation assessments related to climate change and health. By doing so, health authorities can improve their preparedness, maximize the health benefits of cross-sector collaboration, and build climate resilience within their communities.



Examples of the direct and indirect ways climate change can alter water quality and quantity and affect health.

Overview of the Health Impacts of Water Quality, Quantity, and Security in the Context of Climate Change

HEALTH IMPACT OR HAZARD CATEGORY	CLIMATE-RELATED CAUSES	POSSIBLE HEALTH EFFECTS

Water quality, quantity, and security	• Increased precipitation and flooding causing dangerous evacuations, drinking water shortages, disruptions
	• Increased drought leading to regional water shortages, diminished food security, dust storms and habitat loss
	• Increased permafrost melt affecting water accessibility
	• Increased salt-water infiltration affecting water accessibility
	• Increased frequency of harmful algal blooms
	• Higher water temperatures increasing the prevelance of water-borne pathogens
	• Water shortages causing or contributing to international conflict and forced migration
	• Wildfire degrading watersheds
		• Water-borne and food-borne infections, illnesses and deaths
		• Water-borne infections and illnesses:
		  ◦ Acute gastrointestinal illness
		  ◦ Infant mortality
		  ◦ Birth defects
		  ◦ Exacerbation of chronic diseases
		  ◦ Skin diseases
		• Food-borne illnesses:
		  ◦ Food poisoning
		  ◦ Paralytic seafood poisoning
		• Kidney failure
		• Stress and other mental health impacts
		• Respiratory illness
		• Liver failure
		• Injuries, illness, and deaths from flooding and extreme precipitation events
		• Destruction or damage of health infrastructure
		• Health and social services disruptions
		• Disruptions to water systems and water management resulting in impacts such as degraded source water quality
		• Failure of drinking water systems during extreme weather events

7.1 Introduction

Climate change will reduce the quantity and quality of water in all Canadian regions on a seasonal basis (Andrey et al., 2014). The health of Canadians can be affected by climate change effects on water in a number of ways: by an increasing frequency and severity of extreme weather events, such as floods and droughts, as well as the degradation of drinking and recreational water quality due to longer-term warming. These effects may arise because of shifts in ecological boundaries and changes to the cryosphere, and to the freshwater–saltwater interface. Health may also suffer from climate change impacts on water that affect food safety and security, for example, through the contamination of fish and shellfish (see Chapter 8: Food Safety and Security). Both extreme events and longer-term warming can increase pressures on water systems, which are integral to efforts to keep people healthy and safe.

Health outcomes can include both physical and mental health impacts, for example, in the aftermath of a flood or during a drought. Such events can increase health impacts associated with chemical and biological contamination of water supplies such as water-borne illnesses. Illness caused by contamination may be acute, infectious, and restricted to the gastrointestinal tract, or chronic and associated with multiple systemic effects. Changes in water quality and quantity affect different exposure pathways that can interact with multiple social and behavioural factors, leading to negative health outcomes (Trtanj et al., 2016). For example, climate change effects on water can cause the loss of cultural and societal stabilizing factors that affect various determinants of health (e.g., loss of employment in industries that rely on a predictable water supply), which also have longer-term effects on mental health (see Chapter 4: Mental Health and Well-Being).

This chapter outlines the current and possible future health impacts of climate change in Canada related to effects on freshwater, marine, and coastal systems, with a specific focus on the importance of drinking water, wastewater, and stormwater infrastructure in reducing risks. It includes discussion of how climate change affects the sources of contaminants and exposure pathways, including projections of increased health risks, where data are available. Current evidence of climate impacts on fish and shellfish illnesses that affect Canadians is reviewed, and broader climate change implications for water security are explored. The chapter identifies adaptation options that public health authorities can take to protect health, in collaboration with decision makers outside of the health sector. It also identfies important knowledge gaps that would benefit from future research to support actions that help prepare for climate change.

7.2 Methods and Approach

This chapter used a narrative scoping approach to identify information related to the current and projected water-related health impacts of climate change and possible adaptations in Canada. Systematic searches of the Agricola, Medline, and Embase databases were conducted for publications up to January 2019. Systematic searches targeted seven subject areas to support the broader narrative review, including:

- climate change and drinking water;
- climate change, water, and adaptation;
- climate change, water, and algal blooms;
- climate change and water in Canada;
- climate change, water, and extreme weather;
- climate change, water, and the food system; and
- climate change, water, and traditional indigenous uses.

A number of search terms were employed for each subject. Some common search terms included variations of climate change; drinking water; water supply; human(s); health; public health; environmental exposure; diseases; mental health; mortality; morbidity; flood; safety; adaptation; infection; bacteria; pathogen; infectious; parasitic; water-borne; and others.

Additional peer-reviewed and grey literature was identified from the authors' knowledge, reviewers' comments, and targeted searches. Author knowledge and targeted searches were used to incorporate relevant literature published after the completion of systematic searches. Estimates of future trends in streamflow, surface water levels, soil moisture, and groundwater draw on *Canada's Changing Climate Report* (Bush & Lemmen, 2019).

Some degree of caution is warranted when interpreting studies on climate change and water-borne disease. For example, publication bias may affect the evidence base (Levy et al., 2016). Additionally, due to constraints associated with using secondary data sources, studies are often limited in what covariates can be included, which may introduce uncertainty in the estimates. Moreover, pathogens can be transmitted by multiple agents and via multiple pathways (Semenza et al., 2012), and some health outcomes, such as acute gastrointestinal illness (AGI), are known to be under-reported (Thomas et al., 2013).

7.3 Climate Change, Water, and Health

Water quality and quantity are intricately linked and vary depending on geophysical, biological, and social contexts. Water quantity refers to the abundance of water available in an ecosystem or community. Water quality refers to the suitability of available water for a given task (e.g., drinking). Water security is a measure of access to water of a sufficient quantity and quality to protect and promote health and well-being. Hydrogeological factors, including soil, slope, and aquifer composition, as well as climatological factors, such as temperature and precipitation, all influence water quality and quantity via complex and interconnected pathways. Source water quality and quantity are the predominant factors that affect drinking water and drive water treatment requirements (Boholm & Prutzer, 2017). The most significant determinant of water quality is human activity (Trtanj et al., 2016). In most cases of water supply contamination, human activity is the source of contamination, either directly, via human waste entering the water supply, or indirectly, through land-use change, industry, or agriculture (Trtanj et al., 2016).

Climate change-related stressors, such as extreme rain events or rapid spring snowmelts, are increasing the risks of water-borne disease. Generally, floods and high river flows dilute dissolved substances and transport pathogens, while droughts and low river flows concentrate them (Delpla et al., 2009) with health implications for populations using the water source. Healthy natural ecosystems are often able to filter biological and chemical contaminants (e.g., through wetlands), highlighting the value of source water protection to drinking water systems (DWSs) and health protection.

Climate change can affect water resources through multiple pathways, but water resources are principally impacted by climate-driven changes to precipitation and temperature. In addition to an appropriate volume of water, which may be affected by flood or droughts, many human health impacts are mediated by biological or chemical agents in water that humans use, or come in contact with, through drinking water, bathing, recreation, or ceremonial use. The primary implications for human health are illustrated in Figure 7.1. From a Canadian perspective, the negative health effects associated with climate change impacts on water include physical impacts (e.g., physical trauma) from floods, mental health impacts (e.g., due to exposure to extreme weather events such as floods or droughts), and water-borne infectious diseases and other illnesses caused by gradual warming and by chemical and biological contamination. Indirect impacts (e.g., to personal hygiene or food security) are largely driven by limited access to water of a sufficient quantity or quality.

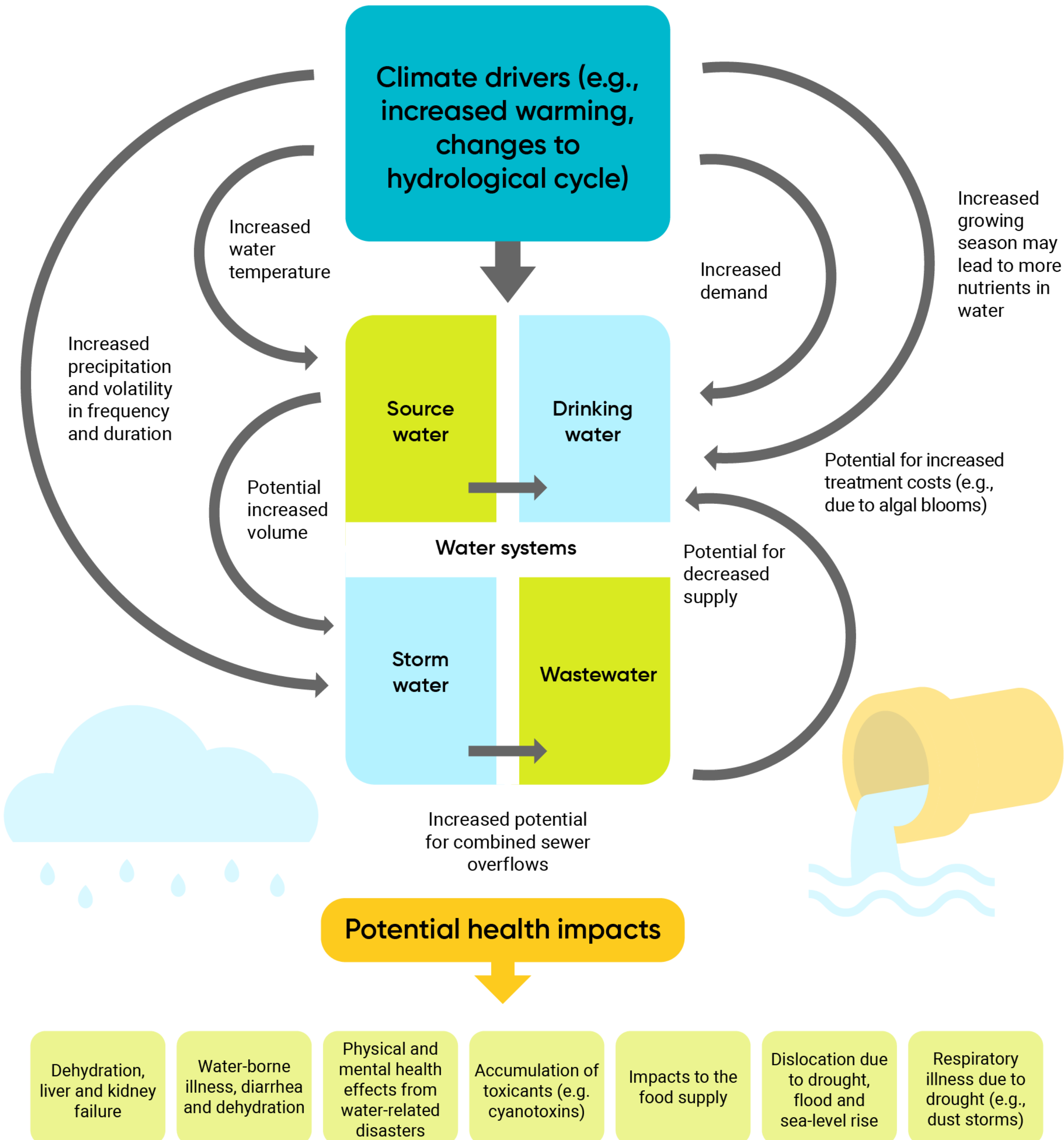


Figure 7.1 Examples of the direct and indirect ways climate change can alter water quality and quantity and affect health.

7.3.1 Indigenous Peoples — Water is Life

First Nations, Inuit, and Métis peoples are diverse, with equally diverse beliefs, views, and experiences; however, water is an area where views are widely shared (McGregor, 2012). Within many Indigenous teachings, water has a variety of meanings, but underpinning all these is that "water is life" (AFN, 2013; Bharadwaj & Bradford, 2018). Water is part of creation stories that many Indigenous Peoples[1] identify with, and because water is considered "life" itself, Indigenous Peoples often feel that they have a sacred connection to water and a responsibility to protect it, now and for future generations (McGregor, 2012; Sanderson et al., 2015). The Assembly of First Nations speaks of this responsibility as a never-ending circle from the "tiny droplets of water falling from the skies to the continuation of its journey to the lakes and rivers and the ground where it is stored" (AFN, 2013, p. 1). Inuit Elders speak of the healing quality of water gathered from the land when compared with municipally treated water, "I feel more alive when I'm drinking river water. More alive. Active." (Watson, 2017, p. 123).

To many Indigenous Peoples, water is sacred and has power, playing roles in their lives beyond hydration — for its aesthetics; as medicine; as a symbol of fertility, purity, strength, and softness; as a home for living beings (some of which are sources of traditional food); as a life-enriching cleansing agent; and an element of interconnectedness (McGregor, 2012; Sanderson et al., 2015; Bharadwaj & Bradford, 2018). Water is not viewed as a discrete aspect of the environment but as part of a holistic system. When considering the role of water, many Indigenous Peoples account for its value beyond that for humans, for example, the plants that water nourishes, the fish that live in water, the traditional medicines that grow in or around water, and the animals that drink water. Water is critical to life and to the physical, emotional, mental, and spiritual well-being of many Indigenous Peoples (McGregor, 2012). Climate-related changes in freshwater availability in the North has had impacts on subsistence food supplies and connection to the land (Goldhar et al., 2013a).

To many Indigenous Peoples, water has a spirit and is to be respected as a living being. Water is considered by many as a relative, or a participant in a caring and compassionate relationship. Many Indigenous Peoples view various water bodies as having different personalities, and water is understood to have feelings and can be sad and/or angry if it is not respected or treated properly. As with all relationships, there are responsibilities on both sides, and water must be respected and allowed to perform its life-giving duties. Across Canada, there are local protocols and ceremonies for giving thanks and for maintaining and establishing a spiritual connection to water (McGregor, 2012).

Indigenous Peoples, along with all plants and animals, have the right to clean and healthy water and have the responsibility to make informed decisions that affect the waters, planning at least seven generations ahead (McGregor, 2012; Sanderson et al., 2015; CWB, 2018). Indigenous Peoples have sovereign, inherent, and treaty rights over the land and waters in their traditional territories and continue to assert and exercise their rights and responsibilities through ceremony and management practices, as traditional stewards of watersheds (AFN, 2013). The *United Nations Declaration on the Rights of Indigenous Peoples*, adopted by Canada, affirms the work needed to achieve reconciliation, including in areas regarding water. Articles 25 and 32 of the declaration support

1 The term Indigenous is used in this chapter to refer collectively to the original inhabitants of Canada and their descendants, including First Nations, Inuit, and Métis peoples, as defined under Section 35 of the *Constitution Act, 1982*. Wherever possible, clear distinctions are made between these three distinct, constitutionally recognized groups. Indigenous Peoples outside of Canada are also referenced in some instances – particularly with respect to international climate policy, processes, and rights – and are identified as such.

the right of Indigenous Peoples to their special relationship with water and to act on their responsibilities to future generations. The declaration calls for states to obtain free and informed consent before approving any project affecting lands or territories and other resources, particularly in connection with the development, use, or exploitation of mineral, water, or other resources (McGregor, 2012). This special relationship with water is important context for considering the impacts of climate change on Indigenous Peoples for the rest of this chapter.

7.3.2 Water Quality

7.3.2.1 Drinking Water Systems and Health

Drinking water systems are designed to provide safe drinking water, and, by extension, to protect and promote human health. Most of Canada's population is serviced by large municipal DWSs, while approximately 15% of the population is serviced by smaller non-municipal systems (Pons et al., 2015). Some Canadians, particularly those living in rural areas, access their drinking water through private water systems (i.e., privately owned systems that provide drinking water to individuals and households that own the systems) such as wells, springs, or surface water (Statistics Canada, 2011). In the Canadian context, there is no universally agreed-upon definition of a small DWS, and there are important differences with regard to the definition and regulation of small systems across provinces and territories (Charrois, 2010; Pons et al., 2015). For this report, large DWSs are defined as those serving populations of 5000 or more, and small systems are those serving populations of less than 5000 (Health Canada, 2005). Some DWS are supplied by surface water, some by groundwater, and others use a mix of surface and groundwater sources. Approximately 10% of the population relies on a groundwater source, and the majority of Canadians with private water supply use groundwater sources (Statistics Canada, 2011; Murphy et al., 2016a).

The most studied health outcomes related to drinking water are AGI and other water-borne diseases. Small and private DWSs across Canada are more vulnerable to contamination and AGI outbreaks than larger municipally managed systems (Hrudey & Hrudey, 2004; Schuster et al., 2005; Uhlmann et al., 2009; Wilson et al., 2009; Charrois, 2010). Investigations of past water-borne disease outbreaks in Canadian DWSs have shown that a high proportion of outbreaks occurred in small DWSs (Moffatt & Struck, 2011), and are most often the result of multiple risk factors such as system failures, lack of treatment, limited monitoring, resource constraints, operator knowledge, or poor-quality source waters (Schuster et al., 2005; Wilson et al., 2009). Private DWSs are commonly untreated and vulnerable to contamination (Schuster et al., 2005), particularly surface water and groundwater under the direct influence of surface water sources (Murphy et al., 2016b). Nevertheless, water-borne disease has been associated with DWSs of all sizes and sources, including the largest recorded outbreak in the United States in Milwaukee, Wisconsin, in 1993 with 403,000 AGI cases (Corso et al., 2003). Although large municipal systems have multiple barriers in place to prevent contamination and reduce the risk of both sporadic and outbreak-related illness, a range of pressures, such as population growth, aging infrastructure, resource constraints, and climate change, are placing unprecedented pressures on these systems (Sharma et al., 2010). Due to these pressures, there is a growing risk that it may become more difficult for large municipal DWSs to reliably provide clean and dependable drinking water supplies to Canadians (Shuster-Wallace et al., 2019; Shuster-Wallace et al., 2020).

Although much of Canada benefits from reliable access to quality drinking water, many Indigenous communities face long-standing challenges to accessing safe drinking water, including long-term drinking water advisories and limited access to quality water or safe DWSs. In Canada's North, Inuit and other northerners often rely on trucked water systems, where water is delivered to individual homes or distribution centres and stored in tanks until it is used (Daley et al., 2018). This system can adversely affect health due to inadequate supply (e.g., tanks do not hold enough water to meet household needs) and quality (e.g., water may be contaminated during storage) (Daley et al., 2014). Water management issues in Indigenous communities are discussed further in section 7.3.4.2 Impacts on Infrastructure.

Contamination of water destined for human consumption (e.g., drinking, cooking, and washing) or recreation (e.g., swimming in open waters) is typically categorized as biological, chemical, or radioactive. Biological contamination is microbial, from either bacteria, protozoa, viruses, or algae, and is usually managed by municipal systems that combine filtration and disinfection (Ashbolt, 2015). Chemical contamination threats are varied and include arsenic, lead, microplastics, and pharmaceuticals (i.e., synthetic hormones) (Kleywegt et al., 2011; Uslu et al., 2013). Many of these contaminants require sophisticated treatment (Kim et al., 2018), which is a challenge for many of Canada's DWSs. Radioactive contamination (e.g., isotopes of radium, uranium, and radon) must be removed by filtration.

Many Canadian DWSs continue to face challenges with their drinking water. For example, between 2011 and 2017, on average, 10% of Canadian households on a municipal DWS reported being subject to a boil water advisory at some point over the past year (Statistics Canada, 2021). A significant proportion (close to 50%) of boil water advisories are issued as a result of drinking water distribution system problems such as line breaks, pressure losses, or planned maintenance work. Most of these boil water advisories were precautionary, and were rescinded when repairs or maintenance was completed (Health Canada, 2015).

Climate change can increase challenges to DWSs, through gradual warming, extreme weather events (e.g., floods, droughts, wildfires), and saltwater intrusion, all of which can increase contamination of waters and the need for treatment. The application of a risk-based approach to monitoring for potential contamination will be necessary as climate change exacerbates current risks to water quality and creates unfamiliar risks in the future.

7.3.2.1.1 Mechanisms Through Which Climate Change Impacts Water Quality

There is a well-documented seasonality to many infectious diseases, including sporadic cases (Lake et al., 2005; Britton et al., 2010; Lal et al., 2013) and outbreaks of water-borne AGI. Outbreaks are considered to occur if two or more epidemiologically linked people have a similar illness after exposure to the same water source (Curriero et al., 2001; Auld et al., 2004). The level of exposure required to experience health impacts differs according to the pathogen and, in many cases, the individual (e.g., less exposure may be required in children than in adults). An overview of climate-sensitive biological agents of water-related illnesses is provided in Table 7.1.

Table 7.1 Climate-sensitive biological agents of water-related illness

PATHOGEN OR TOXIN PRODUCER	EXPOSURE PATHWAY	SELECTED HEALTH OUTCOMES AND SYMPTOMS	MAJOR CLIMATE CORRELATION OR DRIVER (STRONGEST DRIVER(S) LISTED FIRST)
Algae: Toxigenic marine species of *Alexandrium, Pseudo-nitzschia, Dinophysis, Gambierdiscus;* and *Karenia brevis*	Shellfish and fish consumption Recreational waters (including aerosolized toxins) Drinking water	Gastrointestinal and neurological illness caused by shellfish poisoning (paralytic, amnesic, diarrhetic, neurotoxic) or fish poisoning (ciguatera) Asthma exacerbations, eye irritations caused by contact with aerosolized toxins (*K. brevis*)	Increased water temperature, ocean surface currents, ocean acidification, hurricanes (*Gambierdiscus* spp. *and K. brevis*)
Cyanobacteria (multiple freshwater species producing toxins, including microcystin)	Drinking water Recreational waters	Liver and kidney damage, gastroenteritis (diarrhea and vomiting), neurological disorders, and respiratory arrest	Increased water temperature, precipitation patterns
Enteric bacteria and protozoan parasites, including *Salmonella enterica, Campylobacter* spp., toxigenic *Escherichia coli, Cryptosporidium, Giardia*	Drinking water Recreational waters Shellfish consumption	Enteric pathogens generally cause gastroenteritis; some cases may be severe and may be associated with long-term and recurring effects	Changes in air and water temperature, heavy precipitation (especially when preceded by a dry period), and flooding
Enteric viruses, including enteroviruses, rotaviruses, noroviruses, hepatitis A and E	Drinking water Recreational waters Shellfish consumption	Most cases result in gastrointestinal illness; severe outcomes may include paralysis and infection of the heart or other organs	Heavy precipitation, flooding, and changes in air and water temperature

PATHOGEN OR TOXIN PRODUCER	EXPOSURE PATHWAY	SELECTED HEALTH OUTCOMES AND SYMPTOMS	MAJOR CLIMATE CORRELATION OR DRIVER (STRONGEST DRIVER(S) LISTED FIRST)
Leptospira and Leptonema bacteria	Recreational waters Indoor cooling systems that use water	Mild to severe influenza-like illness (with or without fever) to severe cases of meningitis, kidney, and liver failure	Flooding, increased water temperature, heavy precipitation
Vibrio bacteria species	Recreational waters Shellfish consumption	Varies by species but includes gastroenteritis (*V. parahaemolyticus, V. cholerae*), septicemia (bloodstream infection) through ingestion or wounds (*V. vulnificus*), skin, eye, and ear infections (*V. alginolyticus*)	Increased water temperature, sea-level rise, precipitation patterns (as they affect coastal salinity)
Legionella bacteria species, non-tuberculous mycobacteria (suggestive evidence)	Indoor cooling systems that use water	Pneumonia	Air temperature, extreme weather events, proliferation of air conditioning use

Source: Trtanj et al., 2016

Distinct seasonality of water-borne diseases across different hydroclimatic systems has been observed, both in Canada and elsewhere (Bertuzzo et al., 2012; Galway et al., 2014). A number of epidemiological studies have observed a positive association of AGI with ambient air temperature, as well as with flooding and heavy rainfall events, explaining part of these seasonal patterns (Levy et al., 2016). For example, AGI rates in selected watersheds in British Columbia (bacterial and protozoan combined) peak in the early summer among snow-dominated watersheds and in the fall for rain-dominated ones, which roughly corresponds to when each of the two different hydroclimatic regimes experience most surface runoff and groundwater recharge (Galway et al., 2014). Extreme rain events increase this discharge, often measured as turbidity in source water, particularly after a dry period (Chhetri et al., 2017). By understanding hydroclimatic factors, including seasonal changes related to climate change and underlying seasonal AGI trends, DWS designers and operators can take measures to improve filtration and treatment efficiency and reduce contamination and risks of AGI during expected seasonal peaks in disease (Galway et al., 2014).

Box 7.1 Water, watersheds, and health

The watershed represents more than just a drainage basin; it describes a complex socio-ecological system, evolved over millennia, that is connected by water, which all life depends on (Parkes et al., 2010). Watersheds encompass the land contained within the drainage basin and are linked systems, with small streams forming their own watersheds nested within ever-larger catchment areas, up to the global scale (e.g., the Ottawa River is itself a large watershed, which is part of the even larger St. Lawrence River watershed). Watersheds can be described physically as a basin, in which gravity acts upon the water, that enables downstream exposures to upstream pathogen sources.

Increasingly, water management and other natural resources and ecosystem management initiatives are being undertaken at the watershed scale, such as by Ontario's conservation authorities (Conservation Ontario, n.d.). Nationally, watershed-based approaches to ecosystem management have emerged as galvanizing forces for participatory or community-driven action (Bakker & Cook, 2011; Guehlstorf & Hallstrom, 2012; Morris & Brandes, 2013; Gérin-Lajoie et al., 2018). British Columbia alone has more than 230 community-based groups working to protect water quality, many of which are volunteer-driven.

This growing interest in water resources management and environmental protection at the watershed scale creates opportunity for citizen-led efforts to monitor, report on, and respond to health-relevant climate change impacts on water resources. For example, many Indigenous communities have been developing watershed strategies as a means of governance over their resources. Engagement of youth has been pursued by many to create the next generation of "watershed warriors" (AFN, 2013). Numerous First Nations communities in the Prairies have completed source water protection plans (Patrick, 2018) that will benefit human health. Indigenous Peoples are faced with long-standing issues and challenges in reacting or responding to the many competing pressures to protect their watersheds (AFN, 2013; Goldhar et al., 2013a). Organizations focused on governance and management at the watershed scale are critical components of protecting watersheds as social-ecological systems (Canadian Council of Ministers for the Environment, 2016; Picketts et al., 2017).

The patterns, frequency, and intensity of precipitation may influence water-borne AGI through several mechanisms. Precipitation patterns can influence overland flow, runoff, and erosion, and lead to re-suspension of particles and pathogens, increasing the potential for surface and groundwater contamination by pathogens and affecting the effectiveness of DWSs (Semenza et al., 2012). Some research indicates that heavy rain following a period of drought can lead to overland flow events with particularly high pathogen loads and increased risk of surface water contamination (Levy et al., 2016). Additionally, extreme rainfall events may increase microbial concentrations in drinking water supplies due, in part, to increased particulate matter following surface runoff and re-suspension of river bottom sediment by increasing turbidity (Mann et al., 2007; De Roos et al., 2017). Turbidity refers to the cloudiness of water or undissolved solids and is a proxy indicator of water quality. High turbidity has been shown to reduce the effectiveness of water treatment in DWSs and may also provide a medium for microbial growth in source waters (Mann et al., 2007). The influence of snow-related precipitation (e.g., rain-on-snow events, snowmelt, or spring thaws) could also affect the risk of AGI but remains largely unstudied (Jagai et al., 2012).

Nearly 70% of all water-borne disease outbreaks in the United States from 1948 to 1994 occurred after a heavy rain event (Curriero et al., 2001). Heavy rain has also been identified as a contributing factor in Canada's Walkerton, Ontario, tragedy (Auld et al., 2004) and the largest outbreak of AGI in the United States in Milwaukee in 1993. In Milwaukee, a heavy precipitation event quickly saturated the soil, causing surface runoff and associated turbidity, resulting in a compromised water treatment process (Curriero et al., 2001). Unlike the Milwaukee event that was associated with a single large rain event, the Walkerton event followed multiple days of heavy rain that saturated the soil, leading to the contamination of a drinking water production well. The water supply was contaminated with multiple pathogens (Auld et al., 2004) reaching consumers after additional failures in the water treatment process (Hrudey et al., 2003). These examples highlight some of the similarities and differences among DWSs concerning how extreme precipitation can affect water quality under various hydrological conditions and possible implications of future climate change.

In Canada, sporadic AGI cases are likely responsible for a greater burden of illness than AGI outbreaks, but are more challenging to study. Two relatively large 10-year studies in British Columbia recorded an average 19 cases/100,000 and 26.9 cases/100,000, respectively. There were no outbreaks during the two study periods (Uhlmann et al., 2009; Chhetri et al., 2017). Identifying transmission pathways and under-reporting, including the possibility of unreported outbreaks, presents challenges (Hunter & Thompson, 2005). However, emerging evidence suggests that heavy precipitation events can be associated with increases in sporadic AGI in municipal DWSs (Chhetri et al., 2017). While the risk to specific indviduals is small, due to the large populations exposed, the number of cases or population attributable risk is significant. Considering that most AGI cases go unreported, AGI estimates are likely to be quite conservative. In a representative survey in British Columbia, it was estimated that only once in 48.5 cases of cryptosporidiosis and once in 40.7 cases of giardiasis are reported (MacDougall et al., 2008).

Before a membrane-filtration drinking water treatment plant was installed for much of Metro Vancouver in 2010, a significant increase in water-borne disease two to four weeks after heavy rain events (defined as above the 90th percentile) was observed (Chhetri et al., 2017). Using identical methods, another study by the International Joint Commission found similar associations in three municipal DWSs sourcing water from the Great Lakes region (Mezzacapo et al., 2018). In both studies, a dry period, defined as at least 30 days of the previous 60 without precipitation, was a significant mediating factor increasing risk. A preceding dry period of some length has also been observed in other studies (Levy et al., 2016). It is hypothesized that a dry period, or drought, allows for accumulation of pathogens in the environment and source waters, increasing the risk of drinking water contamination (Levy et al., 2016). While these studies cannot be extrapolated to other watersheds across Canada, they do highlight the vulnerability to sporadic illness due to heavy rain events in some municipal systems, independent of outbreaks due to DWS failures. For many regions in Canada, climate change is expected to increase extreme rain events (Chhetri et al., 2017; Bush & Lemmen, 2019). More studies are needed to examine the effects of extreme rain following dry periods on the various types of water treatment available and how each performs in the many types of watershed-level hydroclimatic systems across Canada.

7.3.2.2 Saltwater Intrusion

In coastal regions of Canada, the intrusion of saltwater from the ocean into coastal aquifers is a growing concern, as the saltwater can contaminate the groundwater, making it unusable for drinking or irrigation. Population increases, accompanied by increased groundwater demands, as well as rising sea levels and storm surges, are all driving factors of this phenomenon (Klassen & Allen, 2017). The complex interactions between fresh and saline coastal aquifers make it difficult to study these changes. As saltwater intrusions may last years and even decades, their impacts on water and food security, and implications for human health, can be long-lasting and severe (Luh et al., 2017). Contamination of groundwater by ocean water leads to increased demand on surface water sources and uncontaminated groundwater sources. Small islands with growing populations, such as British Columbia's Gulf Islands, are particularly vulnerable. The increased density of coastal wells on some Gulf Islands has resulted in a depressed water table, resulting in saltwater intrusion and possible contamination of wells located nearest to the coast (Klassen & Allen, 2017). Saltwater intrusion events have also occurred in the Canadian Arctic and Atlantic Canada (Somers & Nishimura, 2012; Thienpont et al., 2012).

7.3.2.3 Pathogens in Sewage Found in Ocean Water

Pathogens found in sewage can end up in ocean water and bioaccumulate in shellfish, particularly filter-feeding bivalves such as oysters, mussels, and clams (Le Guyader et al., 2000), which, when consumed raw or undercooked, can cause sporadic illness and disease outbreaks (Bellou et al., 2013). The pathogens of main concern include norovirus and hepatitis A, both viruses. Norovirus is a very common cause of gastroenteritis, causing symptoms such as nausea, vomiting, diarrhea, and low-grade fever, lasting one to three days. It occurs primarily in the winter months and causes numerous community and facility disease outbreaks. It is usually self-limiting; a small proportion of patients require hospitalization for dehydration (Heymann, 2015). Hepatitis A causes liver infection and manifests as fever, nausea, abdominal pain, and jaundice. Most people recover without treatment, but adults can experience a more serious course with chronic liver disease, and 1% to 2% of cases are fatal (Heymann, 2015). These pathogens can contaminate food through contact with an infected food handler or from direct contact with human sewage.

Vibrio spp. are the most common form of bacteria to affect human health in Canada following the consumption of fish and shellfish (see section 7.3.4 Water Security and Society). However, bacteria other than *Vibrio spp*. are occasionally found in fish and shellfish and have caused outbreaks (Burkhardt & Calci, 2000; Feldhusen, 2000: DePaola et al., 2010). *Salmonella* is the most common cause of such bacterial contamination in Canada, although, on occasion, *Escherichia coli*, *Campylobacter*, and *Shigella* have contaminated fish or shellfish. These bacteria are introduced into the marine environment from animal or human feces or during processing. Agricultural runoff is another possible source of marine contamination and disease outbreaks, although it is uncommon. Although *V. cholerae* are naturally occurring marine bacteria, illness risk is amplified in areas where sewage is not controlled.

Direct contact with human sewage is commonly how shellfish become contaminated (Campos & Lees, 2014). Climatically driven increases in extreme precipitation events may result in an increased number of sewage water releases, particularly in combined stormwater and sewage water systems. Overflows occur when raw sewage enters the environment via accidental or planned discharges from municipal sewer systems, storm drains, or septic systems, or seepage from damaged sewage pipes (Cook et al., 2009; Miller et al., 2018). Numerous shellfish-related disease outbreaks have been reported in association with overflow events (Maalouf et al., 2010). Some studies have linked heavy rainfall to overflows, oyster contamination, and norovirus outbreaks in Canada (Doyle et al., 2004; CBC, 2012). Extreme rainfall also reduces marine water salinity, which enhances norovirus survival (Wang & Deng, 2016).

7.3.2.4 Phytoplankton and Algal Blooms

Phytoplankton are microscopic organisms found in both fresh and marine waters and are sensitive to climate. Two common forms include algae and cyanobacteria (Zimmerman, 2015). Phytoplankton growth is determined by temperature, light, freshwater discharge, salinity, upwelling, and the availability of nutrients (Moore et al., 2008; Finnis et al., 2017; Vandersea et al., 2018). Climate change is providing favourable conditions for algae and cyanobacteria in ocean and freshwaters globally. Reports of blooms are becoming increasingly common in lakes across Canada (Pick, 2016). Some species of freshwater cyanobacteria produce toxins (cyanotoxins) that are harmful to human health when ingested, leading to liver, skin, and nervous system toxicity (Hilborn & Beasley, 2015). Cyanobacteria should not be confused with the toxic marine algae that contaminate shellfish and cause gastrointestinal neurological disease; however, together they are commonly known as “harmful algal blooms” (Carmichael & Boyer, 2016).

Marine biotoxins are produced by phytoplankton found in ocean waters. They accumulate in shellfish or fish and can cause human illness when ingested raw or cooked. Three toxin groups of concern have been found off both the Pacific and Atlantic coasts of Canada and can accumulate in bivalve and invertebrate shellfish. Other marine biotoxins, such as ciguatoxin, occur in tropical waters and can be found in fish imported to Canada (Visciano et al., 2016).

Diarrhetic shellfish poisoning (DSP), characterized by nausea, vomiting, and diarrhea, can last one to three days and is caused by okadaic acid group and *dinophysis* toxins produced by several species of *Dinophysis* and *Prorocentrum* (Taylor et al., 2013a). Saxitoxin describes a group of more than 30 toxins and derivatives produced mainly by *Alexandrium* ssp., causing paralytic shellfish poisoning. This illness is characterized by diarrhea, numbness, tingling, paralysis of the mouth and extremities, headache, and difficulty walking and swallowing, and it can also be fatal (Alexander et al., 2009; Etheridge, 2010). Domoic acid (DA), produced by diatoms called *Pseudo-nitzschia*, causes amnesic shellfish poisoning (ASP), characterized by diarrhea, headache, dizziness, confusion, permanent or short-term memory loss, and seizures. It can also be fatal (Perl et al., 1990; Grattan et al., 2018).

The first reported ASP outbreak was associated with mussels from North American Atlantic waters in 1987 (Perl et al., 1990). In 2011, an outbreak of DSP was associated with the consumption of mussels from British Columbia (Taylor et al., 2013a). Paralytic shellfish poisoning cases are routinely reported in British Columbia and the Atlantic provinces (Prakash et al., 1971; Finnis et al., 2017). On the Pacific Coast of the United States, DA has been found in traditional marine foods, such as razor clams (Grattan et al., 2018). The US Food and Drug Administration has established a regulatory safety level of 20 parts per million of DA for human shellfish consumption. However, a study with coastal Indigenous Peoples who consumed clams from Washington

State showed deficits in memory and recall capacity with repeated DA exposures below this level (Grattan et al., 2018). Health Canada has also established regulatory safety levels for various contaminants, some of which are currently under review. Currently, Health Canada (2020) has established a limit of:

- 20 mg/kg of DA for human shellfish consumption;
- 0.2 mg/kg of DSP toxins in edible shellfish tissue for human consumption; and
- 0.8 mg/kg of paralytic shellfish poisoning toxins in edible shellfish tissue for human consumption.

Temperature and nutrient loading are major determinants of harmful algal blooms and are influenced by temperature and extreme precipitation in both freshwater (IJC, 2017) and oceans, although few studies have directly assessed the link between climate change and marine biotoxins. Gobler et al. (2017) showed that, from 1982 to 2016, increasing ocean temperatures led to an increase in *Alexandrium* and *Dinophysis* bloom season duration and growth rates. Other researchers projected an increase in algal blooms in response to climate change–driven changes to marine ecosystems, particularly warming ocean temperatures in Canada (Glibert et al., 2014; Moore et al., 2015; DFO, 2020).

An increasing number of marine harmful algal blooms and biotoxin outbreaks are being reported worldwide. This is likely due to a combination of climate change, increased nutrient load in coastal waters, heightened awareness, and improved diagnostic capacity (Botana, 2016; Gobler et al., 2017). Harmful algal blooms and disease outbreaks are being reported from new or expanding geographical areas. DSP outbreaks are being reported in new areas of North America and Europe, and cases have been reported in British Columbia, Nova Scotia, and Newfoundland (Todd, 1997; Deeds et al., 2010; Taylor et al., 2013a; Gobler et al., 2017). Paralytic shellfish poisoning has appeared in new areas, such as Iceland (Gobler et al., 2017), and saxitoxin-producing planktons are expanding in other Arctic regions, such as Alaska (Anderson et al., 2019). Ciguatoxins are spreading northward and southward and have now been found in the Canary Islands, Crete, Madeira, and Southern Australia (Botana, 2016).

Harmful algal blooms and disease outbreaks usually occur during summer months, when the temperature is higher and more light is available (Moore et al., 2008). Climate change is increasing both ocean and freshwater temperatures, and this could increase the range, growing season, and growth rate of certain phytoplankton (Moore et al., 2008; Gobler et al., 2017). While some harmful algal blooms occur without anthropogenic inputs, others are caused by large external inputs of nitrogen and phosphorus (e.g., from chemical or manure-based agricultural fertilizers). These nutrients end up in the waterways adjacent to agricultural land, resulting in explosive growth, particularly following a dry spring coupled with an extended warm period (Pick, 2016). This has been observed, for example, in British Columbia freshwater, with the first heavy rains of the fall (Galanis et al., 2014). Cyanobacterial blooms most often occur in warm, nutrient-rich waters with low amounts of mixing among its layers (Hilborn & Beasley, 2015). In addition to more favourable conditions with warming waters, the increased surface runoff associated with extreme precipitation events can transport biological pathogens, as outlined above, and also transfer nutrients into source water, promoting algal growth (Delpla et al., 2009). Lake Erie, the shallowest of the Great Lakes, frequently experiences cyanobacteria blooms, while blooms in the other Great Lakes occur much less frequently (Carmichael & Boyer, 2016). Harmful algal blooms have increased across Canada over the past few decades (DFO, 2020).

The efficacy of water treatment for cyanotoxins ranges from 60% to 99.9% (Zamyadi et al., 2013). Efficacy of treatment varies because each species of cyanobacteria responds to treatment options differently. Monitoring and correctly identifying the species is an important component of treatment; however, this often requires time-consuming analysis by highly qualified personnel. Next-generation gene sequencing is currently being explored as an alternative approach to cyanobacteria identification and screening (Zamyadi et al., 2019), which may reduce barriers to enhanced monitoring. In regions where lake and streamflow rates are projected to decrease in the summer months, the nutrients may become more concentrated. The increased water temperatures that result from this low flow will further promote growth.

Warming may also lead to growth of toxigenic plankton able to survive in low-nutrient conditions, leading to greater risk of ASP in warmer waters (McCabe et al., 2016). Areas of a watershed that have been recently burned by wildfire can cause an increased nutrient load into a water source through depositions of ash (Emelko et al., 2011; Emelko et al., 2016) and may increase the risk of such blooms, at least in freshwater (Martin, 2016). Whether wildfire-derived nutrient loads have an impact in coastal waters is unknown. However, given that nutrient availability is a key determinant of phytoplankton growth, this is a realistic scenario (Sundarambal et al., 2010; Morrison & Kolden, 2015). The number of wildfires in Canada is increasing, highlighting the importance of this nutrient source (Wang et al., 2015). The relationships between wildfires, nutrient loading, algal blooms, and human health warrants further study (Wang et al., 2015; Wotton et al., 2017; Hallema et al., 2018).

7.3.3 Water Quantity

While the demand for water in many Canadian communities is increasing due to growing populations, industry, and agricultural needs, climate change has reduced the availability of water in some locations, with the greatest vulnerability being in Southern Ontario, the Southern Prairies, and the Southern Interior of British Columbia (Andrey et al., 2014). Climate change will continue to cause fluctuations in water quantity across Canada; some locations may experience both reductions and increases, but at different times (Bush & Lemmen, 2019). Indigenous communities, often located in low-lying and flood-prone areas, are particularly vulnerable to these fluctuations (ISC, 2020b; Thistlethwaite et al., 2020). In Canada, mean annual precipitation has increased, on average, with the greatest percentage increases occurring at more northern latitudes (Bush & Lemmen, 2019). Normalized precipitation (precipitation expressed as a percentage) has, on average, increased by 20% across Canada from 1948 to 2012 (Vincent et al., 2015). Despite absolute precipitation typically being lower in Canada's North, from 1948 to 2012, precipitation in that region increased by 30% (Vincent et al., 2015). However, due to a low density of meteorological stations and the associated paucity of data, there is low confidence in this estimate. Smaller increases in normalized precipitation have been observed in some regions of Southern Canada. Additionally, some seasonal differences have been observed. For instance, precipitation has increased in all four seasons in Northern Canada, while in Southern Canada, although it has increased in most seasons, these increases were rarely statistically significant (Bush & Lemmen, 2019).

Due to limited data availability, long-term precipitation trends (greater than 100 years) are available only for Southern Canada. Since 1900, a 5% increase in precipitation has been observed in Southern Canada, while the ratio of snowfall to total precipitation has decreased; this pattern is most pronounced in spring and autumn (Vincent et al., 2015). These shifts toward precipitation falling as rain instead of snow have led to earlier spring melts and increased streamflow in many areas (Vincent et al., 2015).

Table 7.2 Health impacts of drought

PRIMARY IMPACTS	
Impact	Cause
Water- and food-borne diseases	Reduced water availability concentrates pathogens, and associated warmer temperatures may contribute to pathogen prevalence Greater erosion and compacting of soil so that rainfall events lead to increased runoff and associated point and/or non-point sources of pollution
Water-related illness	In coastal communities, groundwater sources may become infiltrated by saltwater in drought or water-scarce conditions, causing hypertension (Naser et al., 2019) and reducing available water for drinking and washing Increase in harmful algal blooms and illness related to harmful algal bloom toxins Inadequate access to water supplies affect hygiene, increasing susceptibility to disease Reduced access to potable water may lead to dehydration and failure of liver, kidney, and other organs after a matter of a few days, or approximately 10% body loss; in the presence of AGI with severe diarrhea, the margin of time to more severe illness or death without water can be only hours
Infectious diseases	Increased abundance of disease-carrying vectors (e.g., mosquitos) due to changes in reservoir species behaviour, impacts on mosquito predators, and reduced flushing of mosquito larvae in urban and suburban environments (see Chapter 6: Infectious Diseases) Increased growth of harmful fungi which may be of increasing importance due to emerging anti-fungicidal resistance (see Chapter 6: Infectious Diseases)
Respiratory impairments	Increased dust storms and an increased concentration of fine particulate matter in the air

SECONDARY IMPACTS

Impact	Cause
Malnutrition and food security	Reduced agricultural outputs and/or negative economic impacts, reducing the ability of Canadians, particularly those with low incomes, to purchase nutritious foods (see Chapter 8: Food Safety and Security)
Mental health	Impacts on Indigenous Peoples who depend upon sometimes transient water sources that sustain them physically, culturally, and spiritually, along with agricultural workers whose families and livelihoods may be threatened (see Chapter 2: Climate Change and Indigenous Peoples' Health in Canada and Chapter 4: Mental Health and Well-Being)
Recreational exposure and injury	Increased recreational water use during warm and dry weather heightens exposure to increased concentration of pathogens in the available water, leading to more illness (e.g., leptospirosis, AGI) Low water levels may increase the likelihood of recreational injuries (e.g., spinal injuries resulting from diving or jumping into bodies of water)
Respiratory impairments	Increased concentration of particulate matter and allergens in the air; smoke from wildfires, in part driven by drought conditions, reduces air quality (see Chapter 5: Air Quality)

Source: Adapted from Yusa et al., 2015

7.3.3.1 Drought

Drought is "a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs" (Yusa et al., 2015, p. 8360). Water scarcity associated with drought is linked to hydrometeorological conditions; other factors, such as human impacts on water resources and increased demand, can exacerbate the effects of drought (Yusa et al., 2015; Cook et al., 2017). The most immediate impact of drought is on availability of water for both humans and the environment, but quantity concerns will progress to quality concerns as drought persists. Lower river flows mean that point sources of pollution could have a higher impact on ecological systems, communities, and health. Drought periods followed by precipitation increase the risk of water-borne disease (Whitehead et al., 2009; Chhetri et al., 2017) (see Chapter 3: Natural Hazards). During drought, pathogens may accumulate in the environment (e.g., in riparian zones); when precipitation returns, heavy loads of contamination are flushed from the landscape into water sources (Whitehead et al., 2009). A Canadian study examining the risk of cryptosporidiosis and giardiasis found risk increased after extreme rain events — events in which rainfalls exceeded the 90th percentile of weekly average precipitation — and that this risk further increased if 30 of the previous 60 days had had no precipitation (Chhetri et al., 2017). Additionally, increased temperatures associated with drought may increase the speed of many chemical processes, lower the amount of dissolved oxygen available for aquatic fauna, and affect growth of micro-organisms (Cook et al., 2017). All of these factors put increased treatment demand on municipal water supply systems and could have implications for human health.

The possible health impacts of drought are presented in Table 7.2. The impacts of drought can be far-reaching and include, for example, the mental health impacts of coping with drought while depending upon non-irrigated agriculture (Edwards et al., 2015).

Concerns about the effects of drought on water security are increasing around the world and across Canada. Extreme temperatures associated with climate change are expected to increase drought risk in Canada at the end of the century under a high emissions scenario, particularly in the southern Canadian Prairies and British Columbia interior (Bush & Lemmen, 2019). Some Canadian cities have had to develop drought preparedness plans, including Tofino, British Columbia, a small coastal tourist town that sources water from a nearby lake (Lloyd, 2017). Tofino's watershed experiences no snowpack, making it entirely dependent on rain that falls during the rainy season to last through the summer months (Lloyd, 2017). In the summer of 2006, Tofino was forced to implement severe water restrictions and rely on imported potable water and a backup unpotable source to allow local businesses to continue to operate (Lloyd, 2017). While smaller island watersheds are notably at a higher drought risk, aquifer-dependent communities can also be at risk. Such is the case with Merritt, British Columbia, a hot and arid inland community that is solely dependent on an aquifer that is slowly depleting (Lloyd, 2017). These realities are leading some regions to weigh the costs of using alternative water sources, such as desalinated sea water, recycled potable water, inter-basin water transfers, and decentralized water sources (Lam et al., 2017).

7.3.3.2 Streamflow and Snowmelt

Streamflow has been correlated with pathogenic contamination of source waters and with turbidity and may therefore influence drinking water contamination and AGI risk (Lake et al., 2005; Jagai et al., 2012). Both high and low flows have been identified as risk factors for degraded water quality (Jalliffier-Verne et al., 2015). As average temperatures rise as a result of climate change, spring snowmelts are projected to occur earlier in many locations throughout Canada, resulting in increased spring flows that may be followed by decreased flows throughout the summer (Bush & Lemmen, 2019). Snowmelt can act on AGI transmission pathways in similar ways to rain events (Jagai et al., 2012), for example, by driving increased contamination of source water, contributing to flood risk, and potentially overwhelming water treatment measures (Chhetri et al., 2017).

7.3.3.3 Extreme Precipitation

Changes in extreme precipitation (measured by a period of a day or less) due to warming have not yet been observed at Canadian weather stations at a national scale but have been observed on much larger scales globally, where more data are available (Westra et al., 2013). Extreme precipitation trends are difficult to observe on a smaller scale because of natural variability. However, Environment and Climate Change Canada projects with high confidence that daily extreme precipitation will increase in Canada, with the return periods — the time between events — projected to decrease (Bush & Lemmen, 2019). Globally, the median increase in extreme precipitation is approximately 7% per 1°C increase in global mean temperature (Westra et al., 2013). Extreme precipitation can affect human health by driving flood events, contributing to source water contamination through runoff, stressing the capacity of DWSs, and other impacts (see Chapter 3: Natural Hazards).

7.3.3.4 Flooding

Flooding is the most frequent and costly natural hazard globally (CRED & UNISDR, 2015; Henstra & Thistlethwaite, 2017) and in Canada (Kovacs & Sandink, 2013). Climate change is anticipated to contribute to an increase in flood events worldwide (IPCC, 2014). In Canada more precipitation will fall as rain rather than snow in the coming decades (Bush & Lemmen, 2019), and regional climate models have projected an increase in rain-on-snow events across North America (Il Jeong & Sushama, 2018). It is unclear what the combined impacts of warm temperatures and reduced snowpack will have on snowmelt-related flooding events (Bush & Lemmen, 2019). Streamflow-related flooding events are also complex, making it difficult to project changes in flood frequency and intensity (Bush & Lemmen, 2019).

Although climate change may not increase flooding in all areas of Canada, a general increase in flood risk is likely in urban areas, where land-use patterns may exacerbate flooding, and in coastal areas where flooding is driven by sea-level rise (Bush & Lemmen, 2019). Many Canadian dams and dikes are vulnerable to failure, and these risks will rise as extreme rain events and flooding increase with climate change (McClearn, 2020). Record-keeping is often sparse and poorly regulated for the country's 14,000 dams (McClearn, 2020). A report issued following the 2017 failure of the Gorie Dam on the North Maitland River in Southwestern Ontario due to heavy rains, noted that, in Ontario, many dams and weirs "are approaching or have exceeded their normal life expectancy" (Greck and Associates Limited, 2018, p. 5).

In Canada, floods are often caused by heavy rain and/or the fast melting of snow and ice due to rapidly rising temperatures in the spring. During these conditions, overland flow of water can transport biological and chemical contaminants from surrounding areas into adjacent surface water bodies or unprotected wells. Abandoned wells can provide a conduit for contaminants to enter an aquifer used by other adjacent, properly sealed wells. Common contaminants are bacteria, viruses, and parasites, or chemical pollution from industrial, agricultural, or residential waste systems. Inundation and increased turbidity can overwhelm drinking water and wastewater treatment systems and are a significant health risk during these events (Hrudey et al., 2003). Globally, floods in coastal areas and riverine estuaries are increasing due to sea-level rise and storm surge from extreme weather events (IPCC, 2014; Kinney et al., 2015). Health risks from flooding can include mortality directly associated with flooding, such as drowning (Lowe et al., 2013); hypothermia (Lowe et al., 2013); injuries, such as broken bones (Doocy et al., 2013); gastrointestinal illness (Vollaard et al., 2004); zoonotic diseases such as hookworm (Kovats & Akhtar, 2008); vector-borne illnesses (Ahern et al., 2005); respiratory issues from exposure to bio-contaminants following a flood (Hulin et al., 2012) (see Chapter 5: Air Quality); mental health impacts (Azuma et al., 2014); and pediatric conditions, such as childhood obesity (Dancause et al., 2013). Health risks from flooding are also discussed in Chapter 3: Natural Hazards, Chapter 4: Mental Health and Well-Being, and Chapter 6: Infectious Diseases. Table 7.3 provides information on the primary and secondary health impacts of floods. Many impacts can be addressed or reduced with adequate warning and preparation, along with adherence to basic safety precautions related to the operation of motor vehicles, the use of combustible fuels in closed spaces, the use and management of electrical infrastructure and equipment, and the proper management and oversight of drinking water supply and treatment systems.

Table 7.3 Health impacts of floods

PRIMARY IMPACTS	
Impact	Cause
Mortality	Drowning or acute trauma (e.g., from debris or building collapse) usually attributable to motor vehicle accidents or high-risk behaviours in flooded areas (e.g., swimming, wading through flood waters, etc.)
Hypothermia	Exposure to floodwater causing a drop in core body temperature
Cardiovascular stress	Exertion and stress related to the event, leading to high blood pressure, heart attacks, and strokes
Physical injuries	Direct contact with floodwater, causing lacerations, skin irritations, bruises, and wound infections
Mental health	Adverse psychological responses to flood events, associated damage, and emergency situations, such as depression, anxiety, and post-traumatic stress disorder; these impacts may be particularly severe for those who face evacuations due to flood events – these impacts may be both a primary and seconday effect of flooding
Infection	Aspiration of water into the lungs, causing pulmonary swelling, lung irritation, and fungal infection
Orthopedic injuries	Contact with water-borne debris, attempts to escape from collapsed structures, falls from ladders, and attempts to rescue people or possessions can cause sprains, strains, and other orthopedic injuries

SECONDARY IMPACTS	
Impact	Cause
Electrocution	Contact with downed power cables/lines, circuits, and electrical equipment in contact with standing water
Burns and explosion-related injuries	Disturbed propane and natural gas lines, tanks, power lines, and chemical storage tanks; toxic gas emissions; rescue boats coming into contact with power lines, leading to fire, chemical, or explosion-related burns
Vector-borne illness	The creation of pools of stagnant water may result in increased mosquito breeding and an associated increase in mosquito-borne illnesses
Impacts to the health system	Disruption or decreased availability of emergency and ongoing health services, because of damage to health infrastructure; decreased ability to provide/access care; displacement of patients and staff; impaired surveillance of illness, injury, or toxic exposure to health care staff; loss of medical records; and loss/impairment of medication and medical devices
Mental health	Adverse psychological responses to flood events, associated damage, and emergency situations, such as depression, anxiety, and post-traumatic stress disorder; these impacts may be particularly severe for those who face evacuations due to flood events – these impacts may be both a primary and seconday effect of flooding
Carbon monoxide poisoning	Health impacts associated with inappropriate use of unventilated cooking tanks (e.g., barbeques), pressure washers, and gas-powered generators
Burns/smoke inhalation	House fires started by candles used during power outages that can be associated with flood events
Dehydration and environmental exposure	Exposure of vulnerable populations to environmental stresses in days following the event, leading to heat exhaustion, heat stroke, heart attack, and stroke

SECONDARY IMPACTS	
Water- and food-borne diseases	Contaminated food and water from sewage overflows; flooding of agricultural areas; transport of sediment, fertilizers, and pesticides into waterways; damage and disruption of drinking water system operations; leakage of toxic materials from industrial sites into waterways Health risks include gastrointestinal issues, infectious diseases such as *Legionella pneumophila*, norovirus, rotavirus, and hepatitis A and C
Respiratory issues	Respiratory contaminants from mould, bacterial, and other fungal growth on damp structures

Source: Adapted from Berry et al., 2014a

7.3.3.5 Projected Sea-Level Rise

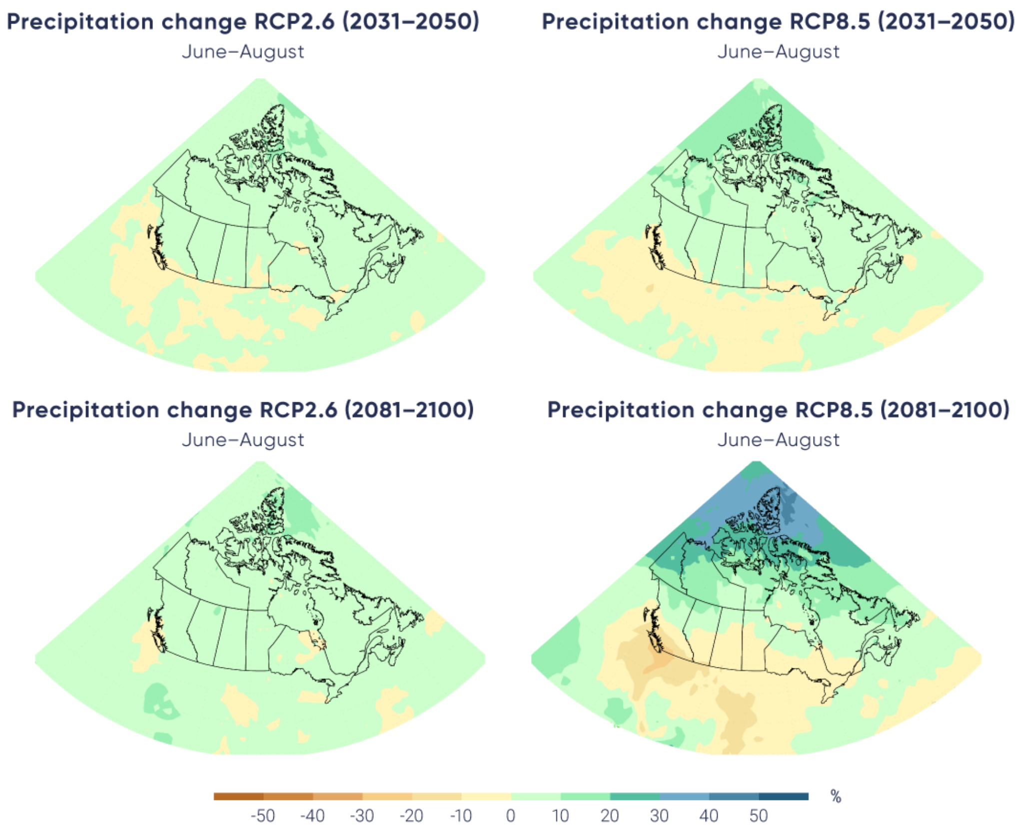
Sea-level rise contributes to flooding and coastal erosion and is important to consider during infrastructure planning and maintenance, as well as for the protection of human and ecosystem health (see Chapter 3: Natural Hazards). Warm water expands; therefore, as oceans absorb heat from the atmosphere, sea-level will rise. Global sea levels may rise by up to 1 metre by 2100 (Bush & Lemmen, 2019). However, because landmasses are slowly moving vertically through uplift and subsidence, the relative sea-level rise experienced on land is variable. In Canada, sea-level change by 2100 will range from −0.9 metre to 1 metre (Bush & Lemmen, 2019). Larger storm surges are projected for Canada's Arctic and Atlantic coasts, which will cause additional coastal flooding in some regions. Storm surges and rising sea levels could place additional pressures on water and wastewater infrastructure located along the coast, in addition to contributing to saltwater intrusion of coastal aquifers, which is already occurring in some regions of Canada, such as the Gulf Islands in British Columbia (Klassen & Allen, 2017).

7.3.3.6 Projected Precipitation

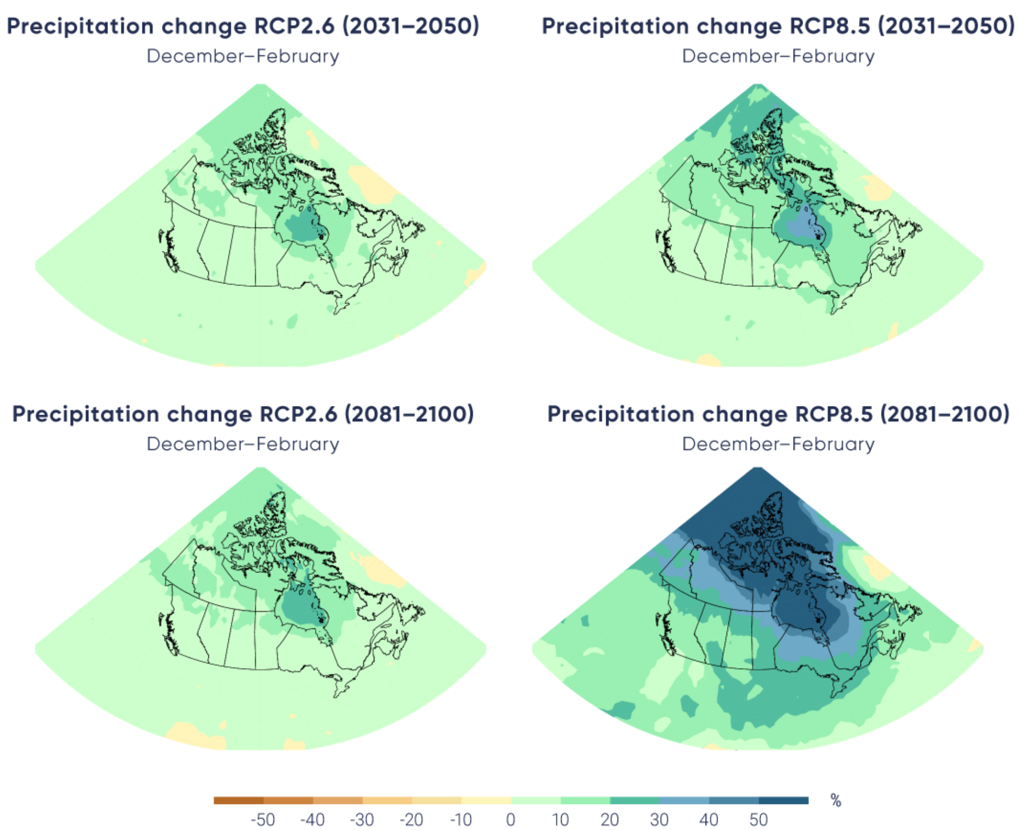
Mean precipitation in Canada is projected to increase or decrease, depending on season and location (Figure 7.2). By mid-century, depending on the emissions scenario used, Canada is projected to experience an increase of around 5.5% to 7% mean precipitation in all seasons nationally. Under a high emissions scenario (Representative Concentration Pathway [RCP]8.5), by the year 2100, this projected increase reaches 24%, with some Arctic regions increasing by more than 30%. Under a low emissions scenario (RCP2.6), a 7% increase is projected nationally (Zhang et al., 2019).

However, under a high emissions scenario (RCP8.5), precipitation is projected to decrease in some regions of Southern Canada during summer months, with much smaller summer decreases projected under a low emissions scenario (RCP2.6). Decreases of mean precipitation of around 30% are projected for Southwestern British Columbia during summer, under a high emissions scenario (Zhang et al., 2019).

a)


Precipitation change RCP2.6 (2031–2050)
June–August
Precipitation change RCP8.5 (2031–2050)
June–August
Precipitation change RCP2.6 (2081–2100)
June–August
Precipitation change RCP8.5 (2081–2100)
June–August
-50 -40 -30 -20 -10 0 10 20 30 40 50
%

b)


Precipitation change RCP2.6 (2031–2050)
December–February
Precipitation change RCP8.5 (2031–2050)
December–February
Precipitation change RCP2.6 (2081–2100)
December–February
Precipitation change RCP8.5 (2081–2100)
December–February
-50 -40 -30 -20 -10 0 10 20 30 40 50
%

c)

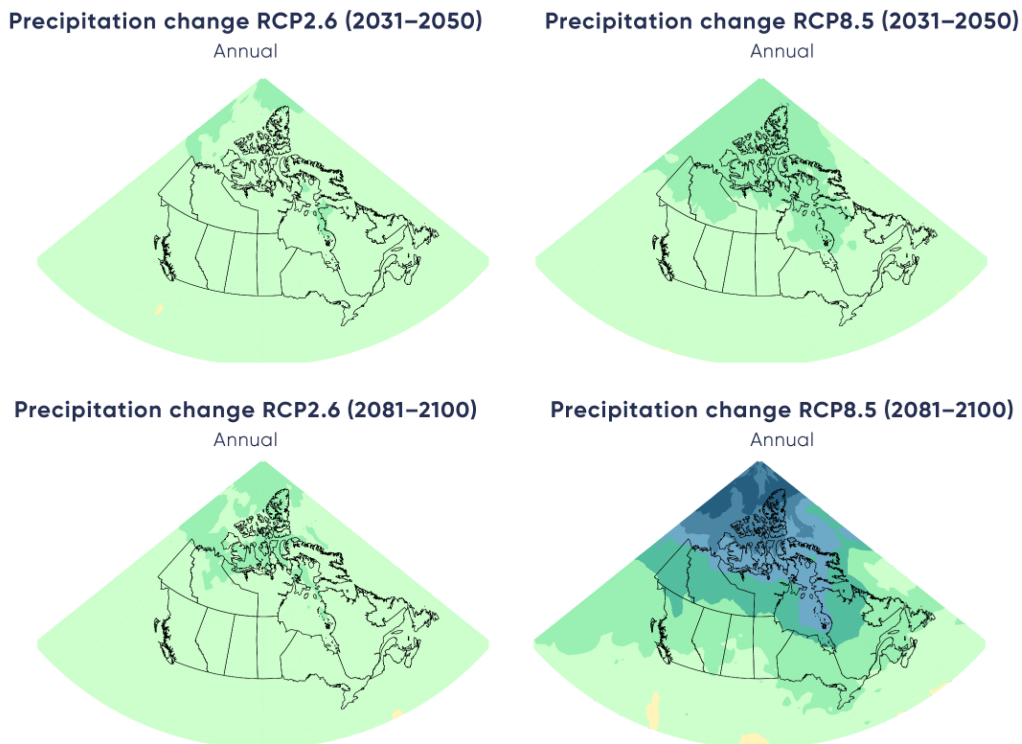


Figure 7.2 Projected precipitation changes for summer (A), winter (B), and annually (C) for two emissions scenarios (RCP2.6 and RCP8.5) by mid and late 21st century. Source: Zhang et al., 2019.

7.3.3.7 Projected Extreme Precipitation

Overall, Canada is expected to experience an increase in precipitation over the next 80 years, with greater intensity in the fall, winter, and spring. The frequency of extreme precipitation events is likely to increase across Canada, and their magnitude is projected to increase in proportion to the amount of warming. For example, under a high emissions scenario (RCP8.5) and averaged across Canada, a rare once in 20-year one-day precipitation event is projected to occur once in 10 years by 2031 to 2050, and once in five years by 2100 (i.e., a four-fold increase in frequency) (Zhang et al., 2019). Under a low emissions scenario (RCP2.6), once in 20-year one-day events are projected to become once in 15-year events by 2031 to 2050, with little additional increase in frequency beyond mid-century. Importantly, larger changes in the frequency of even rarer events is projected. For example, a once in 50-year one-day event is projected to become a once in 10-year event by 2031 to 2050 and a once in five-year event by 2100 under a high emissions scenario (i.e., a five-fold increase in frequency) (Zhang et al., 2019).

7.3.3.8 Projected Freshwater Availability and Scarcity

Canada's Changing Climate Report assessed available literature on observed and projected changes in Canada's cryosphere (snow, ice, and permafrost) (Derksen et al., 2019), including resulting impacts on freshwater availability (Bonsal et al., 2019). Climate-driven changes to streamflow seasonality have already been observed in Canada: for example, earlier spring freshet due to earlier spring snowmelt, higher winter streamflows, and, for many regions, reduced summer flows (Bonsal et al., 2019). A lack of observations (especially in Northern Canada) limits the confidence in trend detection for many freshwater-related variables, but the available measurements indicate that annual streamflow magnitude, surface water, and shallow groundwater levels, droughts, and soil moisture have been highly variable over the past 30 to 100 years and have not exhibited increasing or decreasing trends connected to climate change (Bonsal et al., 2019).

Warming temperatures are expected to decrease the proportion of total precipitation falling as snow, with a shift to increased rain, especially in spring and autumn (Zhang et al., 2019). This will have direct impacts on the flow regime for many streams across the country. For example, Canada's largest Pacific watershed, the Fraser River Basin, is projected to shift from a watershed where peak streamflow is generated by spring snowmelt (nival regime) to a watershed where peak flow will instead be dominated by rainfall-generated flows (pluvial regime) (Curry et al., 2019). Understanding how such changes will influence fisheries and other human uses of the watershed, including those that impact health (e.g., drinking water infrastructure, freshwater quantity, and quality), requires further study.

Ongoing changes to snow cover across Canada driven by a warming climate (Mudryk et al., 2018; Derksen et al., 2019) will contribute to changes in streamflow magnitude, seasonality, and corresponding freshwater availability. Observed declines in mountain glacier mass have, to date, had a limited impact on freshwater availability. However, climate models project that glacier mass could shrink by 85% across western Canada by 2100 under a medium emissions scenario (Derksen et al., 2019). In coming decades, glacier-fed rivers will experience periods of increased summer discharge due to greater meltwater contributions from enhanced glacier melt, but this is a short-term response to melting ice and is unsustainable once ice mass declines past a critical level. The rate and timing of this transition will have important consequences for stream and river water quality and temperature, and for the availability of water for human uses, such as hydroelectricity generation and agriculture (Derksen et al., 2019). Permafrost warming and thaw will result in changes to surface hydrology, which are not yet fully understood, including regionally variable wetting or drying of the landscape, changes to freshwater quantity and quality, and landscape changes due to subsidence and thermokarst events. As a result of increased temperature and evaporation, lower surface water levels of wetlands and lakes are projected in many regions toward the end of the century under a high emissions scenario. It is uncertain to what degree increases in precipitation will offset lower surface water levels (Bonsal et al., 2019).

Annual streamflow is projected to decrease in some southern interior regions in Canada, while increasing in others (mostly northern regions). In some areas where increased evapotranspiration is expected to outweigh increases in precipitation, there is an increased risk of drought and decreased soil moisture (such as in the Southern Prairies and British Columbia Interior). This risk is greater under higher levels of climate warming (Bonsal et al., 2019).

Due to the close link between surface temperature and groundwater recharge, projected changes to temperature and precipitation are expected to influence future groundwater levels. However, given the complexity of groundwater systems and a lack of information, the magnitude and even direction of change is not clear (Bonsal et al., 2019). For example, a major challenge when researching climate change impacts on groundwater is distinguishing effects of climate change from those due to land-use change, such as agriculture. Agricultural irrigation from groundwater sources has the potential to deplete aquifers, particularly in arid environments (Taylor et al., 2013b). More research is needed on groundwater trends and potential impacts due to climate change, particularly in areas that rely on groundwater for drinking water and irrigation.

Soil moisture refers to the water stored in the unsaturated upper layer of soil, and it is an important component of the land energy and water balances that affect agricultural production. Soil moisture is involved in complex feedbacks with both temperature and precipitation. It has a direct impact on plants' transpiration, which is the largest component of total land evapotranspiration (Seneviratne et al., 2010). Therefore, in certain regions where soil moisture becomes limited, evapotranspiration can decrease and may lead to reduced precipitation (Seneviratne et al., 2010). Reduced soil moisture can also increase near-surface air temperature by limiting the amount of energy used by latent heat flux, a process that has been identified as a contributing factor for extreme heat events (Seneviratne et al., 2010), which have substantial impacts on human health (see Chapter 3: Natural Hazards).

Indigenous communities are among those disproportionately affected by decreased precipitation and related effects on water sources. For example, communities along the Yukon River reported changes to traditional drinking water resources, with impacts on their subsistence activities as well. In Pond Inlet, Nunavut, community members reported concerns about water quality due to observed changes in water taste and colour during the summer (ISC, 2019).

In the Fraser River Basin in Northern British Columbia, the snow-dominated system is shifting to a rain-dominated one (Kang et al., 2014; Picketts et al., 2017). In some parts of the basin, such as its tributary the Nechako River, there are projected changes to annual discharge, with earlier peak flows and lower low flows in late summer. Climate change projections indicate that the spring freshet will arrive earlier, and summer flows may decrease (Kang et al., 2014; Picketts et al., 2017). Decreases in snow accumulations will alter water quality, and decreases in flow can have major negative effects on migrating salmon, which have cultural significance for many First Nations Peoples. These changes will affect First Nations and their cultural relationship to water, food security, and the state of drinking water on many reserves, with concurrent implications for health. In many cases, these health impacts may be compounded by a variety of challenges unrelated to climate change (e.g., social issues rooted in colonization) (Berner et al., 2016).

7.3.4 Water Security and Society

Water security has direct implications for drinking water and water systems, food and food systems, cultural and spiritual practices, and recreation. Access to drinking water of a suitable quality and in sufficient supply to sustain health and well-being is a core component of water security. Similarly, water is fundamental to both food production (e.g., crop irrigation, maintaining healthy fish stocks, etc.) and food processing (e.g., manufacturing processed foods, cleaning vegetables before distribution for sale, cooking, etc.). Air temperature, water temperature, and precipitation are the most important climatic variables influencing the occurrence of food-borne disease (Smith & Fazil, 2019) (see Chapter 8: Food Safety and Security). Of the 11 key food-borne pathogens identified by Smith and Fazil (2019) to examine in the context of climate change in Canada, six are influenced, in part, by precipitation, drought, and/or water temperature.

Parts of Canada already face periods of water insecurity, due to impacts on water quality and shortages in water supply. For example, in 2019, Iqaluit, Nunavut, faced an unprecedented shortage of source water after a summer of historically low precipitation (Bell, 2019). As the climate continues to warm, and in the absence of effective adaptation measures, concerns related to water security and human health may increase. Public health and water management practitioners, researchers, and decision makers all have a role to play in protecting and promoting health by working to attain and/or maintain water security.

7.3.4.1 Water and the Food System

Water, in a sufficient supply and of a sufficient quality, is critical to food production and is also used for cleaning, sanitation, and manufacturing activities in the food system (Kirby et al., 2003). Food processing operations require very large amounts of water (Compton et al., 2018). Variability in water supply could disrupt food-processing activities, with long-term disruptions affecting food security. Water may also serve as a vehicle for transmission of chemical and/or microbial contamination of foods during processing (Kirby et al., 2003). Key pathways by which climate change can affect food processing via water impacts include increasing frequency and length of drought periods, which may result in reduced access to water required for processing activities; flooding agricultural fields with contaminated water; and contaminating water used in food processing, such as through floodwater washing contaminants into water sources (Delpla et al., 2009; Schnitter & Berry, 2019). Impacts through any of these routes would necessitate alterations to current Hazard Analysis Critical Control Point (HACCP) steps used to prevent food-borne illness in Canada (CFIA, 2012). Food businesses in Canada are required to have a food safety plan, and the HACCP is a key tool for developing one. In the HACCP approach, water is used for food processing and cleaning, and removing chemical and microbial contaminants on meat, produce, or other raw ingredients.

Water serves as a potential vehicle for the direct transmission of chemical and microbial contaminants to foods during processing. Chemical contaminants can include heavy metals, household and industrial pollutants, pesticides, and nitrates. Microbial contaminants can include pathogenic bacteria, such as verotoxigenic *Escherichia coli*, parasites such as *Toxoplasma gondii*, protozoa such as *Cryptosporidium*, and viruses such as norovirus. As noted in previous sections, extreme weather events associated with climate change can promote the movement of chemicals and pathogens from the surrounding environment into source water at higher levels than usual, potentially overwhelming existing treatment methods.

Both municipally treated and privately sourced water are used in food processing. Such water sources are generally treated for selected chemical and microbial hazards but are not risk-free (Kirby et al., 2003). Water that is untreated or ineffectively treated before use in food processing can transmit contaminants directly to foods. Food-borne disease outbreaks have been traced back to use of contaminated water during food processing (Kirby et al., 2003). Even water containing extremely low levels of a pathogen could result in hazardous exposures to humans via food. Given optimal conditions, transfer of just one pathogen cell to food could result in an infectious dose reaching the consumer, as the pathogen can grow from the period of food processing through distribution, retail, and storage to consumption (see Chapter 8: Food Safety and Security). Using common food processing methods, it is very difficult to completely inactivate all possible pathogens. Some food products, such as leafy greens, are more likely to cause illness, because of the minimal processing involved and the increased likelihood that they will be eaten raw (Jung et al., 2014). Given that small and private DWSs are already associated with water-borne disease outbreaks to a greater extent than larger systems, food processors serviced by such systems are at greater risk (Moffatt & Struck, 2011).

In addition to food contamination from use of water containing harmful pathogens, water shortages may also affect the processing of foods such as meat and produce, both of which have been linked to microbial food-borne disease outbreaks in Canada (Ravel et al., 2009). Water shortages can affect human health through compromised ability to remove contaminants from food; for example, limitations to the use of water for cleaning and sanitizing could result in less efficient removal of contaminants. During periods of low water availability, if alternative interventions or procedures to process foods are unavailable, reduced access to safe, nutritious food could compromise food security and affect human health.

The risk to food processing from water shortages has a seasonal component and is highest during the summer, when water demand for all purposes is greatest (Wiener et al., 2016). This time of year is also optimal for survival of many pathogens in the environment, as higher temperatures support and encourage growth (Smith & Fazil, 2019). While risks to food processing are highest in Southern Canada, depending on food exportation and supply chains, local or regional impacts on food processing from water shortages may be felt nationally.

Nearly 30% of food consumed in Canada is imported from other countries, with the majority of imported food coming from the United States (Statistics Canada, 2009). Climate change impacts on water availability and quality can also affect processing of foods in other countries that export food to Canada. These impacts are specific to the region, commodity, and possible contaminants and could ultimately have an impact on public health in Canada.

7.3.4.1.1 Fishing and Seafood

Climate change is expected to affect marine food sources, through temperature effects on marine ecosystems (e.g., changes in micro-biota and other species higher in the food web), ocean acidification, extreme precipitation events, and subsequent agricultural runoff linked to nutrient loading. The consumption of contaminated raw or undercooked fish and shellfish carries the risk of infection from viruses, bacteria, parasites, and toxins.

Vibrio species are naturally occurring bacteria found in ocean water worldwide, including Canada's Pacific and Atlantic coastal waters. Common species on the Pacific and Atlantic coasts include *V. parahaemolyticus (Vp), V. vulnificus, V. fluvialis, V. alginolyticus* and non-toxigenic *V. cholerae* (Banerjee et al., 2018). *Vp* is the most common species linked to shellfish-related illness in Canada. If ingested, *Vp* can lead to diarrhea, vomiting, nausea, and fever lasting one to seven days, and, in rare cases, to death (BC CDC, 2020). The majority of *Vp* infections are caused by the consumption of raw oysters obtained from commercial fisheries or self-harvested. Other routes of exposure include inadvertently or submerging wounds or ears in contaminated ocean water or swallowing it.

Vp and other *Vibrio* species in bivalve shellfish on the Pacific and Atlantic coasts of Canada increased between 2006 to 2009 and 2010 to 2013 (Banerjee et al., 2018). Every year, 30 to 70 human infections are reported in British Columbia, as are a small number from other parts of the country (BC CDC, 2020). For every case of *Vp* reported in Canada, 92 additional cases are believed to have occurred in the affected community (Thomas et al., 2013). *V. fluvialis* and *V. alginolyticus* each result in zero to four locally acquired cases per year in British Columbia (Khaira & Galanis, 2007; BC CDC, 2020) which typically present as acute gastrointestinal illness. *V. vulnificus* can cause severe infection, including primary septicemia and necrotizing soft-tissue infections. Locally acquired *V. vulnificus* infection is extremely rare in Canada; only five case reports have been published (Abbott, 1986; Kelly, 1991; Vinh et al., 2006; Bigham et al., 2008).

Large *Vp* outbreaks in British Columbia have led to closures of shellfish harvest areas and bans on the sale of raw oysters in restaurants. These measures can threaten both the economic viability of the shellfish harvesting industry and the continued use of the food source (Fyfe et al., 1997; Taylor et al., 2018). Other *Vibrio* species are pathogenic to shellfish and fish and can also cause major economic impacts (Paillard et al., 2004).

Vibrio species are thermophilic, meaning they prefer higher temperatures; therefore, sea surface temperature (SST) is the most important environmental predictor of *Vibrio* concentrations. Higher temperatures lead to higher *Vibrio* concentrations in ocean water and oysters, and, by extension, increased rates of human illness (Cook et al., 2002; Parveen et al., 2008; Haley et al., 2014; Konrad et al., 2017). The SST threshold for *Vp* growth is approximately 15°C (Khaira & Galanis, 2007; Konrad et al., 2017), which means the majority of locally acquired *Vibrio* infections in Canada occur during the summer months.

Although the biologic cycle of *Vibrio* species, with the exception of toxigenic cholera, is not well understood, it is known that *Vibrio* species attach to chitin-containing organisms, particularly zooplanktons, which are considered their natural reservoir (Vezulli et al., 2010). The seasonal variation in *Vibrio* concentrations depends on both SST and the composition of the plankton reservoir (Turner et al., 2009). *Vibrio* concentration is directly related to certain growth stages of zooplankton following phytoplankton blooms, which occur in warmer temperatures (Turner et al., 2009).

The ongoing warming of ocean temperatures and associated extension of summer conditions, driven by climate change, increases the risk of *Vibrio* proliferation in ocean waters. This can result in increased accumulation in bivalve shellfish and, subsequent increased risk to humans. The rate of *Vp* illness has increased over many years, in association with slowly increasing SST; there have also been large outbreaks that occur over a few months following short-term anomalies in SST (Martinez-Urtaza et al., 2010). In the North Atlantic Ocean, both the warming of the Northern Hemisphere and the Atlantic Multidecadal Oscillation are associated with increasing *Vibrio* presence in the water over the last 50 years (Vezzulli et al., 2016). A more rapid increase in *Vibrio* incidence has been observed at higher latitudes (Logar-Henderson et al., 2019). This may be due to ballast water discharge during a period of warmer-than-usual weather (McLaughlin et al., 2005) or the introduction of new strains of *Vp* in warm water transported from other regions during large climatic events such as El Niño (Martinez-Urtaza et al., 2010).

Non-toxigenic *V. cholerae* is emerging in Canada in bivalve shellfish. On the Atlantic coast, it was found in 1% of samples taken between 2006 and 2013 and in 20% of samples taken between 2014 and 2016; on the Pacific coast, it increased from 1% in 2006 to 2009 to 5% in 2010 to 2013 (Banerjee et al., 2018). Human illness caused by locally acquired non-toxigenic *V. cholerae* is rare: in 2018, three confirmed cases were reported on Vancouver Island (CBC, 2019). Increasing incidence of *Vibrio*-related illness has also been noted in Europe and the United States (Newton et al., 2012; Baker-Austin et al., 2013). It is possible that, with increased warming, the incidence of *Vibrio*-related illness will continue to increase (see Chapter 8: Food Safety and Security).

7.3.4.2 Impacts on Infrastructure

The reliable operation of water infrastructure is critical to health. Drinking water, wastewater, and stormwater systems are interdependent and can be affected by climate change impacts, with cascading effects from one to the other. For the purposes of this chapter, DWSs include drinking and wastewater treatment facilities and the infrastructure required to transport water from source, to treatment, to users, to waste treatment, and to discharge point. If DWSs are rendered inoperable or ineffective, water security, and by extension human health, can suffer. Contaminated drinking water or ineffective water systems increase the risk of communicable diseases (Alderman et al., 2012). For example, extreme rainfall events may affect the ability of water system operators to reduce turbidity, which has been associated with health impacts, such as non-specific gastroenteritis (Aramini et al., 2000; Schwartz et al., 2000; Charron et al., 2004). DWSs are therefore a primary defence against water insecurity and associated health outcomes.

The Canadian Infrastructure Report Card 2019 found that, overall in Canada, approximately 70% of potable water infrastructure (i.e., local water and transmission pipes, water treatment facilities, water pumping stations, water reservoirs) is in very good (30%) or good (40%) condition, and 25% is in fair, poor, or very poor condition. In addition, approximately 55% to 65% of wastewater infrastructure is in very good or good condition. For approximately 15% of linear wastewater assets (i.e., sewer pipes and sanitary force mains) the condition is unknown, as they are underground. Regarding stormwater infrastructure, it is estimated that approximately 40% to 60% is in good or very good condition, but large data gaps exist because of limited data collection about condition (BluePlan Engineering, 2019).

DWSs across Canada were not designed with the impacts of climate change in mind and are considered among the infrastructure most vulnerable to climate hazards such as extreme events (flooding, droughts, and storms), permafrost degradation in northern regions, and lower water levels in many parts of the country associated with higher temperatures and saltwater intrusion (Lemmen & Warren, 2004; Moffat & Struck, 2011; Luh et al., 2017). A 2012 survey of 53 Canadian water utilities, conducted by the Canadian Water and Wastewater Association, found that only 30% of respondents were aware of the potential impacts of climate change, and over half (56%) did not have operational plans to address the impacts of climate change (Brettle et al., 2015).

Drinking water infrastructure can be affected, or overwhelmed, by climate change hazards in many ways. For example, the quality of water entering a water treatment system can be affected by a flood (e.g., contaminants from rural or urban areas) or by a wildfire (e.g., organic carbon and nitrogen runoff); these events could directly affect the physical infrastructure itself. If water treatment and infrastructure upgrades are required (e.g., use of more chemicals like chlorine), costs will increase for municipalities (Andrey et al., 2014). Case studies in Manitoba (Genivar, 2007) and Newfoundland (CCPE, 2008) identified potential risks to water treatment system functions (pre-treatment, softening and clarification, disinfection, storage, chemical storage, and valves and pipes) from climate hazards such as flooding, high temperatures, intense rain, drought, ice storms, and intense wind.

Many older cities still use a “combined sewer overflow” design that integrates stormwater and sanitary sewage systems. An increase in heavy precipitation events and/or rain-on-snow or frozen ground events will increase risks of stormwater impacts on sanitary systems, potentially overwhelming systems (Andrey et al., 2014) and heightening the risk of untreated sewage being discharged into adjacent streams and lakes (Madoux-Humery et al., 2016). This can cause contamination of the municipal DWS itself, if an intake is located nearby, and it can also lead to contamination of water bodies used for recreational activities. In Montréal, Quebec, a 10-year study found that 80% of all peak *E. coli* measurements at two municipal drinking water intakes along the St. Lawrence River were linked to combined sewer overflow events that were driven by either 10 mm of rain or snowmelt (Madoux-Humery et al., 2016). The investigators were able to demonstrate a human origin of the fecal contamination. Modern-day sewer designs segregate stormwater from the sanitary sewage in order to avoid this issue, but, even so, stormwater alone can be a source of pathogens due to pathogen reservoirs that exist in the built environment (Turgeon et al., 2011).

Rising sea levels associated with climate change have also been observed to alter groundwater flows in coastal cities in the United States, resulting in an increased likelihood of sewer overflow events as rising groundwater enters aging sewer infrastructure or builds up in areas of high permeability (e.g., in fill materials used during construction) (Rossi & Toran, 2019). In addition to rain events, combined sewer overflows are also affected by land-use change and by changes to local hydrology due to urban growth (Jalliffier-Verne et al., 2015). Opportunities to reduce the likelihood of overflow events include city planning that decreases the area of impervious surfaces and overall demands on aging stormwater systems by reducing the amount of water they need to transport to river systems. This practice would help all cities, with or without combined sewer overflows, to reduce the transfer of biological and chemical contaminants from the city into adjacent waterways, as well as to increase groundwater recharge.

Even after water has been treated to drinking water standards, it may still become contaminated after it leaves the treatment facility and travels through the system. In large systems, this risk is commonly reduced by post-treatment disinfection. Low water pressure events have been associated with elevated AGI in older DWSs that contain cracked and damaged water lines, which may travel adjacent to sewage lines (Gargano et al., 2015). In places where sewage lines run alongside water lines, if leaks form on both lines, the only barrier of protection is to maintain high pressure in the water line relative to that of the sewage line. Heavy precipitation associated with climate change may place added stress on aging infrastructure and make it more prone to failure, thereby increasing the likelihood of these low pressure events (Luh et al., 2017). DWSs generally alleviate some pressures associated with drought, decreased streamflow, and aquifer depletion by making better use of available water sources (e.g., water conservation). Broader source water protection initiatives for both surface and groundwater support such efforts.

Small communities may be more vulnerable to impacts on water security from climate change because of deficits in water system infrastructure, as well as fewer technological, training, and financial resources (Moffat & Struck, 2011). Exacerbating the water security implications of climate change, 8.7% of DWSs, serving in total approximately 4 million Canadians, employed no treatment at all (as of 2006–2007), relying primarily on groundwater (Statistics Canada, 2013). This reliance on groundwater sources may put increased pressure on these systems during times of prolonged water scarcity and, particularly for systems that rely on single sources, increases the urgency for source water protection. Many of these DWSs serve small communities.

7.3.4.2.1 Water Systems in Indigenous Communities

Access to safe drinking water is a challenge for many Indigenous communities in Canada. For example, as of February 15, 2020, 61 First Nations communities were under long-term (greater than one-year) drinking water advisories (ISC, 2020a). The Multi-Barrier Approach to Safe Drinking Water is designed for municipal water service systems with a central water treatment plant, piped distribution system, and coordinated monitoring oversight. In many Indigenous communities, particularly those that are small, remote, and isolated, the water distribution system is unlike traditional municipal water service systems, and often features a mix of private wells, trucked water, piped water, and few or no household water services (Daley et al., 2014; Patrick, 2018). Many Indigenous communities face challenges, including poor source water quality, insufficient water treatment technology, inadequate water distribution systems, as well as local and regional water contamination caused by local industry. Institutional disadvantages, such as inadequate design standards for wastewater disposal, difficulty retaining qualified water treatment plant operators, insufficient funding for water system upgrades, and limits on the capacity of trucked systems to deliver water in the quantity residents require it, also contribute to these challenges (Daley et al., 2014; Patrick, 2018). For some people, a lack of trust in water systems, existence of chemical and biological hazards, cultural preference, taste, or other reasons, lead them to, at times, rely on water gathered from the land (Harper et al. 2011; Goldhar et al., 2013b). This gathered and untreated water may be at increased risk of contamination, including as a result of risks from climate change. Any pathogen found in the water (e.g., vector-borne infectious agents, chemical contamination from nearby pollution sources, or pathogens associated with faulty treatment) may be directly consumed by water users (Martin et al., 2007; Harper et al., 2011), causing negative health outcomes.

Climate change is exacerbating the current water challenges facing Indigenous communities (Ford et al., 2010; Andrey et al., 2014; Patrick, 2018; ISC, 2019). Changing temperatures can directly affect water and sewage treatment facilities, as well as food and drinking water security. Small, rural, and circumpolar communities are particularly vulnerable, having to navigate multiple interacting risks (Berner et al., 2016). Many Indigenous communities have recognized this risk; are concerned about climate change impacts on their water quality, quantity, and security (Picketts et al., 2017; ISC, 2019); and recognize the need for action. For example, the Inuit Tapiriit Kanatami's *National Inuit Climate Change Strategy* (2019) identified the need to adapt to climate change–driven impacts on health, including those related to water, as a priority for climate action. Information on how Indigenous Peoples are adapting to climatic impacts on water quality, quantity, and security is provided in section 7.5 Adaptation to Reduce Risks as well as in Chapter 2: Climate Change and Indigenous Peoples' Health in Canada.

7.3.4.3 Cryosphere

The cryosphere includes all places where water is frozen, including snow, ice, permafrost, and seasonally frozen ground. At lower latitudes and elevations in Canada, this state exists for part of the year, and at higher latitudes and elevations, it lasts year-round (Bush & Lemmen, 2019). The cryosphere, and Arctic regions in particular, are dramatically affected by changes in temperature and precipitation driven by climate change

(Overland et al., 2018). The timing, duration, and intensity of melt periods, as well as the likelihood of precipitation being rain or snow, are all affected by temperature. Snow reflects a large amount of incoming solar radiation back into the atmosphere, and changes in snow depth have impacts on ground temperature and lake and sea ice thickness (Bush & Lemmen, 2019). In Canada, it appears that the length of the year with snow cover declined across the majority of the country, and seasonal snow accumulation has likely declined by 5% to 10% since 1981. Climate models project that snow cover duration will continue to decrease across Canada by mid-century, regardless of the emissions scenario (Bush & Lemmen, 2019).

Changes in the cryosphere are likely to affect the health and well-being of Canadians, particularly those in Northern and Arctic regions, in several ways, including impacts on food security, damage to infrastructure, release of legacy pollutants, impacts on transportation networks, and others (Hovelsrud et al., 2011; AMAP, 2015). Although the processes behind these impacts are complex, in Northern Canada, they can generally be linked to two primary issues: changes in ice conditions and changes to permafrost.

Changes in the quantity and quality of sea ice have wide-ranging impacts on Arctic food systems and navigation (Ford et al., 2009). Reduced sea ice quantity and quality impacts the variety of sea life and their migratory patterns, as well as the overall biodiversity of the region (AMAP, 2017). These changes may, in turn, affect access to traditional food sources for Northern communities (see Chapter 8: Food Safety and Security). In addition to impacts on sea life, changes in the quantity and quality of sea ice also affect the ability of Inuit and other Northern hunters to harvest food, because of reduced ability to travel safely on the ice. Less access to the land also inhibits the ability to pass on traditional knowledge to future generations (ISC, 2019).

The annual development of ice roads relies upon sea ice and ice on rivers and lakes. The use of these roads dramatically reduces shipping costs and transportation time, and they are central to sustaining Northern communities. Climate change is affecting the use of these roads, for example, in Ontario's Far North (Hori et al., 2018), and continued warming will have wide-ranging ramifications for daily life in Northern communities, including by affecting health facility supply chains and access to market foods.

Changes to the natural environment also have direct impacts on other types of built infrastructure across the Arctic. Much existing infrastructure has been built with the expectation of continual permafrost. Changes to permafrost threaten the structural integrity of buildings and roads, including health facilities, and water and wastewater treatment facilities. The degradation of permafrost has resulted in impacts on some DWSs by breaking both drinking water and sewage pipes, which could allow potential contaminants to enter drinking water (Lemmen & Warren, 2004). For example, the City of Iqaluit, Nunavut, has been affected by climate change-related permafrost thaw causing extensive damage to municipal water and wastewater pipes (George, 2019). In addition to risks to infrastructure, legacy contaminants currently stored in the permafrost may be released during permafrost melt (AMAP, 2015) (see Chapter 3: Natural Hazards). Warmer water in freshwater lakes, tundra ponds, and streams may also result in greater bacterial methylation of mercury and increased release of mercury from thawing permafrost (Berner et al., 2016), with potential implications for human health.

7.4 Projected Health Security Risks and Impacts

Projecting future impacts of water scarcity and flooding on global health security is challenging because of our limited ability to model events and responses that are subject to current and future adaptation and greenhouse gas (GHG) mitigation policies, which can change. Although significant progress has been made toward understanding the health impacts of climate change and identifying ways to adapt to them, the complexity of the relationships among water, food, and other social and environmental determinants of health requires a broader understanding of compounding and cascading climatic impacts that can amplify harm (Pescaroli & Alexander, 2018).

Local and regional conflicts in other parts of the world, driven by or exacerbated by water insecurity, may have implications for Canadians and Canadian interests. Water has been a source of conflict throughout history, and many scholars consider this risk to be increasing with population growth, rapid economic development, and climate-induced changes in the hydrologic cycle (Levy & Sidel, 2011; Gleick et al., 2020). The risk of forced migration as a result of climate change may also be increasing, particularly for less developed countries (Rigaud et al., 2018). Water-related impacts that contribute to migration pressure and population displacement include rising sea levels, desertification, floods, monsoons, hurricanes, and cyclones (Dickson et al., 2014; McLeman, 2019).

Future scenarios that could spark international conflict affecting Canada include drought-driven reversal of peace-building efforts in Africa, international conflict over the Indus River, and further instability in the Middle East (McLeman, 2011; McLeman, 2019). Refugee surges and maintenance of refugee camps along borders can provide cover for insurgent groups, and reductions in water security can lead to internal conflicts, both of which destabilize governments and can lead to deployment of Canadian peacekeeping forces (Canadian Parliament Standing Committee on National Defence, 2019; Gleick et al., 2020).

Domestically, increasing water temperatures, driven by climate change, may allow for the successful northern expansion of novel contaminants, such as *Naegleria fowleri*. This pathogen can cause primary amebic meningitis, a very rare but almost always fatal disease of the central nervous system (Health Canada, 2012). No cases of illness associated with *N. fowleri* have yet been reported in Canada. The most northerly known case to date was reported in Minnesota (Gompf & Garcia, 2019).

Climate change is anticipated to increase the frequency and severity of wildfires, primarily due to changes in temperature and precipitation, causing decreases of precipitation in some areas and insufficient increases of precipitation in others to offset the effects of rising temperatures (Wotton et al., 2017). Hot, dry, and strong winds are conditions that produce high risk of extreme wildfire (Bush & Lemmen, 2019). Risk of extreme fire conditions, an increase in fire-spread days, and a lengthened fire season are projected for Canada as a whole, and the Western Prairies in particular (Wang et al., 2015).

In addition to the more commonly discussed health impacts of wildfires (e.g., burns, respiratory effects, mental health impacts), watersheds may be severely affected through effects on water flows and water quality. Long-term (multi-year) effects of wildfires include increased stormwater runoff, increased nutrient (mainly nitrogen and phosphorus) and contaminant loads, increased organic carbon, elevated risks of algal and cyanobacterial blooms, elevated microbial activity, dissolved organic carbon transformation, and presence of fire-fighting chemicals (Khan et al., 2015; Harper et al., 2018; Robinne et al., 2019) (see Chapter 3: Natural Hazards), with implications for human health. Water flows may be affected by changes to vegetation, as well as topographic changes caused by flash floods and landslides associated with wildfires. Changes in water flows may affect the reliability of inflow forecasting methods used by drinking water managers to project the quantity of available water for treatment.

Although municipal DWSs may remain capable of adequately treating source water in environments recently affected by wildfire, the added stress of increased wildfire activity may increase operating costs and strain treatment capacity (Robinne et al., 2019). For example, in the aftermath of the 2016 Fort McMurray wildfire, out of an abundance of caution, the water utility chose to issue a precautionary boil water advisory for three months and saw its annual costs for treatment chemicals increase by 50% (Curtis & Gillis, 2016; Thurton, 2017; Robinne et al., 2019). Recent research has identified communities in Alberta whose source water may be at risk due to wildfires (see Figure 7.3) (Robinne et al., 2019), a situation that will likely worsen due to climate change. To prepare communities and drinking water providers for the impacts of climate change, increased research into the impacts of wildfires on water quality is needed.

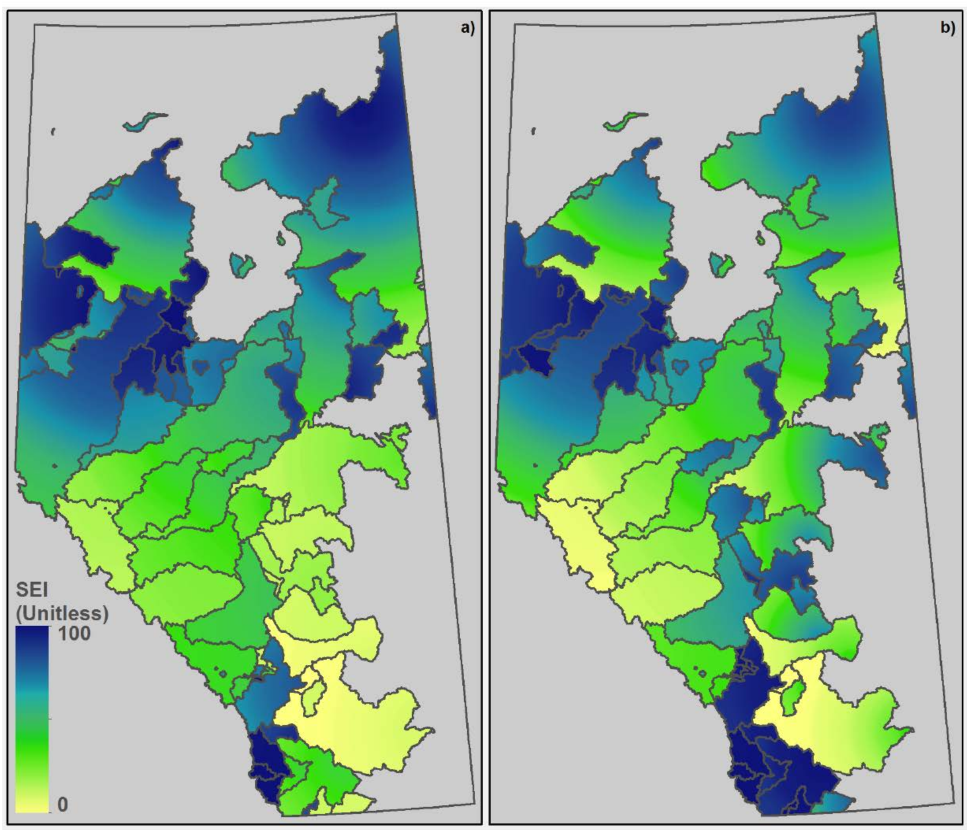


Figure 7.3 Source Exposure Index (SEI) for Alberta and wildfire exposure index for forested watersheds. This figure shows Robinne et al.'s (2019) Source Exposure Index (SEI) for Alberta (a) and wildfire exposure index for forested watersheds (b). In both figures, a higher value indicates higher exposure. The SEI is a spatial index that assesses source exposure based on the availability and demand for water in a watershed, the watershed's forest cover, and the danger of a fire occurring in that area.

7.5 Adaptation to Reduce Risks

To reduce the health impacts of climate change, reducing GHGs is the most important preventative measure. However, regardless of near-term GHG emissions reductions, climate change will continue to pose risks to water quality, quantity, and security in Canada for the foreseeable future. Therefore, there is a pressing need to identify further adaptive actions to reduce or eliminate the anticipated health impacts of climate change. Adapting to the health impacts of climate change involves actions taken by health officials, in collaboration with those in other fields, to understand, assess, prepare for, and help prevent the health impacts of climate change. Adaptive actions often emphasis supporting those most at-risk in society (see Chapter 10: Adaptation and Health System Resilience). It includes the design, implementation, monitoring, and evaluation of specific measures, for example, health and health supporting infrastructures, to reduce health risks. The responsibility for adapting to climate change impacts on water and health is diffuse. Many important health-related adaptation options (e.g., upgrading or replacing water and wastewater systems, flood and drought risk reduction, adaptive agricultural practices, and water storage) are under the purview of decision makers outside of the health sector (e.g., drinking water management, public works and infrastructure, emergency management, civil society) and at different levels of government (municipal, Indigenous, regional, provincial/territorial, or federal).

The federal government has varying levels of responsibility for water governance and management, related to fish habitat, navigation, transboundary waters, water monitoring, and water on federal lands (Zubrycki et al., 2011). To support the reduction of health risks related to water, the federal role is often centred on research, coordination, facilitation of inter-jurisdictional collaboration, education, and outreach. In collaboration with key provincial/territorial, Indigenous, and academic stakeholders, the federal government develops water quality guidance for drinking water (Health Canada, 2019a) and recreational waters (Health Canada, 2012). In Indigenous communities, the federal government generally plays a larger role, due to its responsibility for federal lands (Zubrycki et al., 2011).

Primary responsibility for water governance and management in Canada lies with provincial/territorial governments, with municipalities (ECCC, 2016; Health Canada, 2019b), or with municipal/provincial agencies and corporations, which often take the lead on drinking and wastewater treatment operations. This shared jurisdictional responsibility for water issues, and hence climate change adaptation, is also characterized by participation by a multitude of disciplines and sectors (e.g., DWSs, urban design, agriculture, health, energy), involving diverse risk management methods and terminologies.

Although progress has been made toward improving the uptake of integrated, multisectoral approaches to water management, challenges remain (Shrubsole et al., 2017). Despite human health being a central consideration in almost all water management and governance frameworks, the role of health decision makers is often not explicitly articulated in water management planning and, in practice, is often focused on developing guidelines or standards, monitoring and surveillance, and health communications and response. Through collaboration with health sector officials, decision makers in other sectors have a significant opportunity to reduce health risks from climate change impacts on water through adaptation. Successful health adaptation will require significant intersectoral and intergovernmental coordination. Although not exhaustive, the following section identifies possible adaptive approaches that can reduce the human health consequences of climate change impacts on water quality, quantity, and security.

7.5.1 Climate-Resilient Water Systems

Water systems and water management practices have traditionally been developed with the understanding that past experience was the best indicator of future conditions for the delivery of services. Climate change upends this notion; design parameters of systems built to withstand past climate conditions may not meet future needs (Milly et al., 2008). Past approaches to water management and governance have not adequately incorporated either novel or existing pressures likely to be introduced or exacerbated by climate change. A national survey conducted in 2017 of officials responsible for municipal asset management revealed that information and data about climate change impacts are either unavailable, or poorly integrated into local infrastructure (e.g., water infrastructure) decision making (PSD et al., 2019). Water management planning and water system design should incorporate climate change information (Milly et al., 2008), and water managers, health authorities, and allied professions and sectors should work collaboratively to advance progress toward climate-resilient water systems (Smith et al., 2019).

Resilience is the ability of a system to cope with, respond to, and recover from a shock or stressor in order to continue providing key functions (e.g., a water system can withstand a climate-driven shock without failing to adequately treat water). Climate-resilient water management identifies and implements flexible actions that reduce risks to water quality, quantity, and security in a range of possible future climates to a variety of potential climate shocks and stressors (Smith et al., 2019). Efforts to build climate-resilient water systems have been ongoing since 2007 in Canada. Examples of initiatives to develop new information and tools to support climate-resilient water management to support health include the following:

- The *Northwest Territories Water Stewardship Strategy: A Plan for Action 2016-2020* builds on the momentum of the *Northwest Territories Water Stewardship: A Plan for Action 2011-2015* and aims to ensure the maintenance of the quantity and quality of water resources in the Northwest Territories, secure water supply, and ensure the resilience of freshwater ecosystems (GNWT, 2016).
- The Saskatchewan Water Security Agency is undertaking the project Building Capacity for Community Hydrologic Drought Response, which will increase the ability of municipalities in Saskatchewan to reduce the impacts of drought exacerbated by climate change, including impacts on water supply and quality (NRCan, 2021).
- The Atlantic Canada Water and Wastewater Association is undertaking a project called Incorporating Climate Resilience for Municipal Infrastructure into the Updates of Existing Atlantic Canada Water and Wastewater Design Guidelines (NRCan, 2021).
- The Government of Manitoba, through the project Climate Resiliency: Capacity Building for Manitoba Decision Makers, is increasing the capacity and expertise of professionals (including engineers and planners), the business community in Northern Manitoba, and Indigenous organizations and communities, to reduce climate change impacts, including through adaptations related to land use, water management, and infrastructure (NRCan, 2021).

- The Federation of Canadian Municipalities has developed guides and disseminated information through webinars and networks to support municipalities in efforts to integrate climate change considerations into asset management programs, including those related to water. Key grant programs include the Municipal Asset Management Program, Municipalities for Climate Innovation Program, and Climate and Asset Management Network (PSD et al., 2019).

Many opportunities exist to further integrate climate resilience into water management activities (Smith et al., 2019). The World Health Organization has developed guidance for climate-resilient water safety planning to aid water system decision makers and health authorities in building climate change resilience in water systems and reducing health risks associated with climatic impacts on water resources. This process builds on and leverages the success of existing approaches to water resources management, such as integrated water risk management and climate change adaptation, to ensure that health and climate considerations are adequately captured in water management (WHO, 2017).

Across Canada and internationally, health authorities are increasingly recognizing the need to assess their vulnerability and identify adaptations to reduce the health impacts of climate change, including those related to water issues (Berry et al., 2018) (see Chapter 10: Adaptation and Health System Resilience). Guidance documents and toolkits have been developed to facilitate the completion of vulnerability and adaptation assessments (V&As) related to climate change and health (WHO, 2013; Ebi et al., 2016).

The opportunity exists to increase the understanding of climate change impacts on health through effects on water quality, quantity, and security by conducting V&As at local to regional levels in Canada. A number of previous assessments conducted by health authorities in Canada (Berry et al., 2014b; Grey Bruce Health Unit, 2017; Levison et al., 2017) have included examination of water issues, and many of the 10 projects funded through Health Canada's HealthADAPT initiative also address these issues (Government of Canada, 2020). The participation of health sector officials in broader climate change impact and adaptation assessments, which are often led by the environment department or ministry of the government involved, is also important for increasing understanding of existing and projected impacts of climate change and options for reducing risks to Canadians and for facilitating needed intersectoral collaboration, to make progress in building resilience.

Climate change adaptation actions to reduce risks from impacts related to water often require collaboration with decision makers in other health-relevant sectors. For example, a V&A conducted by the Middlesex-London Public Health Unit in Ontario identified enhanced source water protection as a potential climate change adaptation (Berry et al., 2014b). By working with other sectors to integrate V&A findings into water management processes, the health sector can help to address key upstream determinants of health that help prevent dangerous exposures before illness and injury can affect populations.

Box 7.2 Indigenous water co-governance as a way to address climate change

In the Cowichan Valley, British Columbia, the Cowichan Watershed Board (CWB) undertakes governance and management activities at the watershed scale. The CWB was created after a severe summer drought in 2007 amid stakeholder recognition that a more formal and proactive approach to water management was needed in the face of continued population growth, climate change, and the cumulative impacts of past uncoordinated decision making in the Cowichan-Koksilah watershed. The CWB draws its strength from its governance model, with officials from Cowichan Tribes and the Cowichan Valley Regional District participating as equal partners and co-chairs steering the Board. This partnership, to advance whole-of-watershed health, supports the local recognition of Indigenous rights and is also a deep commitment to moving down the path of reconciliation (CWB, 2018).

Effective water management in watersheds such as the Cowichan-Koksilah watershed has been hampered because the legislative authority and responsibility for water is complex and spread among federal, provincial, and local governments and agencies and because of unextinguished Indigenous rights. Leadership and coordinated decision making are central to the CWB's purpose and structure. The CWB currently does not hold any statutory decision-making powers, although it is anticipated that the CWB may evolve to acquire some form of delegated authority to make local water management decisions. In the meantime, the CWB has endorsed "watershed targets," including ensuring sustainable fish populations, ensuring clean water and adequate summer flow, protecting and preserving riparian and estuarine habitats, conserving water, and increasing local residents' "watershed IQ." To attain these targets, it is necessary to follow the ancient Cowichan Tribes principle, adopted by the CWB, of "Nutsumaat kws yaay'us tthqa" – coming together as a whole to work together to be stronger as partners for the watershed (CWB, 2018).

7.5.2 Adaptation Options to Protect Water Quality, Quantity, and Security

A number of adaptation measures, including new or enhanced policies and programs, are available to reduce health risks from climate change impacts on water quality, quantity, and security (Table 7.4). Many of these actions are most effective when they are tailored to the local or regional context, based on information about climate change impacts gathered through V&As.

Table 7.4 Example adaptations to reduce health risks from climate change impacts on water quality, quantity, and security

Municipal	• Improved or expanded activities related to the safety of municipal water supplies, including water testing (drinking and recreational), water treatment, water delivery, and stormwater management » Integrate climate change considerations into drinking water quality standards and objectives » Publish educational and advisory information on water quality » Advise on issuing boil water advisories • Community-based water monitoring programs • Climate and demographic projections integrated into floodplain mapping and land-use decision making • Vulnerability assessment of water system infrastructure (e.g., vulnerability mapping) • Redundancy in DWSs (e.g., more than one water source) • Mental health support and mental illness prevention and awareness initiatives targeted for those whose livelihoods depend on water (e.g., agriculturally dependent communities) • Water conservation, reuse, and capture-and-storage techniques to reduce climate change impacts • Protocols and procedures for chemical and contaminant risk management during emergencies • Expanding water reuse systems to offset reduced supply, increased demand, or both
Provincial/ territorial	• Enhanced or revised legislation governing municipal and public water supplies, including their construction and operation » Enhance or revise policies, regulations, and protocols regarding water quality inspections » Conduct inspections of municipal drinking water systems and laboratories that test drinking water » Operate water quality testing laboratories » Draft emergency response planning regarding water supplies » Enhance or revise water quality standards and watershed management

Provincial/ territorial (continued)	» Approve designated areas for water treatment plants based on climate risk » Enhance well-water safety » Implement national guidelines for drinking water safety • Mental health support and mental illness prevention and awareness initiatives targeted to those whose livelihoods depend on water (e.g., agriculturally dependent communities) • Protocols and procedures for chemical and contaminant risk management during emergencies • Monitoring of harmful algal bloom outbreaks
Federal	• Research on threats to drinking water in the context of climate change • Development of a recommended set of national guidelines for drinking water safety that integrate information on climate change risks • Nationally integrated approach to monitoring and surveillance for water-borne diseases
Cross-cutting	• Nature-based solutions (e.g., wetlands for agricultural wastewater treatment, buffer zone parks for flood control, etc.) • Climate change and health considerations and climate projections integrated into water resource management activities • Enhanced health risk communications practices to prepare for likely climate change impacts (e.g., advising consumers to avoid produce that may have been in contact with floodwater) • Exploration of equitable economic transition support for communities whose livelihoods are affected by water scarcity • Health education and outreach initiatives for users of gathered water • Decommissioning or renovation of water infrastructure at risk

Source: Adapted from Séguin, 2008; Berry et al., 2014a

For many water-related climate change impacts (e.g., flooding, drought, runoff-driven contamination) and land-use changes, DWS designs informed by watershed scale management can reduce dangerous exposures and risks to health. Adaptation actions can achieve significant health co-benefits as resilience is built; for example, improving community access to water (e.g., beaches, rivers, lakes) can benefit fitness by increasing recreational space, improving residents' sense of connection to the natural environment, and improving overall mental wellness (Gascon et al., 2017).

Nature-based solutions provide important opportunities for communities seeking to reduce land-use based exposures and vulnerabilities. Nature-based solutions are “actions that work with and enhance nature to support biodiversity and help address societal challenges” (Kapos et al., 2019, p. 16). Actions that adopt the design of natural systems or mimic them, as well as efforts to encourage a previously existing natural process (e.g., a wetland), all characterize a nature-based approach to climate adaptation. Nature-based solutions to reduce runoff and stormwater overflow, such as rain gardens (Autixier et al., 2014) and grassed swales (Bäckström, 2003), have been explored as a means of holding back water and allowing for the settling of particulates. These interventions remove contamination from water systems by increasing the hydraulic detention time (Li et al., 2016). Nature-based solutions can also help address both GHG mitigation (e.g., carbon sequestration by protecting existing or creating new green spaces) and adaptation objectives (e.g., improving water quality and reducing flood risk through the development of natural areas that can capture or control water, sometimes known as “blue spaces”). Many such actions offer greater cost savings than traditional grey infrastructure-based approaches, while providing additional co-benefits, including for health. For example, a park designed for flood defence, such as Toronto’s Corktown Common Park (Waterfront Toronto, 2020), may also create recreational spaces and allow for the development of active transport infrastructure (e.g., bicycle and walking paths). Green spaces may also have health benefits for those who suffer from some forms of mental illness and generally may help improve quality of life for those who live or work nearby (Raymond et al., 2017).

Across Canada, various levels of government have experimented with financial incentives to drive land-use change. For example, following widespread flooding, New Brunswick’s provincial government launched a buy-out program for homeowners most at risk of flooding (New Brunswick, 2019). Other regions have provided financial incentives to landowners who take action to protect water quality, such as to farmers who refrain from cultivating directly beside waterways (Clean Water Program, 2020).

Protecting health from water-related risks through an approach involving standards and guidelines, which is informed by familiar threats and past experience, may not increase resilience in the face of unknown or unexpected health risks, unless new knowledge of climate change risks is integrated into these activities. By working with stakeholders to apply a climate lens to guideline development, existing vulnerabilities may be reduced and resilience to future impacts increased. Risks from new pathogens and viruses to the health of Canadians from climate change impacts on water may require improved water quality monitoring and surveillance, as well as early warning capabilities to inform the actions of system operators. The water and public health sectors will need to approach this problem collaboratively and partner with all levels of government.

Leveraging community interest in water quality protection to help inform monitoring efforts may help improve resilience. For example, Indigenous communities across Canada face multi-faceted water system vulnerabilities. Communities in the North face challenges, such as the loss of permafrost, the contamination of tundra pond water sources, and the vulnerability of village sewage lagoons to climate hazards (Berner et al., 2016; McKnight, 2017). Communities recognize that these climate impacts on already stressed DWSs may increase the risk of water-borne disease in the future. Recognizing the growing burden of gastrointestinal illness on their community, a group of Inuit youth in Mittimatalik (Pond Inlet), with the support of Elders and research bodies, are working to apply both Inuit and scientific knowledge to assess the impact of climate change on local water quality and human health (Inuit Tapiriit Kanatami, 2019). Such community-led water monitoring programs have the potential to help inform climate-resilient planning for water systems across

Canada and, in some cases, may incentivize increased community stewardship of water resources. In addition, the Circuit Rider Training Program is a long-term capacity-building program that provides training and mentoring services to operators of First Nations DWSs and wastewater systems (ISC, 2015).

Currently, most municipal DWSs are centralized and often extract large volumes of water from a single source located a great distance from the population it serves. Reliance on a single source is risky, because a serious failure related to that source can have disastrous consequences (Boholm & Prutzer, 2017). In addition, centralized DWSs require large amounts of chemicals for treatment and energy to transport water, as well as a vast infrastructure (Speight, 2018), and can therefore have impacts on the environment. Shifting to less-centralized systems that incorporate multiple water sources (e.g., rainwater, greywater, multiple smaller groundwater supplies) and additional water protection areas can result in more resilient systems that could help mitigate the risks associated with climate change impacts on aging infrastructure (Boholm & Prutzer, 2017). This would also alleviate pressures associated with drought, decreased streamflow, and aquifer depletion by making better use of available water sources. Promoting water-saving practices, such as the use of low-flow showers and toilets and the use of greywater and rainwater, can also help to reduce water consumption.

In some cases, there will be limits to the effectiveness of large land-use changes, new protective infrastructure (either nature-based or traditional), and updates to DWSs or DWS operations, and the extent to which they can be adopted. In these cases, the development, promotion, and adoption of early warning systems with associated risk communications may play an important role in addressing and reducing health impacts from climate change (Wu et al., 2016). Early warning systems have been used with success to reduce the impacts of floods (Alfieri et al., 2012), infectious diseases (Ogden et al., 2019), extreme heat (see Chapter 10: Adaptation and Health System Resilience), and other health hazards by providing sufficient lead time for officials to respond to impending threats. Progress has been made toward integrating climate and weather data into warning systems for some climate-related impacts (e.g., Ogden et al., 2019), in order to better prepare both health officials and citizens. The opportunity exists to expand efforts to reduce risks of climate-related water-borne diseases, for example, by monitoring the human–wildlife interface, such as through the use of bio-sentinels that act as a proxy for human health impacts/risks (e.g., monitoring the health of a particular fish species) (Stephen & Duncan, 2017). This may prove particularly useful for impacts on water quality, such as harmful algal blooms.

Early warning systems can benefit from tools that present the spatial distribution of climate-related hazard exposures, vulnerability factors, and impacts on health in a visual format. The *Federal Flood Mapping Framework* (NRCan, 2018) has resulted in renewed emphasis on flood inundation mapping across Canada. At the local and regional levels, various groups have made efforts to apply innovative approaches to better understand the variation in impacts of floods across geographic regions. For example, in Quebec, a partnership between Laval University, Ouranos, and the Institut national de santé publique du Québec has integrated vulnerability indicators into flood mapping, providing valuable information for health and emergency management authorities to plan emergency response measures (Ouranos, 2018).

7.6 Knowledge Gaps

Climate change impacts on water quality, quantity, and security are complex, and many knowledge gaps exist. The ability to measure and monitor climate change impacts on water resources across Canada's diverse ecosystems and socio-cultural environments, in addition to resulting health outcomes, are basic requirements to address key knowledge gaps (Table 7.5). This work is crucial to developing effective interventions that can build resilience and reduce climate change-related health impacts.

Integrating Indigenous knowledge into efforts to prepare for and respond to climate-driven stressors on water quality, quantity, and security is a key component of research needed to protect health in a changing climate. Research from First Nations, Inuit, and Métis perspectives is lacking and requires attention. Research led by, or in partnership with, Métis communities is a notable gap to date. Climate change impacts and adaptation assessments, and adaptation policies and programs, are well-served when a broad evidence base, informed by different perspectives, communities, and knowledge systems, can be drawn from. Increasing climate research led by First Nations, Inuit, and Métis researchers will benefit all Canadians.

Table 7.5 Key research needs related to the health effects of climate change impacts on water quality, quantity, and security

CLIMATE CHANGE IMPACTS ON WATER RESOURCES AND IMPLICATIONS FOR HUMAN HEALTH
• Relationships between temperature and precipitation on the diverse Canadian flow regimes (e.g., switch in river basins from snow-dominated to rain-dominated regimes) • Impacts of changes in the cryosphere on water resources (e.g., effects of changes in albedo on permafrost and downstream water quality and quantity) • Effects of changes in the cryosphere on releases of chemical contaminant burdens (e.g., persistent organic pollutants and heavy metals) and subsequent impacts on food and water supplies • Impacts of wildfires on source water quality and availability, and how they vary across forest ecosystems • Effects of ocean and freshwater acidification and nutrient runoff from land in the context of climate change (e.g., adaptation in the agricultural sector) on harmful algal blooms

WATER RESOURCE MANAGEMENT AND SOURCE WATER PROTECTION
• Effects of climate change and land-use change on groundwater recharge over short and long timescales • Effective measures for protecting DWSs from increased flooding-related health concerns (e.g., increases in bacterial contamination) • Impacts of projected drought extremes on water resources and the most effective adaptations to protect health (e.g., individual storage capacity; water sharing across multiple jurisdictions) • Effective government, management, and partnership models, including those with First Nations, Inuit, and Métis communities
DRINKING WATER AND DRINKING WATER SYSTEMS
• Factors that make water systems vulnerable to extreme rain events, and effective adaptation measures • Health ramifications and possible DWS stresses from wildfire impacts on source water, particularly for untreated drinking water sources (e.g., "gathered water") • Cost-effective adaptations for DWSs to address emerging contaminants (e.g., harmful algal blooms), which are expected to increase under climate change
PUBLIC HEALTH AND HEALTH CARE
• Health risks associated with water contaminated by residue from burned residential, industrial, and commercial materials as a result of wildfires • Health risks of harmful algal blooms, and how they might increase with climate change • Emerging new or previously rare water-borne pathogens (e.g., northward-moving *Naegleria fowleri*) and effective measures to protect health • Impacts of changes in animal (e.g., waterfowl) and other vector populations on the distribution and transmission of water-borne diseases as the climate continues to change • Health risks associated with water reuse and effective measures to protect health • Effective technologies for producing potable water in future water-stress scenarios

7.7 Conclusion

The quality, quantity, and security of Canada's water resources are being affected by climate change, increasing risks to human health. Expected increases in both average temperatures and temperature extremes, along with heavy precipitation events, droughts, and wildfires in many regions of Canada, will place increased stress on water resources in freshwater, marine, and coastal systems, thereby creating greater risks to human health. A range of climate-sensitive pathogens or toxins currently affect the health of Canadians; these include algae, cyanobacteria, enteric viruses, and *Leptospira*, *Leptonema*, *Vibrio*, and *Legionella* bacteria. In addition, gradual warming and an increase in extreme events will continue to place stress on DWSs, potentially leading to the presence of biological or chemical agents in water, which could further lead to human exposure through drinking water, bathing, recreation, or ceremonial use. Climate change will pose even greater challenges for small and rural systems. The future health impacts due to climate change are uncertain because of a lack of projections for many of these health outcomes and because of the complex pathways through which people are affected, which involve social and behavioural factors.

Similar to other health concerns associated with climate change, evidence suggests that specific populations are at higher risk of these effects, including children, seniors, and people with chronic diseases. The health and well-being of many Indigenous Peoples and communities is disproportionately affected by challenges to water resources, which can arise from a variety of factors, such as insufficient water treatment technology, distribution systems and upgrades, water contamination caused by local industry, and difficulty retaining qualified water treatment plant operators. Climate change impacts on source water will exacerbate the effects of these challenges if further adaptations are not implemented to safeguard water resources and protect health in these communities. First Nations, Inuit, and Métis communities possess countless generations of accumulated knowledge which, through equitable partnerships, could be applied to protect health. Increased partnerships among First Nations, Inuit, and Métis peoples, health authorities, and water managers are needed to identify and address the health impacts specific to Indigenous populations of climate-driven changes to water resources and to implement effective options for community-level adaptation.

In the absence of enhanced efforts to adapt, the health of Canadians will increasingly be affected as the climate continues to change. By working to identify both vulnerabilities to public health and adaptation options, health authorities can reduce and adapt to these impacts and build the climate resilience of water systems. Although some adaptation options exist today, increased research is needed to understand the scope of both current and future impacts and the effectiveness of adaptation strategies and technologies. To evaluate the effectiveness of adaptation options, research is needed to identify the most effective means of monitoring water-related health hazards. Additionally, projections of possible future health impacts and proactive measures for communicating risks to the public, for example, through early warning systems, should be explored.

7.8 References

Abbott, L. P. (1986). *Vibrio* vulnificus in New Brunswick. *Canada Diseases Weekly Report, 12-14*, 57-8.

Ahern, M., Kovats, R. S., Wilkinson, P., Few, R., & Matthies, F. (2005). Global health impacts of floods: epidemiologic evidence. *Epidemiologic reviews*, *27*, 36–46. <https://doi.org/10.1093/epirev/mxi004>

Alderman, K., Turner, L. R., & Tong, S. (2012). Floods and human health: a systematic review. *Environment international*, *47*, 37–47. <https://doi.org/10.1016/j.envint.2012.06.003>

Alexander, J., Benford, D., Cockburn, A., Cravedi, J., Dogliotti, E., Di Domenico, A., … Verger, P. (2009). Scientific Opinion of the Panel on Contaminants in the Food Chain on a request from the European Commission on Marine Biotoxins in Shellfish – Saxitoxin Group. *The EFSA Journal, 7*(4), 1-76. <https://doi.org/10.2903/j.efsa.2009.1019>

Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., & Thielen, J. (2012). Operational early warning systems for water-related hazards in Europe. *Environmental Science & Policy, 21*, 35-49.

Anderson, D. M., Richlen, M. L., & Lefebvre, K. A. (2019). Harmful algal blooms in the Arctic. In E. Osborne, J. Richter-Menge, & M. Jeffries (Eds.), *Arctic Report Card: Update for 2018*. Retrieved from <https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/789/Harmful-Algal-Blooms-in-the-Arctic>

Andrey, J., Kertland, P., & Warren, F. J. (2014). Water and Transportation Infrastructure. In F. J. Warren, & D. S. Lemmen (Eds.), *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation*. Ottawa, ON: Government of Canada.

Aramini, J., McLean, M., Wilson, J., Holt, J., Copes, R., Allen, B., & Sears, W. (2000). Drinking water quality and health-care utilization for gastrointestinal illness in greater Vancouver. *Canada Communicable Disease Report = Releve des Maladies Transmissibles au Canada*, *26*(24), 211–214.

Arctic Monitoring and Assessment Programme (AMAP). (2015). *AMAP Assessment 2015: Human Health in the Arctic*. Oslo, Norway.

Arctic Monitoring and Assessment Programme (AMAP). (2017). *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017*. Oslo, Norway.

Ashbolt, N. J. (2015). Microbial Contamination of Drinking Water and Human Health from Community Water Systems. *Current Environmental Health Reports, 2*(1), 95–106. <DOI:10.1007/s40572-014-0037-5>

Assembly of First Nations (AFN). (2013). *Strategy to protect and advance Indigenous water rights*. Ottawa, ON. Retrieved from <https://www.afn.ca/uploads/files/water/firstnationswaterstrategy.pdf>

Auld, H., MacIver, D., & Klaassen, J. (2004). Heavy rainfall and waterborne disease outbreaks: the Walkerton example. *Journal of Toxicology and Environmental Health. Part A*, *67*(20-22), 1879–1887. <https://doi.org/10.1080/15287390490493475>

Autixier, L., Mailhot, A., Bolduc, S., Madoux-Humery, A. S., Galarneau, M., Prévost, M., & Dorner, S. (2014). Evaluating rain gardens as a method to reduce the impact of sewer overflows in sources of drinking water. *The Science of the Total Environment*, *499*, 238–247. <https://doi.org/10.1016/j.scitotenv.2014.08.030>

Azuma, K., Ikeda, K., Kagi, N., Yanagi, U., Hasegawa, K., & Osawa, H. (2014). Effects of water-damaged homes after flooding: health status of the residents and the environmental risk factors. *International Journal of Environmental Health Research*, *24*(2), 158–175. <https://doi.org/10.1080/09603123.2013.800964>

Bäckström M. (2003). Grassed swales for stormwater pollution control during rain and snowmelt. *Water Science and Technology : a Journal of the International Association on Water Pollution Research*, *48*(9), 123–132.

Baker-Austin, C., Trinanes, J. A., Taylor, N. G. H., Hartnell, R., Siitonen, A., Martinez-Urtaza, J. (2013). Emerging *Vibrio* risk at high latitudes in response to ocean warming. *Nature Climate Change, 3*, 73-77. <https://doi.org/10.1038/nclimate1628>

Bakker, K., & Cook, C. (2011). Water governance in Canada: Innovation and fragmentation. *Water Resources Development*, *27*(02), 275-289.

Banerjee, S. K., Rutley, R., & Bussey, J. (2018). Diversity and Dynamics of the Canadian Coastal *Vibrio* Community: an Emerging Trend Detected in the Temperate Regions. *Journal of Bacteriology*, *200*(15), e00787-17. <https://doi.org/10.1128/JB.00787-17>

Bell, J. (2019). Iqaluit seeks new emergency fix for another looming water shortage. *Nunatsiaq News*. Retrieved from <https://nunatsiaq.com/stories/article/iqaluit-seeks-new-emergency-fix-for-another-looming-water-shortage/>

Bellou, M., Kokkinos, P., & Vantarakis, A. (2013). Shellfish-borne viral outbreaks: a systematic review. *Food and Environmental Virology*, *5*(1), 13–23. <https://doi.org/10.1007/s12560-012-9097-6>

Berner, J., Brubaker, M., Revitch, B., Kreummel, E., Tcheripanoff, M., & Bell, J. (2016). Adaptation in Arctic circumpolar communities: food and water security in a changing climate. *International Journal of Circumpolar Health*, *75*, 33820. <https://doi.org/10.3402/ijch.v75.33820>

Berry, P., Clarke, K., Fleury, M .D. & Parker, S. (2014a). Human Health. In F. J. Warren, & D. S. Lemmen (Eds.), *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (pp. 191-232). Ottawa, ON: Natural Resources Canada. Retrieved from <http://publications.gc.ca/pub?id=9.699408&sl=0>

Berry, P., Enright, P. M., Shumake-Guillemot, J., Villalobos Prats, E., & Campbell-Lendrum, D. (2018). Assessing Health Vulnerabilities and Adaptation to Climate Change: A Review of International Progress. *International Journal of Environmental Research and Public Health*, *15*(12), 2626. <https://doi.org/10.3390/ijerph15122626>

Berry, P., Paterson, J., & Buse, C. (2014b). *Assessment of vulnerability to the health impacts of climate change in Middlesex-London*. London, ON: Middlesex-London Health Unit. Retrieved from <https://www.healthunit.com/climate-change>

Bertuzzo, E., Mari, L., Righetto, L., Gatto, M., Casagrandi, R., Rodriguez-Iturbe, I., & Rinaldo, A. (2012). Hydroclimatology of dual-peak annual cholera incidence: Insights from a spatially explicit model. *Geophysical Research Letters, 39*(5). doi: 10.1029/2011GL050723.

Bharadwaj, L., & Bradford, L. (2018). Indigenous water poverty: Impacts beyond physical health. In H. Exner-Pirot, B. Norbye, & L. Butler (Eds.), *Northern and Indigenous health and healthcare*. Saskatoon, SK: University of Saskatchewan.

Bigham, M., Galanis, E., Gustafson, R., Hoang, L., Louie, K., Faremo, A., Mcintyre, L., Isaac-Renton, J., Daly, P., Gustafson, L., Wong, B., Chong, S., Stone, J., & Rodriguez-Maynez, L. (2008). *Re-emergence of Pathogenic* Vibrio *Vulnificus on the Pacific Northwest Coast in 2007*. Vancouver, BC: Association of Medical Microbiology and Infectious Disease Canada. Retrieved from <http://www.cacmid.ca/wp-content/uploads/2008finalprogram1.pdf>

BluePlan Engineering. (2019). *Canadian Infrastructure Report Card 2019: Monitoring the State of Canada's Core Public Infrastructure*. Retrieved from <http://canadianinfrastructure.ca/downloads/canadian-infrastructure-report-card-2019.pdf>

Boholm, Å., & Prutzer, M. (2017). Experts' understandings of drinking water risk management in a climate change scenario. *Climate Risk Management, 16*, 133–144. doi:10.1016/j.crm.2017.01.003

Bonsal, B. R., Peters, D. L., Seglenieks, F., Rivera, A., & Berg, A. (2019). Changes in freshwater availability across Canada. In E. Bush & D.S. Lemmen (Eds.), *Canada's Changing Climate Report* (p. 261–342). Ottawa, ON: Government of Canada.

Botana, L. M. (2016). Toxicological Perspective on Climate Change: Aquatic Toxins. *Chemical Research in Toxicology*, *29*(4), 619–625. <https://doi.org/10.1021/acs.chemrestox.6b00020>

Brettle, M., Berry, P., Paterson, J., & Yasvinski, G. (2015). Determining Canadian water utility preparedness for the impacts of climate change. *Change and Adaptation in Socio-Ecological Systems, 2*(1). doi: 10.1515/cass-2015-0024.

British Columbia Centre for Disease Control (BC CDC). (2020). Vibrio *parahaemolyticus*. Retrieved from <http://www.bccdc.ca/health-info/diseases-conditions/vibrio-parahaemolyticus>

Britton, E., Hales, S., Venugopal, K., & Baker, M. G. (2010). Positive association between ambient temperature and salmonellosis notifications in New Zealand, 1965–2006. *Australian and New Zealand Journal of Public Health*, *34*(2), 126-129. doi:10.1111/j.1753-6405.2010.00495.x

Burkhardt, W., 3rd, & Calci, K. R. (2000). Selective accumulation may account for shellfish-associated viral illness. *Applied and environmental microbiology*, *66*(4), 1375–1378. <https://doi.org/10.1128/AEM.66.4.1375-1378.2000>

Bush, E., & Lemmen, D. (Eds.). (2019). *Canada's Changing Climate Report*. Ottawa, ON: Government of Canada. Retrieved from <https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/Climate-change/pdf/CCCR_ExecSumm-EN-040419-FINAL.pdf>

Campos, C. J., & Lees, D. N. (2014). Environmental transmission of human noroviruses in shellfish waters. *Applied and Environmental Microbiology*, *80*(12), 3552–3561. <https://doi.org/10.1128/AEM.04188-13>

Canadian Broadcasting Corporation (CBC). (2012). Shellfish harvesting banned off most of N.S. *CBC News*. Retrieved from <https://www.cbc.ca/news/canada/nova-scotia/shellfish-harvesting-banned-off-most-of-n-s-1.1138561>

Canadian Broadcasting Corporation (CBC). (2019). Officials Offer Food Safety Advice as Herring egg Harvest Opens on Vancouver Island. *CBC News*. Retrieved from <https://www.cbc.ca/news/canada/british-columbia/herring-egg-harvest-vancouver-island-food-safety-1.5039174>

Canadian Council of Ministers of the Environment. (2016). *Summary of Integrated Watershed Management Approaches Across Canada*. Retrieved from <https://ccme.ca/en/res/summaryofintegratedwatershedmanagementapproaches acrosscanada.pdf>

Canadian Food Inspection Agency (CFIA). (2012). *Hazard Analysis Critical Control Point (HACCP)*. Retrieved from <http://www.inspection.gc.ca/about-the-cfia/newsroom/food-safety-system/haccp/eng/1346306502207/1346306685922>

Canadian Parliamentary Standing Committee on National Defence. (2019). *Canada's Role in International Peace Operations and Conflict resolutions: Report of the Standing Committee on National Defence*. Retrieved from <https://www.ourcommons.ca/Content/Committee/421/NDDN/Reports/RP10491893/nddnrp16/nddnrp16-e.pdf>

Carmichael, W. W., & Boyer, G. L. (2016). Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes. *Harmful Algae, 54,* 194–212. doi:10.1016/j.hal.2016.02.00.

Canadian Council of Professional Engineers (CCPE). (2008). *Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure.* Canadian Council of Professional Engineers. Retrieved from <https://pievc.ca/wp-content/uploads/2020/12/adapting_to_climate_change_report_final.pdf>

Centre for Research on the Epidemiology of Disasters (CRED) & United Nations Office for Disaster Risk Reduction (UNISDR). (2015). *The Human Cost of Weather Related Disasters 1995–2015.* Geneva, Switzerland. Retrieved from <https://www.preventionweb.net/files/46796_cop21weatherdisastersreport2015.pdf>

Charrois J. W. (2010). Private drinking water supplies: challenges for public health. *Canadian Medical Association Journal = Journal de l'Association Medicale Canadienne*, *182*(10), 1061–1064. <https://doi.org/10.1503/cmaj.090956>

Charron, D., Thomas, M., Waltner-Toews, D., Aramini, J., Edge, T., Kent, R., Maarouf, A., & Wilson, J. (2004). Vulnerability of waterborne diseases to climate change in Canada: a review. *Journal of Toxicology and Environmental Health. Part A*, *67*(20-22), 1667–1677. <https://doi.org/10.1080/15287390490492313>

Chhetri, B. K., Takaro, T. K., Balshaw, R., Otterstatter, M., Mak, S., Lem, M., Zubel, M., Lysyshyn, M., Clarkson, L., Edwards, J., Fleury, M. D., Henderson, S. B., & Galanis, E. (2017). Associations between extreme precipitation and acute gastro-intestinal illness due to cryptosporidiosis and giardiasis in an urban Canadian drinking water system (1997-2009). *Journal of Water and Health*, *15*(6), 898–907. <https://doi.org/10.2166/wh.2017.100>

Clean Water Program. (2020). *Clean Water Program*. Retrieved from <https://www.cleanwaterprogram.ca/>

Compton, M., Willis, S., Rezaie, B., & Humes, K. (2018). Food processing industry energy and water consumption in the Pacific Northwest. *Innovative Food Science & Emerging Technologies*, *47*, 371-383.

Conservation Ontario. (n.d.). *History of Conservation Authorities.* Retrieved from <https://conservationontario.ca/conservation-authorities/about-conservation-authorities/history-of-conservation-authorities>

Cook, A., Lowther, J., Price-Hayward, M., Lee, R. (2009). *Spatial and temporal pattern of norovirus contamination in a Pacific oyster fishery* (P. Lassus, Ed.). Seventh International Conference on Molluscan Shellfish Safety. Nantes, France.

Cook, C., Gavin, H., Berry, P., Guillod, B., Lange, B., Rey Vicario, D., & Whitehead, P. (2017). *Drought planning in England: a primer*. Environmental Change Institute.

Cook, D. W., Bowers, J. C., & DePaola, A. (2002). Density of total and pathogenic (tdh+) *Vibrio* parahaemolyticus in Atlantic and Gulf coast molluscan shellfish at harvest. *Journal of Food Protection*, *65*(12), 1873–1880. <https://doi.org/10.4315/0362-028x-65.12.1873>

Corso, P. S., Kramer, M. H., Blair, K. A., Addiss, D. G., Davis, J. P., & Haddix, A. C. (2003). Costs of Illness in the 1993 Waterborne Cryptosporidium Outbreak, Milwaukee, Wisconsin. *Emerging Infectious Diseases*, *9*(4), 426-431. <https://doi.org/10.3201/eid0904.020417>

Cowichan Watershed Board (CWB). (2018). *Governance Manual – Version 3*. Retrieved from <https://cowichanwatershedboard.ca/wp-content/uploads/2019/08/CWB-Gov-Manual-Version3-Sept-24-2018.pdf>

Curriero, F. C., Patz, J. A., Rose, J. B., & Lele, S. (2001). The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American Journal of Public Health*, *91*(8), 1194–1199. <https://doi.org/10.2105/ajph.91.8.1194>

Curry, C. L., Islam, S. U., Zwiers, F. W., & Déry, S. J. (2019). Atmospheric Rivers Increase Future Flood Risk in Western Canada's Largest Pacific River. *Geophysical Research Letters, 46*(3), 1651-1661. <https://doi.org/10.1029/2018GL080720>

Curtis, P., & Gillis, H. (Eds.). (2016). *Annual Report Fort McMurray Waterworks System Approval.* Edmonton, AB: Alberta Environment and Parks.

Daley, K., Castleden, H., Jamieson, R., Furgal, C., & Ell, L. (2014). Municipal water quantities and health in Nunavut households: an exploratory case study in Coral Harbour, Nunavut, Canada. *International journal of circumpolar health*, *73*(1), 23843.

Daley, K., Hansen, L. T., Jamieson, R. C., Hayward, J. L., Piorkowski, G. S., Krkosek, W.,... & Corriveau, E. (2018). Chemical and microbial characteristics of municipal drinking water supply systems in the Canadian Arctic. *Environmental Science and Pollution Research*, *25*(33), 32926-32937.

Dancause, K. N., Veru, F., Andersen, R. E., Laplante, D. P., & King, S. (2013). Prenatal stress due to a natural disaster predicts insulin secretion in adolescence. *Early Human Development*, *89*(9), 773–776. <https://doi.org/10.1016/j.earlhumdev.2013.06.006>

Deeds, J. R., Wiles, K., Heideman, G. B., 6th, White, K. D., & Abraham, A. (2010). First U.S. report of shellfish harvesting closures due to confirmed okadaic acid in Texas Gulf coast oysters. *Toxicon : official Journal of the International Society on Toxinology*, *55*(6), 1138–1146. <https://doi.org/10.1016/j.toxicon.2010.01.003>

Delpla, I., Jung, A.-V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International, 35*(8), 1225–1233. doi: 10.1016/j.envint.2009.07.001

DePaola, A., Jones, J. L., Woods, J., Burkhardt, W., 3rd, Calci, K. R., Krantz, J. A., Bowers, J. C., Kasturi, K., Byars, R. H., Jacobs, E., Williams-Hill, D., & Nabe, K. (2010). Bacterial and viral pathogens in live oysters: 2007 United States market survey. *Applied and Environmental Microbiology*, *76*(9), 2754–2768. <https://doi.org/10.1128/AEM.02590-09>

Department of Fisheries and Oceans (DFO). (2020). *Marine harmful algal blooms and phycotoxins of concern to Canada*. Canadian Technical Report of Fisheries and Aquatic Sciences 3384. Retrieved from <https://waves-vagues.dfo-mpo.gc.ca/Library/4088319x.pdf>

Derksen, C., Burgess, D., Duguay, C., Howell, S., Mudryk, L., Smith, S., Thackeray, C., & Kirchmeier-Young, M. (2019). Changes in snow, ice, and permafrost across Canada. In E. Bush & D. S. Lemmen (Eds.), *Canada's Changing Climate Report* (p.194–260). Ottawa, ON: Government of Canada.

De Roos, A. J., Gurian, P. L., Robinson, L. F., Rai, A., Zakeri, I., & Kondo, M. C. (2017). Review of Epidemiological Studies of Drinking-Water Turbidity in Relation to Acute Gastrointestinal Illness. *Environmental Health Perspectives*, *125*(8), 086003. <https://doi.org/10.1289/EHP1090>

Dickson, S., Webber, S., & Takaro, T. K. (2014). *Preparing BC for Climate Migration.* Vancouver, BC: Canadian Centre for Policy Alternatives. Retrieved from <https://www.policyalternatives.ca/sites/default/files/uploads/publications/BC%20Office/2014/11/ccpa-bc_ClimateMigration_web.pdf>

Doocy, S., Daniels, A., Packer, C., Dick, A., & Kirsch, T. D. (2013). The human impact of earthquakes: a historical review of events 1980-2009 and systematic literature review. *PLoS currents*, *5*, ecurrents.dis.67bd14fe457f1db0b5433a8ee20fb833. <https://doi.org/10.1371/currents.dis.67bd14fe457f1db0b5433a8ee20fb833>

Doyle, A., Barataud, D., Gallay, A., Thiolet, J. M., Le Guyaguer, S., Kohli, E., & Vaillant, V. (2004). Norovirus food-borne outbreaks associated with the consumption of oysters from the Etang de Thau, France, December 2002. *Euro Surveillance : Bulletin Europeen sur les Maladies Transmissibles = European Communicable Disease Bulletin*, *9*(3), 24–26. <https://doi.org/10.2807/esm.09.03.00451-en>

Ebi, K., Anderson, V., Berry, P., Paterson, J., & Yusa, A. (2016). *Ontario Climate Change and Health Vulnerability and Adaptation Assessment Guidelines: Technical Document.* Toronto, ON: Ontario Ministry of Health and Long-Term Care Public Health Policy and Programs Branch.

Edwards, B., Gray, M., & Hunter, B. (2015). The Impact of Drought on Mental Health in Rural and Regional Australia. *Social Indicators Research, 121,* 177–194. doi:10.1007/s11205-014-0638-2

Emelko, M.B., Silins, U., Bladon, K.D., & Stone, M. (2011). Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies. *Water Research, 45*(2), 461–472.

Emelko, M. B., Stone, M., Silins, U., Allin, D., Collins, A. L., Williams, C. H., Martens, A. M., & Bladon, K. D. (2016). Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. *Global Change Biology*, *22*(3), 1168–1184. <https://doi.org/10.1111/gcb.13073>

Environment and Climate Change Canada (ECCC). (2016). *Water governance and legislation: shared responsibility*. Retrieved from <https://www.canada.ca/en/environment-climate-change/services/water-overview/governance-legislation/shared-responsibility.html>

Etheridge S. M. (2010). Paralytic shellfish poisoning: seafood safety and human health perspectives. *Toxicon : Official Journal of the International Society on Toxinology*, *56*(2), 108–122. <https://doi.org/10.1016/j.toxicon.2009.12.013>

Feldhusen F. (2000). The role of seafood in bacterial food-borne diseases. *Microbes and Infection*, *2*(13), 1651–1660. <https://doi.org/10.1016/s1286-4579(00)01321-6>

Finnis, S., Krstic, N., McIntyre, L., Nelson, T. A., & Henderson, S. B. (2017). Spatiotemporal patterns of paralytic shellfish toxins and their relationships with environmental variables in British Columbia, Canada from 2002 to 2012. *Environmental Research*, *156*, 190–200. <https://doi.org/10.1016/j.envres.2017.03.012>

Ford, J. D., Berrang-Ford, L., King, M., & Furgal, C. (2010). Vulnerability of Aboriginal health systems in Canada to climate change. *Global Environmental Change*, *20*(4), 668-680.

Ford, J. D., Gough, W. A., Laidler, G. J., Macdonald, J., Irngaut, C., & Qrunnut, K. (2009). Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. *Climate research, 38*(2), 137-154.

Fyfe, M., Yeung, S. T., Daly, P., Schallie, K., Kelly, M. T., & Buchanan, S. (1997). Outbreak of *Vibrio* parahaemolyticus related to raw oysters in British Columbia. *Canada Communicable Disease Report = Releve des Maladies Transmissibles au Canada*, *23*(19), 145–148.

Galanis, E., Mak, S., Otterstatter, M., Taylor, M., Zubel, M., Takaro, T. K., Kuo, M., & Michel, P. (2014). The association between campylobacteriosis, agriculture and drinking water: a case-case study in a region of British Columbia, Canada, 2005-2009. *Epidemiology and infection*, *142*(10), 2075–2084. <https://doi.org/10.1017/S095026881400123X>

Galway, L. P., Allen, D. M., Parkes, M. W., & Takaro, T. K. (2014). Seasonal variation of acute gastro-intestinal illness by hydroclimatic regime and drinking water source: a retrospective population-based study. *Journal of Water and Health*, *12*(1), 122–135. <https://doi.org/10.2166/wh.2013.105>

Gargano, J. W., Freeland, A. L., Morrison, M. A., Stevens, K., Zajac, L., Wolkon, A., Hightower, A., Miller, M. D., & Brunkard, J. M. (2015). Acute gastrointestinal illness following a prolonged community-wide water emergency. *Epidemiology and Infection*, *143*(13), 2766–2776. <https://doi.org/10.1017/S0950268814003501>

Gascon, M., Zijlema, W., Vert, C., White, M. P., & Nieuwenhuijsen, M. J. (2017). Outdoor blue spaces, human health and well-being: A systematic review of quantitative studies. *International Journal of Hygiene and Environmental Health*, *220*(8), 1207–1221. <https://doi.org/10.1016/j.ijheh.2017.08.004>

Genivar. (2007). *City of Portage La Prairie water resources infrastructure assessment phase II- pilot study.* Retrieved from <https://pievc.ca/wp-content/uploads/2007/11/City-of-Portage-la-Prairie_Final-Report.pdf>

George, J. (2019). City of Iqaluit says climate change is contributing to its water pipe woes. *Nunatsiaq News.* Retrieved from <https://nunatsiaq.com/stories/article/city-of-iqaluit-says-climate-change-is-contributing-to-its-water-pipe-woes/>

Gérin-Lajoie, J., Herrmann, T. M., MacMillan, G. A., Hébert-Houle, É., Monfette, M., Rowell, J. A., ... Dedieu, J. P. (2018). IMALIRIJIIT: a community-based environmental monitoring program in the George River watershed, Nunavik, Canada. *Écoscience*, *25*(4), 381-399.

Gleick, P., Iceland, C., & Trivedi, A. (2020). *Ending Conflicts over Water.* World Resources Institute. Retrieved from <https://files.wri.org/d8/s3fs-public/ending-conflicts-over-water.pdf>

Glibert, P. M., Icarus Allen, J., Artioli, Y., Beusen, A., Bouwman, L., Harle, J., Holmes, R., & Holt, J. (2014). Vulnerability of coastal ecosystems to changes in harmful algal bloom distribution in response to climate change: projections based on model analysis. *Global Change Biology*, *20*(12), 3845–3858. <https://doi.org/10.1111/gcb.12662>

Gobler, C. J., Doherty, O. M., Hattenrath-Lehmann, T. K., Griffith, A. W., Kang, Y., & Litaker, R. W. (2017). Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(19), 4975–4980. <https://doi.org/10.1073/pnas.1619575114>

Goldhar, C., Bell, T., & Wolf, J. (2013a). Rethinking existing approaches to water security in remote communities: an analysis of two drinking water systems in Nunatsiavut, Labrador, Canada. *Water Alternatives, 6*(3), 462.

Goldhar C., Bell T., & Wolf J. (2013b). Vulnerability to Freshwater Changes in the Inuit Settlement Region of Nunatsiavut, Labrador: A Case Study from Rigolet. *ARCTIC, 67*(1), 1-133. <https://doi.org/10.14430/arctic4365>

Gompf, S. G., & Garcia, C. (2019). Lethal encounters: The evolving spectrum of amoebic meningoencephalitis. *IDCases*, *15*, e00524. <https://doi.org/10.1016/j.idcr.2019.e00524>

Government of Canada. (2020). *HealthADAPT.* Retrieved from <https://www.canada.ca/en/health-canada/programs/health-adapt.html>

Government of Northwest Territories (GNWT). (2016). *NWT Water Stewardship Strategy Action Plan 2016-2020.* Retrieved from <https://www.enr.gov.nt.ca/en/services/water-management-and-monitoring/water-stewardship-nwt>

Grattan, L. M., Boushey, C. J., Liang, Y., Lefebvre, K. A., Castellon, L. J., Roberts, K. A., Toben, A. C., & Morris, J. G. (2018). Repeated Dietary Exposure to Low Levels of Domoic Acid and Problems with Everyday Memory: Research to Public Health Outreach. *Toxins*, *10*(3), 103. <https://doi.org/10.3390/toxins10030103>

Greck and Associates Limited. (2018). *MVCA Gorrie Dam Future Plans Study.* Prepared for Maitland Valley Conservation Authority. Retrieved from <http://www.mvca.on.ca/wp-content/uploads/2018/11/Gorrie-Dam-Future-Plans-Study-Nov.-2018.pdf>

Grey Bruce Health Unit. (2017). *Climate Change and Public Health in Grey Bruce Health Unit: Current conditions and future projections.* Owen Sound, ON: Grey Bruce Health Unit. Retrieved from <https://www1.publichealthgreybruce.on.ca/Portals/0/Topics/Healthy_Environments/Climate%20Change%20in%20GBHU%20-%20Report%20%282017%29.pdf>

Guehlstorf, N., & Hallstrom, L. K. (2012). Environmental Reviews and Case Studies: Participatory Watershed Management: A Case Study from Maritime Canada. *Environmental Practice*, *14*(2), 143-153.

Haley, B. J., Kokashvili, T., Tskshvediani, A., Janelidze, N., Mitaishvili, N., Grim, C. J., Constantin de Magny, G., Chen, A. J., Taviani, E., Eliashvili, T., Tediashvili, M., Whitehouse, C. A., Colwell, R. R., & Huq, A. (2014). Molecular diversity and predictability of *Vibrio* parahaemolyticus along the Georgian coastal zone of the Black Sea. *Frontiers in Microbiology*, *5*, 45. <https://doi.org/10.3389/fmicb.2014.00045>

Hallema, D. W., Robinne, F. N., & Bladon, K. D. (2018). Reframing the challenge of global wildfire threats to water supplies. *Earth's Future*, *6*(6), 772-776.

Harper, A. R., Doerr, S. H., Santin, C., Froyd, C. A., & Sinnadurai, P. (2018). Prescribed fire and its impacts on ecosystem services in the UK. *The Science of the total Environment*, *624*, 691–703. <https://doi.org/10.1016/j.scitotenv.2017.12.161>

Harper, S. L., Edge, V. L., Schuster-Wallace, C. J., Berke, O., & McEwen, S. A. (2011). Weather, water quality and infectious gastrointestinal illness in two Inuit communities in Nunatsiavut, Canada: potential implications for climate change. *EcoHealth*, *8*(1), 93–108. <https://doi.org/10.1007/s10393-011-0690-1>

Health Canada. (2005). *Guidance for providing safe drinking water in areas of federal jurisdiction - Version 1*. Retrieved from <http://publications.gc.ca/site/eng/459848/publication.html>

Health Canada. (2012). *Guidelines for Canadian Recreational Water Quality.* Retrieved from <https://www.canada.ca/content/dam/canada/health-canada/migration/healthy-canadians/publications/healthy-living-vie-saine/water-recreational-recreative-eau/alt/pdf/water-recreational-recreative-eau-eng.pdf>

Health Canada. (2015). *Guidance for Issuing and Rescinding Boil Water Advisories in Canadian Drinking Water Supplies*. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada. Ottawa, ON. Retrieved from <https://www.canada.ca/en/health-canada/services/publications/healthy-living/guidance-issuing-rescinding-boil-water-advisories-canadian-drinking-water-supplies.html>

Health Canada. (2019a). *Guidelines for Canadian Drinking Water Quality - Summary Table*. Retrieved from <https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table.html>

Health Canada. (2019b). *Drinking water quality in Canada*. Retrieved from <https://www.canada.ca/en/health-canada/services/environmental-workplace-health/water-quality/drinking-water.html>

Health Canada. (2020). *Health Canada's Maximum Levels for Chemical Contaminants in Foods.* Retrieved from <https://www.canada.ca/en/health-canada/services/food-nutrition/food-safety/chemical-contaminants/maximum-levels-chemical-contaminants-foods.html>

Henstra, D., & Thistlethwaite, J. (2017). *Flood Risk Management: What Is the Role for the Government of Canada?* Centre for International Governance Innovation. Retrieved from <https://www.cigionline.org/sites/default/files/documents/Policy%20Brief%20No.103_0.pdf>

Heymann, D. (Ed.). (2015). *Control of Communicable Diseases Manual* (20th ed.). Washington, DC: APHA Press.

Hilborn, E. D., & Beasley, V. R. (2015). One health and cyanobacteria in freshwater systems: animal illnesses and deaths are sentinel events for human health risks. *Toxins*, *7*(4), 1374–1395. <https://doi.org/10.3390/toxins7041374>

Hori, Y., Cheng, V. Y., Gough, W. A., Jien, J. Y., & Tsuji, L. J. (2018). Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change*, *148*(1-2), 109-122.

Hovelsrud, G. K., Poppel, B., van Oort, B., & Reist, J. D. (2011). Arctic Societies, Cultures, and Peoples in a Changing Cryosphere. *Ambio*, *40*(Suppl 1), 100–110. <https://doi.org/10.1007/s13280-011-0219-4>

Hrudey, S. E., & Hrudey, E. (2004). *Safe Drinking Water: Lessons from Recent Outbreaks in Affluent Nations*. London, United Kingdom: IWA Publishing.

Hrudey, S. E., Payment, P., Huck, P. M., Gillham, R. W., & Hrudey, E. J. (2003). A fatal waterborne disease epidemic in Walkerton, Ontario: comparison with other waterborne outbreaks in the developed world. *Water science and technology : a journal of the International Association on Water Pollution Research*, *47*(3), 7–14.

Hulin, M., Simoni, M., Viegi, G., & Annesi-Maesano, I. (2012). Respiratory health and indoor air pollutants based on quantitative exposure assessments. *The European Respiratory Journal*, *40*(4), 1033–1045. <https://doi.org/10.1183/09031936.00159011>

Hunter, P. R., & Thompson, R. C. (2005). The zoonotic transmission of Giardia and Cryptosporidium. *International Journal for Parasitology*, *35*(11-12), 1181–1190. <https://doi.org/10.1016/j.ijpara.2005.07.009>

Il Jeong, D., & Sushama, L. (2018). Rain-on-snow events over North America based on two Canadian regional climate models. *Climate Dynamics, 50*(1-2), 303–316. doi:10.1007/s00382-017-3609-x

Indigenous Services Canada (ISC). (2015). *Circuit Rider Training Program.* Retrieved from <https://www.sac-isc.gc.ca/eng/1313424571273/1533818103401>

Indigenous Services Canada (ISC). (2019). *Community Voices on Climate Change and Health Adaptation in Northern Canada.* Ottawa, ON. Retrieved from <http://www.climatetelling.info/uploads/2/5/6/1/25611440/19-012-climate-change-c2-ang.pdf>

Indigenous Services Canada (ISC). (2020a). *Ending long-term drinking water advisories.* Retrieved from <https://www.sac-isc.gc.ca/eng/1506514143353/1533317130660>

Indigenous Services Canada (ISC). (2020b). *Flooding in First Nations communities.* Retrieved from <https://www.sac-isc.gc.ca/eng/1397740805675/1535120329798>

Inuit Tapiriit Kanatami (ITK). (2019). National Inuit Climate Change Strategy. Retrieved from <https://www.itk.ca/wp-content/uploads/2019/06/ITK_Climate-Change-Strategy_English.pdf>

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and Sectoral Aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White, Eds.). Cambridge, United Kingdom: Cambridge University Press.

International Joint Commission (IJC). (2017). *Human Health Effects of Cyanobacterial Toxins in the Great Lakes Region: A Science and Monitoring Assessment.* Retrieved from <https://www.ijc.org/sites/default/files/2019-04/HPABAlgalBloomFinal.pdf>

Jagai, J. S., Griffiths, J. K., Kirshen, P. K., Webb, P., & Naumova, E. N. (2012). Seasonal patterns of gastrointestinal illness and streamflow along the Ohio River. *International Journal of Environmental Research and Public Health*, *9*(5), 1771–1790. <https://doi.org/10.3390/ijerph9051771>

Jalliffier-Verne, I., Leconte, R., Huaringa-Alvarez, U., Madoux-Humery, A. S., Galarneau, M., Servais, P., Prévost, M., & Dorner, S. (2015). Impacts of global change on the concentrations and dilution of combined sewer overflows in a drinking water source. *The Science of the Total Environment*, *508*, 462–476. <https://doi.org/10.1016/j.scitotenv.2014.11.059>

Jung, Y., Jang, H., & Matthews, K. R. (2014). Effect of the food production chain from farm practices to vegetable processing on outbreak incidence. *Microbial Biotechnology*, *7*(6), 517–527. <https://doi.org/10.1111/1751-7915.12178>

Kang, D. H., Shi, X., Gao, H., Déry, S. J. (2014). On the changing contribution of snow to the hydrology of the Fraser River Basin, Canada. *Journal of Hydrometeorology, 15*(4), 1344-1365.

Kapos, V., Wicander, S., Salvaterra, T., Dawkins, K., & Hicks, C. (2019). *The Role of the Natural Environment in Adaptation, Background Paper for the Global Commission on Adaptation*. Washington, DC: Global Commission on Adaptation.

Kelly, M. T. (1991). Pathogenic *Vibrio*naceae in patients and the environment. *Undersea Biomedical Research, 18*(3), 193-6.

Khaira, G., & Galanis, E. (2007). Descriptive epidemiology of *Vibrio* parahaemolyticus and other *Vibrio* species infections in British Columbia: 2001-2006. *Canada Communicable Disease Report = Releve des Maladies Transmissibles au Canada*, *33*(11), 12–22.

Khan, S. J., Deere, D., Leusch, F. D., Humpage, A., Jenkins, M., & Cunliffe, D. (2015). Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles?. *Water research*, *85*, 124–136. <https://doi.org/10.1016/j.watres.2015.08.018>

Kim, S., Chu, K. H., Al-Hamadani, Y. A. J., Park, C. M., Jang, M., Kim, D.-H., Yu, M., Heo, J., Yoon, Y. (2018). Removal of contaminants of emerging concern by membranes in water and wastewater: A review. *Chemical Engineering Journal, 335*(1), 896–914. doi:10.1016/j.cej.2017.11.044

Kinney, P. L., Matte, T., Knowlton, K., Madrigano, J., Petkova, E., Weinberger, K., Quinn, A., Arend, M., & Pullen, J. (2015). New York City Panel on Climate Change 2015 Report. Chapter 5: Public health impacts and resiliency. *Annals of the New York Academy of Sciences*, *1336*, 67–88. <https://doi.org/10.1111/nyas.12588>

Kirby, R. M., Bartram, J., & Carr, R. (2003). Water in food production and processing: quantity and quality concerns. *Food Control*, *14*(5), 283-299.

Klassen, J., & Allen, D. M. (2017). Assessing the risk of saltwater intrusion in coastal aquifers. *Journal of Hydrology, 551*, 730–745. doi:10.1016/j.jhydrol.2017.02.044

Kleywegt, S., Pileggi, V., Yang, P., Hao, C., Zhao, X., Rocks, C., Thach, S., Cheung, P., & Whitehead, B. (2011). Pharmaceuticals, hormones and bisphenol A in untreated source and finished drinking water in Ontario, Canada--occurrence and treatment efficiency. *The Science of the Total Environment*, *409*(8), 1481–1488. <https://doi.org/10.1016/j.scitotenv.2011.01.010>

Konrad, S., Paduraru, P., Romero-Barrios, P., Henderson, S. B., & Galanis, E. (2017). Remote sensing measurements of sea surface temperature as an indicator of *Vibrio* parahaemolyticus in oyster meat and human illnesses. *Environmental Health*, *16*(1), 92. <https://doi.org/10.1186/s12940-017-0301-x>

Kovacs, P., & Sandink, D. (2013). *Best Practices for Reducing the Risk of Future Damage to Homes from Riverine and Urban Flooding: A Report on Recovery and Rebuilding in Southern Alberta.* Toronto, ON: Institute for Catastrophic Loss Reduction. Retrieved from <http://www.iclr.org/images/Alberta_flood_risk_2013_PDF.pdf>

Kovats, R. S., & Akhtar, R. (2008). Climate, climate change and human health in Asian cities. *Environment and Urbanization, 20*(1), 165–175. doi:10.1177/0956247808089154

Lake, I. R., Bentham, G., Kovats, R. S., & Nichols, G. L. (2005). Effects of weather and river flow on cryptosporidiosis. *Journal of Water and Health*, *3*(4), 469–474. <https://doi.org/10.2166/wh.2005.048>

Lal, A., Baker, M. G., Hales, S., & French, N. P. (2013). Potential effects of global environmental changes on cryptosporidiosis and giardiasis transmission. *Trends in Parasitology*, *29*(2), 83–90. <https://doi.org/10.1016/j.pt.2012.10.005>

Lam, K. L., Stokes-Draut, J. R., Horvath, A., Lane, J. L., Kenway, S. J., & Lant, P. A. (2017). Life-cycle energy impacts for adapting an urban water supply system to droughts. *Water Research*, *127*, 139–149. <https://doi.org/10.1016/j.watres.2017.10.016>

Le Guyader, F., Haugarreau, L., Miossec, L., Dubois, E., & Pommepuy, M. (2000). Three-year study to assess human enteric viruses in shellfish. *Applied and Environmental Microbiology*, *66*(8), 3241–3248. <https://doi.org/10.1128/AEM.66.8.3241-3248.2000>

Lemmen, D., & Warren, F. (Eds.). (2004). *Climate change impacts and adaptation: A Canadian perspective*. Ottawa, ON: Natural Resources Canada.

Levinson, M., Whelan, M., & Butler, A. (2017). *A Changing Climate: Assessing Health Impacts & Vulnerabilities Due to Climate Change within Simcoe Muskoka*. Barrie, ON: Simcoe-Muskoka District Health Unit.

Levy, B. S., & Sidel, V. W. (2011). Water rights and water fights: preventing and resolving conflicts before they boil over. *American Journal of Public Health*, *101*(5), 778–780. <https://doi.org/10.2105/AJPH.2010.194670>

Levy, K., Woster, A. P., Goldstein, R. S., & Carlton, E. J. (2016). Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. *Environmental Science & Technology*, *50*(10), 4905–4922. <https://doi.org/10.1021/acs.est.5b06186>

Li, H., Li, K., & Zhang, X. (2016). Performance evaluation of Grassed swales for stormwater pollution control. *Procedia Engineering, 154*, 898–910. doi:10.1016/j.proeng.2016.07.481

Lloyd, E. (2017). *Drought Disaster Planning and Adaptation in Rural British Columbia* [Master's Thesis, Royal Roads University]. Royal Roads University. Retrieved from <https://viurrspace.ca/handle/10613/5021>

Logar-Henderson, C., Ling, R., Tuite, A. R., & Fisman, D. N. (2019). Effects of large-scale oceanic phenomena on non-cholera *vibrio*sis incidence in the United States: implications for climate change. *Epidemiology and Infection*, *147*, e243. <https://doi.org/10.1017/S0950268819001316>

Lowe, D., Ebi, K. L., & Forsberg, B. (2013). Factors increasing vulnerability to health effects before, during and after floods. *International Journal of Environmental Research and Public Health*, *10*(12), 7015–7067. <https://doi.org/10.3390/ijerph10127015>

Luh, J., Royster, S., Sebastian, D., Ojomo, E., & Bartram, J. (2017). Expert assessment of the resilience of drinking water and sanitation systems to climate-related hazards. *The Science of the Total Environment*, *592*, 334–344. <https://doi.org/10.1016/j.scitotenv.2017.03.084>

Maalouf, H., Pommepuy, M., & Le Guyader, F. S. (2010). Environmental Conditions Leading to Shellfish Contamination and Related Outbreaks. *Food and Environmental Virology, 2*(3), 136-45.

MacDougall, L., Majowicz, S., Doré, K., Flint, J., Thomas, K., Kovacs, S., & Sockett, P. (2008). Under-reporting of infectious gastrointestinal illness in British Columbia, Canada: who is counted in provincial communicable disease statistics? *Epidemiology and Infection*, *136*(2), 248–256. <https://doi.org/10.1017/S0950268807008461>

Madoux-Humery, A. S., Dorner, S., Sauvé, S., Aboulfadl, K., Galarneau, M., Servais, P., & Prévost, M. (2016). The effects of combined sewer overflow events on riverine sources of drinking water. *Water Research*, *92*, 218–227. <https://doi.org/10.1016/j.watres.2015.12.033>

Mann, A. G., Tam, C. C., Higgins, C. D., & Rodrigues, L. C. (2007). The association between drinking water turbidity and gastrointestinal illness: a systematic review. *BMC Public Health*, *7*, 256. <https://doi.org/10.1186/1471-2458-7-256>

Martin, D., Bélanger, D., Gosselin, P., Brazeau, J., Furgal, C., & Déry, S. (2007). Drinking water and potential threats to human health in Nunavik: adaptation strategies under climate change conditions. *Arctic*, 195-202.

Martin, D. A. (2016). At the nexus of fire, water and society. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*, 1696. doi:10.1098/rstb.2015.0172

Martinez-Urtaza, J., Bowers. J. C., Trinanes, J., & DePaola, A. (2010). Climate anomalies and the increasing risk of *Vibrio* parahaemolyticus and *Vibrio* vulnificus illnesses. *Food Research International, 43*(7), 1780-90. <https://doi.org/10.1016/j.foodres.2010.04.001>

McCabe, R. M., Hickey, B. M., Kudela, R. M., Lefebvre, K. A., Adams, N. G., Bill, B. D., Gulland, F. M., Thomson, R. E., Cochlan, W. P., & Trainer, V. L. (2016). An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, *43*(19), 10366–10376. <https://doi.org/10.1002/2016GL070023>

McClearn, M. (2020). Climate change threatens Canada's dams - but who's keeping track? *The Globe and Mail*. Retrieved from <https://www.theglobeandmail.com/canada/article-climate-change-will-push-canadas-dams-to-their-limits-but-due-to/>

McGregor, D. (2012). Traditional knowledge: Considerations for protecting water in Ontario. *International Indigenous Policy Journal, 3*(3), 1-21. <https://doi.org/10.18584/iipj.2012.3.3.11>

McKnight, E. (2017). Characterizing and monitoring the water properties and dynamics of Lhù'ààn Mān̈ (Kluane Lake), Yukon, in the face of climate change. *ARCTIC, 70*(4), 435-40. doi:10.14430/arctic4692

McLaughlin, J. B., DePaola, A., Bopp, C. A., Martinek, K. A., Napolilli, N. P., Allison, C. G., Murray, S. L., Thompson, E. C., Bird, M. M., & Middaugh, J. P. (2005). Outbreak of *Vibrio* parahaemolyticus gastroenteritis associated with Alaskan oysters. *The New England Journal of Medicine*, *353*(14), 1463–1470. <https://doi.org/10.1056/NEJMoa051594>

McLeman, R. (2011). *Climate change, migration and critical international security considerations: IOM Migration Research Series.* Geneva, Switzerland: International Organization for Migration. Retrieved from <https://publications.iom.int/system/files/pdf/mrs42.pdf>

McLeman, R. (2019). International migration and climate adaptation in an era of hardening borders. *Nature Climate Change*, *9*(12), 911-918. doi:10.1038/s41558-019-0634-2

Mezzacapo, M., Takaro, T. K., Buckeridge, D., Foldy, S., & Boehme, J. (2018). *Data Challenges for Environmental Factors and Gastrointestinal Illness in Great Lakes Cities*. International Association for Great Lakes Research Annual Meeting 2018.

Miller, A., Cumming, E., & McIntyre, L. (2018). *Summary Working Group Report of the Environmental Transmission of Norovirus into Oysters.* Vancouver, BC: Environmental Health Services and BC Centre for Disease Control.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science, 319*(5863), 573-574. doi:10.1126/science.1151915.

Moffatt, H., & Struck, S. (2011). *Water-borne disease outbreaks in Canadian Small Drinking Water Systems.* National Collaborating Centres for Public Health. Retrieved from <https://www.ncceh.ca/sites/default/files/SDWS_Water-borne_EN.pdf>

Moore, S. K., Johnstone, J. A., Banas, N. S., & Salathé, E. P. (2015). Present-day and future climate pathways affecting *Alexandrium* blooms in Puget Sound, WA, USA. *Harmful Algae*, *48*, 1–11. <https://doi.org/10.1016/j.hal.2015.06.008>

Moore, S. K., Trainer, V. L., Mantua, N. J., Parker, M. S., Laws, E. A., Backer, L. C., & Fleming, L. E. (2008). Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health, 7*(Suppl. 2), S4.

Morris, T., & Brandes, O. M. (2013). *The state of the water movement in British Columbia: a waterscape scan & needs assessment of BC watershed-based groups*. POLIS Project on Ecological Governance, University of Victoria & Real Estate Foundation of British Columbia.

Morrison, K. D., & Kolden, C. A. (2015). Modeling the impacts of wildfire on runoff and pollutant transport from coastal watersheds to the nearshore environment. *Journal of Environmental Management*, *151*, 113–123. <https://doi.org/10.1016/j.jenvman.2014.12.025>

Mudryk, L., Derksen, C., Howell, S., Laliberté, F., Thackeray, C., Sospe - dra-Alfonso, R., Vionnet, V., Kushner, P., & Brown, R. (2018). Canadian snow and sea ice: historical trends and projections. *The Cryosphere, 12*, 1157–1176. doi:10.5194/tc-12-1157-2018

Murphy, H. M., Thomas, M. K., Medeiros, D. T., McFadyen, S., & Pintar, K. D. M. (2016a). Estimating the number of cases of acute gastrointestinal illness (AGI) associated with Canadian municipal drinking water systems. *Epidemiology and Infection*, *144*(7), 1371–1385. <https://doi.org/10.1017/S0950268815002083>

Murphy, H. M., Thomas, M. K., Schmidt, P. J., Medeiros, D. T., McFadyen, S., & Pintar, K. D. (2016b). Estimating the burden of acute gastrointestinal illness due to Giardia, Cryptosporidium, Campylobacter, E. coli O157 and norovirus associated with private wells and small water systems in Canada. *Epidemiology and Infection*, *144*(7), 1355–1370. <https://doi.org/10.1017/S0950268815002071>

Naser, A. M., Rahman, M., Unicomb, L., Doza, S., Gazi, M. S., Alam, G. R., Karim, M. R., Uddin, M. N., Khan, G. K., Ahmed, K. M., Shamsudduha, M., Anand, S., Narayan, K., Chang, H. H., Luby, S. P., Gribble, M. O., & Clasen, T. F. (2019). Drinking Water Salinity, Urinary Macro-Mineral Excretions, and Blood Pressure in the Southwest Coastal Population of Bangladesh. *Journal of the American Heart Association*, *8*(9), e012007. <https://doi.org/10.1161/JAHA.119.012007>

Natural Resources Canada (NRCan). (2018). *Federal Flood Mapping Framework.* Retrieved from <http://ftp.geogratis.gc.ca/pub/nrcan_rncan/publications/ess_sst/308/308128/gip_112_v2_0_en.pdf>

Natural Resources Canada (NRCan). (2021). *Building Regional Adaptation Capacity and Expertise (BRACE) Program.* Retrieved from <https://www.nrcan.gc.ca/climate-change/impacts-adaptations/building-regional-adaptation-capacity-and-expertise-brace-program/21324>

New Brunswick. (2019). *Residents affected by flooding can apply for disaster relief and increased advance payments*. Retrieved from <https://www2.gnb.ca/content/gnb/en/news/public_alerts/public_alert.2019.05.0281.html>

Newton, A., Kendall, M., Vugia, D. J., Henao, O. L., & Mahon, B. E. (2012). Increasing rates of *vibrio*sis in the United States, 1996-2010: review of surveillance data from 2 systems. *Clinical Infectious Diseases, 54 Suppl 5*(0 5), S391–S395. <https://doi.org/10.1093/cid/cis243>

Ogden, N. H., Lindsay, L. R., Ludwig, A., Morse, A. P., Zheng, H., & Zhu, H. (2019). Weather-based forecasting of mosquito-borne disease outbreaks in Canada. *Canada Communicable Disease Report = Releve des Maladies Transmissibles au Canada*, *45*(5), 127–132. <https://doi.org/10.14745/ccdr.v45i05a03>

Ouranos. (2018). *Atlas web de la vulnérabilité de la population québécoise aux aléas climatiques.* Retrieved from <https://atlas-vulnerabilite.ulaval.ca/projet/>

Overland, J., Dunlea, E., Box, J. E., Corell, R., Forsius, M., Kattsov, V., Olsen, M. S., Pawlak, J., Reiersen, L. O., & Wang, M. (2018). The urgency of Arctic change. Polar Science, 21, 6-13. doi:10.1016/j.polar.2018.11.008

Paillard, C., Le Roux, F., & Borrego, J. J. (2004). Bacterial disease in marine bivalves, a review of recent studies: trends and evolution. *Aquatic Living Resources, 17*(4), 477-98. <https://doi.org/10.1051/alr:2004054>

Parkes, M. W., Morrison, K. E., Bunch, M. J., Hallström, L. K., Neudoerffer, R. C., Venema, H. D., & Waltner-Toews, D. (2010). Towards integrated governance for water, health and social–ecological systems: The watershed governance prism. *Global Environmental Change*, *20*(4), 693-704.

Parveen, S., Hettiarachchi, K. A., Bowers, J. C., Jones, J. L., Tamplin, M. L., McKay, R., Beatty, W., Brohawn, K., Dasilva, L. V., & Depaola, A. (2008). Seasonal distribution of total and pathogenic *Vibrio* parahaemolyticus in Chesapeake Bay oysters and waters. *International Journal of Food Microbiology*, *128*(2), 354–361. <https://doi.org/10.1016/j.ijfoodmicro.2008.09.019>

Patrick, R. (2018). Adapting to Climate Change through Source Water Protection: Case Studies from Alberta and Saskatchewan, Canada. *International Indigenous Policy Journal, 9*(3). doi:10.18584/iipj.2018.9.3.1

Perl, T. M., Bédard, L., Kosatsky, T., Hockin, J. C., Todd, E. C., & Remis, R. S. (1990). An outbreak of toxic encephalopathy caused by eating mussels contaminated with domoic acid. *The New England Journal of Medicine*, *322*(25), 1775–1780. <https://doi.org/10.1056/NEJM199006213222504>

Pescaroli, G., & Alexander, D. (2018). Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis, 38*(11), 2245-2257. <https://doi.org/10.1111/risa13128>

Pick, F. R. (2016). Blooming algae: a Canadian perspective on the rise of toxic cyanobacteria; *Canadian Journal of Fisheries and Aquatic Sciences, 73*(7), 1149–1158. <https://doi.org/10.1139/cjfas-2015-0470>

Picketts, I. M., Parkes, M. W., & Déry, S. (2017). Climate change and resource development impacts in watersheds: insights from the Nechako River Basin, Canada. *The Canadian Geographer, 61*(2), 196-211. <https://doi.org/10.1111/cag.12327>

Pons, W., Young, I., Truong, J., Jones-Bitton, A., McEwen, S., Pintar, K., & Papadopoulos, A. (2015). A Systematic Review of Waterborne Disease Outbreaks Associated with Small Non-Community Drinking Water Systems in Canada and the United States. *PloS one*, *10*(10), e0141646. <https://doi.org/10.1371/journal.pone.0141646>

Prakash, A., Medcof, J. C., & Tennant, A. D. (1971). *Paralytic shellfish poisoning in eastern Canada.* Fisheries Research Board of Canada. Retrieved from <https://waves-vagues.dfo-mpo.gc.ca/Library/1498.pdf>

Public Sector Digest Inc. (PSD), Canadian Water Network, Canadian Water and Wastewater Association, Federation of Canadian Municipalities. (2019). *Cases Studies: Using Better Data to Identify Climate Change-Related Infrastructure Vulnerabilities in Canadian Communities.* Retrieved from <https://cwn-rce.ca/wp-content/uploads/Case-Studies-Using-Better-Data-to-Identify-Climate-Change-Related-Infrastructure-Vulnerabilities-in-Canadian-Communities.pdf>

Ravel, A., Greig, J., Tinga, C., Todd, E., Campbell, G., Cassidy, M., Marshal, B., & Pollari, F. (2009). Exploring historical Canadian food-borne outbreak data sets for human illness attribution. *Journal of Food Protection*, *72*(9), 1963-1976.

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy, 77*, 15-24. <https://doi.org/10.1016/j.envsci.2017.07.008>

Rigaud, K. K., de Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K., Schewe, J., Adamo, S., McCusker, B., Heuser, S., & Midgley, A. (2018). *Groundswell: Preparing for Internal Climate Migration.* Washington, DC: World Bank. Retrieved from <https://openknowledge.worldbank.org/handle/10986/29461>

Robinne, F.N., Bladon, K.D., Silins,U., Emelko, M.B., Flannigan, M.D., Parisien, M.A., Wang, X.,. Kienzle, S.W., & Dupont, D.P. (2019). A Regional-Scale Index for Assessing the Exposure of Drinking-Water Sources to Wildfires. *Forests, 10*(5), 384. <https://doi.org/10.3390/f10050384>

Rossi, R. J., & Toran, L. (2019). Exploring the potential for groundwater inundation in coastal US cities due to interactions between sewer infrastructure and global change. *Environmental Earth Sciences, 78*(8), 258. doi:10.1007/s12665-019-8261-9

Sanderson, D., Picketts, I. M., Déry, S. J., Fell, B., Baker, S., Lee-Johnson, E., & Auger, M. (2015). Climate change and water at Stellat-en First Nation, British Columbia, Canada: Insights from western science and traditional knowledge. *The Canadian Geographer, 59*(2), 136-150.

Schnitter, R., & Berry, P. (2019). The Climate Change, Food Security and Human Health Nexus in Canada: A Framework to Protect Population Health. *International Journal of Environmental Research and Public Health*, *16*(14), 2531. <https://doi.org/10.3390/ijerph16142531>

Schuster, C. J., Ellis, A. G., Robertson, W. J., Charron, D. F., Aramini, J. J., Marshall, B. J., & Medeiros, D. T. (2005). Infectious disease outbreaks related to drinking water in Canada, 1974-2001. *Canadian Journal of Public Health = Revue Canadienne de Sante Publique*, *96*(4), 254–258. <https://doi.org/10.1007/BF03405157>

Schwartz, J., Levin, R., & Goldstein, R. (2000). Drinking water turbidity and gastrointestinal illness in the elderly of Philadelphia. *Journal of Epidemiology and Community Health*, *54*(1), 45–51. <https://doi.org/10.1136/jech.54.1.45>

Séguin, J. (Ed.). (2008). *Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity*. Ottawa, ON: Health Canada. Retrieved from <http://publications.gc.ca/collections/collection_2008/hc-sc/H128-1-08-528E.pdf>

Semenza, J. C., Herbst, S., Rechenburg, A., Suk, J. E., Höser, C., Schreiber, C., & Kistemann, T. (2012). Climate Change Impact Assessment of Food- and Waterborne Diseases. *Critical Reviews in Environmental Science and Technology*, *42*(8), 857–890. <https://doi.org/10.1080/10643389.2010.534706>

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews, 99*(3-4), 125–161. doi:10.1016/j.earscirev.2010.02.004

Shamkhali Chenar, S., & Deng, Z. (2017). Environmental indicators for human norovirus outbreaks. *International Journal of Environmental Health Research*, *27*(1), 40–51. <https://doi.org/10.1080/09603123.2016.1257705>

Sharma, A., Burn, S., Gardner, T., & Gregory A. (2010). Role of decentralised systems in the transition of urban water systems; Water Science and Technology. *Water Supply, 10*(4), 577–583. doi:10.2166/ws.2010.187

Shrubsole, D., Walters, D., Veale, B., & Mitchell, B. (2017). Integrated Water Resources Management in Canada: the experience of watershed agencies. *International Journal of Water Resources Development, 33*(3), 349-359. <https://doi.org/10.1080/07900627.2016.1244048>

Shuster-Wallace, C., Sandford, R., & Merril, S. (2019). *Water futures for the world we want: Opportunities for research, practice, and leadership in achieving SDG6.* Saskatoon, SK: University of Saskatchewan. Retrieved from <https://gwf.usask.ca/documents/water_futures_for_the_world_we_want.pdf>

Shuster-Wallace, C., Sandford, R., & Merril, S. (2020). Climate change, pollution and urbanization threaten water in Canada. *The Conversation*. Retrieved from <https://theconversation.com/climate-change-pollution-and-urbanization-threaten-water-in-canada-127876>

Smith, B. A., & Fazil, A. (2019). Climate change and infectious diseases: The challenges: How will climate change impact microbial food-borne disease in Canada? *Canada Communicable Disease Report, 45*(4), 108-113. <https://doi.org/10.14745/ccdr.v45i04a05>

Smith, D. M., Matthews, J. H., Bharati, L., Borgomeo, E., McCartney, M., Mauroner, A., Nicol, A., Rodriguez, D., Sadoff, C., Suhardiman, D., Timboe, I., Amarnath, G., & Anisha, N. (2019). *Adaptation's thirst: Accelerating the convergence of water and climate action*. Background Paper prepared for the 2019 report of the Global Commission on Adaptation. Washington, DC. Retrieved from <http://www.iwmi.cgiar.org/Publications/Other/PDF/adaptations-thirst-gca-background-paper.pdf>

Somers, G., & Nishimura, P. (Eds). (2012). *Managing groundwater resources: Assessing the impact of climate change on salt-water intrusion of coastal aquifers in Atlantic Canada*. Prince Edward Island Environment, Labour and Justice. Retrieved from <http://www.gov.pe.ca/photos/original/cle_WA2.pdf>

Speight, V. (2018). Sustainable water systems of the future: how to ensure public health protection? *Perspectives in Public Health, 138*(5), 248–249. doi:10.1177/1757913918790146

Statistics Canada. (2009). *Human Activity and the Environment: Annual Statistics*. Retrieved from <https://www150.statcan.gc.ca/n1/en/pub/16-201-x/16-201-x2009000-eng.pdf?st=2TCSV5or>

Statistics Canada. (2011). *Households and the environment survey (HES).* Retrieved from <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=3881>

Statistics Canada. (2013). *Survey of Drinking Water Plants 2011*. Minister of Industry. Retrieved from <https://www150.statcan.gc.ca/n1/en/pub/16-403-x/16-403-x2013001-eng.pdf?st=JPnR4dOl>

Statistics Canada. (2021). *Table 38-10-0277-01 Treatment of main source of water by households, Canada, provinces and census metropolitan areas (CMA).* Retrieved from <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810027701>

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: guiding human development on a changing planet. *Science, 347*(6223), 1259855. <https://doi.org/10.1126/science.1259855>

Stephen, C., & Duncan, C. (2017). Can wildlife surveillance contribute to public health preparedness for climate change? A Canadian perspective. *Climatic Change, 141*(2), 259-271.

Sundarambal, P., Balasubramanian, R., Tkalich, P., & He, J. (2010). Impact of biomass burning on ocean water quality in Southeast Asia through atmospheric deposition: field observations. *Atmospheric Chemistry and Physics*, *10*(23), 11323-11336. <https://doi.org/10.5194/acp-10-11323-2010>

Taylor, M., Cheng, J., Sharma, D., Bitzikos, O., Gustafson, R., Fyfe, M., Greve, R., Murti, M., Stone, J., Honish, L., Mah, V., Punja, N., Hexemer, A., McIntyre, L., Henry, B., Kendall, P., Atkinson, R., Buenaventura, E., Martinez-Perez, A., Galanis, E., … Team, T. (2018). Outbreak of *Vibrio* parahaemolyticus Associated with Consumption of Raw Oysters in Canada, 2015. *Food-borne Pathogens and Disease*, *15*(9), 554–559. <https://doi.org/10.1089/fpd.2017.2415>

Taylor, M., McIntyre, L., Ritson, M., Stone, J., Bronson, R., Bitzikos, O., Rourke, W., Galanis, E., & Outbreak Investigation Team. (2013a). Outbreak of Diarrhetic Shellfish Poisoning associated with mussels, British Columbia, Canada. *Marine Drugs*, *11*(5), 1669–1676. <https://doi.org/10.3390/md11051669>

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., … Holger, T. (2013b). Ground water and climate change. *Nature Climate Change, 3*(4), 322–329. doi:10.1038/nclimate1744

Thienpont, J. R., Johnson, D., Nesbitt, H., Kokelj, S. V., Pisaric, M .F., Smol, J. P. (2012). Arctic coastal freshwater ecosystem responses to a major saltwater intrusion: A landscape-scale palaeolimnological analysis. *The Holocene, 22*(12), 1451-1460. <https://doi.org/10.1177/0959683612455538>

Thistlethwaite, J. Miano, A., Henstra, D., & Scott, D. (2020). *Indigenous Reserve Lands in Canada Face High Flood Risk*. Centre for International Governance and innovation. Retrieved from <https://www.cigionline.org/sites/default/files/documents/PB%20no.159.pdf>

Thomas, M. K., Murray, R., Flockhart, L., Pintar, K., Pollari, F., Fazil, A., Nesbitt, A., & Marshall, B. (2013). Estimates of the burden of food-borne illness in Canada for 30 specified pathogens and unspecified agents, circa 2006. *Food-borne Pathogens and Disease*, *10*(7), 639–648. <https://doi.org/10.1089/fpd.2012.1389>

Thurton, D. (2017). Fort McMurray seeing big spike in water-treatment costs. *CBC News Edmonton*. Retrieved from <https://www.cbc.ca/news/canada/edmonton/fort-mcmurray-wildfire-water-treatmentcosts-contaminants-1.3973249>

Todd, E. C. (1997). Seafood-associated diseases and control in Canada. *Revue scientifique et technique (International Office of Epizootics)*, *16*(2), 661–672. <https://doi.org/10.20506/rst.16.2.1058>

Trtanj, J., Jantarasami, L., Brunkard, J., Collier, T., Jacobs, J., Lipp, E., McLellan, S., Moore, S., Paerl, H., Ravenscroft, J., Sengco, M., & Thurston, J. (2016). Climate Impacts on Water-Related Illness. In A. Crimmins, J. Balbus, J. L. Gamble, C. B. Beard, J. E. Bell, D. Dodgen, R. J. Eisen, N. Fann, M. D. Hawkins, S. C. Herring, L. Jantarasami, D. M. Mills, S. Saha, M. C. Sarofim, J. Trtanj, & L. Ziska (Eds.), *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (p. 157-187). Washington, DC: U.S. Global Change Research Program. <http://dx.doi.org/10.7930/J0R49NQX>

Turgeon, P., Michel, P., Levallois, P., Archambault, M., & Ravel, A. (2011). Fecal Contamination of Recreational Freshwaters: the Effect of Time-Independent Agroenvironmental Factors. *Water Quality, Exposure and Health, 3*(2), 109–118. doi:10.1007/s12403-011-0048-5

Turner, J. W., Good, B., Cole, D., & Lipp, E. K. (2009). Plankton composition and environmental factors contribute to *Vibrio* seasonality. *The ISME Journal*, *3*(9), 1082–1092. <https://doi.org/10.1038/ismej.2009.50>

Uhlmann, S., Galanis, E., Takaro, T., Mak, S., Gustafson, L., Embree, G., Bellack, N., Corbett, K., & Isaac-Renton, J. (2009). Where's the pump? Associating sporadic enteric disease with drinking water using a geographic information system, in British Columbia, Canada, 1996-2005. *Journal of Water and Health*, *7*(4), 692–698. <https://doi.org/10.2166/wh.2009.108>

Uslu, M. O., Jasim, S., Arvai, A., Bewtra, J., & Biswas, N. (2013). A survey of Occurrence and Risk Assessment of Pharmaceutical Substances in the Great Lakes Basin. *Ozone: Science and Engineering, 35*(4), 249-262. doi:10.1080/01919512.2013.793595

Vandersea, M. W., Kibler, S. R., Tester, P. A., Holderied, K., Hondolero, D. E., Powell, K., Baird, S., Doroff, A., Dugan, D., & Litaker, R. W. (2018). Environmental factors influencing the distribution and abundance of *Alexandrium* catenella in Kachemak bay and lower cook inlet, Alaska. *Harmful Algae*, *77*, 81–92. <https://doi.org/10.1016/j.hal.2018.06.008>

Vezzulli, L., Grande, C., Reid, P. C., Helaouet, P., Edwards, M., Hofle, M. G., Brettar, I., Colwell, R. R., Pruzzo, C. (2016). Climate influence on *Vibrio* and associated human diseases during the past half-century in the coastal North Atlantic. *Proceedings of the National Academy of Science of the United States of America, 113*(34), E5062-71. <https://doi.org/10.1073/pnas.1609157113>

Vezzulli, L., Pruzzo, C., Huq, A., & Colwell, R. R. (2010). Environmental reservoirs of *Vibrio* cholerae and their role in cholera. *Environmental Microbiology Reports*, *2*(1), 27–33. <https://doi.org/10.1111/j.1758-2229.2009.00128.x>

Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., Wang, X. L. (2015). Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes. *Journal of Climate, 28*(11), 4545–4560. doi:10.1175/JCLI-D-14-00697.1

Vinh, D. C., Mubareka, S., Fatoye, B., Plourde, P., & Orr, P. (2006). *Vibrio* vulnificus Septicemia After Handling Tilapia Species Fish: A Canadian Case Report and Review. *The Canadian Journal of Infectious Diseases & Medical Microbiology = Journal Canadien des Maladies Infectieuses et de la Microbiologie Medicale*, *17*(2), 129–132. <https://doi.org/10.1155/2006/164681>

Visciano, P., Schirone, M., Berti, M., Milandri, A., Tofalo, R., & Suzzi, G. (2016). Marine Biotoxins: Occurrence, Toxicity, Regulatory Limits and Reference Methods. *Frontiers in Microbiology*, *7*, 1051. <https://doi.org/10.3389/fmicb.2016.01051>

Vollaard, A. M., Ali, S., van Asten, H. A., Widjaja, S., Visser, L. G., Surjadi, C., & van Dissel, J. T. (2004). Risk factors for typhoid and paratyphoid fever in Jakarta, Indonesia. *JAMA*, *291*(21), 2607–2615. <https://doi.org/10.1001/jama.291.21.2607>

Wang, J., & Deng, Z. (2016). Modeling and Prediction of Oyster Norovirus Outbreaks along Gulf of Mexico Coast. *Environmental Health Perspectives*, *124*(5), 627–633. <https://doi.org/10.1289/ehp.1509764>

Wang, X., Thompson, D. K., Marshall, G. A., Tymstra, C., Carr, R., & Flannigan, M. D. (2015). Increasing frequency of extreme fire weather in Canada with climate change. *Climatic Change, 130*(4), 573–586. doi:10.1007/s10584-015-1375-5

Waterfront Toronto. (2020). *Corktown Common Park.* Retrieved from <https://waterfrontoronto.ca/nbe/portal/waterfront/Home/waterfronthome/projects/corktown+commo>

Watson, V. (2017). Perception of water among the Inuit community in Iqaluit, Nanvut: An anti-colonialist feminist political ecology [Master's Thesis, York University]. Toronto, ON: York University. Retrieved from <https://yorkspace.library.yorku.ca/xmlui/bitstream/handle/10315/34466/Watson_Victoria_C_2017_Masters.pdf?sequence=2&isAllowed=y>

Wiener, M. J., Jafvert, C. T., & Nies, L. F. (2016). The assessment of water use and reuse through reported data: A US case study. *The Science of the Total Environment*, *539*, 70–77. <https://doi.org/10.1016/j.scitotenv.2015.08.114>

Westra, S., Alexander, L. V., & Zwiers, F. W. (2013). Global Increasing Trends in Annual Maximum Daily Precipitation. *Journal of Climate, 26*(11), 3904–3918. <https://doi.org/10.1175/JCLI-D-12-00502.1>

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal, 54*(1), 101–123. <https://doi.org/10.1623/hysj.54.1.101>

Wilson, J., Aramini, J., Clarke, S., Novotny, M., Quist, M., & Keegan, V. (2009). *Retrospective surveillance for drinking water-related illnesses in Canada, 1993-2008*. Novometrix Research Inc. Retrieved from <http://www.ncceh.ca/sites/default/files/DW_Illnesses_Surveillance_Aug_2009.pdf>

World Health Organization. (2013). *Protecting health from climate change: vulnerability and adaptation assessment.* Geneva, Switzerland. Retrieved from <https://apps.who.int/iris/handle/10665/104200>

World Health Organization. (2014). *Constitution of the World Health Organization.* Retrieved from <https://www.who.int/governance/eb/who_constitution_en.pdf>

World Health Organization. (2017). *Climate-resilient water safety plans: managing health risks associated with climate variability and change.* Geneva, Switzerland. Retrieved from <https://apps.who.int/iris/bitstream/handle/10665/258722/9789241512794-eng.pdf?sequence=1&isAllowed=y>

Wotton, M. B., Flannigan, M. D., & Marshall, G. A. (2017). Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters, 12*(9). doi:10.1088/1748-9326/aa7e6e

Wu, X., Lu, Y., Zhou, S., Chen, L., & Xu, B. (2016). Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. *Environment International, 86*, 14-23. <https://doi.org/10.1016/j.envint.2015.09.007>

Yusa, A., Berry, P., J Cheng, J., Ogden, N., Bonsal, B., Stewart, R., & Waldick, R. (2015). Climate Change, Drought and Human Health in Canada. *International Journal of Environmental Research and Public Health*, *12*(7), 8359–8412. <https://doi.org/10.3390/ijerph120708359>

Zamyadi, A., Dorner, S., Sauvé, S., Ellis, D., Bolduc, A., Bastien, C., & Prévost, M. (2013). Species-dependence of cyanobacteria removal efficiency by different drinking water treatment processes. *Water Research*, *47*(8), 2689–2700. <https://doi.org/10.1016/j.watres.2013.02.040>

Zamyadi, A., Romanis, C., Mills, T., Neilan, B., Choo, F., Coral, L. A., Gale, D., Newcombe, G., Crosbie, N., Stuetz, R., & Henderson, R. K. (2019). Diagnosing water treatment critical control points for cyanobacterial removal: Exploring benefits of combined microscopy, next-generation sequencing, and cell integrity methods. *Water Research*, *152*, 96–105. <https://doi.org/10.1016/j.watres.2019.01.002>

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G. & Kharin, V. V. (2019). Changes in Temperature and Precipitation Across Canada. In E. Bush & D. S. Lemmen (Eds.), *Canada's Changing Climate Report*. Ottawa, ON: Government of Canada. Retrieved from <https://changingclimate.ca/CCCR2019>

Zimmerman, L. (2015). Phytoplankton. In *Biological Resources*. Retrieved from <https://coast.noaa.gov/data/docs/nerrs/Reserves_ACE_SiteProfile.pdf>

Zubrycki, K., Roy, D., Venema, H. D., & Brooks, D. B. (2011). *Water Security in Canada: Responsibilities of the federal government*. Winnipeg, MB: International Institute for Sustainable Development. Retrieved from <https://www.iisd.org/system/files/publications/water_security_canada.pdf>