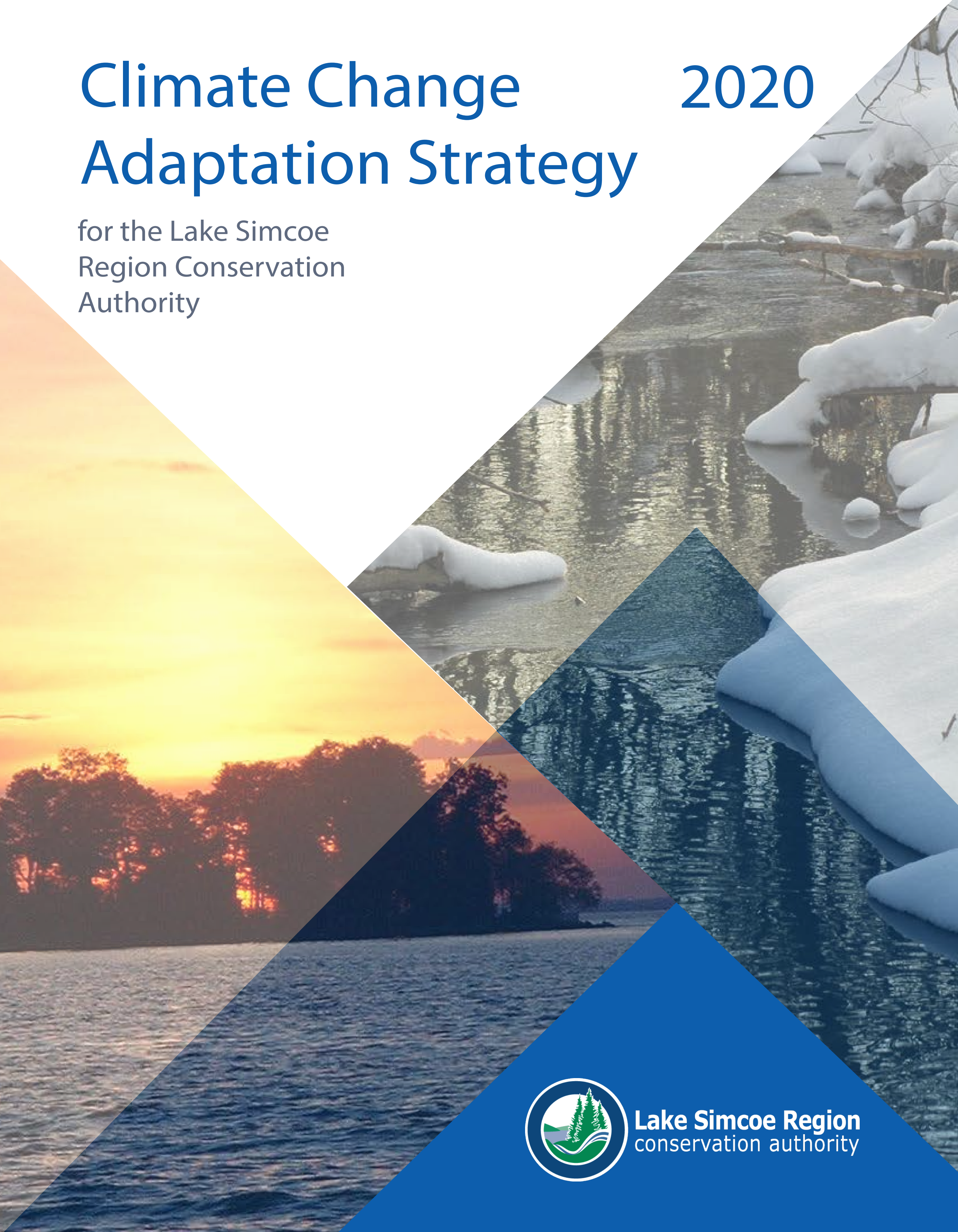
Climate Change Adaptation Strategy

2020

for the Lake Simcoe
Region Conservation
Authority



Lake Simcoe Region
conservation authority

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Acknowledgements

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Foreword

Indigenous peoples are known to be stewards of the Earth and have a Sacred Responsibility to maintain the symbiotic relationship with the Earth.

There are many teachings & stories passed down from the Creator with regard to practices of Humility, Respect, Courage, Love, Honesty, Truth and Wisdom. These are the 7 Grandfather Teachings. Along with these, there are lessons on the 7th Generation. These teachings illustrate how each generation is responsible to ensure the survival and quality of life for the next 7 generations. Hundreds of years ago, our people lived with knowledge and respect for our existence; they knew the actions they took would impact the lives we have today.

Climate forecasts tend to look at short term consequences and are focused on financial impacts as opposed to sustainability of the human species and life in general. Our targets of unceasing development are folly. Long-term sustainability and health of the planet need to be primary goals. The impacts of our choices today will be a legacy of consequences left for others. The 80-year trends outlined in these pages do not represent a finale of climate impacts on the people of this planet.

After we are long gone and our 7th generation descendants walk this earth, we need to decide what kind of life they will inherit. The decisions we make today will be what our future generations will inherit from us. Let us ensure that our Mother, the Earth, is still healthy enough to sustain them.

James L. Porte

Environmental Health Adaptation Coordinator

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Executive Summary

Overview and Purpose

There is no doubt that our climate is changing. We have the data to show it and we know that people are feeling its impact. At the Lake Simcoe Region Conservation Authority, we know that our approach to climate change adaptation needs to be strategic. That's why one of our strategic priorities for 2016-2020 was to develop a Climate Change Adaptation Strategy. This strategy reviews the potential impacts of a changing climate on watershed function and recommends changes to our programs and services to ensure they remain effective at protecting the Lake Simcoe watershed in projected future climates.

To do this, we first down-scaled global climate projections to the local level. In other words, we took data about what is happening at the global scale and localized it to our watershed. We also focused our attention and efforts on water quality and quantity, tributary ecosystems (rivers and streams), terrestrial natural heritage (land) and the lake ecosystem. We completed a full assessment of each area, then identified watershed functions that have a 'high' or 'very high' vulnerability to climate change and developed recommended actions to increase or maintain their resilience.

Vision and Goals

Vision: To enhance the resilience of water resources, natural heritage systems and communities within the Lake Simcoe watershed to climate change.

Goals:

1. To ensure that people, properties and communities **remain sufficiently protected** as climate conditions change.
2. To increase watershed **resistance and resilience to climate change** through conservation, restoration, and improvement of natural ecosystems.
3. To **enhance our knowledge** of our watershed's natural environment and its response to a changing climate through science and monitoring for informed and adaptive decision-making
4. To facilitate **partnerships** and connect people to the watershed in order to **build awareness and capacity** to adapt to a changing climate in the Lake Simcoe watershed.

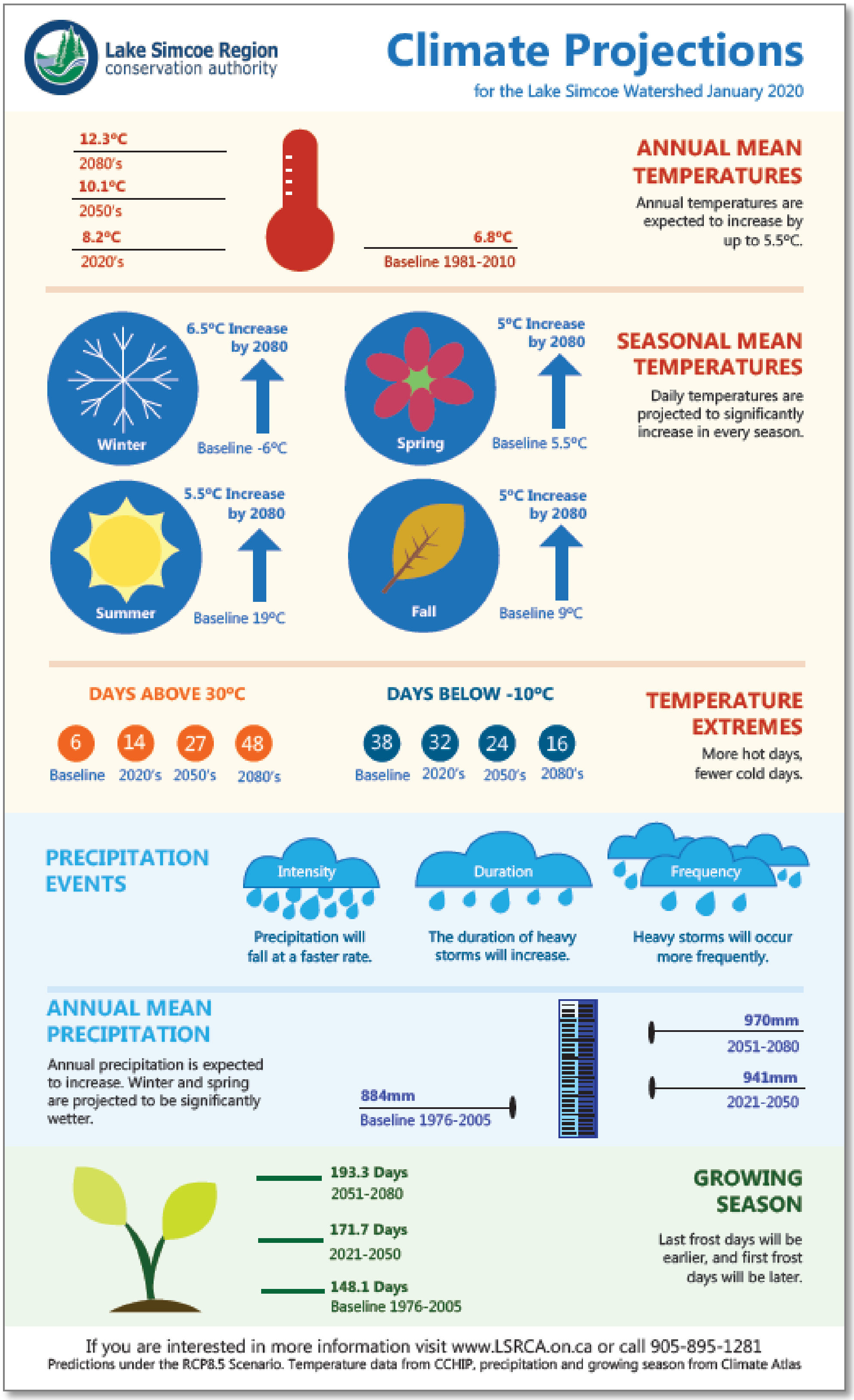
Climate change projections

By downscaling global climate models to the Lake Simcoe watershed, we gained a better understanding of how the local climate is expected to change in the coming century.

Downscaled climate projections for the Lake Simcoe watershed were provided by the Climate Change Hazards Information Portal (https://www.cchip.ca/) and the Climate Atlas of Canada (https://climateatlas.ca/) based on a suite of 25-37 GCMs, statistically downscaled to the Shanty Bay weather station, which has the longest uninterrupted climate data series in the watershed. Representative Concentration Pathways (RCPs) are emission scenarios identified by the International Panel on Climate Change (IPCC). Two RCPs are used here to project future climate impacts: the high carbon scenario (RCP 8.5), assuming emissions continue unabated and a mid-carbon scenario (RCP 4.5), assuming GHG reduction technologies and policies are adopted.

While the projections were developed based on best-available science, there are always uncertainties. We will ensure an adaptive management approach to monitor and assess the effectiveness of the recommendations and modify as necessary.

Local trends and projections for the Lake Simcoe watershed (based on RCP 8.5)



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Climate Projections

for the Lake Simcoe Watershed January 2020

ANNUAL MEAN TEMPERATURES

Annual temperatures are expected to increase by up to 5.5°C.

12.3°C
2080's

10.1°C
2050's

8.2°C
2020's

6.8°C
Baseline 1981-2010

SEASONAL MEAN TEMPERATURES

Daily temperatures are projected to significantly increase in every season.

Winter
6.5°C Increase by 2080
Baseline -6°C

Spring
5°C Increase by 2080
Baseline 5.5°C

Summer
5.5°C Increase by 2080
Baseline 19°C

Fall
5°C Increase by 2080
Baseline 9°C

TEMPERATURE EXTREMES

More hot days, fewer cold days.

	Baseline	2020's	2050's	2080's
DAYS ABOVE 30°C	6	14	27	48
DAYS BELOW -10°C	38	32	24	16

PRECIPITATION EVENTS

Intensity
Precipitation will fall at a faster rate.

Duration
The duration of heavy storms will increase.

Frequency
Heavy storms will occur more frequently.

ANNUAL MEAN PRECIPITATION

Annual precipitation is expected to increase. Winter and spring are projected to be significantly wetter.

970mm
2051-2080

941mm
2021-2050

884mm
Baseline 1976-2005

GROWING SEASON

Last frost days will be earlier, and first frost days will be later.

193.3 Days
2051-2080

171.7 Days
2021-2050

148.1 Days
Baseline 1976-2005

If you are interested in more information visit www.LSRCA.on.ca or call 905-895-1281
Predictions under the RCP8.5 Scenario. Temperature data from CCHIP, precipitation and growing season from Climate Atlas

Anticipated Climate Change Impacts

The following subsections outline the anticipated impacts of climate change on various aspects of watershed function.

Tributary Water Quality

Water quality varies with seasonal differences in runoff volumes, weather conditions and water levels. The sensitivity of water quality to meteorology means that it will be impacted by climate change. Specifically, within the Lake Simcoe watershed, the greatest impacts to water quality will be in changes phosphorus, chloride, and total suspended solids.

Phosphorus

Although phosphorus is an essential nutrient for plants, at high concentrations it encourages excessive plant growth, which in turn decreases oxygen levels and disrupts ecosystems. The total amount of phosphorus (phosphorus load) flowing into Lake Simcoe comes from several sources but is generally highest in the most urbanized subwatersheds. **As extreme rain events become more frequent, they will lead to increased phosphorus loading, perhaps dominated by large "pulse" events.**

Chloride

Chloride is a naturally occurring element essential for the health of all organisms, but too much chloride has a negative impact on our aquatic ecosystems. Most chloride in the watershed comes from winter road salt application, which has resulted in concentrations being above the chronic guidelines, established by the Canadian government, in urban catchments or near major highways. **With varying winter temperatures and more freeze-thaw cycles, our need for road salt increases, leading to increased concentrations of chloride.**

Total Suspended Solids

Total suspended solids (TSS) includes things like silt, sand, microorganisms, plant or animal matter, and industrial wastes that remain suspended in the water column. Excessive amounts of TSS can negatively impact streams and rivers as it can transport phosphorus, decrease light penetration, and alter aquatic habitats. Most monitoring stations in our watershed have shown concentrations exceeding the Canadian guidelines during low water or storm conditions. **As rain events have become more intense, urban subwatersheds have been particularly at risk for increased TSS which can transport contaminants into aquatic ecosystems.**

Water Quantity

Aquatic ecosystems require a range of surface water levels throughout the year to function and support the species living within them. Increased frequency and intensity of rain events, or more frequent snow melt events, can affect all aspects of the water cycle and movement of water through the watershed.

Groundwater Recharge

"Significant groundwater recharge areas" are important areas on the landscape that replenish our underground aquifers (which are sources of drinking water for many) and support the eventual discharge of groundwater to wetlands and coldwater streams. **Warming winter temperatures may allow more rain or snowmelt to seep into the ground and recharge the aquifers. Conversely, drier summers may reduce groundwater recharge.** Although impacts to groundwater may not be experienced for many years to come, it's important to protect these recharge areas now to minimize any impacts.

Streamflow

Changes in precipitation patterns are already leading to changes in streamflow, including both low-flow periods getting longer and high-flow periods becoming more intense. When low-flow periods get longer it can lead to increased water temperatures, degraded water quality, and reduced stream habitats and connectivity. At the other end of the spectrum, extreme flooding isn't much better. It can increase erosion and flush nutrients and pollution into streams, increasing the water's turbidity (murkiness). **As climate change continues, both low-flow and flooding conditions are expected to increase.**

Flooding

Climate projections forecast an increase in winter and spring precipitation, as well as an increase in the frequency, intensity and duration of storms. This means **the potential for more frequent flooding events will increase, especially in the winter season,** which can damage infrastructure, personal property and endanger lives.

Stream and River Ecosystems

Warming water temperatures, reduced snowpack, more frequent drought, and more extreme precipitation patterns will habitats for local aquatic species. Since individual species have specific habitat requirements, some species may be able to cope with or even thrive under new conditions, while others may struggle.

Loss of Coldwater Fish Habitat

Coldwater streams have always been managed as the most sensitive features on the landscape. **Under future climate change conditions, it is expected that only 12% of the watershed's streams will remain cold by 2065.** In response to warming streams with less dissolved oxygen, coldwater fish will seek refuge in these few remaining cooler groundwater-fed streams. Crowded into ever-shrinking habitat, populations of coldwater species such as brook trout may become stressed, increasing their susceptibility to disease, competition for resources and risk of predation for juveniles.

Fish Reproduction

Since both water temperature and streamflow changes are cues for fish to spawn, climate change is expected to affect spawning success. For example, an earlier spring thaw or erosion from extreme weather events is likely to reduce reproductive success and survival of young fish. **Overall, a changing climate is expected to have negative impacts that may reduce reproductive success, meaning fewer fish in the tributaries.**

Other Indicator Species

Aquatic insects, worms and mollusks that live on the bottom of streams are excellent indicators of water quality. The changes in stream flow, temperature, and water quality described above may lead to changes in these communities, including a **shift towards more generalist species** with higher thermal tolerances, at the expense of more sensitive species and **overall species diversity may decrease.**

The Lake Ecosystem

Lake Simcoe provides watershed residents with many valuable socioeconomic and ecosystem services, such as drinking water and wastewater assimilation, tourism, recreation, and irrigation, contributing an estimated $922.7 million annually to Ontario's economy. Unfortunately, climate change is impacting significant aspects of the lake ecosystem, and these important services will be impacted as a result.

Lake Ice

Lake ice cover is not only critical to ecosystem functions in the lake but also to the winter recreational economy, cultural heritage, and winter transportation. Ice record data indicates that the period of ice cover on Lake Simcoe has been decreasing, and in recent years, open water has even remained throughout the winter. Lake ice is highly vulnerable to climate change. Climate modelling predicts that this will only continue, and that **the duration of open water may extend by up to 47 days (from 257 days in the baseline period [1971-2000] to 304 days by 2100).** This can impact lake processes as thin ice or open water allows sunlight to enter the water column in the winter.

Stratification

Lake stratification is the separation of the water in a lake into distinct layers, based on water temperature and density, with the warmest (less dense) layer near the top and the coldest (most dense) layer at the bottom of the lake. Stratification is a natural process and occurs on an annual basis, with intervening periods of mixing as seasonal air temperatures change. Measurements of the timing and duration of water column stratification in Lake Simcoe since the 1980s show that stratification is occurring earlier in spring and ending later in fall. As this period of stratification extends, **deep waters in the lake may become more depleted in oxygen, impacting the coldwater fishery.**

Dissolved Oxygen

During summer, dissolved oxygen in deep water decreases primarily because of the decomposition of organic matter. This has the potential for negative impacts to fish and other organisms in the lake, particularly those coldwater loving species that return to the colder deeper waters of the lake during the summer. Since stratification is expected to extend under climate change, **the end-of-summer dissolved oxygen level in Lake Simcoe may decrease by up to 1 mg/L by 2100.** However, the amount of dissolved oxygen may actually increase in winter, as decreasing lake ice allows light into the water and photosynthesis can occur, producing oxygen.

Phosphorus

Phosphorus is an important element in the lake ecosystem, but in high concentrations can lead to eutrophication, where excessive nutrients can stimulate the growth of aquatic plant life, resulting in decreased oxygen levels. Excess nutrients can also cause harmful algal blooms. Although phosphorus loading from human activities is the main source in Lake Simcoe, low oxygen conditions can also result from the release of stored phosphorus from lake-bottom sediment. **With climate change contributing to an extended period of stratification, this re-release of phosphorous from lake sediments will likely become an ever-growing challenge.**

Algae

Algae is valuable to the lake. It forms the basis of the aquatic food chain, supporting organisms like invertebrates and fish. Climate change is projected to alter the size structure of algal communities as warmer, more stable water bodies favour smaller, lighter species over heavier forms that need frequent water column mixing to remain in the sunlit areas.

Warming temperature and earlier ice-off timing also results in earlier spring algae blooms, which is expected to negatively impact young fish growth and survival and reduce recreational enjoyment of the lake. **A trend toward warmer surface waters, and a longer period of water column stratification, may also give a competitive advantage to more harmful cyanobacteria (i.e. blue-green algal blooms).**

Aquatic Plants

Aquatic plants are an important part of the lake ecosystem. They provide habitat for fish and invertebrates, reduce shoreline erosion, and contribute to nutrient cycling and primary production. **As water temperatures warm and the growing season lengthens, increased plant growth in the lake is expected. Unfortunately, non-native species from warmer climates may be the ones that benefit the most.**

Pathogens

Climate change projections for the watershed forecast warmer temperatures and more frequent and intense precipitation events, combined with extended dry periods, which indicate that **pathogen outbreaks (e.g. E. coli) and beach closures may become more common in the future.**

Fish Communities

Projected increases in water temperature and **decreased dissolved oxygen levels due to climate change are likely to impair coldwater fish species (e.g. lake trout)** in the lake, impacting their spawning, growth and survival rates. On the other hand, **warmer water conditions will allow warmwater species such as smallmouth bass to thrive.** Additionally, warmer waters will allow more southern species to move into the lake if migration routes exist.

Terrestrial Natural Heritage

When natural communities are healthy, resilient, and connected, they form a robust natural heritage system that provides the functions and services upon which we depend. These systems are vital for creating habitat, enabling the movement of species, and maintaining biological diversity. These ecological functions, in turn, provide valuable ecosystem services that contribute to human wellbeing such as shade, clean air and recreational activities.

Wetlands

Wetlands, which cover 18% of the watershed, are particularly vulnerable to changes in water quantity and quality. Changes in streamflow and groundwater discharge, along with changes in temperature and atmospheric carbon dioxide, will likely alter the distribution and abundance of vegetation found within wetlands and increase their vulnerability to drying.

In the Lake Simcoe watershed, **90% of the swamps, 84% of the marshes, 50% of the fens and 100% of the bogs are vulnerable to drying up by 2100.** Vernal ponds and ephemeral pools (seasonal pools of water that provide habitat for distinctive plants and animals) are likely to be early victims of climate change due to their sensitive nature and can therefore be used as early climate change indicators (a type of “canary in the coal mine” if you will). **Wetlands within the watershed provide flood protection services valued at $169 million, which is very likely to be reduced as wetlands become degraded or lost as a result of climate change.**

Woodlands

Woodlands, which cover 35% of the watershed, provide vital habitat to a range of species. Many of the tree species within the watershed will be impacted by changing temperature and rain/snow patterns. **Communities with a poor ability to adapt (e.g. boreal forests) are likely to experience impaired growth and reproduction, increasing their susceptibility to pests and disease.**

More frequent **extreme weather events such as drought, sustained high winds, and ice storms, associated with climate change have the potential to damage trees** and cause hazards from falling limbs. Increased freeze thaw cycles and drought events can stress trees and decrease the average age of trees within a forest.

Timing of Life Cycle Events

For many species, seasonal changes in temperature trigger transitions in seasonal life cycle events. For example, the timing of bud and leaf emergence, as well as wildlife breeding, migration and stages of development occur, at least partly, in response to temperature. A**s the climate continues to change, there will be mismatches in the timing of these important life cycle events**, such as migratory birds arriving before their food sources emerge.

Species Range Shifts

As air temperatures warm, populations of species at the northern limit of their range may become more abundant or colonize new habitat, whereas those species at the southern limit of their range may be threatened. As current habitats become unsuitable for some species, it is important to maintain habitat connectivity to facilitate movement between climate refuges to allow them to colonize new areas. **Protecting and enhancing ecological connectivity will become increasingly important as the climate continues to change.**

Invasive species

As both terrestrial and aquatic habitats shift under a new climate, the potential spreading of new or existing invasive species will increase. These invaders, such as the round goby or dog-strangling vine, often lack predators and out-compete local native species, allowing them to quickly grow and alter community dynamics.

Recommendations for action

The LSRCA has developed a suite of recommended actions to address the projected impacts of climate change on natural systems and associated effects on watershed communities. While most recommendations are targeted to LSRCA programs, services and operations, many will require partner collaboration in order to achieve successful results. The full list of recommendations is provided in **Chapter 8** of this strategy.

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Chapter 1

Introduction

1.1 The Lake Simcoe watershed

The Lake Simcoe watershed is located in south-central Ontario, approximately 60 km north of Toronto and 30 km southeast of Georgian Bay. The watershed is approximately 3,400 km^2 in size and includes the Cities of Barrie and Orillia, the Towns of Newmarket, Aurora, Bradford West Gwillimbury, East Gwillimbury, Uxbridge, Georgina, and others, as well as the lands of the Chippewas of Georgina Island First Nation (**Figure 1-1**).

The area draining into Lake Simcoe supports 8,620 km of watercourses (**Figure 1-1**). Six major tributaries account for the majority of the drainage into Lake Simcoe; five of which – the West Holland River, East Holland River, Black River, Pefferlaw Brook, and the Beaver River – originate in the Oak Ridges Moraine and flow north toward the lake. A sixth major tributary, the Talbot River, flows from the northeast, and forms part of the Trent-Severn Waterway, connecting Lake Ontario to Georgian Bay.

As it is located on the northern edge of the Greater Toronto Area, the Lake Simcoe watershed is experiencing rapid population growth. The population has increased in the watershed by approximately 50% since the 1980s and is currently slightly more than 400,000 people. The provincial growth plan is projecting an additional 150,000 people in the watershed by 2031 (MMAH, 2019). Since 2002, urban area in the watershed has increased from 7% to 8% of the total land base (LSRCA, 2018) and will continue to expand to support this growing population. In recent decades, this increase in urban land use has had major impacts on watershed function and has strongly influenced the direction taken by LSRCA programs and services. In the future, the combined effects of climate change and land use change will make watershed management increasingly complicated.

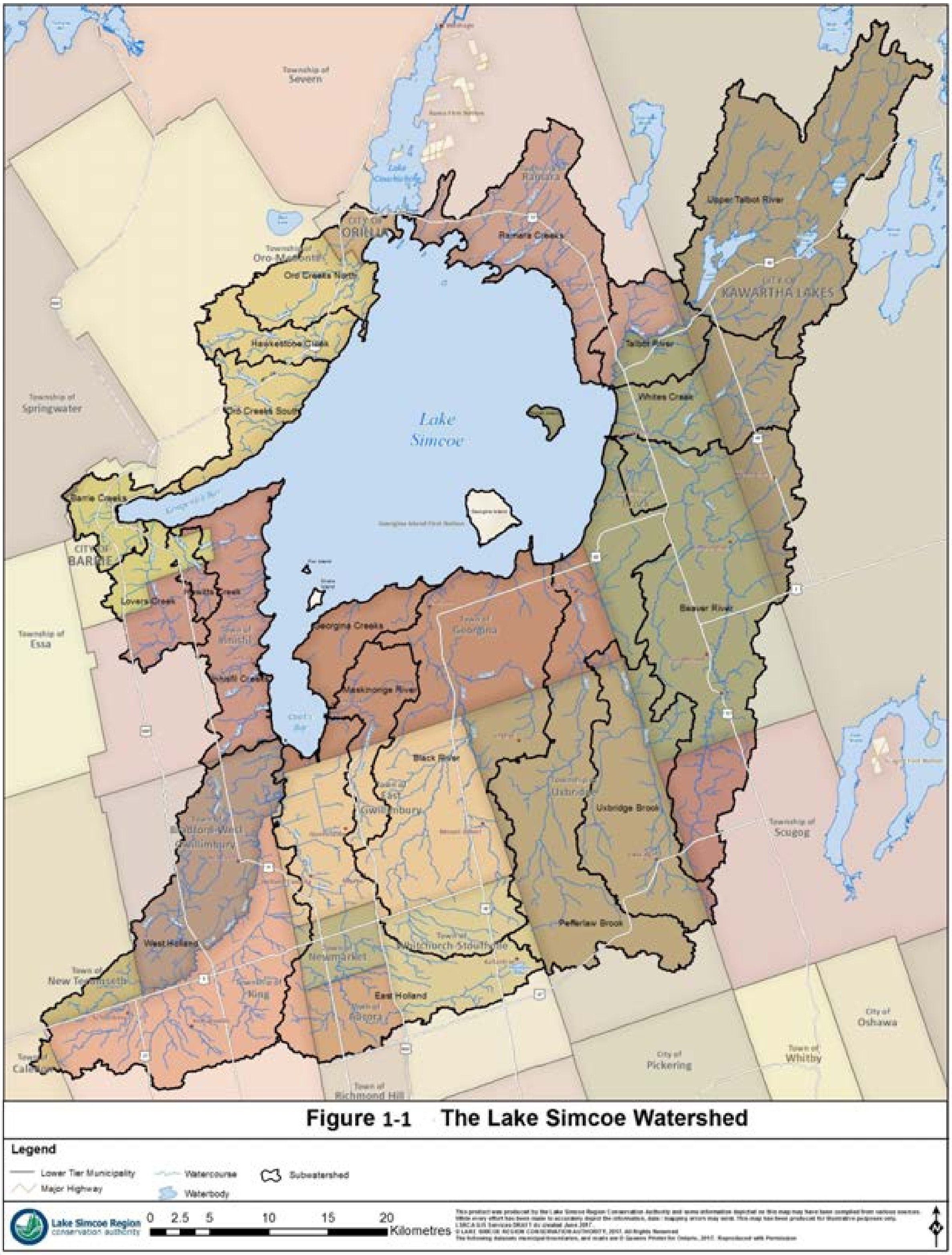


Figure 1-1 The Lake Simcoe Watershed

The remainder of the watershed supports a mix of farmland (including the Holland Marsh) and natural areas including woodlands, wetlands, and small scattered areas of native grassland (both tallgrass prairie and alvar) (**Figure 1-2**).

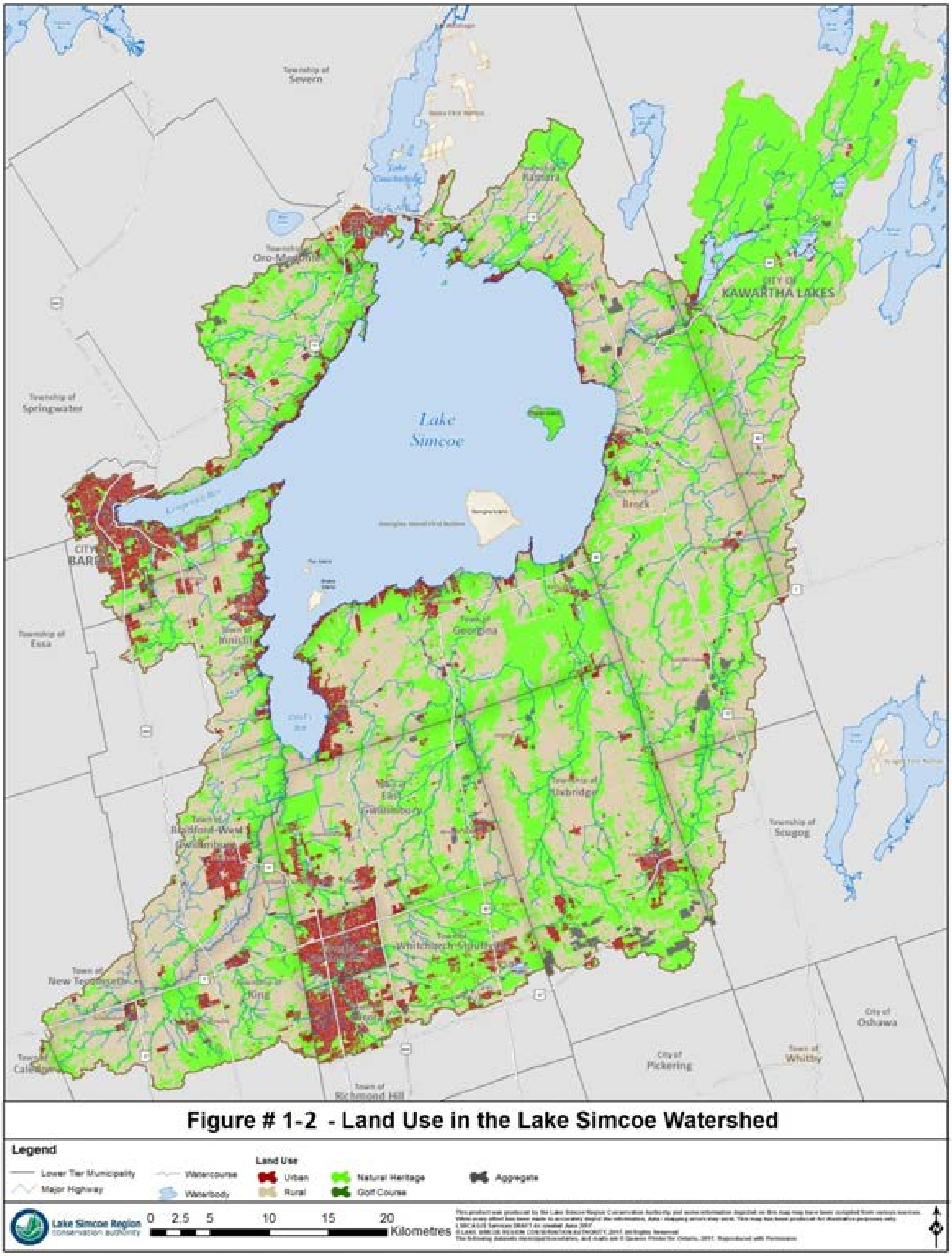


Figure 1-2 Land Use in the Lake Simcoe Watershed

1.2 Climate change adaptation

Climate change affects all aspects of the Lake Simcoe watershed, from natural areas and wildlife, to farming, urban areas, and the lake itself. In fact, there is clear evidence that climate change is underway, and is already affecting watershed function, including stream flow, phosphorus loading, and the period of ice cover on Lake Simcoe (LSRCA, 2013).

Of course, the impacts of a changing climate are not limited to the Lake Simcoe watershed. Climate change is one of the defining global environmental issues of the current age. The scientific community agrees that it is caused by increasing greenhouse gas emissions into the atmosphere which results in shifting weather patterns that threaten people and ecosystems (IPCC, 2014). Even in small concentrations, some gases (e.g. carbon dioxide, methane and nitrous oxide) act as a barrier to keep some of the sun's warmth from reflecting into space.

These gases occur naturally and are essential for the survival of humans and many other organisms by maintaining the earth's temperature within a habitable range. However, industrialization, deforestation, and large-scale agriculture have increased the concentration of greenhouse gases in the atmosphere to levels not seen in three million years. The relationship between population growth and greenhouse gas emissions is complex but in general, the concentration of greenhouse gases in the atmosphere has grown as the global population increased since the Industrial Revolution. The Intergovernmental Panel on Climate Change is categorical in its conclusion that climate change is real and that human activities are the primary cause (IPCC, 2014). Therefore, action must be taken to reduce the negative impacts of climate change.

Recognizing the increasing importance of climate change as a driver for watershed health and quality of life in the Lake Simcoe watershed, the Lake Simcoe Region Conservation Authority's Strategic Plan (LSRCA, 2016) identifies a number of strategic initiatives intended to ensure that the Authority's programs and services address this emerging crisis. This Climate Change Adaptation Strategy is one part of that approach, and is intended to identify particular aspects of watershed function which may be at significant risk due to climate change and to recommend actions by LSRCA and its partners to retain and promote resiliency within the watershed.

1.3 Developing a climate change adaptation strategy

This strategy was developed using the state-pressure-response framework, wherein an assessment was made of the current state of watershed health, the additional pressures expected due to climate change, and potential responses by LSRCA and its local partners.

An initial review of the peer-reviewed literature, government reports, LSRCA monitoring data, and dialogue with subject matter experts identified a suite of aspects of watershed function which may be at risk due to climate change (**Table 1-1**). The current **state** of each of these aspects of watershed function was described using monitoring data from Lake Simcoe or its watershed, when available from LSRCA, MECP, or MNRF. Monitoring data was not available to describe the current state of some aspects of watershed function; in these cases, the current state remains undescribed.

Table 1-1 The potential impacts of climate change on the Lake Simcoe watershed were assessed with respect to these select aspects of watershed function.

Tributary water quality	Water quantity	Tributary ecosystems	The lake ecosystem	Terrestrial natural heritage
Phosphorus loading Phosphorus concentration Nitrogen concentration Chloride concentration Total suspended solids concentration Dissolved organic carbon concentration Pesticides Stormwater management ponds	Groundwater recharge Groundwater levels, flow and availability Groundwater discharge Streamflow and flooding Stormwater management	Fish habitat availability Fish reproduction Fish overwintering survival Water quality impacts on fisheries Interspecific competition Invasive species Benthic invertebrate community composition	Water levels Water temperature Duration and timing of stratification Ice duration and thickness Phosphorus loading Phosphorus concentration Chloride concentration Dissolved oxygen concentration Light penetration Aquatic communities and biodiversity Harmful algal blooms Pathogens Invasive species	Ecosystem services Wetland cover Wetland hydrology and water quality Wetland community composition Woodland cover and community composition Extreme weather events Species range shifts Invasive species Pests and disease Breeding phenology Migration penology

The relationship between weather or climate and these important aspects of watershed function was described based on published studies, models, or relationships observed in existing monitoring data. In some cases, this relationship can be quantified (and graphed), in many cases however, the description must remain semi-quantitative in the absence of much more detailed modelling.

The potential further **pressure** which climate change can exert on watershed function was determined based on how tightly coupled the climate variable-watershed function relationship described above is, and the intensity and certainty associated with projected changes in each of the climate variables. This assessment was done in a semi-quantitative format, following a standard risk assessment matrix (see text box below). A semi-quantitative approach is appropriate for a study such as this one, which is intended to identify how climate change will affect complex natural systems, and to provide general guidance for program response (Charron, 2016). More detailed analysis may be needed in the future to develop technical, sector-specific policies or guidelines.

Appropriate **responses** by LSRCA to increase or maintain resilience in those aspects of watershed function identified as being at High or Very High risk were identified in dialogue and workshop with subject matter experts within LSRCA and its local partners. This dialogue was supported by a jurisdiction scan of activities undertaken by other conservation authorities, and organizations with similar mandates, and a review of LSRCA's current programs that may have either direct or indirect contribution to climate change adaptation.

The results of this analysis are presented in chapters three to seven, which cover the major themes in watershed management.

Conducting a vulnerability assessment

Predicting how climate change could affect a complex natural system such as the Lake Simcoe watershed, and identifying aspects of watershed function which may require particular attention in the future, requires the use of vulnerability assessments (Charron, 2016).

According to the IPCC (2007), vulnerability is an integrated measure of the exposure and sensitivity to climate change, and certainty that the projected changes will occur. Numerous (though similar) approaches to conducting vulnerability assessments exist. The Canadian Council of Ministers of the Environment (2015) developed one such for climate adaptation at the watershed-scale, which was used in developing this strategy. The CCME approach included three steps:

Step 1. Determine the sensitivity and exposure of each aspect of watershed function to climate change

For each aspect of watershed function under consideration, an assessment is conducted of how 'exposed' it is to climate changes, and how 'sensitive' it is to projected changes. Sensitivity relates to the strength of relationship between watershed function, and weather variables, as described below (**Table 1-2**).

Table 1-2 'Sensitivity' of watershed function to a changing climate

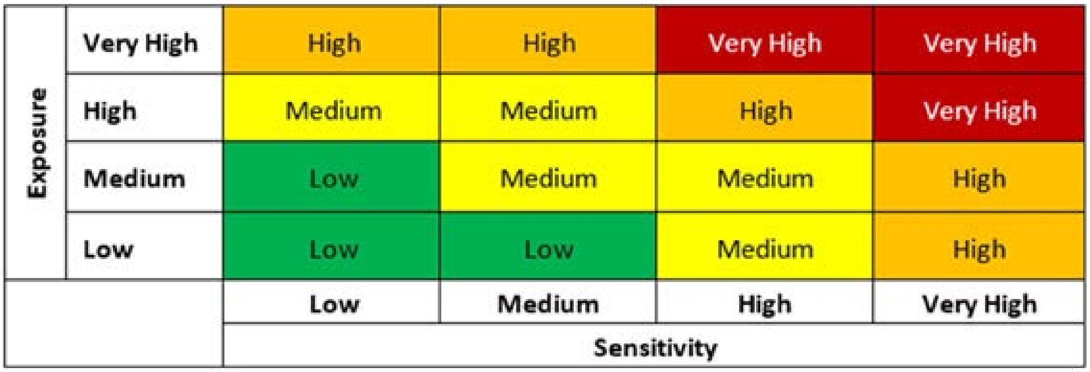
Very high	Weather or climate is a central driver to this aspect of watershed function
High	Weather or climate play a significant role in this aspect of watershed function
Medium	Weather or climate play a moderate role in this aspect of watershed function
Low	In its current state, this aspect of watershed function shows very limited evidence of a relationship to climate

Exposure relates to the extent of the watershed function under consideration. Or the extent of compounding stresses (**Table 1-3**). For example, potential changes to phosphorus loading from watercourses across the watershed resulting from more extreme rainfall would be defined as having a "high" extent, as all precipitation eventually enters a watercourse. The potential changes associated with nutrient loading in tile drains would have a "medium" extent however, as tile drains occur in only localized areas in the watershed.

Table 1-3 'Exposure' of watershed function to a changing climate

Very high	This aspect of watershed function is widespread, and changes in the particular climate variable is expected to affect its entire extent
High	This aspect of watershed function is widespread, and changes in the particular climate variable may affect some of its extent within the watershed
Medium	Either due to the nature of the projected climate change, or the structure of the watershed, effects are expected to be localized throughout the watershed
Low	Occurrences of this aspect of watershed function, and resulting climate stresses, are very localized in nature, either due to the nature of the stress, or structure of the watershed

These rankings are then converted to an overall exposure-sensitivity ranking following the diagram in Figure 1-3.

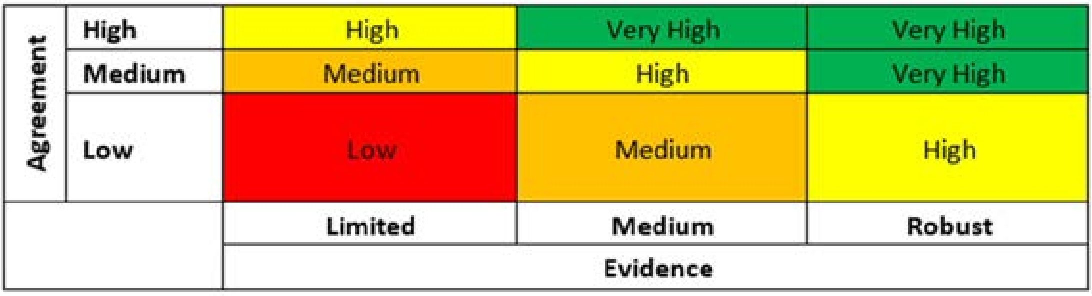


Exposure	Very High	High	High	Very High	Very High
	High	Medium	Medium	High	Very High
	Medium	Low	Medium	Medium	High
	Low	Low	Low	Medium	High
		Low	Medium	High	Very High
		Sensitivity			

Figure 1-3 Sensitivity and exposure of watershed function to climate change

Step 2. Determine the confidence in projections for each climate variable

For each climate variable of interest, a similar assessment is undertaken to determine the strength of evidence and level of agreement available in published studies (Figure 1-4, Table 1-4, Table 1-5). The strength of the evidence and level of agreement in the literature are not necessarily one and the same. For example, many global circulation models exist to predict changes in average annual air temperature resulting from increased atmospheric carbon (see Chapter 2 – Climate Trends and Projections). Projections from these models are generally consistent with one another, which would result in a ranking of ‘Robust’ evidence and ‘High’ agreement. Similarly, many models exist of potential changes in annual precipitation (Robust evidence), but model projections range substantially (Medium agreement). Other factors, such as projections of changes in growing season have been less studied, and thus have less robust evidence supporting projections (Limited evidence).



Agreement	High	High	Very High	Very High
	Medium	Medium	High	Very High
	Low	Low	Medium	High
		Limited	Medium	Robust
		Evidence		

Figure 1-4 Strength of evidence and level of agreement in climate change projections

Table 1-4 Strength of evidence for projected climate change

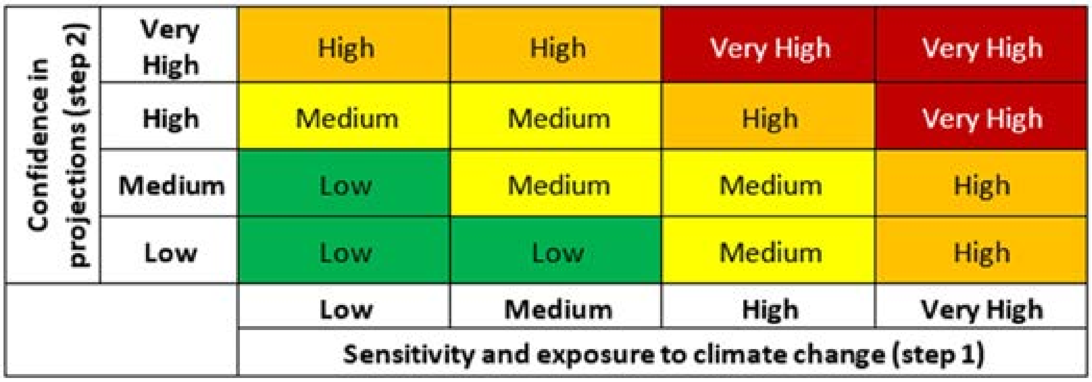
Robust	Multiple GCMs or other models exist, developed by recognized climate authorities to predict change in this climate variable
Medium	A few quantitative models exist, including either mechanistic or statistical models
Low	None or very few quantitative models available; non-peer reviewed LSRCA data or conceptual models may be available

Table 1-5 Level of agreement in climate projections

High	Projections give substantially similar results; results from all models either project positive change or negative change in the climate variable of interest
Medium	Model predictions range substantially, including some which project a positive change in the climate variable, and some which predict a negative change
Low	Potential changes in the climate variable of interest continues to be debated in the literature

Step 3. Determine overall vulnerability

Finally, for each watershed function variable – climate variable relationship, an overall vulnerability rank is determined (Figure 1-5).



Confidence in projections (step 2)	Very High	High	High	Very High	Very High
	High	Medium	Medium	High	Very High
	Medium	Low	Medium	Medium	High
	Low	Low	Low	Medium	High
		Low	Medium	High	Very High
		Sensitivity and exposure to climate change (step 1)			

Figure 1-5 Vulnerability of watershed function to climate change

Recommendations for action were developed for the aspects of watershed function which have at least one relationship in which they had either High or Very High vulnerability.

Chapter 2

Climate Trends and Projections

2.1 Introduction

Global temperatures, and other climate variables, are influenced by several factors, including the concentration of greenhouse gases. These gases, which include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3), have been increasing exponentially since the Industrial Revolution, driven by factors such as population growth, industrialization, deforestation, and large scale agriculture (**Figure 2-1**).

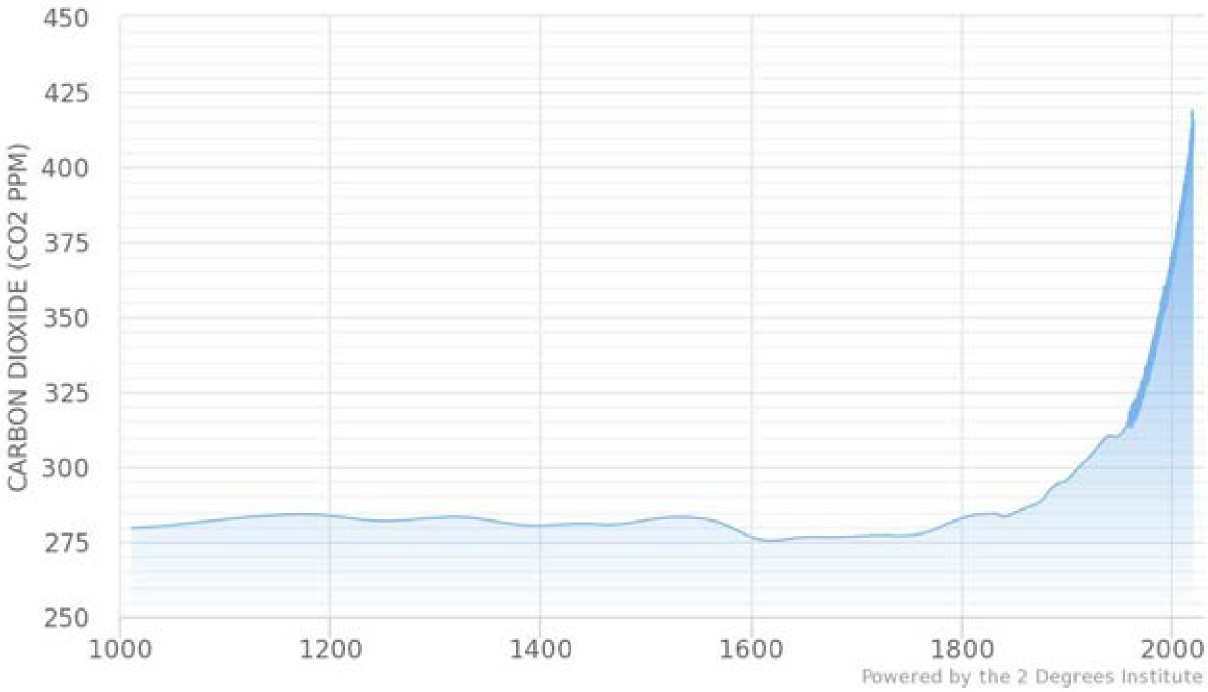


Figure 2-1 Historic global carbon dioxide levels from 1010 to 2019. Data source: the 2 Degrees Institute.

Understanding how these increases in greenhouse gas concentrations impact the Lake Simcoe watershed requires four steps: developing emissions **scenarios**, developing **general circulation models**, **downscaling** the results of those models to the watershed, and conducting a **vulnerability assessment**. The **vulnerability assessment** for each theme area can be found in **Chapters 3 to 7** of this report. This chapter describes the downscaled projections, the steps taken to develop them, and compares them to climate records from the Lake Simcoe watershed, with particular focus on a historic 30-year baseline period (1981 to 2010).

General circulation models (GCMs) are mathematical descriptions of atmospheric circulation which describe the ways in which energy, water, greenhouse gases, land use, the ocean and other factors interact with the atmosphere, how those interactions are manifested in changes in atmospheric temperature and moisture, and how those changes circulate globally. Over the years, several models have been developed independently by climate scientists and have been used internationally, nationally and regionally to predict changes to climate resulting in changes to their input variables. The generally accepted best practices are to use an ensemble of the latest generation of climate models (CMIP5) in vulnerability assessments such as these, in order to account for biases which may exist in any one model, and to explicitly address and incorporate uncertainty in the resulting projections (Charron, 2016).

One of the primary inputs to GCMs is atmospheric greenhouse gas concentration, which in of itself is projected in what the IPCC calls **scenarios**. Scenarios are intended to represent plausible future greenhouse gas emissions and concentrations, based on factors such as population growth, energy consumption, and the degree to which emissions are controlled through technology and policy. Establishing and agreeing on a set of pre-defined scenarios to be used in climate modelling allows greater coordination internationally in research, modelling, and policy development actions. However, as with GCMs, typically a suite of scenarios is used in vulnerability assessments, in order to manage uncertainty, and to explicitly examine the potential implications of changes in policy and population trajectories.

There have been several iterations of scenarios developed, the most current of which are called Representative Concentration Pathway (RCP) scenarios (IPCC, 2014). Four RCP scenarios have been defined by the scientific community: the high carbon scenario (RCP8.5), which is a business-as-usual scenario, assuming that emissions continue unabated; two mid-carbon scenarios (RCP4.5 and RCP6), which assume that a range of GHG reduction technologies and policies are adopted by the global community; and a low-carbon scenario (RCP2.6), which represents much more aggressive adoption of emission reduction technologies, supported by significant socioeconomic changes (**Figure 2-2**). Based on emissions in recent decades, this adaptation strategy relies predominantly on moderate (RCP4.5) and high-carbon (RCP8.5) scenarios.

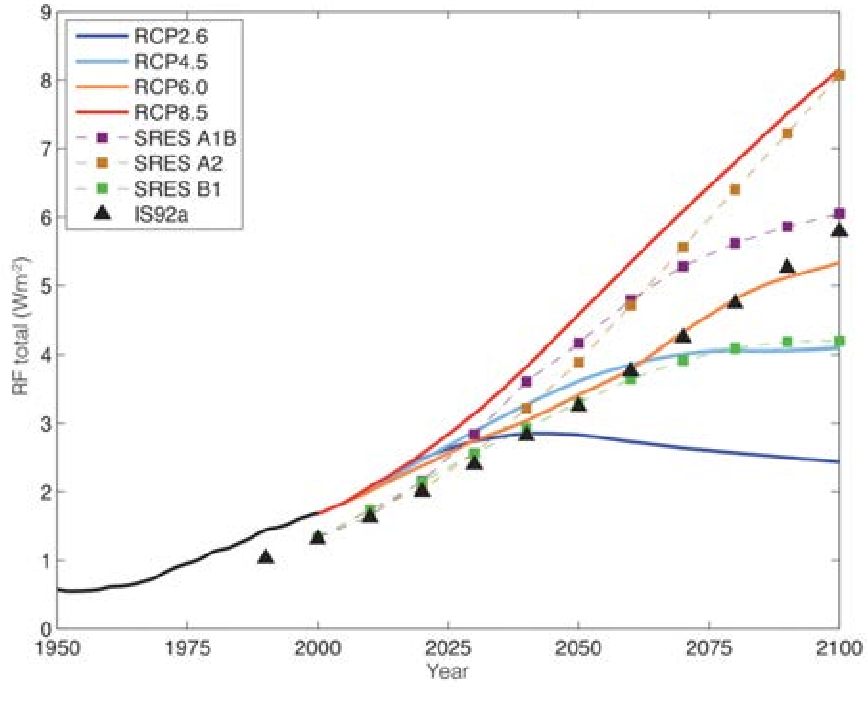


Figure 2-2 Historical global greenhouse gas emissions and projected scenarios, representative concentration pathways (RCP) and special report on emissions scenario (SRES), expressed as the amount of change in solar energy over time or radiative forcing (RF)

This report also makes reference to the Special Report on Emissions Scenarios (SRES) A2 and B1 emissions trajectories (IPCC, 2000) within the vulnerability assessment chapters, although these are not reported as stand-alone projections. The SRES represent an earlier generation of scenarios, which were slightly more optimistic than the current RCP scenarios. Generally, the A2 scenario is midway between RCP8.5 and RCP6, although the B1 scenario assumption is similar to the RCP4.5 (Figure 2-2).

2.2 Climate modelling

The output resulting from GCMs is applied locally by **downscaling** to local conditions. This study adopted a statistical downscaling approach, called the delta approach, which adds the projected difference (or delta) in climate variables from a GCM to climate data from a historic period of record from one (or more) climate stations. This method is computationally simple and efficient to downscale from multiple GCMs to multiple stations with ease. Dynamic downscaling is a more computationally intensive approach which takes the output of GCMs and applies it to more detailed regional models. While dynamic downscaling allows greater latitude for examining potential interactions between changing climate variables, that level of detail was not required in this adaptation strategy.

Most of the downscaled climate projections for the Lake Simcoe watershed were provided by the Climate Change Hazards Information Portal (Risk Science International, 2016), based on a suite of 37 General Circulation Models (Table 2-1), statistically downscaled to the Shanty Bay weather station. The Shanty Bay weather station was selected as the basis for downscaling as it represents the longest uninterrupted climate data series in the Lake Simcoe watershed. Additional projections were obtained from the Climate Atlas of Canada (Prairie Climate Centre, 2019). These projections give an indication of expected changes in a range of climate variables which may impact watershed function, as described in the following sections.

Table 2-1 General circulation models used in developing Lake Simcoe Climate Adaptation Strategy

Model	Organization
ACCESS1-0	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
ACCESS1-3	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration
BCC-CSM1-1-M	Beijing Climate Center, China Meteorological Administration
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University
CanESM2	Canadian Centre for Climate Modelling and Analysis
CCSM4	National Center for Atmospheric Research
CESM1-BGC	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CESM1-CAM5	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CMCC-CESM	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
FGOALS-s2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
FIO-ESM	The First Institute of Oceanography, SOA, China
GFDL-CM3	Geophysical Fluid Dynamics Laboratory

Model	Organization
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA Goddard Institute for Space Studies
GISS-E2-H-CC	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA Goddard Institute for Space Studies
HadGEM2-AO	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
HadGEM2-CC	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
HadGEM2-ES	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
INMCM4	Institute for Numerical Mathematics
IPSL-CM5A-LR	Institut Pierre-Simon Laplace
IPSL-CM5A-MR	Institut Pierre-Simon Laplace
IPSL-CM5B-LR	Institut Pierre-Simon Laplace
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)
MPI-ESM-MR	Max Planck Institute for Meteorology (MPI-M)
MRI-CGCM3	Meteorological Research Institute
NorESM1-M	Norwegian Climate Centre

As can be seen, specific climate change projections depend on a series of decisions and assumptions made in modelling, scenario development, and downscaling. As a result, opinions vary somewhat in precise predictions in local changes in air temperature, precipitation, and other climate factors. To see an example of how the approach, assumptions, and projections used in this study relate to other data sources available in Ontario, see **Appendix 1**.

2.3 Local climate trends and projections

2.3.1 Air temperature

Air temperature is a climate variable with a long period of record in the Lake Simcoe watershed, and a relatively large number of locations where it has been monitored. There are, for example, 107 climate stations within a 50 km radius of the centre of Lake Simcoe, which were averaged to obtain historical temperature records for the watershed.

Historical trends

Between 1900 and 1980, air temperature in the watershed has remained relatively stable. However since climate impacts began to be observed around 1980, the decadal average temperature has steadily increased by 0.02°C per decade, increasing overall by approximately 0.9°C by 2016 (**Figure 2-3**). In fact, 11 out of the 13 warmest years on record have occurred since 1980 (**Figure 2-3**).

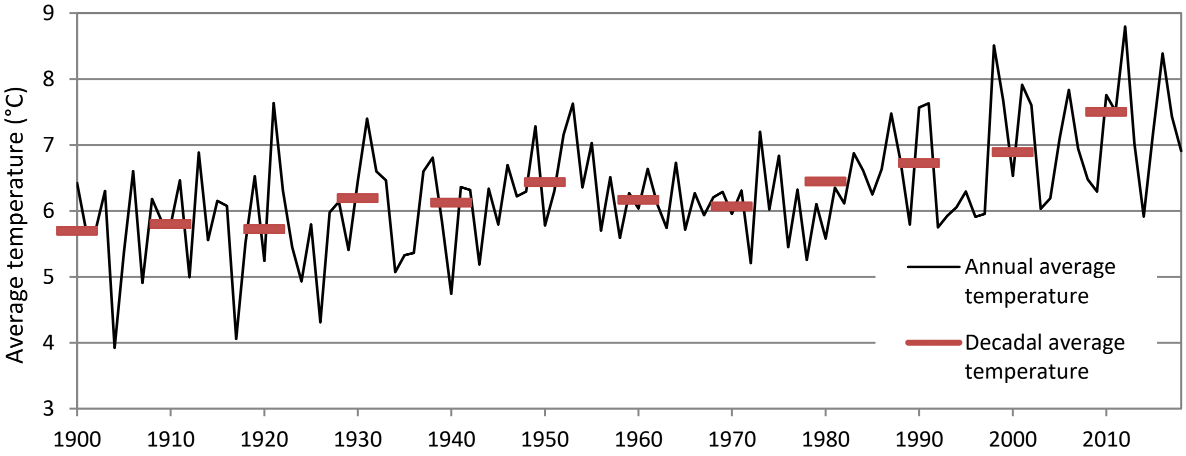


Figure 2-3 Annual average temperatures (black line) observed across 107 meteorological stations in the watershed. The red lines show the decadal average. Data source: Environment Canada daily timeseries averaged across 107 climate stations.

Warming has been most pronounced in the winter (Dec, Jan, and Feb), where the decadal average has increased by 3.6°C since the 1900s. It has also increased in the other seasons, although not as drastically. In the spring (Mar, Apr, and May) decadal average air temperature has increased by 1.5°C; in summer (Jun, Jul, and Aug) it has increased by 0.8°C, and in autumn (Sep, Oct, and Nov) by 1.2°C (**Figure 2-4**).

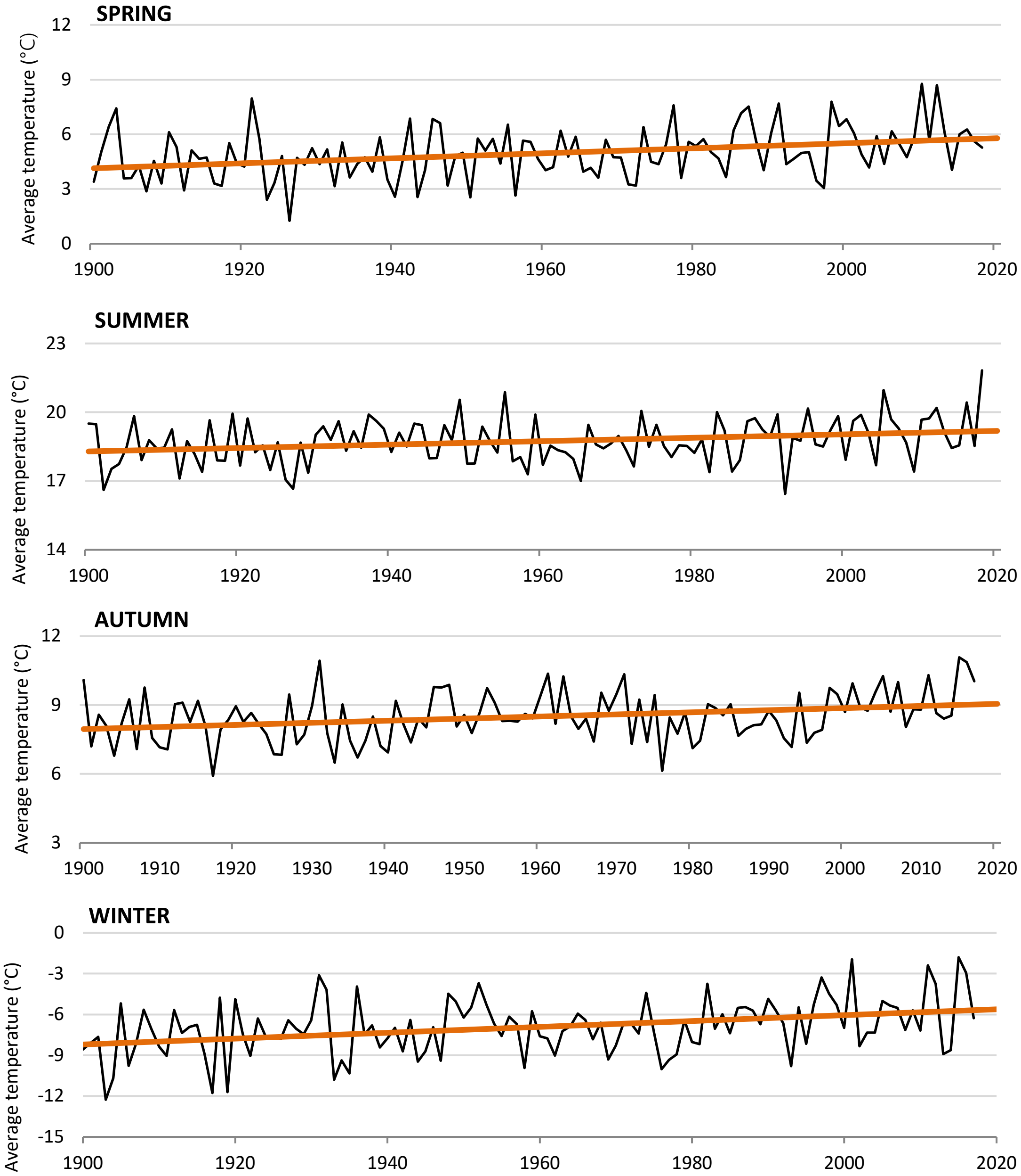


Figure 2-4 The observed temperatures averaged across 107 climate stations in the watershed presented seasonally between 1900 and 2017. The orange lines show the rate of warming in spring (0.013°C per year), summer (0.006°C per year), autumn (0.009°C per year), and winter (0.021°C per year). Trends are significant at $p<0.05$. Data source: Environment Canada daily timeseries averaged across 107 climate stations.

Projected trends

By the end of the century, the average annual temperature is projected to increase by 3°C and 5.5°C in the RCP4.5 and RCP8.5 scenarios, respectively. In both cases, increases are projected to be more pronounced in winter than in other seasons (**Figure 2-5**). These temperature increases may, in fact, outstrip increases elsewhere. The northern hemisphere is already warming faster than the southern hemisphere, with the rate of warming accelerating toward the poles (Vaughan et al., 2013), suggesting that the northern hemisphere may increase more than the global average.

Unfortunately, this projected increase is above the 2°C agreed to in the Paris Climate Agreement. It may however be possible (under the RCP4.5 scenario) for the global increase to remain below 2°C, but for the Lake Simcoe watershed to increase by 3°C.

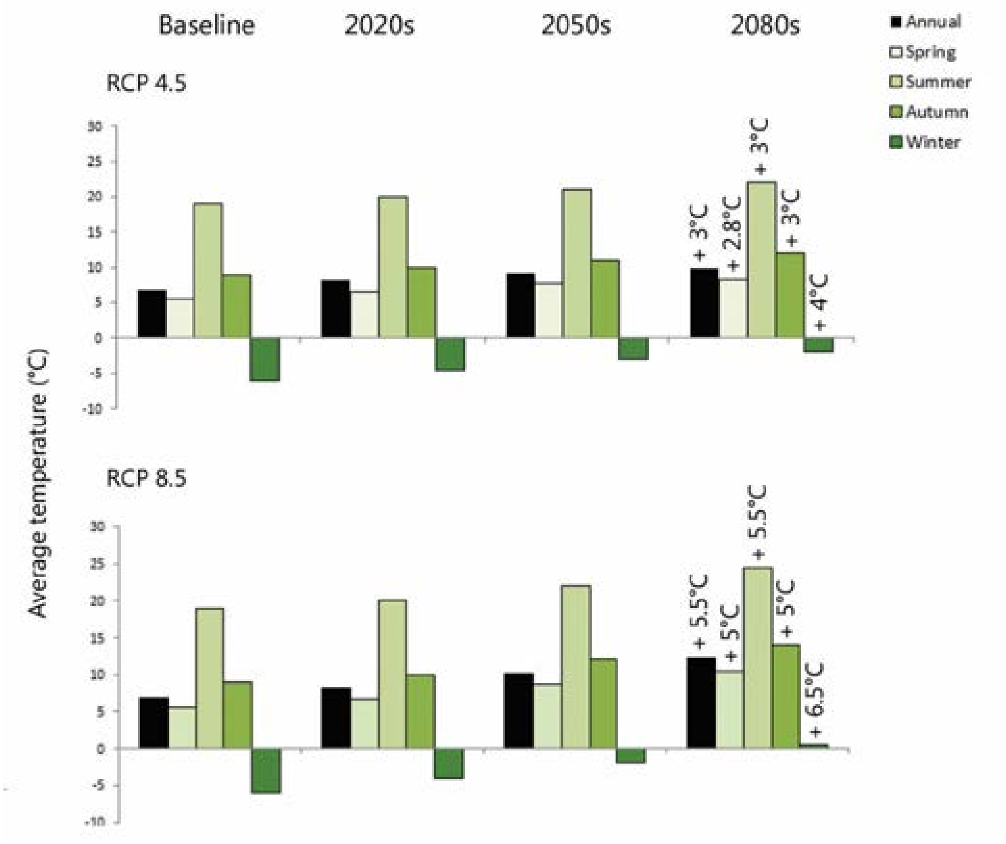


Figure 2-5 Mean annual and seasonal air temperatures projections in the RCP4.5 and RCP8.5 scenarios compared to the 1981 to 2010 baseline. Values in the 2080s show the departure, or increase (°C), from the baseline average for both climate scenarios. Data source: Environment Canada (baseline) and Climate Change Hazards Information Portal (projections).

As is projected with average annual temperature, it is expected that average minimum (T_{min}) and average maximum temperatures (T_{max}) will also increase, both annually and seasonally. Again, as with annual average, those increases are expected to be greatest in the winter (**Figure 2-6**). Additionally, the mean number of frost days (days in which T_{min} is lower than 0°C) will decrease by up to 48.6 days by 2080 (RCP8.5; (Prairie Climate Centre, 2019).

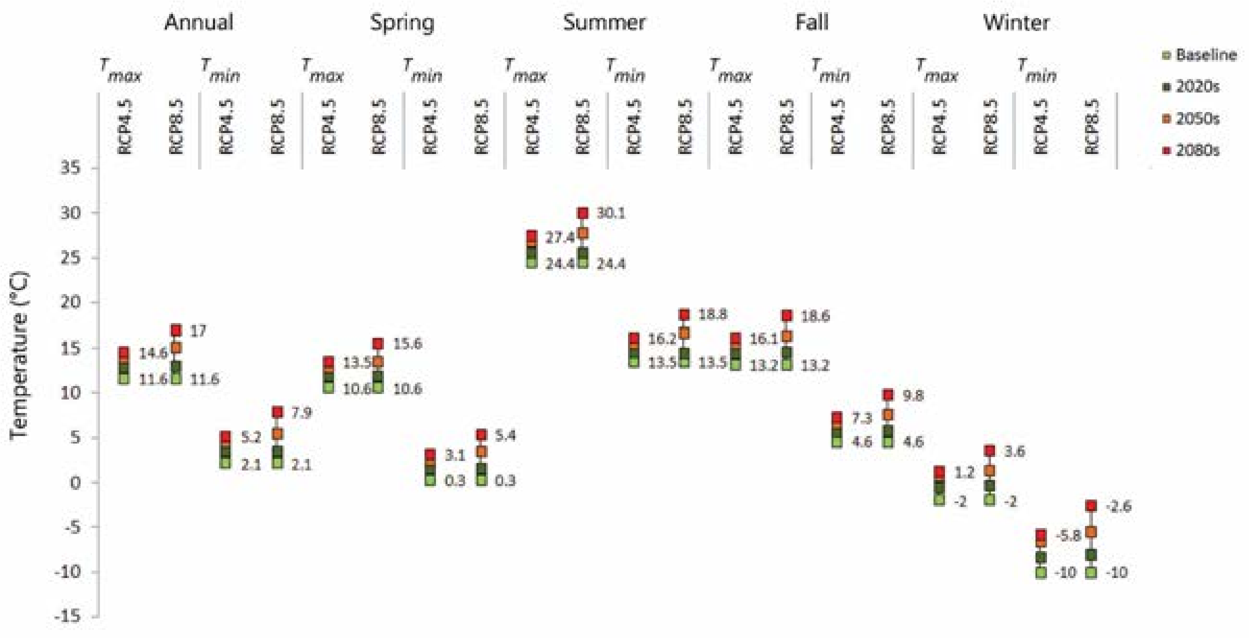


Figure 2-6 The seasonal change in mean minimum (Tmin) and mean maximum (Tmax) temperatures compared to the 1981 to 2010 baseline in the RCP4.5 and RCP8.5 scenarios. Data source: Environment Canada (baseline) and Climate Change Hazards Information Portal (projection).

Extreme temperatures

Changes in extreme high temperatures are of particular interest from a human health standpoint. Under the RCP8.5 scenario, average summer maximum temperatures are projected to increase by 5.7°C to an average of 30.1°C by the end of the century. This is due, in part, to a projected increase in the number days with temperature above 30°C from the current average of 6.3 per year to an average of 47.6 per year in the 2080s (**Figure 2-7**). The number of days with temperature above 35°C is also projected to increase from the current average of one per year to an average of 10.3 per year in the 2080s. Higher maximum temperatures and more frequent hot and very hot days imply that heat waves are likely to become more common.

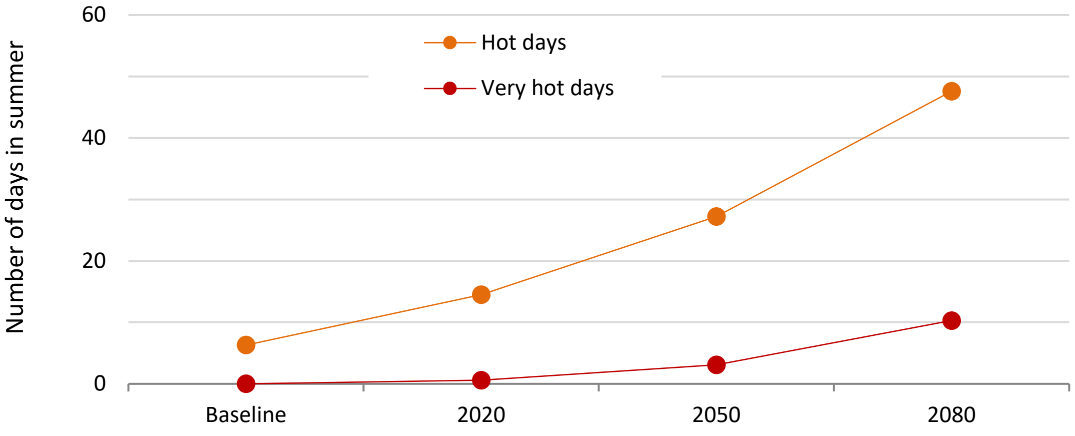


Figure 2-7 The average annual number of hot (> 30°) and very hot (> 35°) days in the summer (June, July and August) at Shanty Bay climate station based on the RCP8.5 climate scenario. Data source: Environment Canada (baseline) and Climate Change Hazards Information Portal (projection).

Minimum temperatures are also critically important for watershed function and LSRCA operations. Under the RCP8.5 scenario, the minimum temperature in winter is projected to increase by 7.4°C to an average of -2.6°C by the end of the century. This end-of-century winter low resembles the current winter high of -2°C, suggesting that winters are becoming milder and may remain above freezing for longer throughout the season.

The number of freezing and non-freezing days, and the number of days with temperatures below -10°C, can act as surrogates for the stability of snow and ice conditions during the winter. In winters during the baseline period, there has been an average of 6.3 days above freezing per year. Under the RCP8.5 scenario, the average number of days above freezing is projected to increase to an average of 36.1 per winter by the end of the century (**Figure 2-8**). The number of days with temperatures below -10°C is projected to decrease from the current average of 38.4 per year to an average of 15.8 per year by the 2080s. Together, these projections suggest that that winter temperatures are likely to remain above freezing for much of the season by the end of the century.

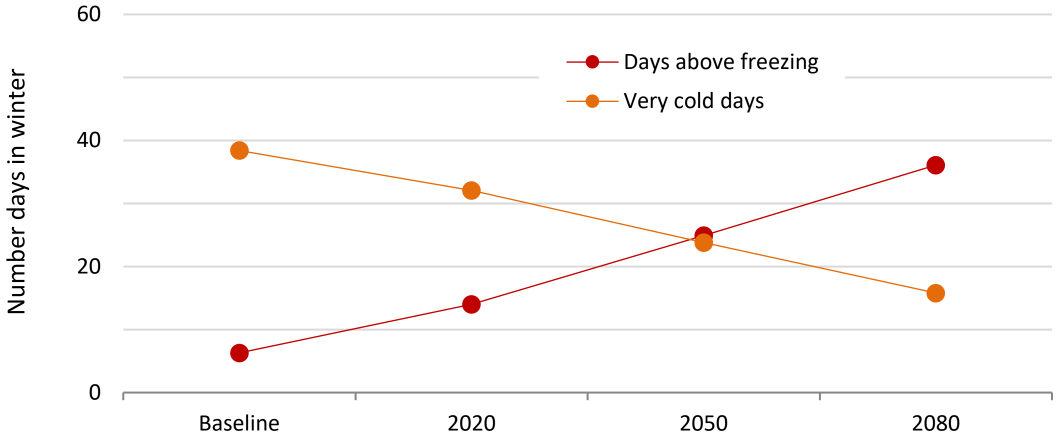


Figure 2-8 Projected annual average number of days above freezing (days with temperature greater than 0°C) and the number of very cold days (days with temperatures lower than - 10°C) at Shanty Bay climate station in the RCP8.5 scenario. Data source: Environment Canada (baseline) and Climate Change Hazards Information Portal (projection).

If this is correct, the frequency of freeze-thaw cycles may change as well. Based on projections, the mean annual number of freeze-thaw cycles will decrease from 76.2 per year in the baseline period to 56.5 and 47.5 per year by the 2050s and 2080s respectively in the RCP8.5 scenario, with decreases most pronounced in the “shoulder seasons” (**Figure 2-9**).

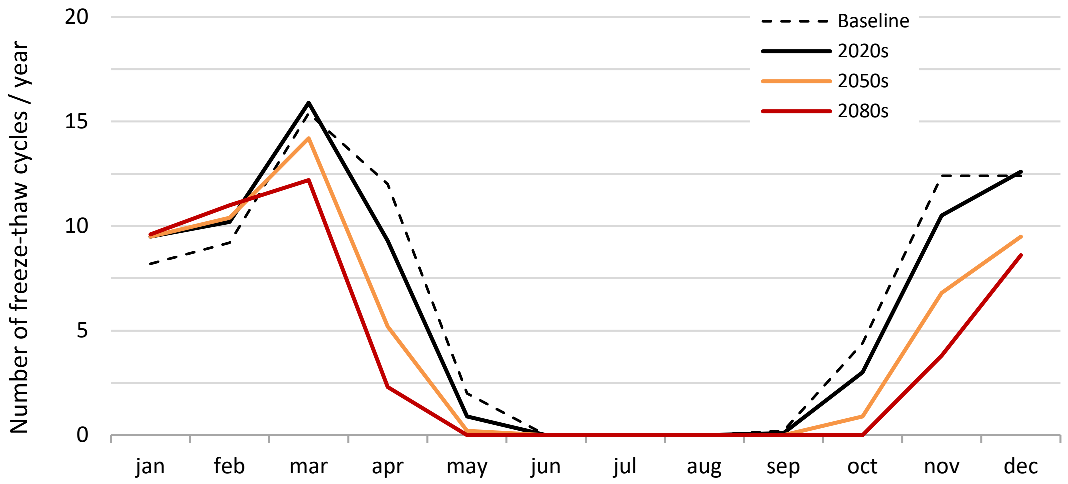


Figure 2-9 The mean monthly number of freeze-thaw cycles per year at Shanty Bay climate station, defined as the mean number of days per year where both the minimum temperature is below freezing (0°C) and the maximum temperature is above freezing (0°C) in the RCP8. 5 scenario. The baseline period is 1973-2015. Data source: Climate Change Hazards Information Portal

Key Points – Air temperature

- The annual average air temperature in the watershed increased by 0.9°C between 1900 and 2016, with the rate of warming accelerating since 1980.
- Eleven of the 13 warmest years on record have occurred since 1980.
- This warming has increased in all seasons, but has been most pronounced in winter, increasing by 3.6°C between 1900 and 2016.
- Average annual air temperature could further increase by up to 3°C in the RCP4.5 scenario and 5.5°C in the RCP8.5 scenario by the 2080s.
- Projections suggest that the coldest winter days in the 2080s will be similar to the current warmest winter days (i.e. about -2 °C).
- Under the RCP8.5 scenario, summer maximum temperatures could increase by 5.7°C to an average of 30.1°C by the end of the century. The number of days with temperatures over 30° could increase by over seven times, and the number of days above 35°C could increase by an order of magnitude
- In winter, the number of days above freezing could increase by over five times and the number of very cold days (i.e. below -10°C) could decrease by more than half by the 2080s (RCP8.5).
- The number of freeze-thaw cycles is expected to increase in the winter, but decrease in the spring and fall by the end of the century, as temperatures warm.

2.3.2 Growing season

Both agricultural and natural systems in the Lake Simcoe watershed could be impacted by a change in the length of the growing season. The length of the growing season can be defined as the period from the last day of frost in the spring to the first day of frost in the fall. **Figure 2-10** provides a summary of the growing season duration and mean temperature at Shanty Bay climate station.

The duration of the growing season remained relatively similar between the early 20th century (1900 to 1930) and the current baseline (1981 to 2010), with only a modest increase in air temperature throughout the growing season. According to the Climate Atlas, the duration of the growing season is projected to increase by approximately 45 days, from 148.1 in the baseline (1976-2005) period to 193.3 by 2080 (RCP8.5). More substantial warming during the growing season (approximately 5°C) is also expected by the end of the century, resembling the mean increase in annual warming described above. In principle, a longer growing season could indicate increased productivity and provide more opportunities for agriculture; however, as described later, other projected changes in the local climate may offset the extent to which these gains can be realized.

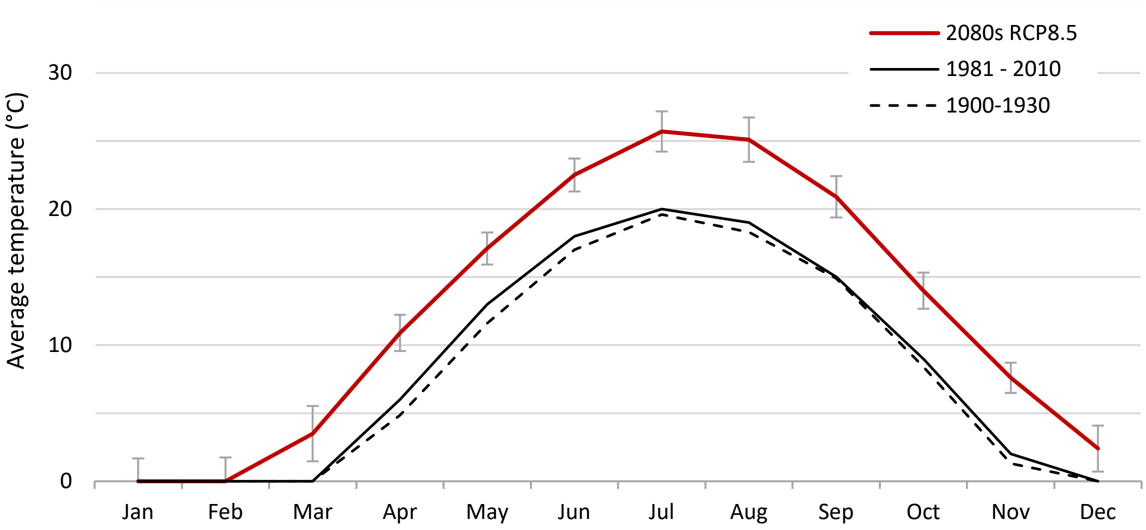


Figure 2-10 Average monthly temperatures during the growing season in three different climate periods. The 1900 to 1930 and 1981 to 2010 climate periods were calculated from Environment Canada watershed-wide averaged daily timeseries, and the 2080s climate period was calculated from downscaled climate projections in the RCP8.5 scenario at Shanty Bay climate station. Length of the growing season is that period when average temperature remains above zero.

2.3.3 Precipitation

Managing the quantity and quality of water in Lake Simcoe's tributaries is a primary function of the Lake Simcoe Region Conservation Authority. Accordingly, precipitation is a key climate variable influencing the LSRCA's work.

Climate change is expected to include changes in precipitation patterns, driven by changes in global air temperatures, and atmospheric physics. For example, warmer air temperature holds more moisture, and for every 1°C increase, the atmosphere can hold about 7% more moisture (Iribarne and Godson, 2013).

Historical trends

Data from Environment Canada's Shanty Bay weather station was used to describe historic trends and develop future projections. While precipitation tends to be more localized in nature than other climate variables, and Shanty Bay may experience more lake-effect precipitation than the watershed as a whole (EarthFx, 2010), the relatively long period of record available from this station makes it useful in assessments such as these.

Average annual precipitation at the Shanty Bay weather station was 968.7mm between 1973 and 2018, although considerable variation occurs from year to year (**Figure 2-11**). No trend over the period of record is evident in this data.

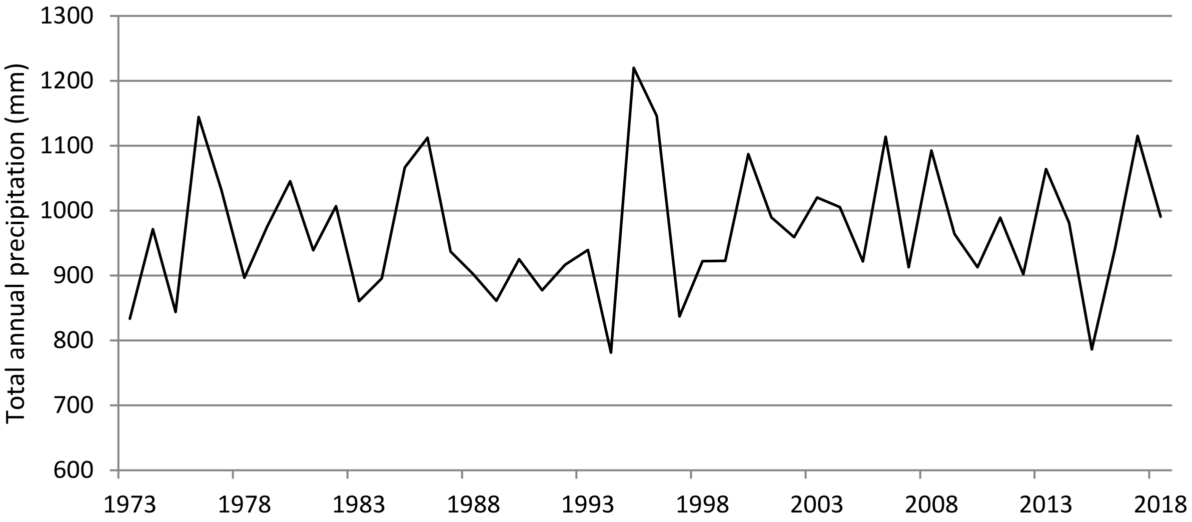


Figure 2-11 Total annual precipitation at the Shanty Bay climate station between 1973 and 2018.No significant trend observed. Data source: Environment Canada.

As with temperature, seasonal precipitation patterns are also important, to monitor as the climate changes. Seasonal precipitation normal for the baseline period show higher amounts in the autumn and less in the spring (**Figure 2-12**). Under future climate scenarios, these patterns may shift and other seasons such as winter may experience higher precipitation.

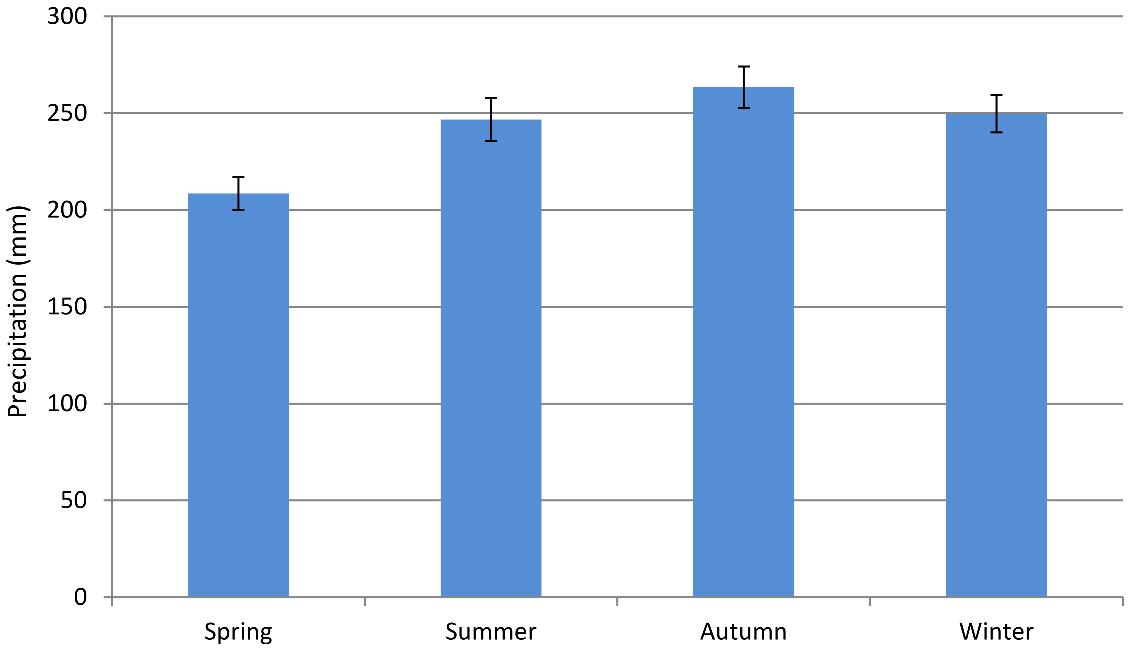


Figure 2-12 The seasonal 1981 to 2010 precipitation normals for the Shanty Bay climate station. Error bars represent the standard error of the mean. Data source: Environment Canada.

In the Lake Simcoe watershed, the average winter snow accumulation in the baseline period (1981 to 2010) was 188.5 cm. No significant decrease in snow accumulation has been detected yet, despite increases in air temperature over this period (**Figure 2-13**). This relatively stable precipitation record may be due, in part, to the influence of lake effect snow on this station located in Shanty Bay. In the northern hemisphere, the mean annual snow cover extent has significantly declined between 1967 and 2012, and that decline was strongly associated with increasing air temperature (Vaughan et al., 2013).

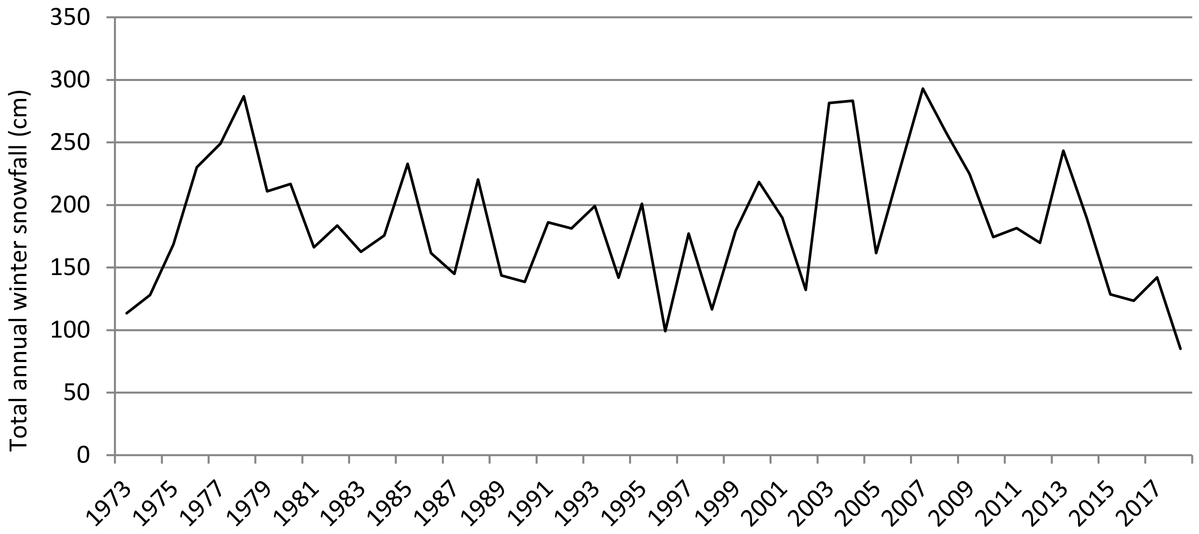


Figure 2-13 Total annual winter (Dec-Jan-Feb) snow accumulation at the Shanty Bay climate station between 1973 and 2018). Data source: Environment Canada.

Georgian Bay, and in fact Lake Simcoe itself, play a role in influencing local precipitation patterns. As cold air passes over the relatively warm surfaces of these waterbodies, moisture content in the air increases, which can be deposited as precipitation down-wind. As water bodies remain ice-free for longer periods due to increasing air temperatures (e.g. Stainsby et al., 2011), projections suggest that warmer winters will result in an increase in lake-effect precipitation in winter, and more of that precipitation occurring as rain or freezing rain (Notaro et al., 2015). This could have wide-ranging impacts, from flooding, to road management, to public safety and emergency response.

Projected trends

Total annual precipitation at the Shanty Bay climate station is projected to increase between 6.9% and 10.1% by the 2080s in the RCP4.5 and RCP8.5 scenarios, respectively (**Figure 2-14**). The larger increase in precipitation predicted in the RCP8.5 projection is associated with higher atmospheric temperatures and greater atmospheric moisture-holding capacity assumed in this scenario.

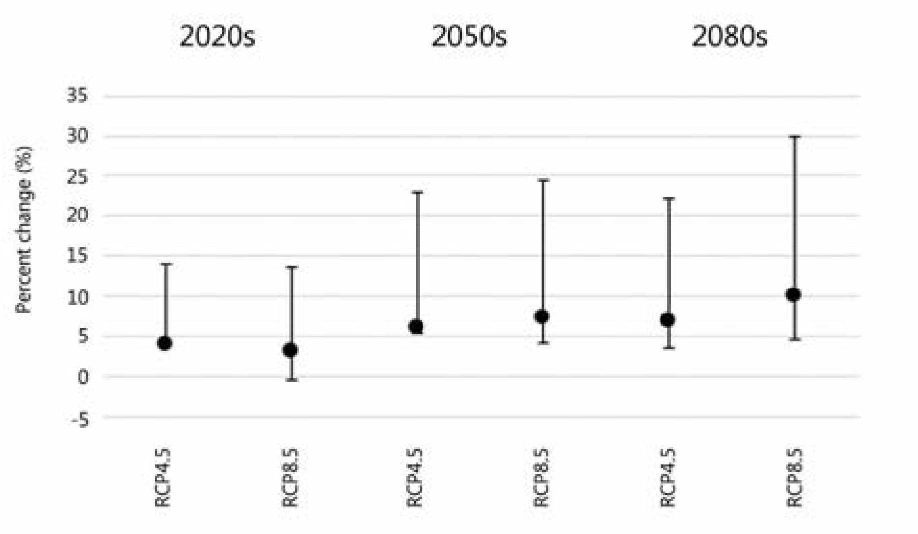


Figure 2-14 The percent change (%) in annual precipitation based on two climate projection scenarios. The dots represent the mean change and the error bars represent the mean minimum and mean maximum change in the RCP4.5 and RCP8.5 scenarios in three different time periods (2020s, 2050s and 2080s). Data source: Climate Change Hazards Information Portal.

Seasonal precipitation patterns are likely to shift as shown in **Figure 2-15**. In the RCP8.5 scenario, autumn precipitation will remain relatively similar (+ 5%) while summer will decrease slightly (- 3.6 %). The greatest change will occur in winter (+ 23%) and spring (+ 20%), although the projection variability increases substantially in the 2050s and 2080s.

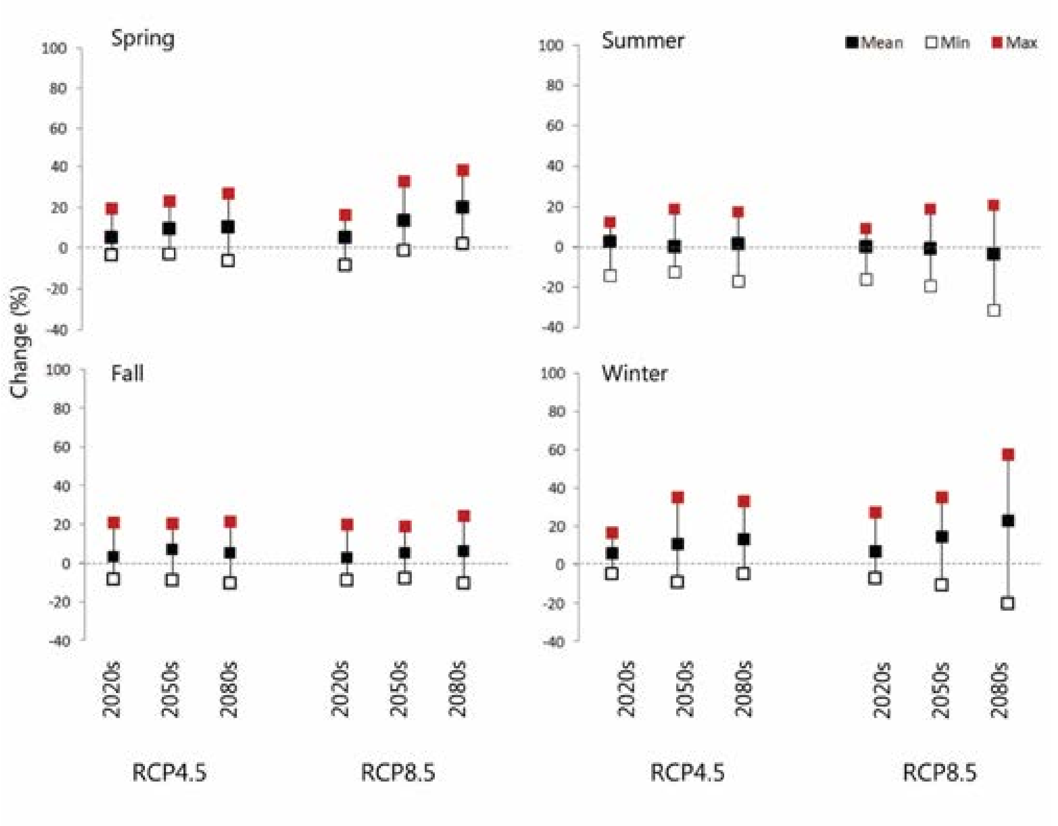


Figure 2-15 The seasonal percent change in the mean, minimum and maximum precipitation at Shanty Bay climate station for three climate periods (2020s, 2050s, 2080s) in the RCP4.5 and RCP8.5 scenarios.

A key aspect of changes to seasonal precipitation under climate change is the amount that occurs as rain or freezing rain rather than snow. In the winter, more rain and freezing rain is likely as temperatures rise above freezing and more frequently remain above freezing for longer (Groisman et al., 2016). Additionally, more rain-on-snow events may occur as winter temperatures increase and fluctuate (Jeong and Sushama, 2017), causing more surface runoff throughout the year. This can affect watershed indicators including winter contaminant loading and flooding, as discussed in **Chapters 3 and 4**.

Extreme precipitation

Of perhaps greater importance than total precipitation is extreme precipitation, or events with a very high volume of rain or snowfall. Climate change can impact the probability of extreme precipitation events, causing them to occur more frequently (Fischer and Knutti, 2015).

Extreme precipitation is driven by local meteorological events that are poorly captured by General Circulation Models. As such, it is difficult to predict the specific frequency and magnitude of these events using statistically downscaled climate projections. However, some indication of trends is available from the modelling.

In this report, extreme precipitation is defined as the number of days with a volume of precipitation greater than 20 mm falling over 24 hours. The Climate Atlas of Canada (Prairie Climate Centre, 2019) summarizes past extreme events since 1950, and projects to 2095 as shown in **Figure 2-16**). The average number of days of extreme precipitation is expected to increase from 5.5 per year in the baseline period

(1976 to 2005) to between 7.1 (RCP4.5) and 7.6 (RCP8.5) per year, with the upper range increasing to between 9.9 and 13.3 per year by 2080.

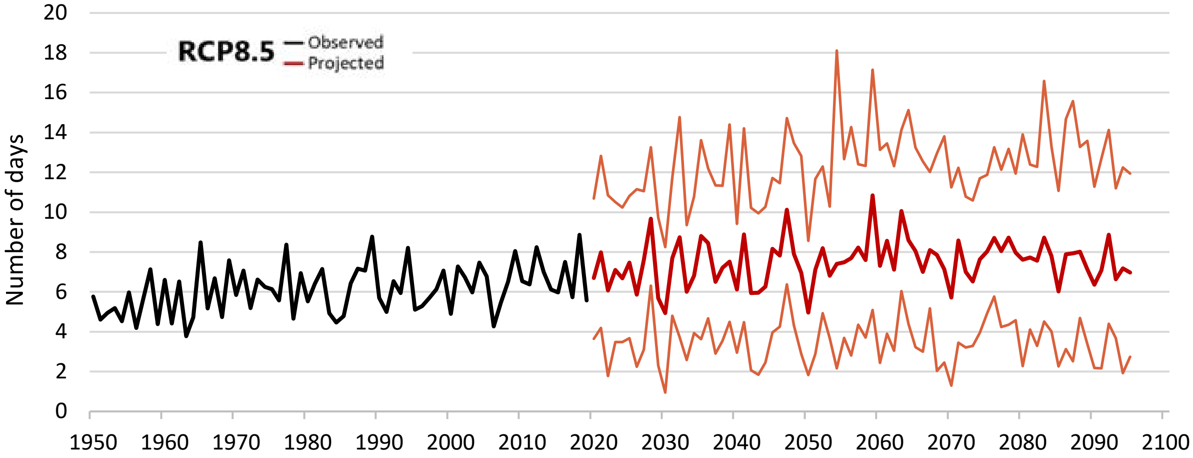


Figure 2-16 Historical and projected number of days per year with more than 20 mm precipitation in the RCP8.5 scenario. Inset table shows the range (low, mean, and high) values for both RCP4.5 and RCP8.5 in the Climate Atlas of Canada baseline period (1976 to 2005) and the end of century (2051 to2080). Data source: Climate Atlas of Canada.

One way of measuring extreme precipitation is with the "1-day max" which represents the greatest volume of precipitation received during a 24-hour period in any given year. The baseline 1-day max in Table 2-2 was obtained by averaging the observed annual 1-day max between 1976 and 2005. Similarly, the 1-day max in each of the two future climate periods (2021 to 2050 and 2051 to 2080) is the average of the projected annual values for those periods. By the end of the century, the average 1-day max could increase up to 15.3% under the RCP8.5 scenario (Table 2-2).

Table 2-2 The average 1-day maximum precipitation volume (and percent change) for the baseline (1976-2005) and two future climate periods (2020s, 2050s and 2080s) in the RCP4.5 and RCP8.5 scenarios. Data source: Climate Atlas of Canada.

		RCP4.5		**RCP8.5**	
	Baseline (1976-2005)	**2021 - 2050**	**2051 - 2080**	**2021 - 2050**	**2051 - 2080**
1-day max	39 mm	42 mm (+ 7.7%)	43 mm (+ 10.2%)	42 mm (+ 7.7%)	45 mm (+ 15.3%)

A common way of predicting storm events are intensity-duration-frequency (IDF) curves, and they are similarly useful for visualizing anticipated climate impacts on precipitation. Under the RCP8.5 scenario, the 2-year and 100-year storm events are expected to be 10-18% more intense by the end of the century (Figure 2-17). IDF curves are commonly used in designing stormwater infrastructure to be able to manage extreme storm events, and as these events intensify with climate change, the design of stormwater management will need to change in order to keep pace.

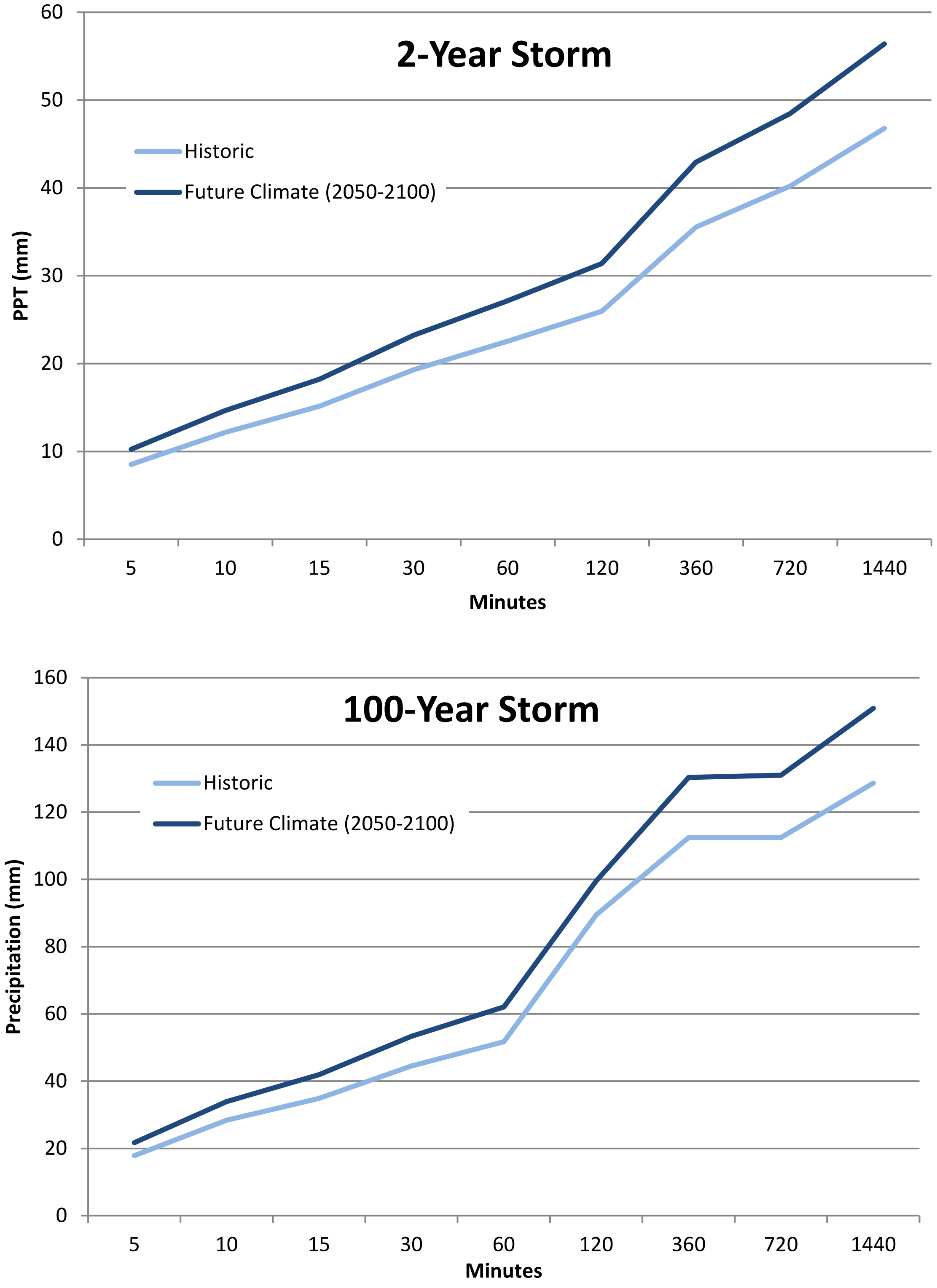


Figure 2-17 Intensity-duration-frequency (IDF) curves at the Barrie WPCC ID:6110557 Station for the historic (1979-2007) and future (2050-2100) time periods under the RCP8.5 scenario. Data Source: Western University (2018).

Researchers at the University of Regina converted IDF curves of this sort to daily precipitation predictions, using a probabilistic distribution (Wang et al., 2014; 2016). While the results of this analysis come with a high level of uncertainty, four of the five models used predict that daily rain events will become larger over time. The greatest range in model output is around the 90th percentile unfortunately (**Figure 2-18**), which is the design standard for Low Impact Development features in the Lake Simcoe watershed.

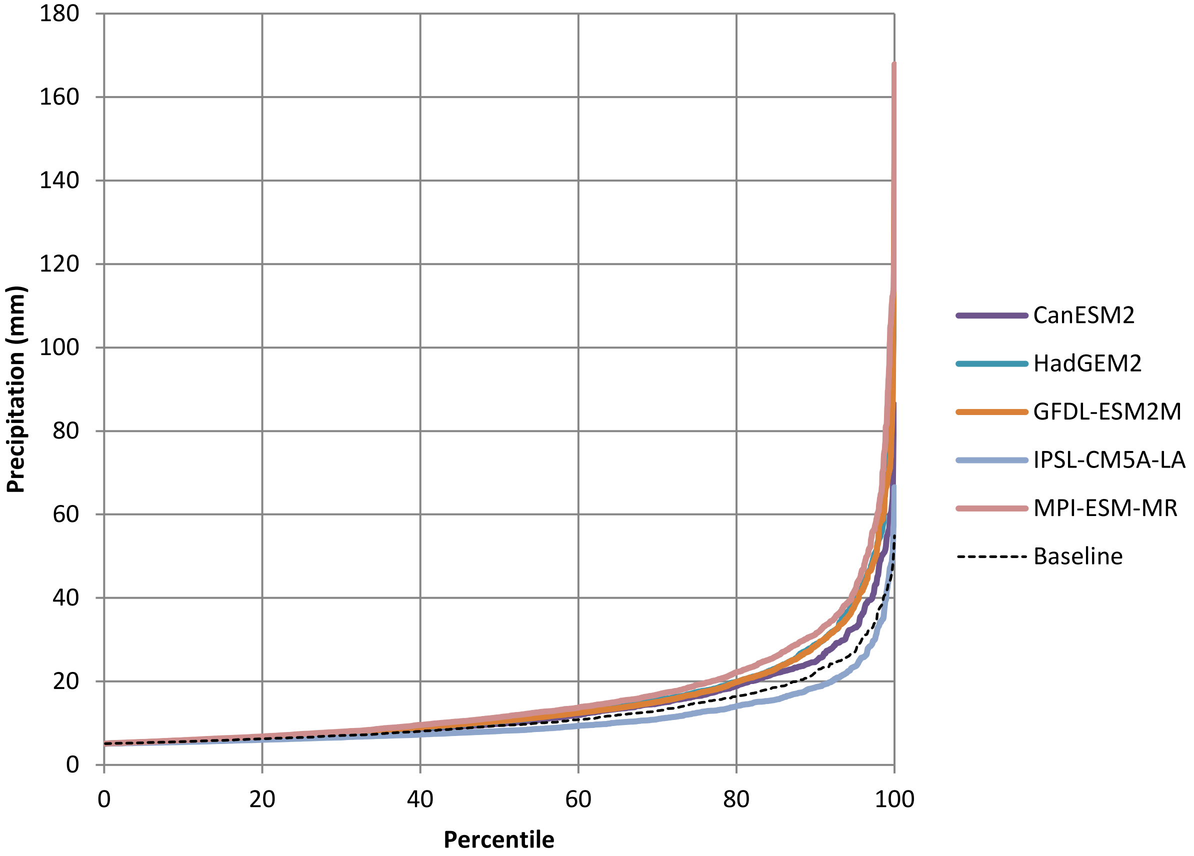


Figure 2-18 Rainfall frequency distribution in the Lake Simcoe watershed (2070-2099) as predicted by five Global Climate Models (GCMs) under the RCP8.5 scenario. Data provided by Wang and Huang (2013).

Key Points – Precipitation

- Average annual precipitation at the Shanty Bay weather station was 968.7 mm between 1973 and 2018 and has not changed significantly during this time period.
- This annual average is predicted to increase by 6.9% under the RCP4.5 scenario and by 10.1% under the RCP8.5 scenario by the end of the century.
- Historically, seasonal precipitation has ranged from a low of 208.8 mm in the spring to a high of 263.4 mm in autumn.
- Under both climate scenarios, precipitation is expected to increase in spring (+ 20%), winter (+ 23%), and autumn (+ 5%), and decrease in summer (- 3.6%).
- The average number of days with more than 20 mm of precipitation has been 5.5 per year between 1976 and 2005. By the end of the century, this is projected to increase to 7.1 under the RCP4.5 scenario or 7.6 under the RCP8.5 scenario.
- By the end of the century, the 1-day maximum precipitation could increase by 10.2% in the RCP4.5 scenario and 15.3% in the RCP8.5 scenario.
- Under the RCP8.5 scenario, the intensity of the 2-year and 100-year storm events are expected to be up to 18% more intense by the end of the century, and daily rain events will likely become larger over time.
- Projections suggest that extreme precipitation events will capture a greater percentage of total annual precipitation than they do currently, with longer periods of low or no precipitation between them.

2.3.4 Moisture deficit

When adequate surface moisture exists, increasing air temperatures results in increased evaporation. As described earlier, air temperatures in the Lake Simcoe watershed are projected to increase across all seasons, and the distribution of precipitation will shift toward the cooler months. Models also predict an increase in the likelihood of extreme temperature and precipitation events. During periods of low precipitation, particularly when air temperatures are higher, moisture deficits can occur if more soil moisture is lost to the atmosphere than is returned as precipitation. The moisture index, expressed as the difference between the mean total precipitation and the mean actual evapotranspiration, provides information about the amount of available moisture at the soil surface. A moisture deficit exists when the index is below zero, and this can be further compounded by prolonged periods of dry conditions, which can lead to drought. The climatological factors leading to drought are complex and not all factors were directly assessed in this report.

By the 2080s, under the RCP8.5 scenario, the moisture index is projected to increase from baseline conditions in the winter and early spring (Figure 2-19). As temperatures increase in the spring and summer, the moisture index is projected to decline, and larger moisture deficits are projected to occur in the summer months. The greatest moisture deficit is expected to occur in June, and is projected to increase from 27 mm in the baseline period to 34.4 mm. These projections suggest that summers will become drier as the number of hot and very hot days increases (as described earlier in this chapter) and less moisture will be available due to reduced precipitation and increased evapotranspiration.

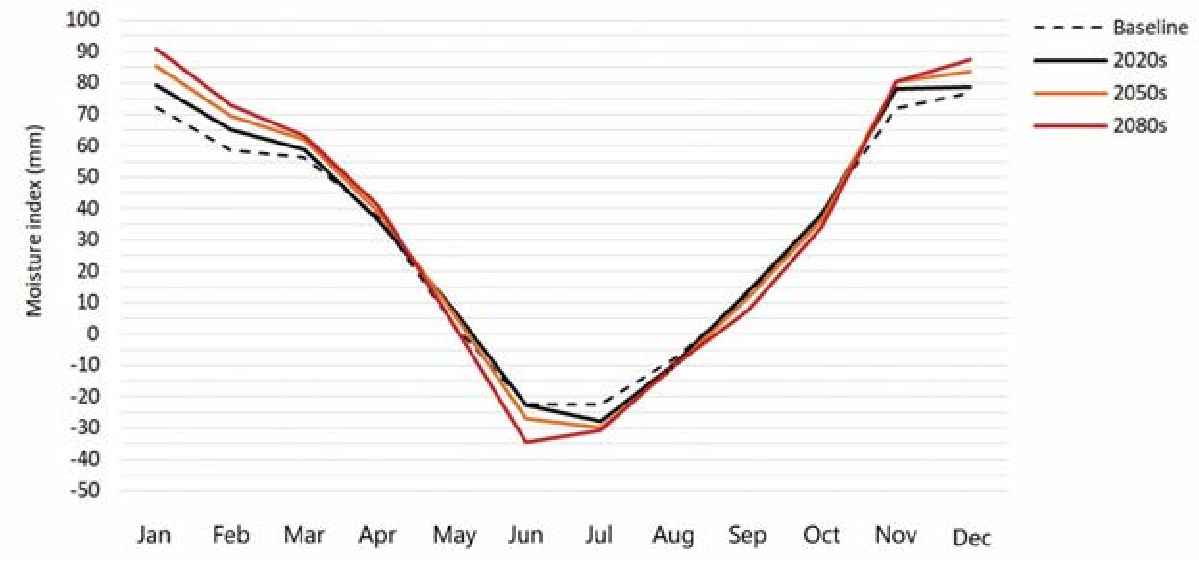


Figure 2-19 Historical and projected moisture index for the Shanty Bay climate station, expressed as the difference between the monthly total precipitation (mm) and the monthly evapotranspiration (mm). Data source: Environment Canada (baseline) and Climate Change Hazards Information Portal (projections).

Key Point – Moisture deficit

- Projected increases in temperature and changes in precipitation patterns under the RCP8.5 scenario suggest that summer soil moisture deficits will increase, particularly in June, from 27mm to 34.4mm.

These observed and projected climatic changes in the Lake Simcoe watershed are likely to significantly influence watershed features and functions, ecosystem services, public health, and the overall quality of life for residents. The following chapters examine these relationships in more detail.

Chapter 3

Tributary Water Quality

3.1 Introduction

The quality of the water in Lake Simcoe's tributaries is of critical importance to the watershed's aquatic and human populations. These tributaries flow into the lake and create the region's 18 distinct subwatersheds. Water quality is measured by the concentration of different constituents in the water. Monitoring changes in these concentrations is crucial since they have the potential to alter the ability of aquatic environments to sustain healthy ecosystems. As water quality is eroded, these healthy ecosystems, along with their services, may be lost (Carr and Neary, 2008). Hence, clean water within Lake Simcoe's tributaries is essential for both ecological and human well-being.

In the context of the Lake Simcoe watershed, rural and agricultural activities have historically represented the primary drivers of water quality impairment through their impacts on landscape, vegetation, and ecological function. Over time, land use evolution, deforestation, urban expansion and an increase of impervious area (catchment waterproofing), have also contributed to water quality degradation (Delpla et al., 2009). While these traditional drivers continue to threaten the water quality of tributaries, climate change has emerged as an additional stressor that can directly and indirectly impair water quality.

The impact of climate change on the frequency, intensity, extent and magnitude of existing water quality problems has rendered the phenomenon a growing concern on LSRCA's management agenda. As ambient air and water temperatures increase, and as rainfall patterns continue to shift towards a more variable regime, their impacts on the interactions between atmospheric, terrestrial, and aquatic processes and human activities within the watershed have the propensity to further degrade water quality (Delpla et al., 2009). The key chemical parameters that are susceptible to changing climatic conditions and whose levels, concentrations, and loads have been closely tracked through LSRCA's robust monitoring programs are phosphorus, nitrogen, chloride, and total suspended solids (TSS). There are, however, emerging contaminants that are likely to be impacted by climate change but currently lack comprehensive monitoring data. Anticipating and monitoring ongoing changes to these parameters will be crucial in safeguarding water quality within the Lake Simcoe watershed.

3.2 Factors affecting water quality

Water quality relates to the chemical, physical, and biological content of water. It is controlled by climatic variability, as well as hydrological, biogeochemical, and anthropogenic influences, and is a direct reflection of the inputs received from the air and surrounding landscape (Murdoch, 2000). Inputs can be direct, such as atmospheric deposition, or indirect, such as water that falls on the adjacent watershed and travels through variable portions of the ecosystems; each of which may transform the chemistry of the water. The hydrologic flowpath that water takes through the watershed and the resulting transformations that take place along that route will determine its chemical characteristics when it enters the surface-water system.

Human intervention can significantly affect water quality through both point and non-point sources of pollution. Point sources of pollution are direct inputs of contaminants to the surface water or groundwater system and include municipal and industrial wastewater discharges, ruptured underground storage tanks, and landfills. Non-point sources refer to contaminants that typically travel to waterways through surface runoff and infiltration. This can include nutrients, pesticides, and suspended sediments that are washed from agricultural fields into streams, or runoff from urban areas that carries debris from the streets into a receiving stream or water body. Each of these activities can have a negative impact on the aquatic ecosystem and can make water unsuitable for established or potential uses.

Water quality is also dependent on natural factors (such as geology, topography, meteorology, hydrology and biology) and varies with seasonal differences in runoff volumes, weather conditions and water levels. Most notably, geological, hydrological and climatic influences exert important influences on water quality (Bartram and Ballance, 1996). Many aspects of water quality are interlinked with water quantity due to its impact on the concentration and inflow of contaminants. Changes in the climate can directly impact streamflow, inflow from runoff, groundwater seepage, and evaporation rates (Dove-Thompson, 2011). Hence, the impacts of climate change on hydrology can significantly affect water quality. At the same time, changes in hydrologic flowpaths and other natural and anthropogenic factors controlling nutrient movement from the landscape to streams have important impacts on the timing, magnitude, and chemistry of runoff entering lakes, rivers, and streams. The impact of climate drivers on water quality relate to both their potential to create new conditions in which contaminant and sediment pathways can be introduced, as well as their potential to compound existing hydrologic and environmental stressors as they are superimposed onto existing changes in the catchment.

3.3 Phosphorus

3.3.1 Current state in the Lake Simcoe Watershed

Phosphorus is an essential nutrient for plants and is a natural component of healthy rivers. However, it can have negative impacts on human and ecosystem health if present in high concentrations (Carpenter et al., 1998). Eutrophication is the process that occurs when high concentrations of nitrogen and phosphorus pollute the water and boost the growth of algae and aquatic plants. This excessive growth interferes with use of the water for fisheries, recreation, industry, and agriculture. As these plants die and decompose, they deplete oxygen, which reduces biodiversity by creating unsuitable conditions for fish and other aquatic organisms. Blooms of cyanobacteria (blue-green algae), which can produce dangerous toxins, are another prominent symptom of eutrophication. In addition to contributing to the loss of biodiversity, these blooms prevent recreational or domestic use of affected water bodies due to public health concerns.

In order to evaluate the progress towards achieving existing water quality objectives and to help understand the link between phosphorus loading and biotic impairment, estimates of total phosphorus (TP) loads are used. Phosphorus loading refers to the total amount of phosphorus that gets carried into Lake Simcoe. It is expressed in metric tonnes or in kilograms and is measured over a hydrological year. Although average annual phosphorus loads have declined since the early 1990s, phosphorus continues to be one of the most prevalent pollutants in the Lake Simcoe watershed. As such, it has been scrutinized closely through LSRCA's monitoring program. Phosphorus loads are measured from the following five main sources within our watershed: tributaries, polders, sewage treatment plants, septic systems and atmospheric deposition. Based on these measurements, tributaries account for the largest source of phosphorus loading in the Lake Simcoe watershed.

The source of phosphorus entering tributaries and the rate of phosphorus loading are heavily influenced by land-use changes. Urban development changes the land from natural, porous surfaces like soil and grasses to hard surfaces like pavement and asphalt. In urban areas, rainwater and snow melt cannot seep into the ground naturally, so the stormwater runs over the hard surfaces and washes into tributaries, and eventually the lake. Meanwhile, in agricultural areas, rainfall and melting snow provide water that runs over the ground, picking up fertilizers and contaminants from feedlots, manure storage, and bare fields. Just as the distinct features of urban and agricultural land produce different pathways for phosphorus loading, these features may also respond differently to climate change and may subsequently exhibit different water quality outcomes.

In order to examine the impacts of land use on phosphorus loading, phosphorus loading data is collected and analyzed by subwatershed. The data is represented in **Figure 3-1** in two ways: by numeric values in the table and by colors in the map. The impacts of land use on phosphorus loading and export rate become obvious when looking at the distribution across the watershed. The stations with the highest loads are generally found in the subwatersheds with the most development in the basin. These include the West Holland station, downstream of the Holland Marsh, at 14.5 tonnes; and the East Holland station, found downstream of Newmarket and Aurora, with an average annual load of 12.4 tonnes. Barrie Creeks and the East Holland River, both urbanized catchments, had the highest export rates. Agricultural areas in the watershed also tend to have higher phosphorus export rates.

2012/2013 - 2014/15 Average Annual Phosphorus Load by Subwatershed (tonnes/year)

1	West Holland River	14.5
2	East Holland River	12.4
3	Georgina Creeks	2.5
4	Maskinonge River	1.6
5	Black River	4.6
6	Pefferlaw River / Uxbridge Brook	5.7
7	Beaver River	4.1
8	Whites Creek	1.3
9	Talbot River	3.4
10	Ramara Creeks	1.6
11	Oro Creeks North	2.6
12	Hawkestone Creek	0.4
13	Oro Creeks South	0.7
14	Barrie Creeks	4.0
15	Lovers Creek	0.9
16	Hewitts Creek	0.2
17	Innisfil Creeks	3.1
18	Fox Island	0.003
19	Snake Island	0.017
20	Georgina Island	0.2
21	Thorah Island	0.056

2012/2013 - 2014/15 Average Annual Phosphorus Export Rate by Subwatershed (tonnes/km²/year)

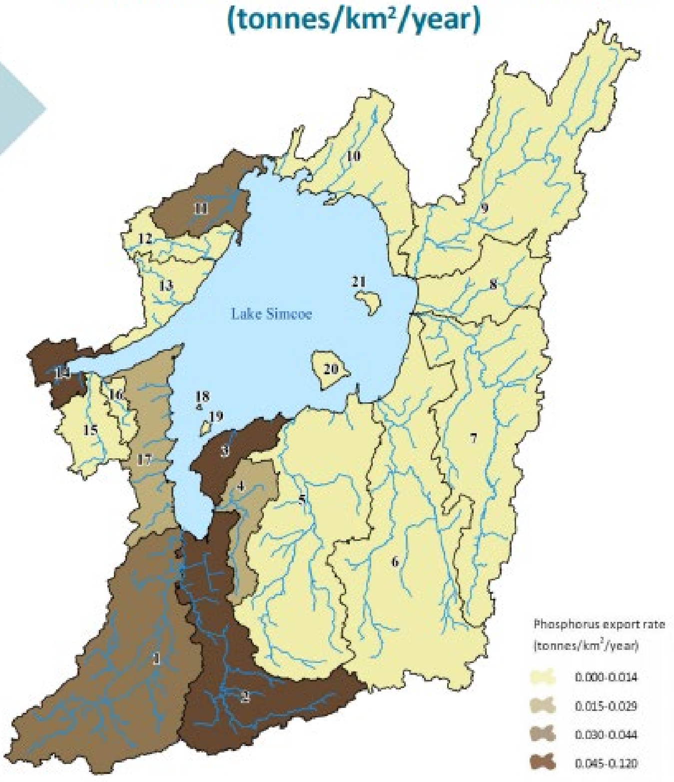


Figure 3-1 Average phosphorus loads per year and phosphorus export rates, 2012-2014, by subwatershed or island. Source: Lake Simcoe Phosphorus Loads Report, Update 2012/13- 2014/15.

Phosphorus concentrations are measured against the Provincial Water Quality Objective (PWQO) of 0.03 mg/L. Just as with phosphorus loading, phosphorus concentrations follow similar trends in relation to land use. Land under intense urban and agricultural use tends to correspond with higher concentrations, while land under the highest level of natural cover in the basin has the lowest average concentration.

In 2016, six of the subwatersheds failed to meet the PWQO the majority of the time (**Figure 3-2**). Based on the latest trend analysis, the majority of stations showed decreasing concentrations in the historical analysis, but many of those stations displayed no trend in the short-term analysis (2005-2014), which may suggest that reductions are becoming harder to achieve.

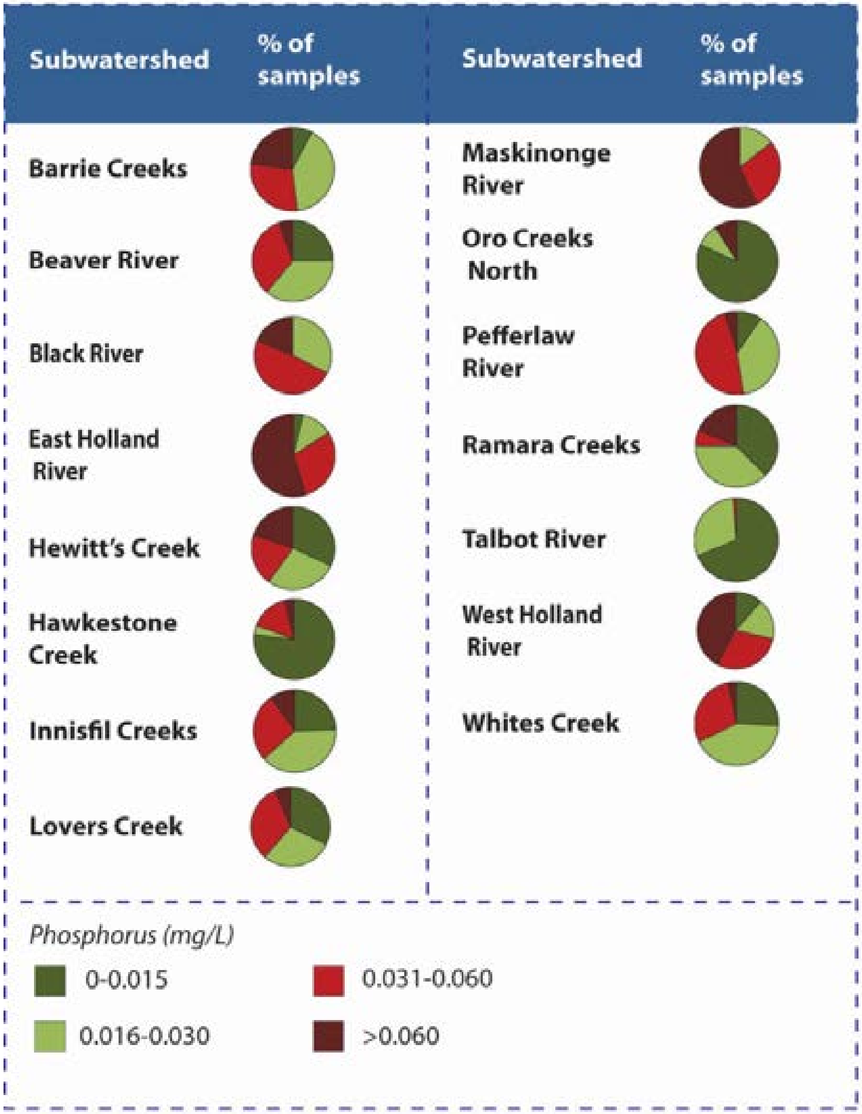


Figure 3-2 Summary of phosphorus conditions at the Lake Simcoe tributary water quality stations in 2016. Results expressed as the proportion (%) of samples collected at specific concentration ranges.

3.3.2 Climate drivers

Total Precipitation

Non-point pollution resulting from runoff is one of the major causes of water quality degradation. Runoff impairs water quality by carrying sediment and contaminants - including phosphorus - from the land to surface waters. As runoff travels across the landscape and into watercourses, watersheds incur losses of sediment-bound and dissolved phosphorus. However, not all precipitation that falls in a watershed contributes to runoff and streamflow.

As shown in **Figure 3-3** and **Figure 3-4**, TP loads vary according to flow, but not according to precipitation. This is because there are many other factors that determine how much, and at what rate, precipitation flows into streams. For example, impervious surfaces, such as parking lots and roads, act as a "fast lane" for rainfall – moving water quickly off the landscape and into stormwater infrastructure or directly into streams. The timing, frequency, and intensity of rainfall can impact the rate of soil saturation and the proportion of rainfall flowing into streams. Meanwhile, temperature and wind may impact the amount of rainfall that returns to the atmosphere through evaporation and transpiration. Therefore, whether or not projected increases in average precipitation impact phosphorus loads will not depend solely on the changes in the amount of precipitation falling, but also on the pattern of rainfall and the existing land-use and climate conditions that influence how precipitation translates into flows.

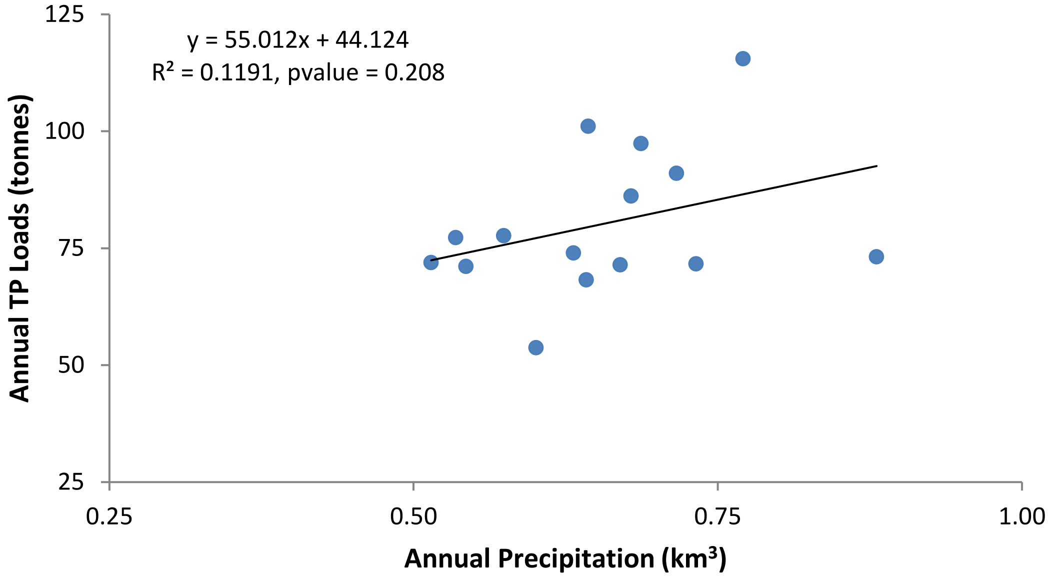


Figure 3-3 Relationship between annual precipitation (km^3) and annual TP loads (tonnes) from all sources (2000-2014).

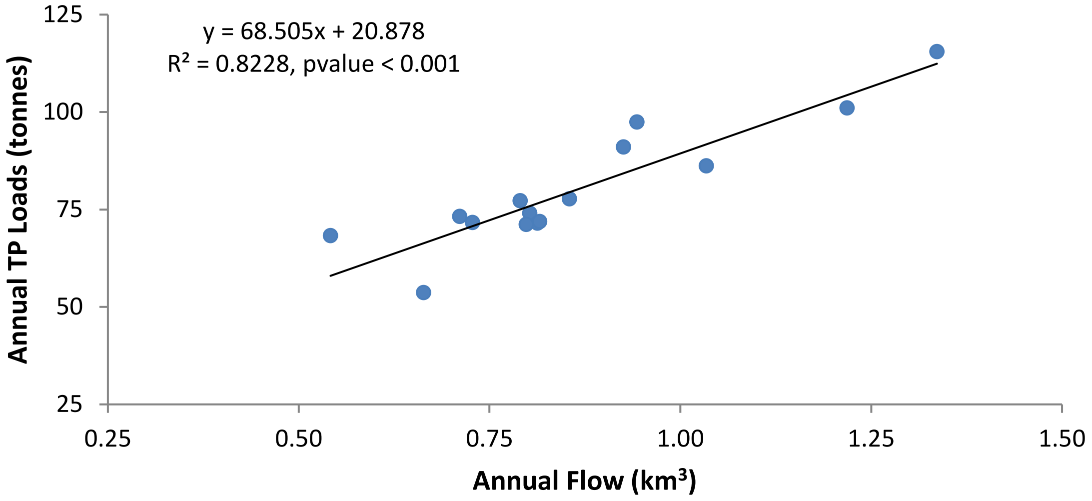


Figure 3-4 Relationship between annual flow (km3) and annual TP loads (tonnes) from all sources (2000-2014).

More extreme precipitation patterns

More extreme precipitation patterns refer to more intense rainfall events and more periods of summer droughts. Intense rainfall events and drought conditions directly affect water quality through their impact on surface runoff to waterbodies and dilution capabilities. During intense rainfall events, soil may become saturated to full capacity or may be unable to absorb rainfall as quickly as it arrives. As a result, the precipitation may pool or flow along the surface, causing flooding and runoff.

Water from floods and runoff carries non-point sources of phosphorus from the surrounding landscape of roads and developed areas, lawns, farmland, and other rural areas to rivers and smaller tributaries. Studies have found that total phosphorus loading is positively related to heavy rainfall events (Ockenden et al., 2016). In fact, a study of small watersheds in Wisconsin has indicated that only a few storms per year can dominate annual total phosphorus loading (LaBeau et al., 2015). Similar trends have been observed in the Lake Simcoe watershed (O'Connor et al., 2013; 2017). These extreme events encourage rapid phosphorus transport that is delivered in pulses rather than gradually. Meanwhile, low flow conditions during drought are associated with higher phosphorus concentrations due to reduced dilution capabilities (Ockenden et al., 2016).

In order to monitor the impact of intense rainfall events and low flow conditions on phosphorus loads, LSRCA collected daily and episodic water quality samples for a full year at two stations. This data was paired with continuous flow data and was used to calculate actual annual tributary load. The river systems under study were the mainly agricultural Beaver River and the highly urbanized East Holland River. The results of the study, displayed in **Figure 3-5** and **Figure 3-6**, reveal distinct responses to rainfall variations between the river systems.

The Beaver River was characterized by longer periods of elevated flows, occurring in December and March and typically lasting approximately 2-3 weeks. These elevated flows were accompanied by high concentrations and total phosphorus loads that quickly dropped off after the peak flow. In contrast, the East Holland River experienced shorter, more intense peaks in flow throughout the year, attributed to its urban landscape. The high flow events were accompanied by high TP loads that receded with flow and accounted for the bulk of phosphorus loading. In both rivers, low summer flows were associated with higher concentrations and lower TP loads.

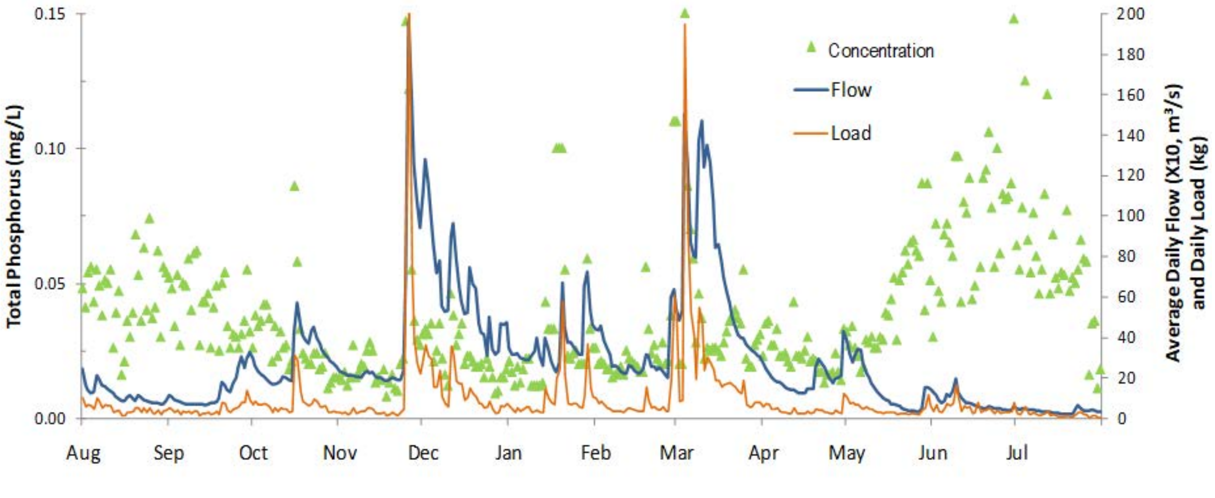


Figure 3-5 Average daily flow, daily load, and total phosphorus concentrations at the Beaver River station.

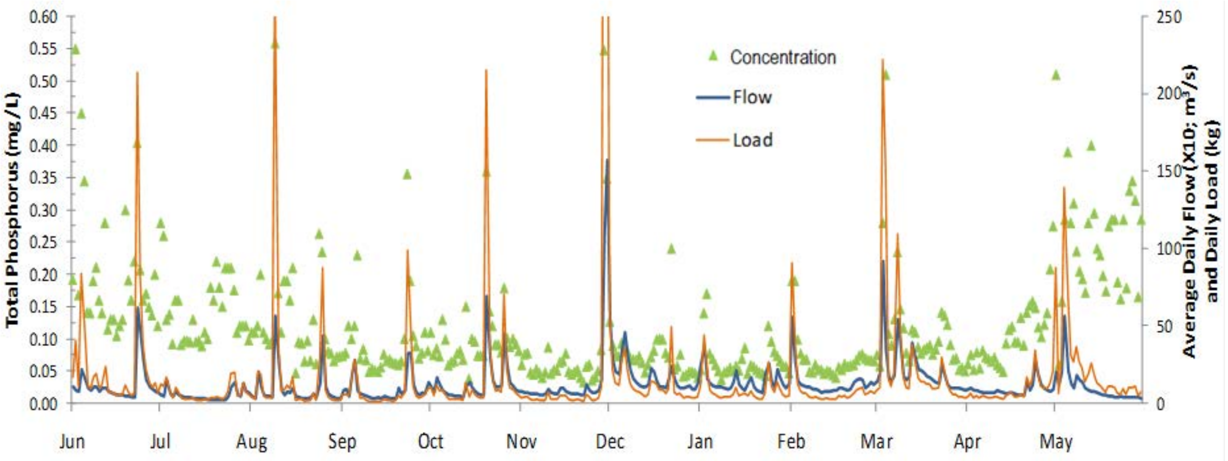


Figure 3-6 Average daily flow, daily load, and total phosphorus concentrations at the East Holland River station.

With climate change expected to increase the intensity of extreme rainfall events, the contribution of high flow events to the annual loads will be enhanced. Rising temperatures and more droughts will lengthen periods of low flow during the times of greatest eutrophication risk (summer), with a corresponding increase in the length of time that nutrients can be retained. Hence, there is a greater chance of prolonged periods of high concentrations, potentially exceeding thresholds. The combination of intensifying rainfall events and drought conditions is especially concerning since the concentrations of phosphorus reaching waterways may be enhanced when low flows are followed by extreme rewetting.

More winter rainfall

For much of southern Ontario, climate change is expected to bring warmer winters, with more of the precipitation falling as rain rather than snow (Natural Resources Canada, 2015). Changes in snow accumulation can ultimately alter phosphorus loading through its impact on seasonal patterns of stream flow. Historically, winter precipitation occurring as snow has accumulated in the watershed until the spring, when snowmelt augments stream flow to form a distinct snowmelt peak (or spring freshet) that often results in maximum annual stream flow (Pierson et al., 2010). The accumulation of snow limits phosphorus export, whilst the high flows during spring runoff are associated with the maximum export rates. As the climate warms and a greater proportion of winter precipitation likely falls as rain, less snow will accumulate. As a result, stream flow will increase throughout winter and decrease during the spring. This increased winter stream flow and phosphorus export will lead to a significant shift in the seasonal timing of nutrient delivery, with winter export becoming greater while the spring peak in phosphorus export gradually disappearing. This is supported by a study conducted by Crossman et al. (2013), which predicted that the greatest increase in phosphorus entering Lake Simcoe will occur during the winter months due to this increased precipitation. These changes can have profound impacts on ecosystem function, since greater phosphorus loading during the winter could lead to shifts in the timing of the spring blooms.

Evidence of shifting seasonal flows is already being recorded within the Lake Simcoe watershed. Historically, peak flow has occurred in March, April, and May in response to snow melt, while typically only residual runoff occurs in January and February. However, seasonal site-specific flow analyses spanning back to the 1960s are showing trends of rising winter flows and declining spring flows (**Figure 3-7).** Our data also indicates that flows and TP loads are most closely correlated during these two seasons (**Figure 3-8**). Therefore, as winter flows rise and spring flows decline, we will likely see a corresponding shift in TP loads; meaning that the bulk of TP loading may coincide with the seasons in which minimal phosphorus interception and uptake by vegetation is occurring.

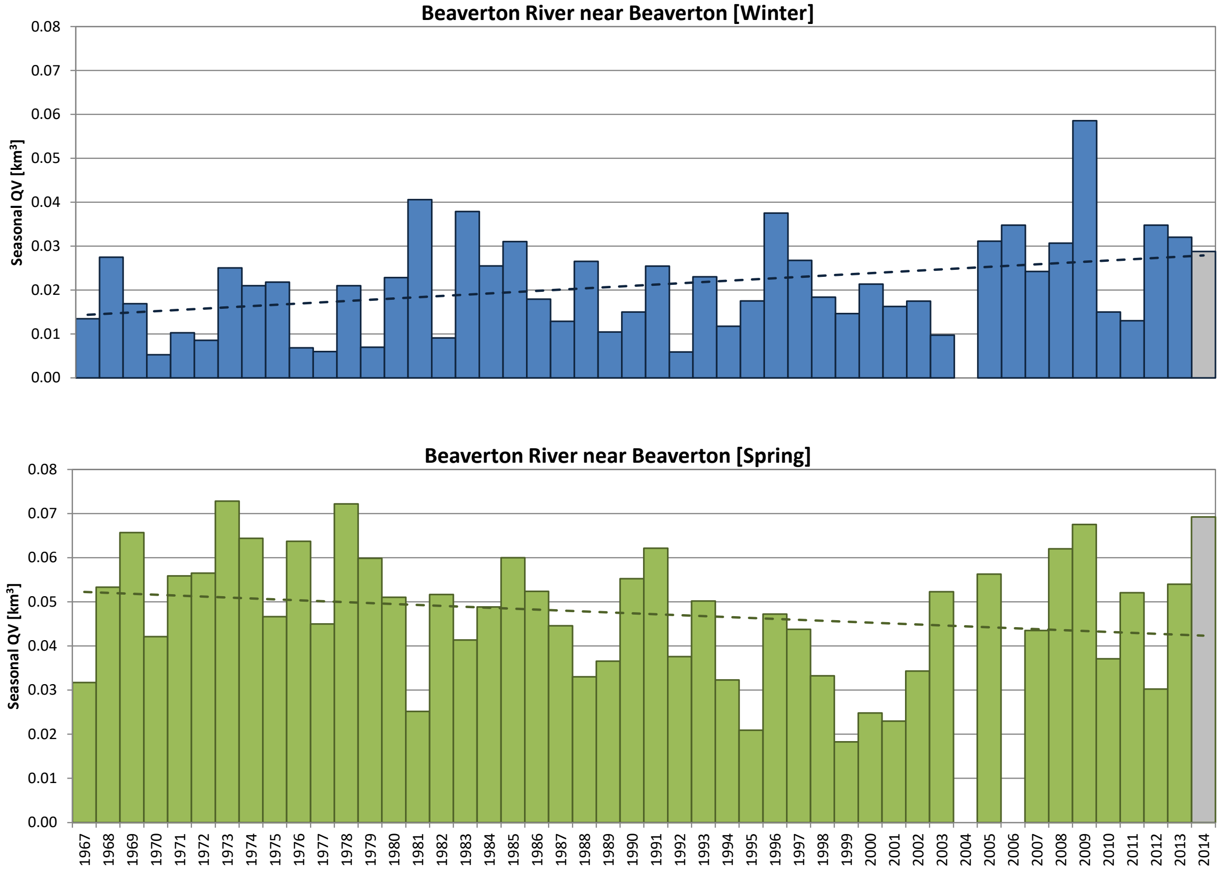


Figure 3-7 Average winter (top) and spring (bottom) flows at Beaverton River (1967-2014). Winter includes Dec 1st to Feb 28/29th, and Spring includes Mar 1st - May 31st.

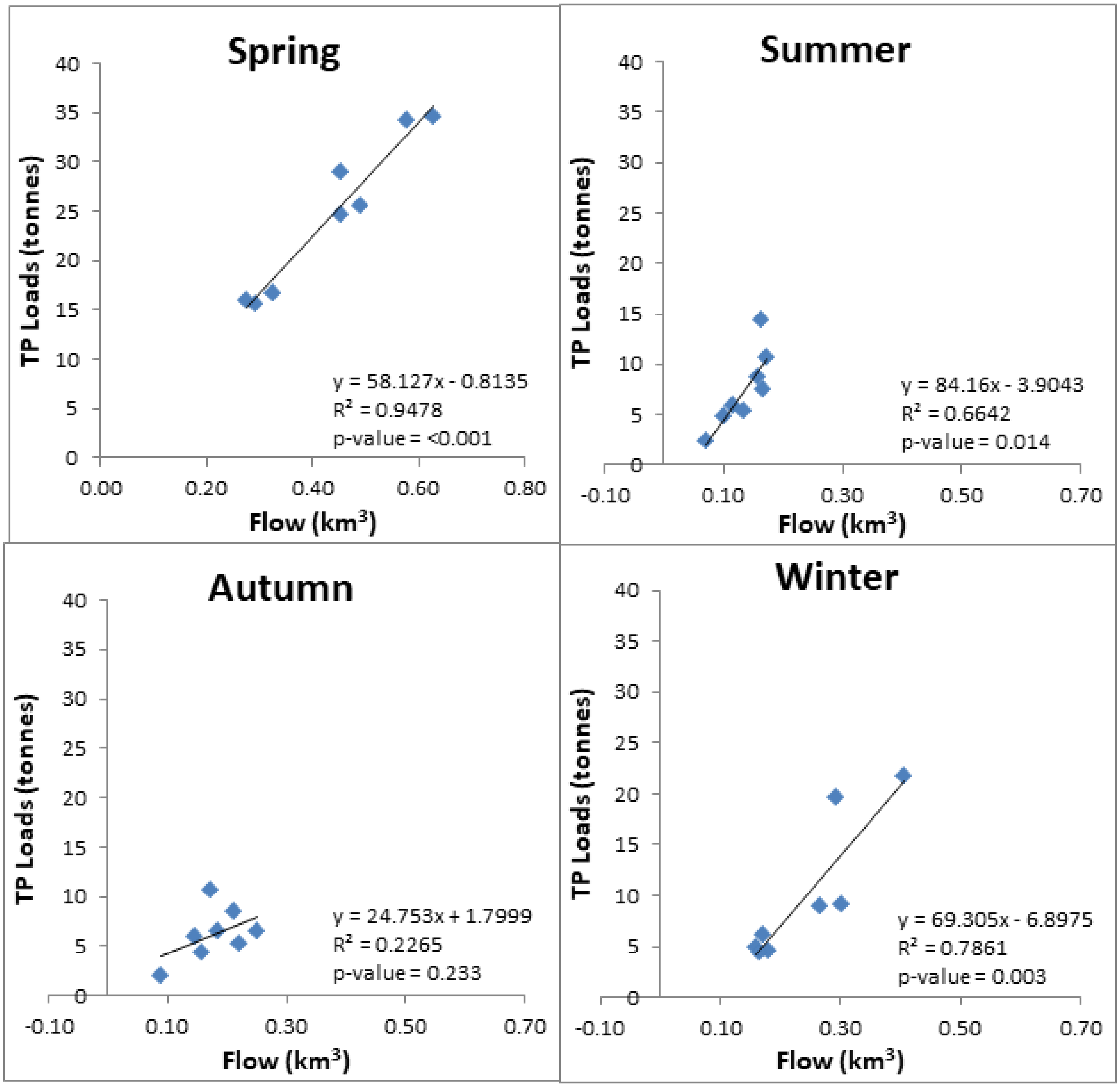


Figure 3-8 Seasonal relationship between flows and TP loads (2007-2014) into Lake Simcoe. Seasons are Winter (Dec 1 to Feb 28/29), Spring (Mar 1 - May 31), Summer (Jun 1 to Aug 31), and Autumn (Sep 1 to Nov 30).

Longer growing season

Climate change has the potential to alter the pattern of phosphorus loading from agriculture through its impact on the agroclimatic conditions suitable for field crop growth. While much of the world will see diminished agricultural production as a result of climate change, Canadian farmers will have an opportunity to expand their seasons and types of crops they produce. Throughout the 20th century, southern Ontario has experienced a lengthening of the growing season; characterized by earlier start and later end dates (Qian et al., 2010; Qian et al., 2012). This same trend is projected for the Lake Simcoe watershed, with the growing season expected to last up to 45 days longer by the 2080s.

A lengthening of the growing season can enable changes in phosphorus uptake by crops. As one of the 17 essential elements required for plant growth, phosphorus is taken up by plants from the soil (Vance et al., 2003). This uptake ultimately reduces the amount of phosphorus available for transport by runoff. As temperatures rise and the growing season lengthens, more crops can be grown, and plants may become more productive. Subsequently, a greater proportion of the phosphorus within soils can be taken up by plants and the amount left for transport into surface waters may be reduced (Lemmen and Warren, 2004).

Key Points – Phosphorous

- The impact of changes in precipitation on phosphorus loading to streams will depend both on the amount of precipitation falling as well as the pattern of rainfall and the existing land-use and climate conditions that influence how precipitation translates into streamflow.
- The combination of intensifying rainfall events and drought conditions predicted for the summer season can increase the concentrations of phosphorus reaching waterways when low flows are followed by extreme rewetting.
- As winter flows rise and spring flows decline, a corresponding shift in total phosphorus loads will likely be observed.
- As temperatures rise and the growing season lengthens, more crops can take up a greater proportion of the phosphorus within soils, and the amount left for transport into surface waters may be reduced.

3.4 Nitrogen

3.4.1 Current state of nitrogen in the Lake Simcoe Watershed

Nitrogen circulates in various forms in nature through a series of microbial transformations. The important processes in the nitrogen cycle include fixation, ammonification, nitrification, and denitrification. Throughout this process, nitrogen can enter surface waters directly from rainfall, groundwater recharge, or in surface runoff.

Nitrate serves as the primary source of nitrogen for aquatic plants in well oxygenated systems, and as nitrate levels increase, there is an increasing risk of algal blooms and eutrophication in surface waters that are not phosphorous-limited (CCME, 2012). However, the freshwater systems in the Lake Simcoe watershed, as in many others are limited by the availability of phosphorous. Concerns regarding the impact of climate change on nitrate concentrations in surface waters revolve around changes in soil conditions. As these conditions shift, they may change the rate of enzymatic and microbial activity or change the land’s ability to bind nitrogen, each of which may alter the availability of nitrogen within the natural system. High nitrogen availability in soils enhances the soil processes that result in nitrous oxide (N_2O) emissions (Del Grosso, 2012). This is particularly concerning given that N_2O is over 300 times more effective in trapping heat than carbon dioxide. This means that as soil conditions change, it could create a positive feedback loop that accelerates climate change.

Total nitrogen concentrations in the Lake Simcoe tributaries are usually low and are below the objective of 2.9 mg/L the majority of the time (**Figure 3-9**). Most subwatersheds experience just a few exceedances of this objective, with the exception of the North Schomberg River station, which is in a predominantly agricultural land-use area. Nearly half of the samples collected at this station since 2002 have exceeded the objective. Though some subwatersheds show increasing trends for nitrates in the long-term period, most of those subwatersheds show no significant or decreasing short-term trends. As of 2014, only the Talbot River at Lock 41 and the Whites Creek stations showed increasing short-term trends. Both stations are in subwatersheds that are dominated by natural heritage features and agricultural land-uses.

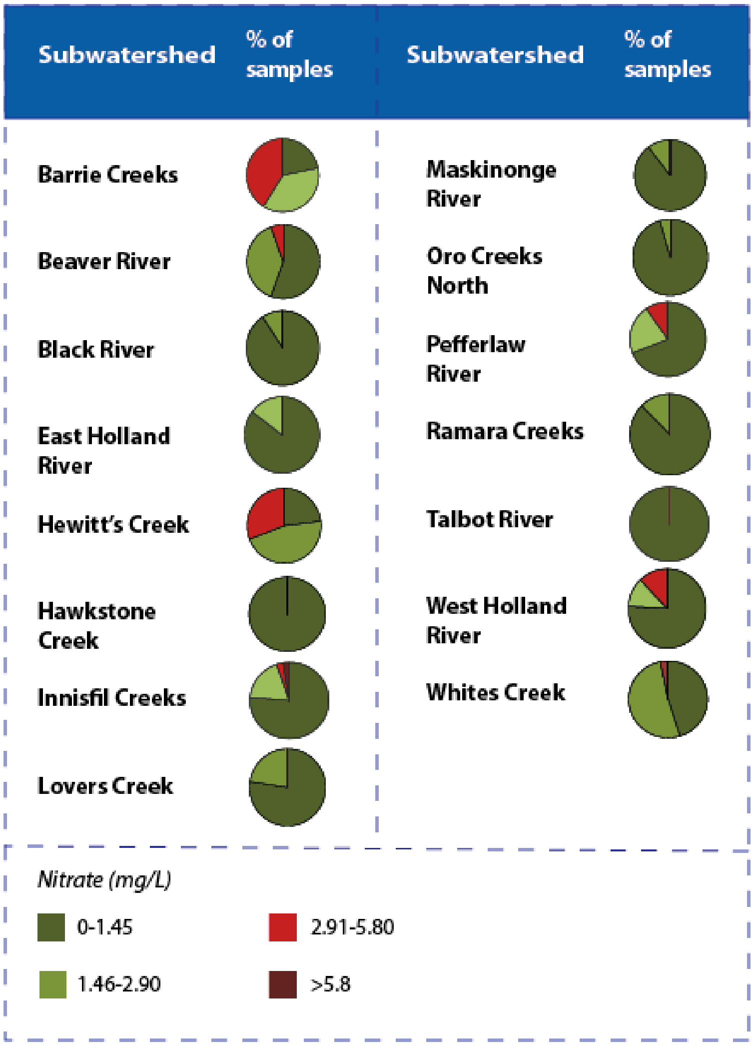


Figure 3-9 Summary of nitrate conditions at the Lake Simcoe tributary water quality stations in 2016. Results expressed as the proportion (%) of samples collected at specific concentration ranges.

3.4.2 Climate drivers

Rising temperatures

Soil temperature is influenced by air temperature. Hence, there is growing concern regarding the potential impacts of rising temperatures on soil conditions. A study by Qian et al. (2011) investigated the relationship between air and soil temperature and found a significant positive trend in spring and summer mean soil and air temperature across Canada. This warming trend was characterized by a soil temperature increase of 0.26–0.30°C/decade in spring between 1958 and 2008 and is consistent with atmospheric warming. As temperatures within the Lake Simcoe watershed continue to rise throughout the 21st century, it is anticipated that this trend in soil warming will persist.

Warming soils will have a profound effect on nitrogen cycling through its impact on enzymatic efficiency. A moderate increase in soil temperature can lead to a large increase in enzymatic activity, which subsequently increases nitrogen availability (Sardans et al., 2008). As a result, rising soil temperatures increase the mineralization and release of nitrogen from soil organic matter. Moreover, more frequent intense rainfall events lead to the mobilization of this nitrogen as it is flushed into streams, causing higher lake, river, and stream nitrate concentrations (Delpla et al., 2009). This is especially important under high flow conditions following droughts – which are expected to increase in frequency – as nitrogen loads build up in the soil before being flushed.

Milder winter temperatures

Soil microbial processes continue in unfrozen soils during the winter, and nitrogen-rich by-products accumulate until snowmelt washes it from the soils. Regional projections for the Lake Simcoe watershed suggest that the probability of frost will decline by up to 30% by 2080 (see **Chapter 2 – Climate Trends and Projections**). Traditionally, frozen soil conditions have decreased mid-winter microbial processing of nitrogen. As the probability of frost declines, soil microbial processes will have the opportunity to remain active for a greater proportion of the winter months. Hence, climate change may indirectly enable the creation and accumulation of more nitrogen throughout the winter months.

Agricultural tile drains

In agriculture, tile drainage is a type of drainage system that removes excess water from soil below the surface in order to lower the groundwater table; thus, ensuring that a crop's roots won't become water logged. While the practice can dramatically improve crop yields, the discharge of this unfiltered water directly into streams raises environmental concerns. By lowering the water table, tile drains allow more water to infiltrate into the soil and percolate through the soil profile. This water can transport essential plant nutrients, particularly nitrogen, out of the root zone (Nangia et al., 2010). Because it is not held by the soil, nitrate can leach out of the soil and into tile flow quite easily. Current tile drainage systems provide no filtration of intercepted water. If nitrogen-rich soil solution enters the tile drain, nitrogen-rich water is discharged.

Nitrogen losses are related to the amount of tile flow, with higher tile flows being associated with more nitrogen transport (Ghane et al., 2016). Climate change has the potential to alter tile flows through changes in precipitation and infiltration capacity. Studies have shown that warmer temperatures and wetter conditions lead to higher flows and enhanced mineralization and nitrification; resulting in higher nitrogen losses by tile drainage (Wang et al., 2015). Moreover, changes in frozen soil conditions may contribute to rising tile flows. Typically, frozen soils reduce infiltration and, as a result, surface runoff from rainfall or snowmelt increases while tile drain discharge decreases (Johnsson and Lundin, 1991; Kane and Chacho, 1990). However, it is likely that rising winter temperatures will result in reduced frost formation. Unfrozen soil conditions will allow this drainage system to remain active, thereby increasing nitrogen leaching and discharge (Dardashti, 2010). One study in particular, located in eastern Canada, found that average annual drainage outflows will increase in a warmer and wetter climate, with significant increases occurring during the months of March and April (Dardashti, 2010). By enhancing drainage flows, particularly during the winter months, it appears that the anticipated reduction in soil frost associated with climate change may alter both the magnitude and the seasonality of nitrogen loading.

Key Points – Nitrogen

- Rising soil temperatures increase the mineralization and release of nitrogen from soil organic matter, making it more susceptible to mobilization during intense rainfall events.
- As the probability of frost declines, soil microbial processes will have the opportunity to remain active for a greater proportion of the winter months, accumulating more nitrogen in soils.
- By enhancing tile drainage flows, particularly during the winter months, it appears that the anticipated reduction in soil frost associated with climate change may alter both the magnitude and the seasonality of nitrogen loading.

3.5 Chloride

3.5.1 Current state of chloride in the Lake Simcoe Watershed

Chloride is a naturally occurring element that is essential for the health of all organisms, including humans. However, it can have detrimental impacts at high concentrations. More specifically, high chloride concentrations can cause acidification of streams (Kaushal et al., 2005) and can disrupt osmoregulation in aquatic organisms leading to impaired survival, growth, and/or reproduction. The toxicity of chloride to aquatic organisms can have acute (short-term) effects at high concentrations and chronic (long-term) effects at lower concentrations (MOE, 2003).

Background chloride concentrations in natural surface waters are typically below 10 mg/L. Increased levels of chloride in surface waters are typically the result of the application of road salt for winter accident prevention, which represents the primary anthropogenic source of chloride to the environment. Road salts enter the surface waters through runoff/meltwater, losses at salt storage and snow disposal sites, or from the release of salts stored in surface soils. While elevated chloride levels are primarily found around urban centers and near major roads and highways, chloride levels have been found to be steadily increasing across the Lake Simcoe watershed and in the lake itself.

The current Canadian Water Quality Guideline (CWQG) for the protection of aquatic life is 120 mg/L for chronic exposure and a benchmark concentration of 640 mg/L was set for acute exposure. The acute guideline estimates the point at which severe effects to the aquatic ecosystem are likely to occur over a 24 to 96-hour exposure period.

Even more so than lake concentrations, chloride concentrations in many of the tributaries are reaching concerning levels. **Figure 3-10** summarizes the 2016 monitoring data and reveals that the majority of samples are above the chronic guideline in five subwatersheds (Barrie Creeks, East Holland River, Hewitt's Creek, Lovers Creek, and Maskinonge River). With winter salt being the main source of chloride in surface waters it is not surprising that all five of these stations are within an urban catchment or near a major highway. Of all subwatersheds, only three reported exceedances of the acute guideline, those being Barrie Creeks, East Holland River, and West Holland River, which represent the most urbanized subwatersheds. When examining long-term trends, the vast majority of stations are showing increasing trends, with the remaining stations showing no significant trends. It is encouraging that an examination of short-term chloride trends (2005-2014) shows that some progress is being made. Based on the short-term trend analysis, only 3 stations are showing increasing trends, 2 stations are showing decreasing trends, and the rest are showing no significant trend, indicating that concentrations may be stabilizing.

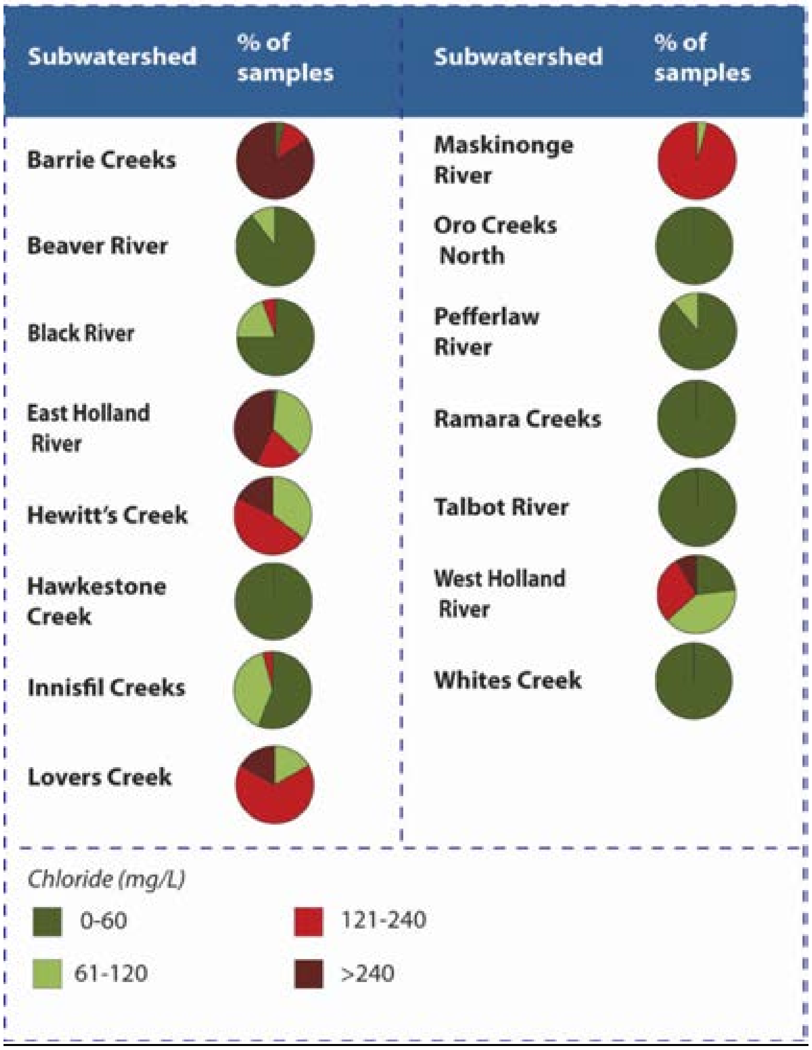


Figure 3-10 Summary of chloride conditions at the Lake Simcoe tributary water quality stations for 2016. Results expressed as the proportion (%) of samples collected at specific concentration ranges.

3.5.2 Climate drivers

More frequent freeze-thaw cycles and wetter winter conditions

When salt is applied to roads, driveways, and parking lots, it dissolves the snow and ice. The resulting brine eventually runs off into streams, lakes or storm sewers; subsequently increasing chloride concentrations of surface waters (Novotny et al., 2008). Studies conducted by Sander et al. (2007) and Kilgour et al. (2013) have identified weather variability as a factor affecting salt-application. In particular, the studies found that annual road salt application in the Minneapolis/St. Paul Metropolitan Area was strongly correlated with the total amount of snowfall received and the total number of days with snowfall. This correlation was further supported by data from within the Toronto area, which attributed over 50% of the variation in local road salt application to cumulative snowfall.

While snow clearing is an important aspect of road salt use, hazards associated with freezing conditions can also represent a great threat to public safety. As winter temperatures rise, a reduction in road-salt application may not necessarily take place. With climate projections forecasting warmer winter temperatures and more precipitation to the Lake Simcoe region (**see Chapter 2 – Climate Change Trends and Projections**), the question is whether precipitation will fall as snow, sleet, freezing rain, or rain. Based on regional projections, freeze-thaw cycles may become more common in January and February. This raises concerns regarding the frequency of freezing rain events, sleet, and ice storms, since these events are associated with freeze-thaw temperatures. If warming temperatures increase the proportion of precipitation falling as freezing rain and sleet, then municipalities and contractors may be prompted to apply more road salt to address public safety concerns, further augmenting chloride concentrations in surface waters. Alternatively, warming temperatures may delay the onset of sub-freezing temperatures and advance the onset of spring. As the length of time in which freezing-conditions occur is shortened, so is the period of time that calls for road-salt application. Hence, increased road salt application in response to freeze-thaw cycles and wetter conditions may be partially offset by a reduction in road salt applications associated with shorter winters.

LSRCA tracks chloride concentrations in various tributaries throughout our watershed with the use of conductivity meters. The conductivity readings taken by these meters, which represent the water's ability to conduct electricity, can be used as a surrogate for chloride concentrations. A preliminary analysis of the data collected by the conductivity meter located in the East Holland River subwatershed – one of the most highly urbanized subwatersheds with consistently high chloride concentrations – may be showing early indications of a relationship between winter severity and chloride concentrations. Based on the air temperature and conductivity data collected from this meter over the course of three consecutive winters, the proportion of winter days in which air temperatures were between -5°C and 5°C (which represent days that hover around the freezing mark) coincide with the proportion of measurements that exceeded the acute guideline (**Figure 3-11**). Given that the vast majority of measurements over the course of all three winters were above the chronic guideline regardless of winter severity, this data certainly highlights the concerns regarding current chloride concentrations and their guideline exceedances. Perhaps more concerning, however, is the indication that these exceedances may be further enhanced – at least in the short term – as winter temperatures rise and increasingly hover around the freezing mark.

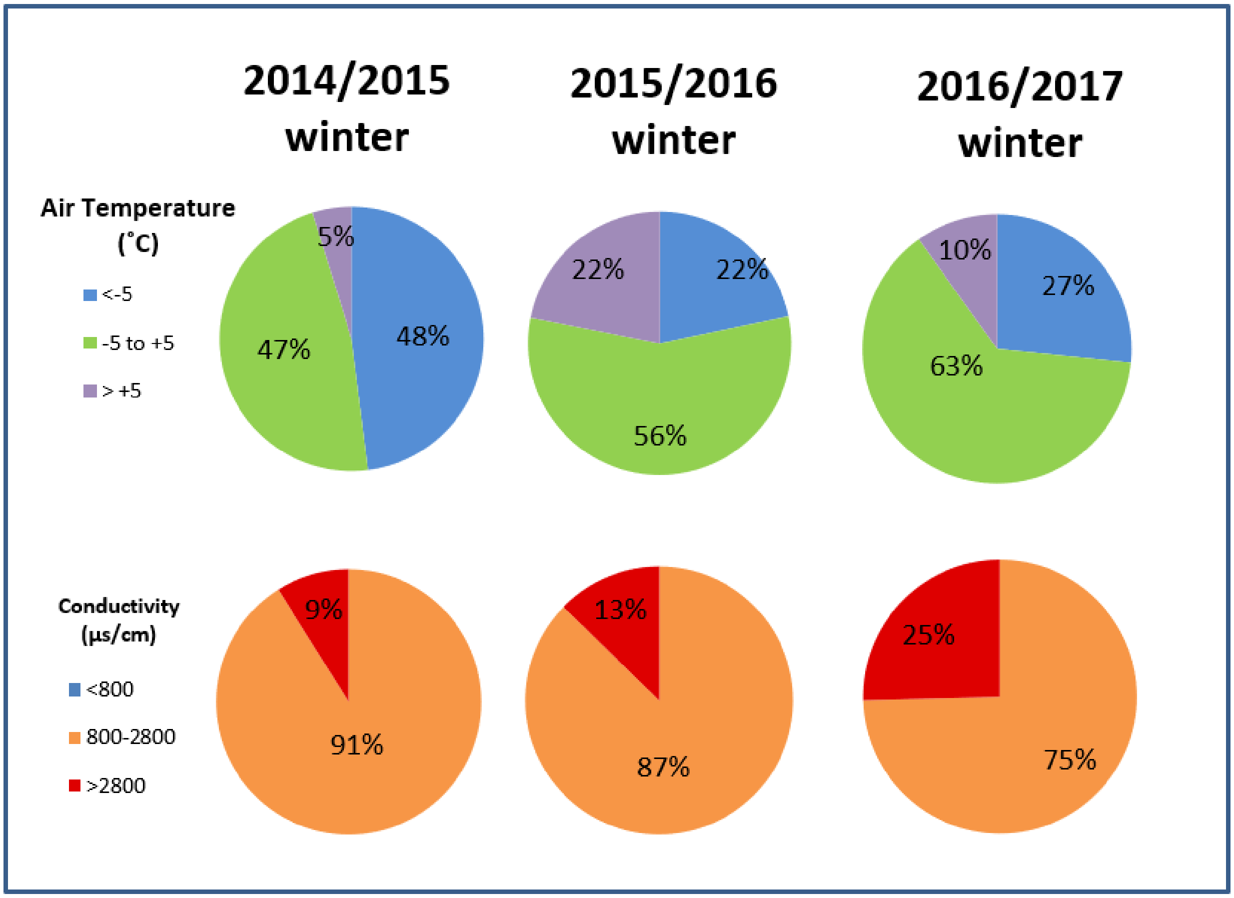


Figure 3-11 Air temperature and conductivity measurements taken by the conductivity meter at Holland Landing, located in the East Holland River subwatershed. Conductivity is used as a surrogate for chloride concentrations.

Chloride from road salt can also migrate into shallow sub-surface water, impacting the quality of shallow aquifers, especially in urban areas. Studies have shown that 40-55% of chloride applied as road salt enters shallow aquifers, resulting in elevated chloride concentrations in both groundwater and baseflow (Howard and Haynes, 1993; Perera et al., 2013). Because chloride accumulates in waterbodies, continual elevated salt application can affect aquatic communities (see **Chapter 5 – Tributary Ecosystems**) as well as drinking water where supply wells are shallow (Kelly, 2008).

The chloride concentration in the Holland Landing monitoring well has steadily increased since 2004 (**Figure 3-12**). This well is located in a shallow unconfined groundwater aquifer within an urban area (see well details in **Table 4-1**) and therefore is likely more vulnerable to the application of road salt. The well is also located adjacent to the Holland River and any groundwater discharge could impact this ecosystem, particularly as the chloride concentration approaches the Canadian Water Quality Guideline of 120 mg/L.

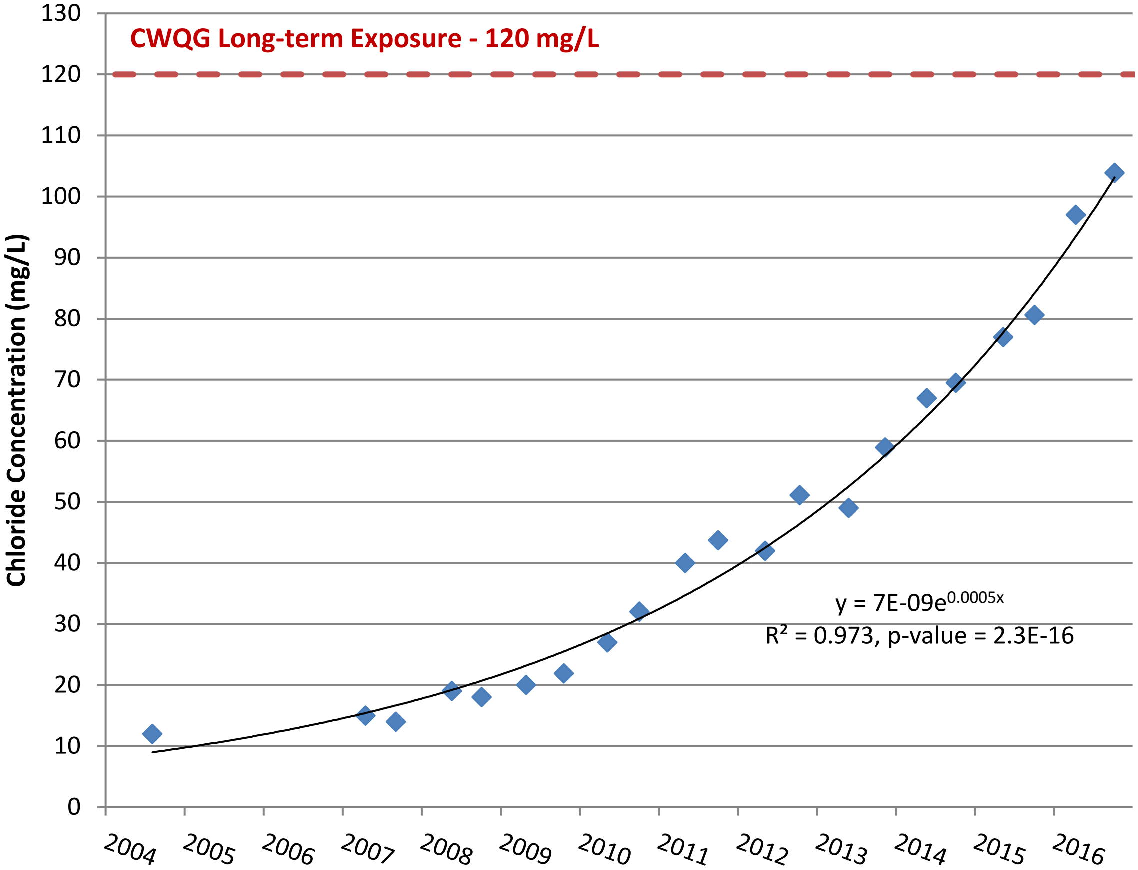


Figure 3-12 Chloride concentration in the Holland Landing monitoring well from 2004-2016. This well is part of the Provincial Groundwater Monitoring Network and chloride concentrations are approaching the Canadian Water Quality Guideline (CWQG).

Key Points – Chloride

- As winter temperatures rise and increasingly hover around the freezing mark, more road salt may be applied to keep paved surfaces safe for the public.
- Increased road salt application in response to freeze-thaw cycles and wetter conditions may be partially offset by a reduction in road salt applications associated with shorter winters.
- Application of road salt can also migrate into shallow groundwater, increasing the chloride concentration in aquifers, as has been observed in the Holland Landing monitoring well.

3.6 Total suspended solids (TSS)

3.6.1 Current state of TSS in the Lake Simcoe Watershed

Total Suspended Solids (TSS) is a measure of any material in suspension in the water column. This can include a wide variety of materials, such as silt, microorganisms, decaying plant and animal matter, and industrial wastes. It is an important measure because TSS can act as a transport mechanism for a variety of other parameters, some in a benign form such as clay-bound aluminum, while others such as phosphorus can cause excessive nutrient loading downstream. Excessive amounts of TSS can also have negative impacts on aquatic organisms because of shading, abrasive action, habitat alteration, sedimentation, and interference with light transmission.

Most flowing waters have considerable day-to-day variation in suspended solids, linked primarily to fluctuations in precipitation. Therefore, more flexible guidelines have been established for TSS. The Canadian Council of Ministers of the Environment (CCME) outlines that the concentration of suspended solids in stream water should not be increased by more than 25 mg/L above background levels during any short-term exposure period and no more than 5 mg/L over background levels for long term exposure (CCME, 2002). Background levels are site-specific, but can be generalized for the watershed at 5 mg/L in clear flow conditions, making the short-term guideline about 30 mg/L and the long-term guideline about 10mg/L.

In 2016, the TSS concentrations in all of the subwatersheds were below the short-term guideline the majority of the time (**Figure 3-13**). However, most stations experienced TSS concentrations that exceed both the long-term and short-term guidelines during storm events. Sites with constantly elevated concentrations of TSS, which tend to be located in urbanized subwatersheds, are particularly at risk for problems associated with TSS. The East Holland River had the highest number of samples over the short-term and long-term exposure guideline. The pattern of low concentrations during low flows and higher concentrations during high flows may be exacerbated, at least in part, by farming practices and pressures from urban development. TSS trends are similar to phosphorus where concentrations tend to be decreasing in comparison to the earlier parts of the record but have been stabilizing or increasing in the last decade or so.

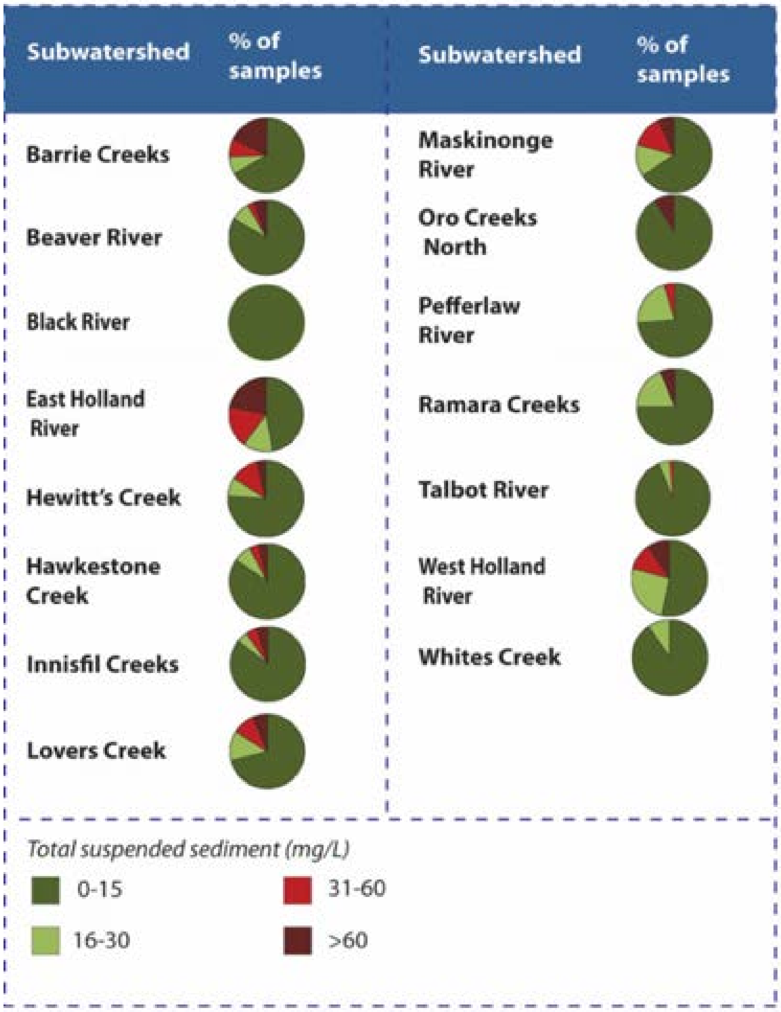


Figure 3-13 Summary of TSS conditions at the Lake Simcoe tributary water quality stations in 2016. Results expressed as the proportion (%) of samples collected at specific concentration ranges.

3.6.2 Climate drivers

More intense rainfall events

In the context of climate change, TSS will be affected by the increased intensity of rainfall events and their ensuing impact on surface runoff and bank erosion. Erosion rates are a function of both rainsplash and runoff. In areas with more level ground, rainsplash is the dominant factor causing erosion. Runoff becomes an increasingly important factor as ground slope increases. Splash erosion detaches soil material, while runoff carries this material as it flows downhill (Battany and Grismer, 2000). More frequent intense rainfall events coincide with heavier runoff events and more soil erosion, especially where soils are loose or exposed (e.g. tilled agricultural fields, construction sites). Consequently, high TSS concentrations are expected during and following these rain events as soil from pervious areas and accumulated grit and dirt from impervious surfaces are washed into streams (Ganpat and Isaac, 2017).

Evidence of a relationship between high flow periods and elevated TSS concentrations has been recorded in both agricultural and urban catchments in the Lake Simcoe watershed (Figure 3-14 and Figure 3-15). While both catchments experienced elevated TSS concentrations during high flow events, these events occurred less often and at a lesser magnitude at the Beaver River station, which is mainly agricultural, than in the East Holland River station, which is highly urbanized. The current and anticipated increase in the frequency of these high-flow events is of concern given their propensity to enhance erosion. As these events disturb and displace mass quantities of soil, private and public infrastructure and property can be damaged, which can subsequently disrupt transportation, energy, communication, and other essential services.

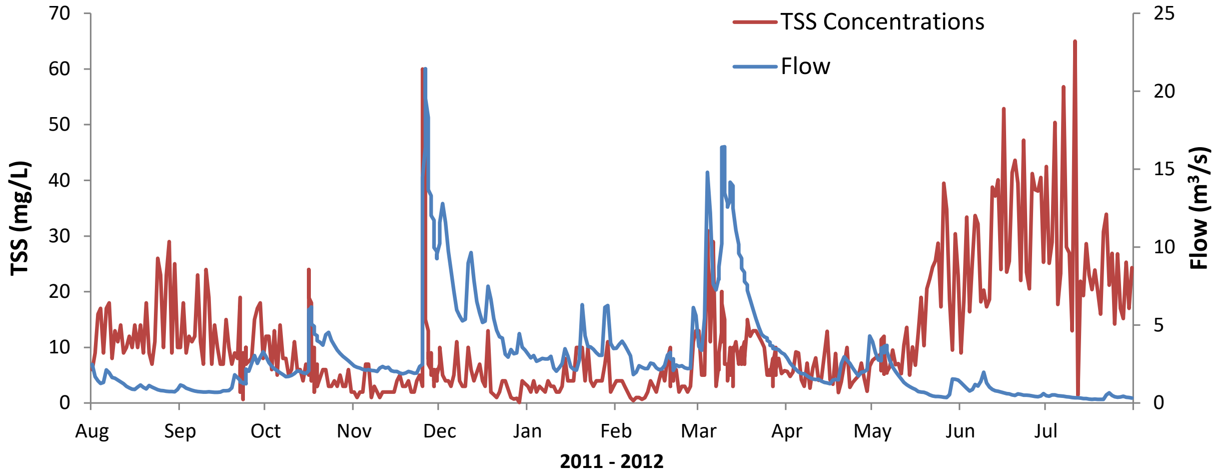


Figure 3-14 Average daily TSS concentrations at the Beaver River station (agricultural catchment).

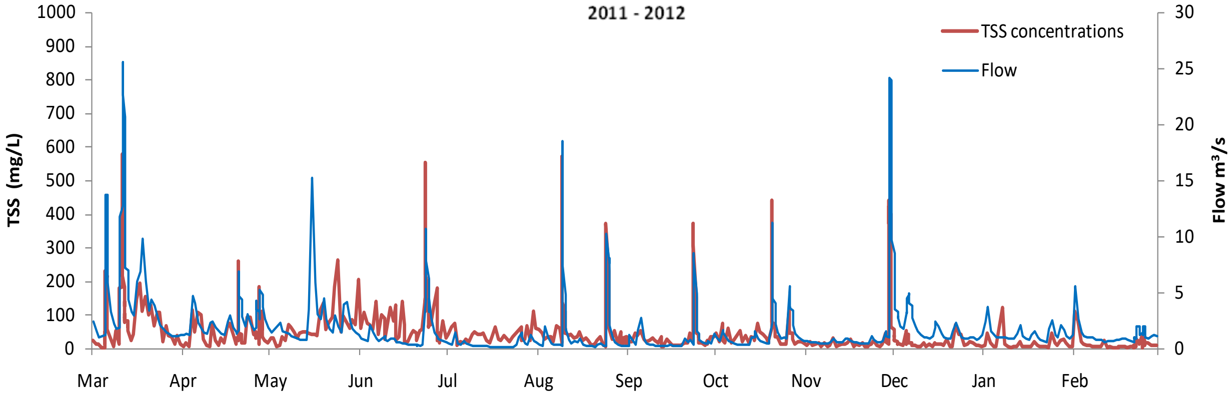


Figure 3-15 Average daily TSS concentrations at the East Holland River station (urban catchment).

Key Points – Total Suspended Solids (TSS)

- More frequent extreme rainfall events are expected to cause heavier runoff events and more soil erosion, especially where soils are loose or exposed. Consequently, high TSS concentrations are expected during and following these rain events.

3.7 Dissolved Organic Carbon

Dissolved organic carbon (DOC) describes the organic material dissolved in water, which results from decomposition of plants and animals. DOC is an important food supplement for many bacteria and microorganisms in the watershed. As these organisms are consumed, DOC moves through the food web;

once plants and animals die, they degrade into detritus and DOC, becoming available for uptake once again. This cycle is known as a microbial loop, and it plays an important role in carbon budgets (Allen, 2017). While many microorganisms depend on carbon for growth, threshold DOC concentrations exist, below which DOC enhances primary productivity, and above which it hinders primary productivity (Seekell et al., 2015). With excess DOC, the leftover carbon must be disposed of via increased metabolic activity and respiration. These carbon fluxes affect carbon balance at the organism and ecosystem level.

Studies suggest that DOC concentrations have been increasing across the watershed.A study by Oni et al. (2014) found that the Whites Creek, Beaver River, Pefferlaw River, Black River, and East Holland River subwatersheds experienced a 13% overall increase in mean DOC export between the 1994–1997 and 2007–2009 periods. While DOC trends have primarily been assessed from a land-use change perspective, there is now concern that climate change will exacerbate these trends as the impacts of warming temperatures and shifting rainfall patterns on DOC export become better understood.

In general, the rate at which soil organic matter decomposes increases in response to rises in temperatures (Jennings et al., 2009). Therefore, DOC concentrations will rise as soil temperatures rise and the nutrients released from soil organic matter can be washed into surface waters (Weyhenmeyer and Karlsson, 2009). By enhancing the rate of microbial breakdown, high summer temperatures are expected to increase the concentration of DOC in the streams during low flows (Oni et al., 2011). However, the presence of a temperature optimum, acclimation to higher temperatures, and depletion of more labile carbon stores in the soil have all been found to contribute to reductions in decomposition rates during long-term studies (Jennings et al., 2009). Furthermore, the concentration of DOC in soils and in streams may not always show an immediate response to a rise in temperature (Clark et al., 2005). Therefore, as soils warm, a delayed corresponding increase in DOC concentration may be experienced in the short-term, followed by declining DOC concentrations in the long-term.

Changes in DOC export are further complicated by shifting rainfall patterns. In winter, DOC stored in soils is flushed by rainfall or snowmelt, with the highest concentrations often coinciding with high runoff levels (Jennings et al., 2009). Therefore, changes in temporal rainfall patterns will exert similar impacts on DOC as they do on phosphorus. A study by Huntington et al. (2016) found that increasing winter temperatures and more runoff will be associated with significant increases in projected DOC concentration and export. Currently, the bulk of export is believed to occur in the spring and summer seasons, but this is expected to shift towards greater export in winter and early spring due to warmer spring temperatures, earlier snowmelt, and more rainfall in this period (Oni et al., 2014). Therefore, higher winter flows could prompt a seasonal shift in the timing of DOC delivery.

DOC delivery may also be impacted by a greater onset of quick flow events. Greater precipitation or discharge is known to increase the concentration and flux of DOC (Jung et al., 2014). In the watershed, an increased number of quick flow events are believed to be responsible, at least in part, for increases in summer DOC flux (Oni et al., 2014). Changes in future precipitation are expected to manifest as more intense storms that deliver more rainfall and produce higher discharge. As a result, more pulsed inputs of DOC to tributaries may occur, meaning that DOC export will likely become flashier in the future.

Wetlands are an important source of DOC, but there is uncertainty regarding how climate change will impact wetland DOC export. Some studies have linked climate change to a decrease in wetland discharge and DOC outflow (Schindler et al. 1996, Clair et al. 1998), while others have argued that declining water levels will expose wetland sediment to aeration and lead to increased DOC (Oni et al. 2012). Whether wetlands can maintain their status as a carbon sink will depend on the changes in magnitude and variability of temperature and precipitation, along with a wetland's existing topography.

Key Points – Dissolved Organic Carbon

- As soils warm, a delayed corresponding increase in DOC concentration may be experienced in the short-term, followed by declining DOC concentrations in the long-term.
- Increasing winter temperatures and more runoff will be associated with significant increases in projected 21st century DOC concentration and export.
- As a result of more frequent intense storm events, more pulsed inputs of DOC to tributaries may occur, meaning that DOC export will likely become flashier in the future.
- Whether wetlands can maintain their status as a carbon sink will depend on changes in magnitude and variability of temperature and precipitation, along with existing topography.

3.8 Pesticides

The term "pesticide" refers to all chemicals that are used to kill or control pests. This includes herbicides, insecticides, fungicides, nematocides, and rodenticides. Surface waters are particularly vulnerable to pesticide contamination because runoff from most agricultural areas drains directly into streams. Many pesticides are potent chemicals with potential effects on human and ecological health, even at very low concentrations. Once they have entered an organism, they can bioaccumulate in food chains and can consequently also influence human health (Pesticide Action Network, 2010). Their cumulative impact is dependent on their toxicity, persistence, degradation process, and environmental fate (FAO, 2018). Despite their potential toxicity, pesticides continue to be widely used to improve crop yields.

The most recent survey of pesticide use in Ontario reported that from 2008 to 2013 overall pesticide usage had increased by 12.4% (Farm and Food Care Ontario, 2015). This rise is largely driven by an increase in the overall hectares planted with corn and soybean, which account for the bulk of pesticide application. In light of a changing climate, both crop yields and pesticide are expected to increase.

Increases in extreme rainfall and flow events can encourage pesticide leaching and reduce pesticide residue on crops, rendering them more vulnerable to pests (Delcour et al., 2015). In response, farmers may have to spray more often during the growing season. Meanwhile, higher moisture and higher temperatures may aid pest and disease invasions, which can also increase the need for pesticides (Delcour et al., 2015). Currently, the majority of pesticides used on Ontario are herbicides, but climate change may result in a greater need for insecticides and fungicides (Farm and Food Care Ontario, 2015). In addition, a lengthening of the active growing season may allow for increased farming, introduction of new crops and a northward crop expansion (Noyes et al., 2009). While this may offer an opportunity to grow new or more crops, the introduction of these crops to new ecosystems and a lengthening of the period in which they require upkeep may ultimately result in a need for additional pesticide applications. With 36% of the watershed classified as agricultural land-use, local changes in the frequency of pesticide application may increase the risk of surface water contamination and subsequent ecological and human exposure to pesticides.

Key Points – Pesticides

- Increases in extreme rainfall events can encourage pesticide leaching in the form of increased flow, which will reduce pesticide residue on crops and render them more vulnerable to pests, requiring more frequent application.
- Additionally, higher moisture and higher temperatures may aide pest and disease invasions, which are expected to increase the need for pesticides.
- Based on the most recent survey, the vast majority of pesticides used on Ontario are herbicides, but climate change may result in a greater need for insecticides and fungicides in the future.
- A lengthening of the active growing season may potentially allow for increased farming, introduction of new crops and a northward crop expansion, all of which may require a need for additional pesticide application.

3.9 Stormwater management ponds

Since 1995, all new development within the Lake Simcoe watershed has been required to include Level 1 stormwater management (SWM) facilities to treat stormwater runoff. These facilities are designed to remove approximately 80% of suspended solids and can reduce phosphorus runoff by 60-90%. By design, stormwater ponds trap silt, sand and other materials, which results in the reduction of pond volume over time, which can hinder their function. Moreover, ponds accumulating particulate phosphorus in the anoxic zone may ultimately become a source of soluble phosphorus (LSRCA, undated). In order to maintain the efficiency of stormwater ponds, LSRCA has actively conducted SWM pond retrofits that aim to enhance their performance.

Loading of suspended solids into watercourses depends on the amount and patters of precipitation, land use, and climate conditions. Increases in rainfall-runoff intensity from extreme events can increase contaminant suspension in runoff and transport it downstream. The current requirement for suspended solids removal is a long-term average removal of 80%. In order to continue to meet this requirement in a changing climate, stormwater infrastructure will need to be designed to control higher amounts of suspended solids that result from more extreme events.

Urban stormwater is a significant contributor of phosphorus to tributaries of Lake Simcoe. The Lake Simcoe Phosphorus Offsetting Policy (LSPOP) provides funding for projects that contribute to phosphorus reduction (e.g. SWM pond retrofits and LID). More intense storms due to climate change could lead to a higher potential for system bypass. Performance monitoring of LSPOP projects may result in design guidance adjustments to anticipated LID performance, including phosphorus reduction.

Additionally, excess road salt entering SWM ponds has become an emerging threat to their performance that will need to be considered in future monitoring and retrofit efforts. In regions with road salting, such as in the Lake Simcoe watershed, ponds have distinct chloride regimes. In summer and fall, SWM ponds are fed by runoff and/or creek streamflow or washout from soils and shallow aquifers; all of which represent natural sources of chloride. With the onset of winter salting operations, concentrations of chloride in runoff, and subsequently in SWM ponds, dramatically increase. Water with higher concentrations of chloride is denser and can enhance chemical stratification. This stratification can be especially resistant to vertical mixing and can contribute to low oxygen concentrations in bottom layers

(McEnroe, 2013). A lack of oxygen in pond sediment can lead to the release of metals and nutrients from the sediment, thereby lessening the ponds' ability to improve water quality. Furthermore, the accumulation of salt in SWM ponds contributes to river chloride concentrations that exceed the chronic exposure guideline as it is slowly released throughout the year.

Evidence of stratification has been recorded at various SWM ponds within the Lake Simcoe watershed, including a commercial lot that was monitored continuously for the ice-free period of 2015 and 2016. During this period, the bottom water chloride concentration remained distinct from the surface layer, indicating stratification (**Figure 3-16**). Subsequent investigations into the impact of land use types on chemical profiles revealed that commercial, institutional, and residential catchments all exhibit chemical stratification, with the severity of stratification and highest chloride concentrations relating to the amount of salt application area in the catchment (Lembcke et al., 2017). Increased salt application in response to changing winter precipitation patterns will continue to enhance chemical stratification in these ponds and subsequently hinder their effectiveness. Hence, mitigation measures will need to be incorporated into future SWM pond retrofits in order to abate the environmental and economic impacts associated with excess salt entering SWM ponds.

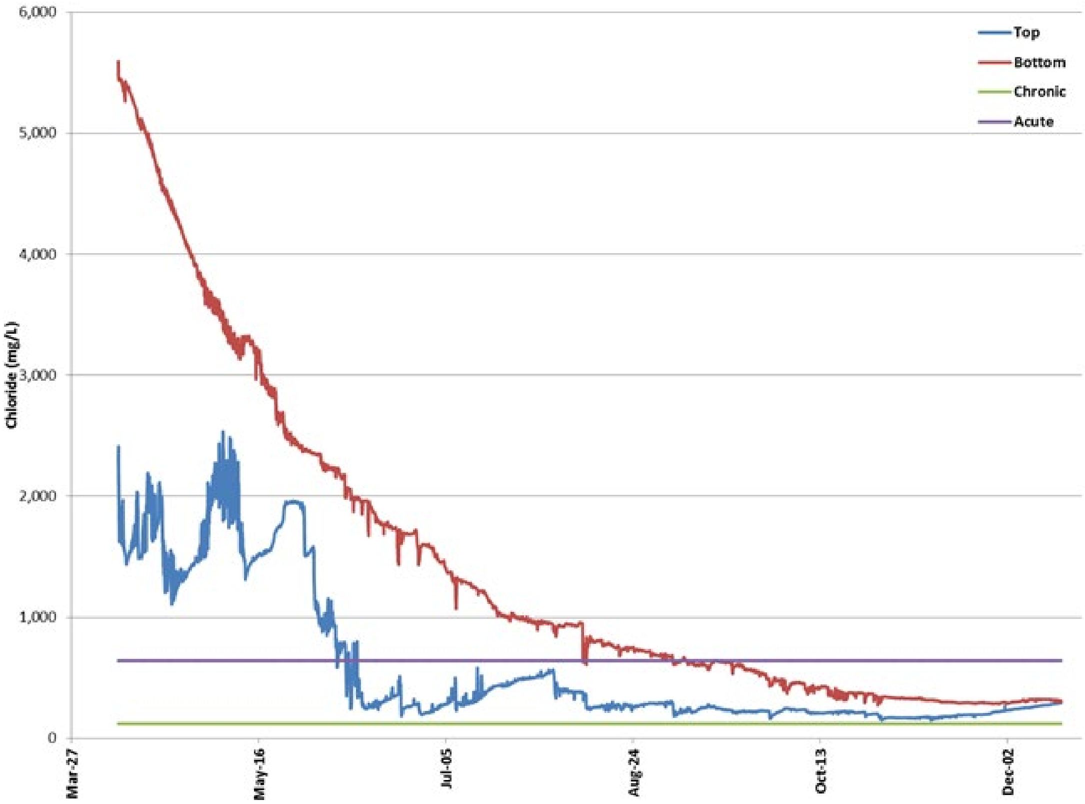


Figure 3-16 Persistent chemical stratification (April through December) in the permanent pool of a commercial parking lot stormwater management pond, compared to the chronic and acute Canadian Water Quality Guidelines.

The temperature of stormwater discharge to streams is an important concern for fish habitat. Warm water can negatively impact aquatic life and causes a decrease in dissolved oxygen. Stormwater ponds often have bottom-draws in an effort to release cooler water from the pond, but this may create concerns related to high salt concentrations due to pond stratification. Future climate predictions, including rising air temperatures, may worsen the impact of warm stormwater discharge on receiving water bodies. Other methods for temperature mitigation should be considered such as cooling trenches, underground cooling chambers, providing shading, increasing permanent pool depth, and orienting a facility to minimize sun exposure (LSRCA, 2016).

Soil erosion is a naturally occurring process where water transports soil particles. The extent of erosion depends on vegetative cover, slope, soil type, and the amount of energy influencing the interaction of water and/or wind with the soil. Sediment-laden runoff can damage downstream systems, so it is important to minimize erosion at the source, contain sediment on site, and treat runoff containing sediment. The current requirement is to provide a temporary sediment pond with 185 m^3/ha of permanent pool storage along with a minimum of 125m^3/ha of active storage. Due to anticipated increases in rainfall intensity due to climate change, these storage sizing requirements for sediment and erosion control may need to be reconsidered for the Lake Simcoe watershed. As mentioned above, increased velocities should be taken into account when creating erosion and sediment control plans.

3.10 Current and future vulnerability assessment

The current and future vulnerability of each watershed indicator for water quality (**Table 3-1**) was developed based on the methodologies described in **Chapter 1 – Introduction**. In summary, the current vulnerability score is a combination of an indicator's degree of sensitivity and exposure to climate change in the present. The future vulnerability combines climate model projections and the degree of confidence to an indicator's current vulnerability score to provide the overall vulnerability score for each indicator.

Table 3-1 Current and future vulnerability of water quality to climate change in the Lake Simcoe watershed

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future
Phosphorus Loading - pulsed	More extreme rainfall	increased runoff and flooding that transports phosphorous into streams	H	VH	VH	VH	VH
Phosphorus concentrations – drought	Drought	Low flow conditions decrease the dilution capabilities of streams	H	VH	VH	H	VH
Phosphorus Loading - Winter	Warmer winter temperatures (more rainfall)	Increased winter flows and decreased summer flows	VH	VH	VH	H	VH
Nitrate concentrations - summer	Warmer summer temperatures	Increased nitrate released from soil organic matter and increased activity of microorganisms	M	M	M	H	M
Nitrate concentrations - winter	Warmer winter temperatures	Less soil frost leads to increased winter activity of microorganisms	L	L	L	H	M
Nitrate concentrations – winter (agricultural tile drains)	Warmer winter temperatures – agricultural tile drains	Unfrozen soils and higher flows lead to more nitrogen seepage and drainage	H	M	M	H	M

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
Chloride concentrations	Warmer winter temperatures (freeze-thaw)	Wetter winter conditions and increased frequency of freeze-thaw cycles leads to more application of winter salt	VH	H	VH	H	VH
TSS concentrations	More extreme rainfall	Increased soil erosion from high flow events	VH	H	VH	VH	VH
Erosion	More extreme rainfall	Increased rainfall can wash away topsoil	VH	H	VH	VH	VH
DOC concentrations - summer	Warmer temperatures	Increased microbial activity	M	H	M	H	M
DOC concentrations - winter	Warmer winter temperatures	Increased flows in winter and decreased flows in the spring	L	H	M	H	M
DOC concentrations - pulsed	More extreme rainfall	Increased runoff and flooding that transports DOC from surrounding landscape	H	H	H	VH	VH
DOC concentrations - wetlands	Drought (wetlands)	Drying of wetlands leads to decreased DOC discharge OR increased DOC resulting from exposed sediment	M	M	M	H	M
Pesticides - rainfall	More extreme rainfall	pesticide leaching (reduced residue on crops)	L	M	L	VH	M
Pesticides - temperature	Warmer temperatures	Increased farming, introduction of new crops and a northward crop migration	L	M	L	H	M

Recommended actions were developed to address these vulnerabilities as the climate changes and they are summarized in **Chapter 8**.

Chapter 4

Water Quantity

4.1 Introduction

Water resources in the Lake Simcoe watershed are driven by the hydrologic cycle (Figure 4-1). When water falls to the ground as precipitation (e.g. rain or snow), it can either absorb into the soil or runoff to a surface waterbody (e.g. stream, wetland, or lake). Water absorbed into the soil infiltrates downwards through spaces in the soil and bedrock, where it recharges the groundwater. Groundwater flows slowly through subsurface soils and rock formations where it may eventually discharge into surface waterbodies, contributing to streamflow. Surface water flows downstream from waterbody to waterbody, eventually reaching the ocean. During many phases of the hydrologic cycle, water can be taken up by plants and transpired or directly evaporated to return into the atmosphere to start the cycle again. This is a general overview of how water travels through the hydrologic cycle; these processes and how they are affected by climate and climate change is discussed further in subsequent sections.

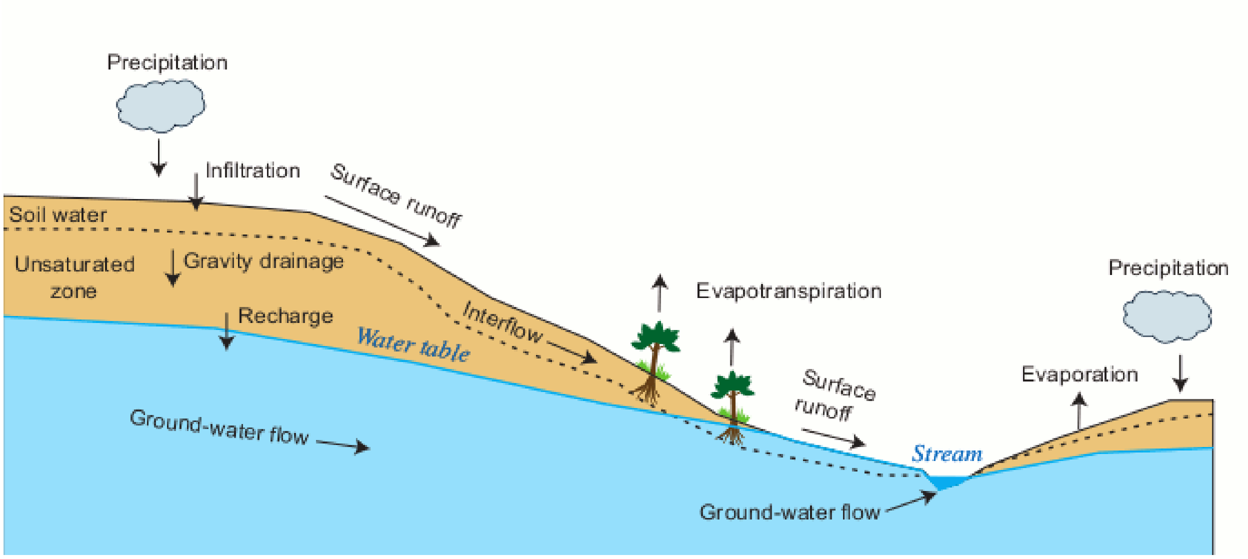


Figure 4-1 The hydrologic cycle (USGS, 2008)

Surface water is the component of the hydrologic cycle that moves overland within lakes, rivers, streams, and wetlands. Surface flow is comprised of both groundwater discharge and overland flow from precipitation and snowmelt runoff. Groundwater discharge to rivers and streams remains relatively constant between seasons, and so forms an important part of the surface water system, particularly when runoff is at its lowest, typically in the summer. Changes in flow regime throughout the year are important for aquatic ecosystems and affect the physical properties of a stream or river.

Groundwater is defined as the water found at, and below, the depth where spaces in soil and rock are filled, or saturated, with water. Above the saturated soils/rock lies the unsaturated (or vadose) zone, where spaces between particles contain both water and air, and where water is described as soil moisture. These two zones (saturated and unsaturated) are separated by what is called the water table.

An aquifer is an area of underground soil or rock that has many spaces between solid particles that store and transmit water easily. Groundwater is pumped from aquifers with wells to provide water for human use. The Oak Ridges Moraine aquifer is a thick sedimentary complex spanning the southern boundary of the watershed. Groundwater discharge from the moraine provides an important source of baseflow to headwater tributaries and wetlands.

While separating surface and groundwater into distinct systems enables easier descriptions of water processes, there is no actual separation and the two interact constantly within the hydrologic cycle.

4.1.1 Factors affecting water quantity

Climatic factors including air temperature, precipitation, and evapotranspiration affect the quantity of water in a system. Warmer air can hold more water, causing more frequent and intense precipitation events which can lead to more surface runoff and less groundwater recharge as the ground becomes saturated quicker during these events. In winter, as air temperatures drop and the ground freezes, precipitation usually falls as snow and groundwater recharge is slowed or stopped by ground frost and the accumulation of snow. Typically, this remains the case until warmer spring temperatures thaw the ground, snowfall turns to rain, and accumulated snow melts in one large pulse called a spring freshet.

Evapotranspiration is water lost to the atmosphere by two processes, evaporation and transpiration. Evaporation is the loss of water from open water bodies, such as lakes, wetlands, and bare soil; transpiration is the loss of water from living plants. Factors affecting rates of evapotranspiration include net solar radiation, surface area of open bodies of water, wind speed, density and type of vegetative cover, availability of soil moisture, air and water temperature, reflective land-surface (albedo) characteristics, and season.

Soil and bedrock properties also exert a significant influence on the availability of water within each phase of the hydrologic cycle. The underlying geology and type of soil present at the surface is one factor that will determine how much water will infiltrate during a precipitation event, and how much will runoff into surface water bodies. For example, loose soils (e.g. sands and gravels) and permeable bedrock will promote groundwater recharge, whereas tighter soils (e.g. silt and clay) and unfractured bedrock will allow less water to infiltrate and reduce groundwater recharge and discharge in a system.

The type of land cover can also significantly alter the surface runoff, evaporation, and infiltration phases of the water cycle. Developed areas have less natural vegetation and more impervious surfaces (e.g. roads, parking lots or building roofs), which do not allow as much water to infiltrate into the ground. Vegetated natural areas will impact groundwater recharge since plant roots utilize soil moisture and groundwater for plant growth, decreasing recharge; however, vegetation can also intercept falling precipitation and slow surface runoff, which can increase recharge. In general, however, LSRCA data indicates that more natural vegetation will increase evapotranspiration rates and decrease baseflow compared to developed areas.

4.1.2 Importance of water resources

Clean surface and ground water are essential for human life and play an integral role in ecological processes and the agricultural, commercial and industrial sectors. As such, balancing water uses and ensuring an adequate supply for each is vital. Residents in the Lake Simcoe watershed rely on both surface water and groundwater for domestic use. Surface water is also important for recreational activities including swimming, boating and fishing for both residents and tourists.

Aquatic ecosystems require a range of surface water levels throughout different periods of the year to maintain function and support the species living within them. Typically, these levels are maintained through groundwater inputs, which sustain the communities through the driest summer periods.

Groundwater inputs also provide cooler water, which maintains a thermal regime suitable for cold- and cool-water species. Additionally, high flow pulses following precipitation events are important for shaping the channels, flushing the systems and providing connectivity with surrounding habitats.

4.1.3 Climate change and water quantity

Climate is intimately interwoven into the hydrologic cycle. Climate change can impact water resources through changes in precipitation patterns, temperature, soil and air moisture, evapotranspiration, freeze-thaw cycles, and extreme weather events (Huntington, 2006).

Based on climate projections, in general the watershed is expected to see warmer winters with more precipitation falling as rain than snow; warmer springs, with snowmelt occurring earlier; hotter, drier summers with increased chances of drought; and warmer autumns, extending the growing period. Due to warmer air temperatures, more intense, isolated precipitation events and more extreme weather are also expected. Detailed climate projections are outlined in **Chapter 2 –Climate Trends and Projections**.

As a result, numerous changes are expected to occur throughout the hydrologic cycle. Groundwater recharge is expected to increase in the winter and decrease in the spring and summer, impacting the amount of groundwater within aquifers as well as discharge rates in these seasons. Additionally, climate change is expected to alter streamflow regimes, causing more winter flooding and lower summer flow rates. Because the hydrologic cycle in interconnected, changes in one phase can affect all other phases and so the impacts of climate change on water resources may be far-reaching throughout the watershed.

4.2 Groundwater recharge

4.2.1 Overview

Temperature and precipitation are the greatest climatic factors affecting recharge rates. In winter when temperatures are lower and the ground is frozen, water cannot infiltrate as easily and either accumulates as snow which then melts in the spring or runs off to surface waterbodies. In contrast, during periods of high precipitation (generally in the spring and fall in Ontario), recharge rates are higher as more water is available. However, during very intense precipitation events the soil becomes saturated and recharge drastically slows, causing excess water to run off into surface waterbodies instead of infiltrating into the ground.

4.2.2 Current status

Average annual precipitation in the watershed ranges from 781.3 mm/year to 1220 mm/year (data range: 1973-2018; standard deviation = 99.4) and is the primary source of recharge to aquifers. Recharge rates in the watershed range from 0 to 675 mm/year, (**Figure 4-2**) with a mean of 164 mm/year and is highest in areas along the boundaries between surficial soils of high permeability (e.g. gravels and sands) and low permeability (e.g. silts, tills and clays). In these areas, the low permeability soils generate overland runoff that flows onto high permeability soils, where it infiltrates and recharges the groundwater system (AquaResource and Golder, 2010). The Oak Ridges Moraine is considered to be a regionally significant recharge area with estimated average recharge of 360mm/year, reflecting the coarse-grained nature of the surficial soils and moraine topography. Other areas of relatively high recharge include the Oro Moraine and the Carden Alvar.

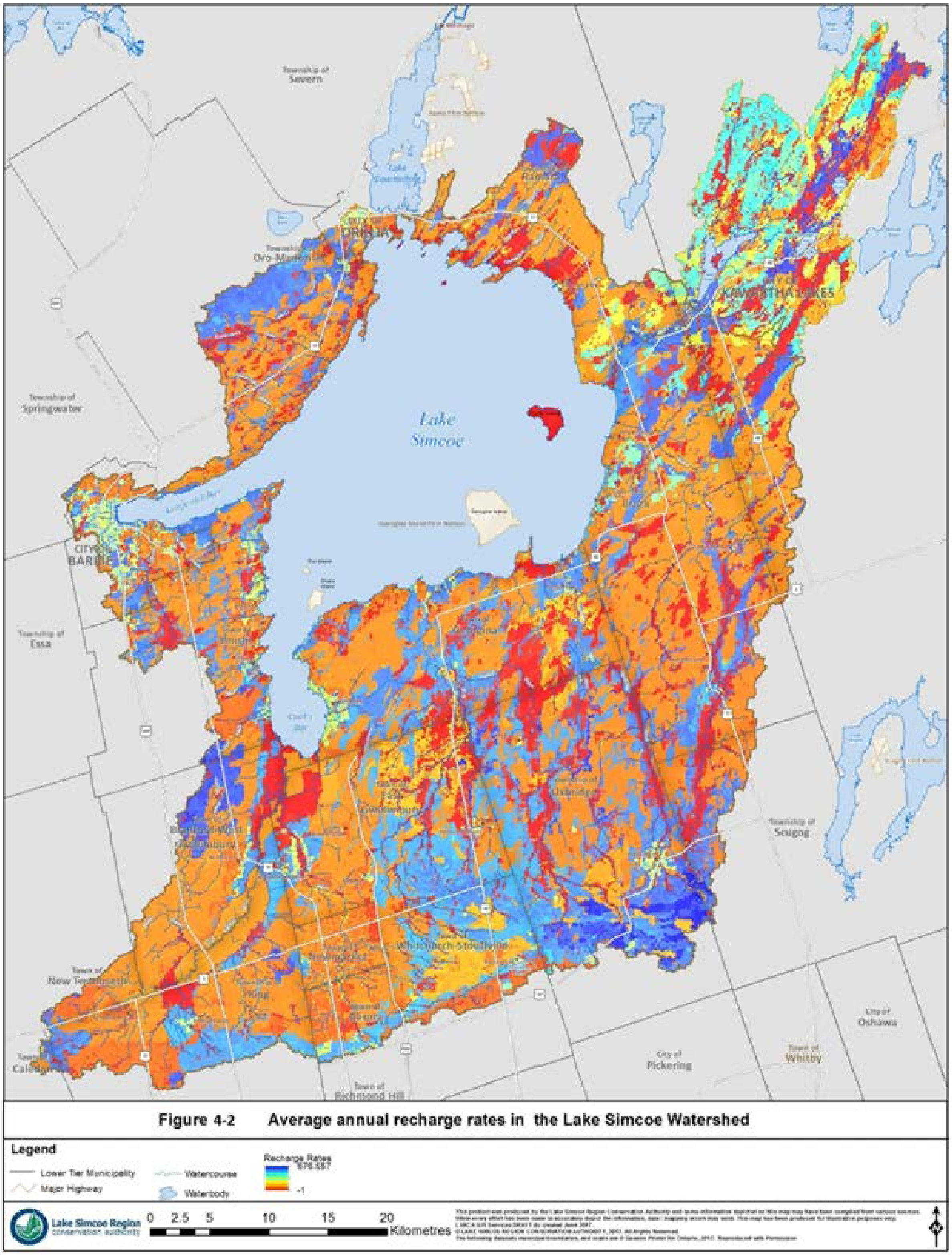


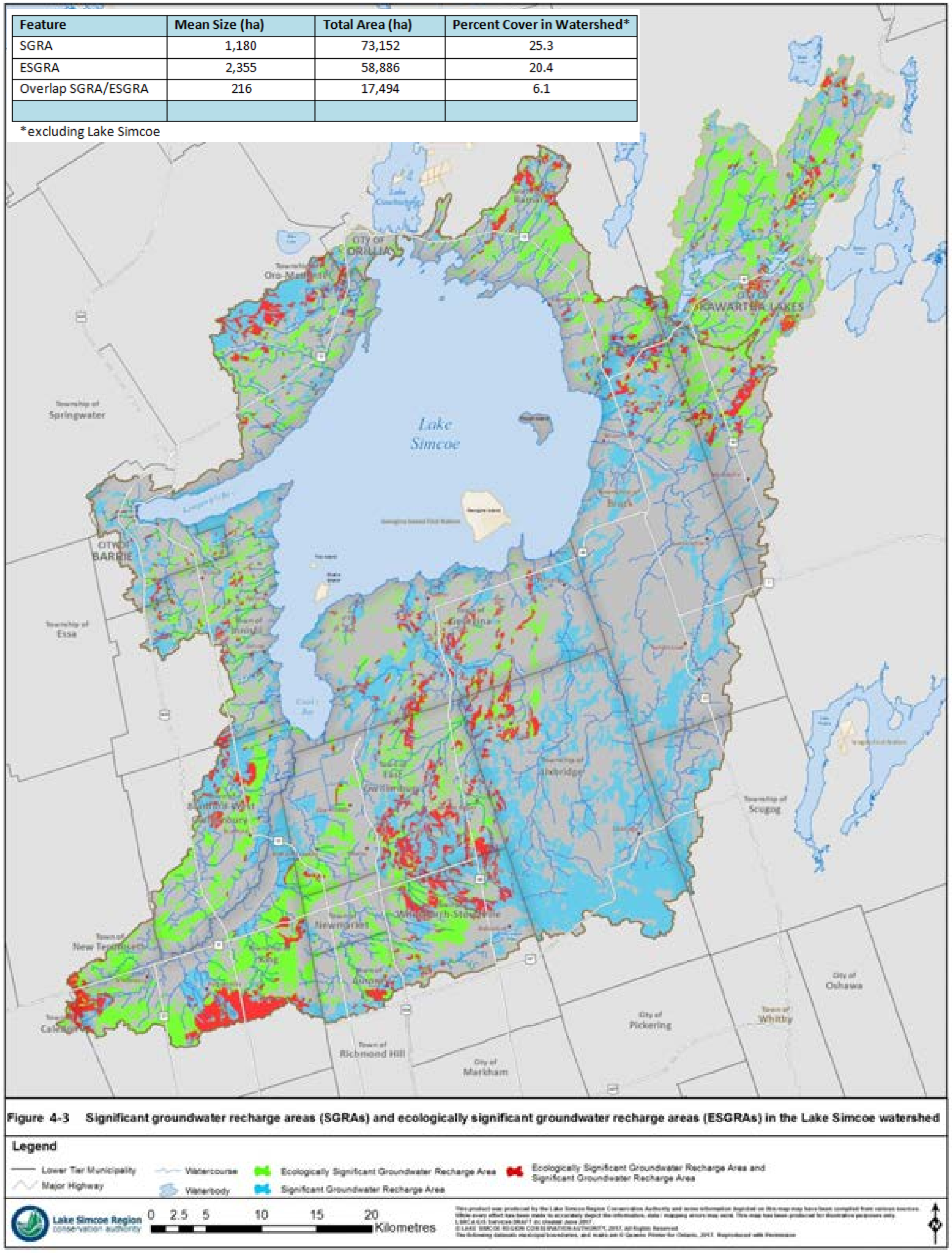
Figure 4-2 Average annual recharge rates in the Lake Simcoe watershed.

Areas that infiltrate relatively high volumes of precipitation and maintain water levels in an aquifer are called significant groundwater recharge areas (SGRAs). SGRAs represent areas where recharge is at least 15% greater than the mean recharge across the watershed. Areas where groundwater recharge provides the water that sustains sensitive ecological communities (e.g. coldwater streams and wetlands) are called ecologically significant groundwater recharge areas (ESGRAs). ESGRAs are determined from reverse particle tracking which shows the groundwater flow path (distance and extent) from the ecological feature to where the water originated at surface (i.e. where recharge that sustains the feature originates) (Marchildon et al., 2015).

SGRAs are found throughout the watershed but are concentrated in areas of high soil permeability (e.g. the Oak Ridges and Oro Moraines, and other areas with sandy soils). As expected, areas with tighter soils (e.g. the Schomberg Clay Plains) have few to no SGRAs. ESGRAs are scattered more evenly throughout the watershed and are typically found near wetland or stream features. The locations of SGRAs and ESGRAs in the Lake Simcoe watershed are shown in **Figure 4-3**.

In contrast to SGRAs, ESGRAs are not necessarily related to the volume of recharge that may be occurring but are instead determined by their importance to ecological communities. Therefore, ESGRAs will not always coincide with an SGRA, as they may not represent areas of high volumes of recharge. However, where ESGRAs and SGRAs do overlap, these areas provide very significant volumes of recharge to ecologically sensitive features and for human use. Overlap areas cover approximately 6% of the land in the watershed (**Figure 4-3**) and will be important to protect since they provide high volumes of groundwater to ecologically significant features.

Climate change impacts such as higher temperatures, reduced summer precipitation and extended growing season can contribute to reduced recharge rates. Lower recharge rates in areas of combined ESGRA-SGRA have the potential to impact ecologically significant features such as wetlands and coldwater streams. As the climate changes, it will become increasingly important to protect recharge rates, especially within the high volume ESGRA areas and to ensure that permitting of groundwater extraction considers the impact of climate change.



Feature	Mean Size (ha)	Total Area (ha)	Percent Cover in Watershed*
SGRA	1,180	73,152	25.3
ESGRA	2,355	58,886	20.4
Overlap SGRA/ESGRA	216	17,494	6.1

*excluding Lake Simcoe

Figure 4-3 Significant groundwater recharge areas (SGRAs) and ecologically significant groundwater recharge areas (ESGRAs) in the Lake Simcoe watershed

Figure 4-3 Significant groundwater recharge areas (SGRAs) and ecologically significant groundwater recharge areas (ESGRAs) in the Lake Simcoe watershed (Earthfx, 2014). Areas where SGRAs and ESGRAs overlap may be more resilient to climate change. Note: ESGRAs have not been fully mapped in Durham Region

4.2.3 Climate change risk and vulnerabilities

Groundwater recharge is influenced by climate change through changes in precipitation and evapotranspiration. Models predict that with climate change, summer precipitation will decrease and evapotranspiration will increase over a longer growing season (see **Chapter 2 – Climate trends and projections**). Over time, less water will become available for recharge, potentially reducing summer water storage as plant and human water demands continue to increase. In addition, wind can further increase water loss from evaporation and runoff on drier soils (Jykarma and Sykes, 2007). Understanding the dynamics of climate driven changes to recharge timing, volume and location may provide information for identifying vulnerable groundwater areas.

According to climate models, the amount and timing of recharge occurring in each season is expected to shift in response to climate change. These shifts will be variable across the watershed, with areas of high soil or bedrock permeability (e.g. SGRAs and alvars) experiencing increased recharge and areas including stream valleys and other discharge areas seeing localized decreases in net recharge (EarthFx, 2014). As such, some areas may be more resilient to the impacts of climate change if recharge rates are maintained or increase into the future. However, because travel times of groundwater from the capture zone to discharge point can take upwards of 10,000s of years, impacts to recharge may only be apparent in the long term (Chen et al., 2004). Additionally, it is unknown whether any increases in recharge will balance any deficits resulting from climate change under future scenarios and how this will affect water budgets across the watershed.

The Tier 2 water budget, ESGRA and climate change assessment for the Ramara Creeks, Talbot River and Whites Creek subwatersheds evaluated the effects of climate change on the regional hydrologic and hydrogeologic conditions (EarthFx, 2014). This study modelled a series of nine long-term (29-year) climate change scenarios. The percentile method was used to select the GCM/Emissions scenarios for a baseline (1971-2000) and future (2041-2070) period. Overall, the study predicted that changes to groundwater recharge under various climate change scenarios would vary seasonally. This modelling was only completed for this study area, although results may be extrapolated to other subwatersheds.

Change in significant recharge timing

Historically, large significant recharge events occur in the spring, when increased precipitation and melting snow infiltrate through the thawing ground and into the water table. However, with projected warmer winter temperatures and increased precipitation, this significant recharge period is expected to occur earlier in the year.

Winter air temperatures and the number of winter days above freezing are predicted to under future climate conditions (see **Chapter 2 - Climate Trends and Projections**). Additionally, the likelihood of frost occurring is predicted to decrease by up to 30% by 2080. Together these data suggest that as the ground becomes less frozen and precipitation increases throughout the winter period, the significant amount of recharge we typically see in the spring may shift earlier. This agrees with Okken and Klove (2010) who found that increasing temperatures are expected to reduce snow cover and soil frost in northern environments above 60° latitude, increasing the potential for maximum recharge occurring earlier in the year in shallow unconfined aquifers. A study by Jyrkama and Sykes, (2007) also found evidence that climate change will likely result in increased winter recharge rates due to changes in the volume and timing of spring melt, allowing more water to recharge in colder months.

Warmer and wetter winters allow more water into the groundwater system. The tier 2 water budget and climate change assessment predicted that recharge would significantly increase in the fall and winter months, compared to baseline scenarios (EarthFx, 2014) (**Figure 4-4**).

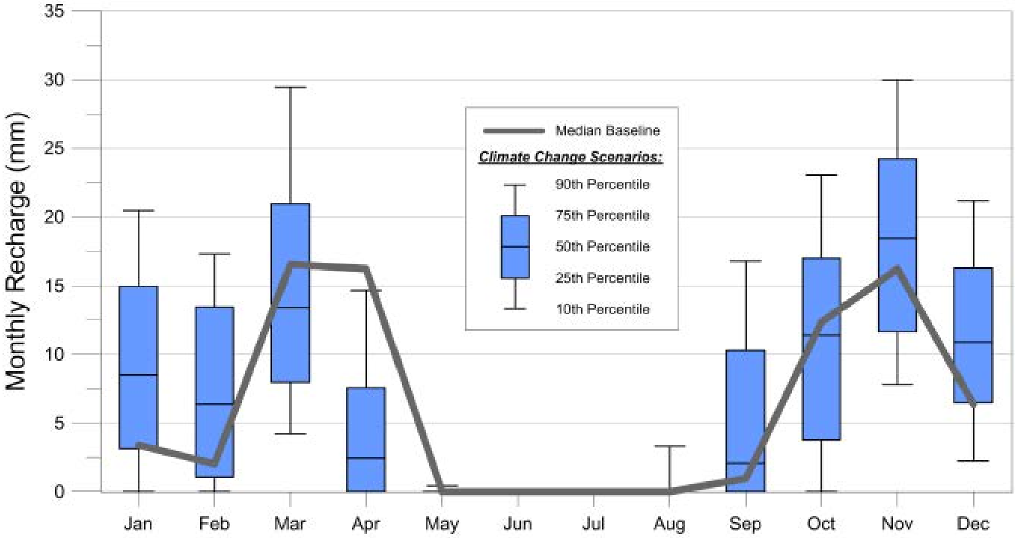


Figure 4-4 Median monthly groundwater recharge is expected to increase significantly in the late fall and winter months, and decrease in March and April (Earthfx, 2014).

Changes in groundwater recharge are not only expected to be seasonal but will also vary spatially throughout the watershed. As mentioned above, areas with more permeable soils will infiltrate more water from the surface to an aquifer. As climate change progresses, certain areas of the watershed such as the Carden Alvar (**Figure 4-5**) are expected to increase in annual recharge by up to 60 mm/year, and much of this increase may occur over the winter months.

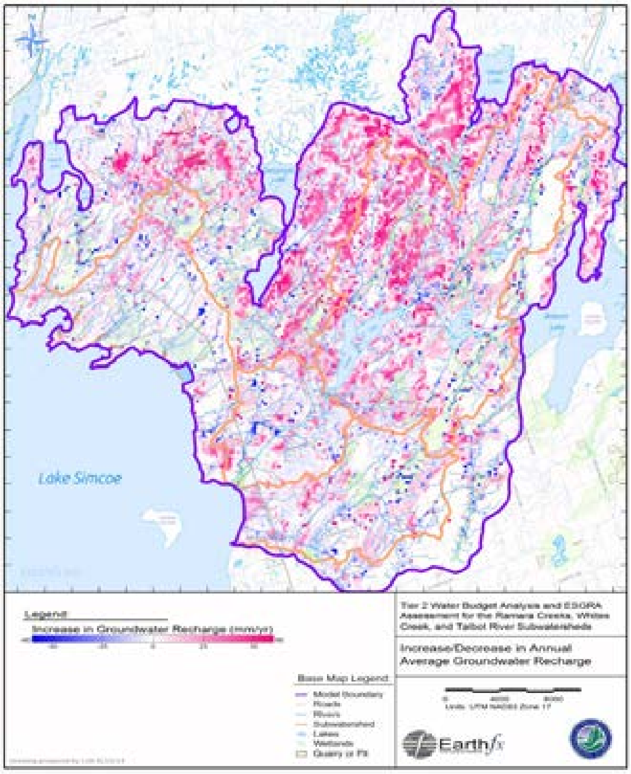


Figure 4-5 Projected changes in groundwater recharge under climate change models (Earthfx, 2014). Recharge is expected to increase primarily in alvar-dominated soils, with little to no increase in till covered areas.

The majority of recharge occurring in the Oak Ridges Moraine area discharges to streams on the flanks of the moraine with the remaining water moving to deeper aquifers. Although climate change is not likely to reduce recharge volume in the Oak Ridges Moraine, it is possible that recharge will increase in the winter as more cold-season precipitation enters the groundwater system. As a result, recharge volumes in the early spring will likely decrease and occur earlier in the season in the future. The greatest impacts are expected to be the cascading impact on the timing and volume of groundwater discharge to streams and wetlands (further discussed below).

Increased winter recharge is not necessarily a negative impact of climate change since it can replenish aquifers throughout the year. However, it can affect water resources throughout the rest of the hydrological cycle (e.g. decreased freshet volumes, lower spring recharge, or longer low-flow periods).

Decreased summer recharge

While the total summer precipitation is only projected to decrease slightly in future climate scenarios, the precipitation is expected to fall in heavier, more isolated events (see **Chapter 2 – Climate Trends and Projections**). So, while summer precipitation is becoming heavier and more frequent, the total volume of precipitation is decreasing due to shorter and more isolated events. During intense storm events, the soil becomes quickly saturated and more water flows overland to surface waterbodies, leaving less to infiltrate into the soil and recharge groundwater aquifers.

Additionally, during the summer months, air temperatures and rates of evapotranspiration increase, removing soil moisture that could otherwise infiltrate to the water table. Together, these are expected to decrease overall groundwater recharge rates throughout the summer period (Earthfx, 2018), which can affect groundwater discharge to surface water and extend the low flow period, as will be discussed in further sections.

A decrease in summer recharge may have the greatest impact on ecological features depending on groundwater inputs from ESGRAs. Since ESGRAs provide an important but not necessarily large volume of groundwater to these sensitive features, they may be more vulnerable to decreased recharge. Depending on groundwater travel times, it may take a longer time to observe any impacts (Earthfx, 2011), but sustained decreases in recharge may impair ecological function over time.

These impacts can be further exacerbated by human influences such as water takings and land development. For example, during dry summers, municipal and agricultural water takings may increase to meet demand. Additionally, increased development leads to more impervious surfaces, which can further reduce recharge. It is important to protect both SGRAs and ESGRAs to mitigate some of these effects as climate change continues. Projected changes in groundwater recharge can ultimately influence groundwater levels and the availability of these water resources for human consumption and discharge to surface waterbodies.

Key Points – Groundwater Recharge

- Areas where SGRAs and ESGRAs overlap may be more resilient to climate change
- As winter temperatures increase, the timing of significant groundwater recharge rates is expected to shift earlier in the year, as more precipitation falls as rain and the ground remains less frozen throughout the season.
- Areas where ESGRAs exist, but not SGRAs (i.e. areas that provide important groundwater inputs, but recharge is not significant) may represent areas more vulnerable to climate change.
- Following more freeze-thaw cycles and less snow accumulation throughout the winter, spring recharge rates will likely decrease, impacting the rest of the hydrologic cycle.
- As summer temperature and evapotranspiration rates increase, and extreme precipitation events become more common, groundwater recharge in this season may decrease.
- Climate change impacts may be delayed or minimized in areas where groundwater travel times are slow.

4.3 Groundwater levels, flow and availability

4.3.1 Overview

To understand historical changes in water levels and therefore water availability, static water levels and temperature data can be collected continuously using of data loggers. Within the Lake Simcoe watershed, the LSRCA operates 13 monitoring wells as part of the Provincial Groundwater Monitoring Network (PGMN) at 9 sites (**Figure 4-6**). Of these monitoring wells, seven are considered shallow wells and six are deep (**Table 4-1**). Nine of the wells also appear to be screened in unconfined aquifers. An unconfined aquifer is a geologic unit that allows water to flow easily within it and where water infiltrating from ground surface can directly move into the aquifer without obstruction. As a result of the communication between atmospheric conditions and unconfined aquifers, climate-influenced changes in groundwater physical properties and levels are expected to first be observed in these aquifers before confined or significantly deeper aquifers.

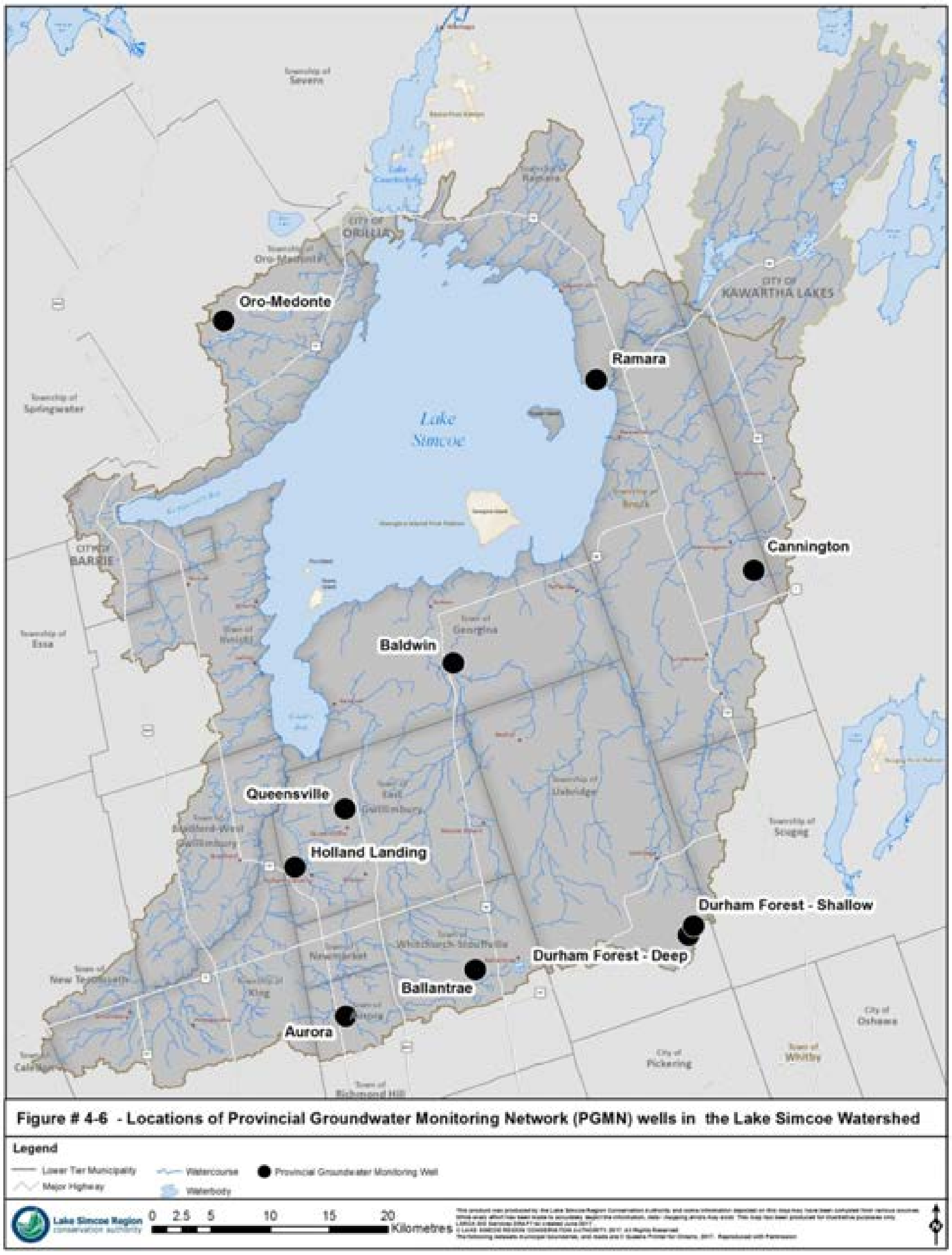


Figure 4-6 The locations of Provincial Groundwater Monitoring Network (PGMN) wells in the Lake Simcoe watershed

A number of climatic factors may be impacting groundwater levels, flow and availability. During wet periods, as more precipitation infiltrates into the groundwater, water within the unsaturated zone will likely increase and groundwater levels and discharge are likely to increase. Increased soil moisture near the surface may increase flood risk during spring when streamflow is already high. Climatic impacts to groundwater systems from persistent and severe dry periods have also been shown to alter the rate of flow in aquifers (Chen et al., 2004). Factors impacting groundwater flow and availability interact in complex ways; therefore, it may take several years before the impacts of climate change on groundwater systems become evident. Continued data collection (particularly at established PGMN monitoring sites with a long data record), research and adaptive management will support the understanding of these interactions over time.

4.3.2 Current status

The current status of groundwater resources in the Lake Simcoe watershed were assessed based on PGMN data as well as tier 1 and 2 water budgets. The long-term and short-term (seasonal) data were analyzed to determine any significant trends in water level over time.

Long-term water level trends

While it is difficult to isolate purely climate-driven effects on water level, especially because of the numerous permitted water takings in the watershed, long term groundwater level trends may provide an indication of significant climate shifts. To understand these long-term trends in groundwater level, the entire data period for each PGMN well was analyzed. Water level trends (in metres above sea level [masl]), period of record and aquifer characteristics are listed in **Table 4-1**.

Table 4-1 Descriptions of the Provincial Groundwater Monitoring Network wells in the Lake Simcoe watershed. Wells deeper than 20m are considered deep and unconfined aquifers are influenced by surface conditions.

Well ID	Location Name	Well Depth	Aquifer	Period of Record	Water Level Trend	Geologic Formation
W0000063-3	Holland Landing	Shallow	Unconfined	2001-2018	Increase 0.3 masl	Oak Ridges Moraine Aquifer Complex
W0000283-1	Aurora	Deep	Unconfined	2003-2018	Increase 1.5 masl	Isolated channel sediments
W0000025-1	Queensville	Shallow	Unconfined	2001-2018	Decrease 0.7 masl	Newmarket Till
W0000071-1	Ballantrae	Deep	Confined	2001-2018	Increase 0.8 masl	Scarborough Formation
W0000298-2	Baldwin	Shallow	Unconfined	2003-2018	Decrease 5.0 masl	Newmarket Till
W0000298-3	Baldwin	Deep	Confined	2003-2018	Decrease 1.7 masl	Scarborough Formation
W0000298-4	Baldwin	Deep	Confined	2003-2018	Decrease 0.3 masl	Bedrock Aquifer
W0000039-1	Durham Forest	Shallow	Unconfined	2001-2018	Increase 0.2 masl	Newmarket Till
W0000032-1	Durham Forest	Deep	Unconfined	2001-2018	Increase 0.7 masl	Newmarket Till
W0000062-1	Cannington	Shallow	Unconfined	2001-2018	Increase 0.5 masl	Newmarket Till
W0000408-1	Ramara	Shallow	Confined	2005-2018	Increase 0.5 masl	Bedrock Aquifer
W0000293-2	Oro-Medonte	Shallow	Unconfined	2003-2018	Increase 0.6 masl	Newmarket Till
W0000293-3	Oro-Medonte	Deep	Unconfined	2003-2018	Increase 1.5 masl	Newmarket Till

The water levels in most wells, with the exception of Baldwin and Queensville, show a slight upward trend with an average rate of 0.07 m/yr. Large fluctuations in groundwater levels could be attributed to changes in temperature and precipitation affecting the recharge of this aquifer over the long-term, and/or to changes in permitted water takings. It should be noted that there is currently no simple mechanism for separating out long-term changes in groundwater levels associated with climate change rather than other drivers (e.g. water takings). Further work needs to be done to determine how the PGMN can be used to assess and climate-related trends.

Short-term water level trends

Short-term water level trends can provide an understanding of changes in the aquifer on a seasonal basis. Wells in unconfined aquifers may show significantly more seasonal water level fluctuations than deeper wells as a result of their interaction with the surface. The magnitude of water level changes within the well can provide some indication of the susceptibility of the aquifer to withstand drought and local water taking activities, and its resilience to climate change.

Short-term water level trends can also provide insight on the response of an aquifer to precipitation events and recharge processes. The short term water level trends displayed by the PGMN wells, within the Lake Simcoe watershed, indicated that the majority of wells experience seasonal water level fluctuations. In general, higher groundwater levels are observed during late winter and spring in response to increased recharge from snow melt and precipitation events (**Figure 4-7**). Lower groundwater levels are observed during the summer and autumn when average precipiation is at its lowest. The exceptions to this trend are the Durham forest (deep well), Ballantrae, and Oro-Medonte wells, which are influenced by nearby permitted water takings (e.g. municipal drinking water supply wells or groundwater extraction by an aggregate pit).

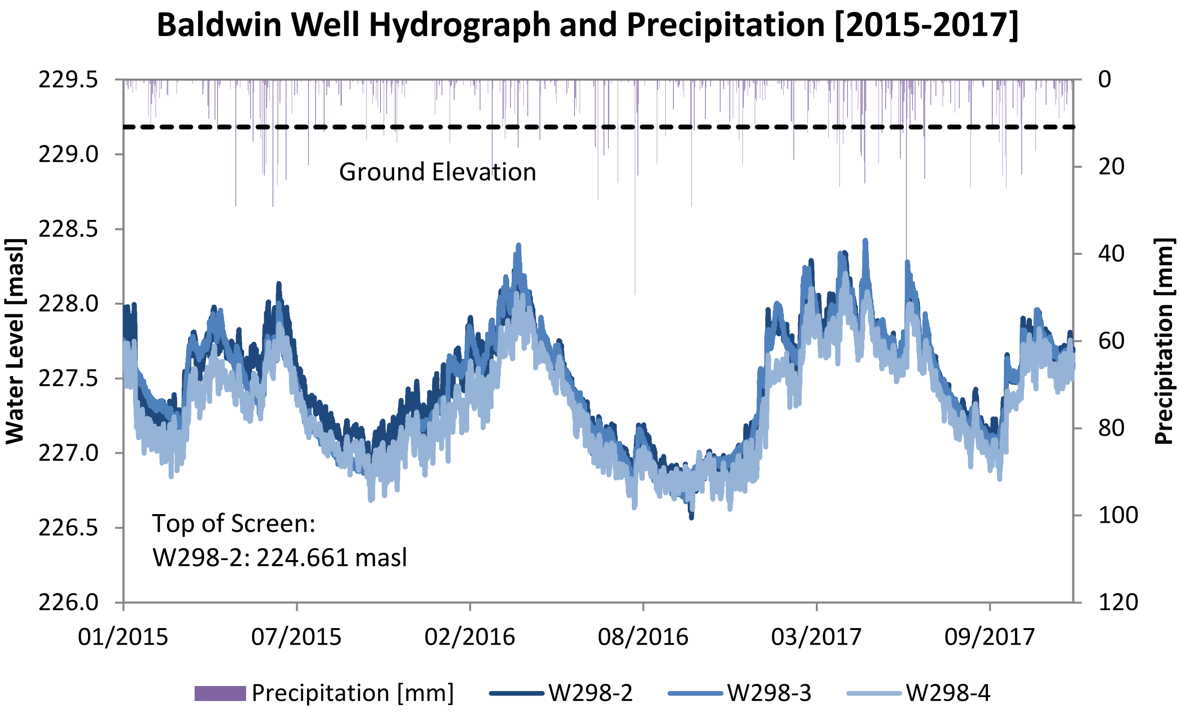


Figure 4-7 Groundwater level and precipitation at the shallow (W298-2) and deep (W298-3 and W298-4) depth Baldwin wells showing seasonal trends.

Monitoring multiple depths at the same location can give information about the underlying aquifer. They can also provide insight into long-term, climate-driven changes in the available water within aquifers. However, current understanding of climate impacts on seasonal water levels is limited and a more detailed analysis of all factors impacting water levels is recommended in order to adjust for potential influences from other factors.

Water budgets

Groundwater models and water budgets are useful tools for understanding the movement and interaction groundwater systems and other components of the hydrologic cycle. Groundwater models try to recreate the current groundwater system in order to run simulations to predict future groundwater conditions (e.g. water levels or flow direction). Water budgets are calculations that determine the distribution of water within the different components of the hydrologic cycle in order to quantify the amount of present at a specific location. For each of Lake Simcoe's subwatersheds, current and future groundwater conditions were estimated using groundwater models of varying complexity. Water budget estimates were produced from the model, giving a range of outputs including water supply, consumption and reserve estimates, as well as permitted and non-permitted water extractions (Earthfx, 2010). Various elements of the hydrological cycle (e.g. precipitation, evapotranspiration) were quantified to identify areas where water supply may become stressed in the future.

Tier 1 water budget estimates were completed for all subwatersheds in 2009 and provided a rough estimate of future water demand and stress levels based on current usage and projected growth (SGBLS SPR, 2009). This assessment estimated that two subwatersheds would be significantly stressed in the future and four would be moderately stressed (**Table 4-2**). Tier 2 water budgets have also since been completed, which take a more in-depth assessment of water inputs and demands. These assessments showed that while the estimated future stress level of four of these subwatersheds remain the same, two (Uxbridge and Hewitts) are now expected to have low levels of future stress. Most of these areas with higher projected stress to water resources are the more developed subwatersheds with more demand for water (from higher population densities).

Table 4-2 Model estimates of future stress on groundwater resources for various subwatersheds from Tier 1 and Tier 2 water budgets

Subwatershed	**Tier 1 Assessment**		**Tier 2 Assessment**	
	Future Water Demand (%)	Future Stress Level	Future Water Demand (%)	Future Stress Level
Barrie Creeks	165	Significant	-	Significant
East Holland River	75	Significant	35.2	Significant
Maskinonge River	20	Moderate	14.1	Moderate
West Holland River	13	Moderate	10.5	Moderate
Uxbridge Brook	17	Moderate	5	Low
Hewitts Creek	11	Moderate	9	Low
Black River	5	Low	7.7	Low
Pefferlaw Brook	4	Low	5	Low
Beaver River	3	Low	5	Low
Innisfil Creeks	3	Low	3	Low
Lovers Creek	9	Low	9	Low
Talbot River	4	Low	6.5	Low
Whites Creek	0	Low	0.2	Low
Georgina Creeks	6	Low	4.9	Low
Hawkestone Creek	1	Low	0.8	Low
Oro Creeks North	1	Low	0.8	Low
Oro Creeks South	6	Low	3.1	Low
Ramara Creeks	1	Low	2.5	Low

🟩 10 – 24% of available supply being taken

🟥 25% or more of available supply being taken

The tier 2 stress and drought assessment for Ramara Creeks, Whites Creek and Talbot River (EarthFx, 2014) showed that under current and future (20-year) conditions, groundwater stress in the subwatersheds is low (0.2 - 6.5% water demand). However, the two-year (extreme) and 10-year (historic) drought conditions scenario predicted significant impacts on water resources, with the greatest impacts observed in headwater tributaries, which are sustained mainly by groundwater discharge that occurs where the streambed intersects the water table. Further research into the predicted climate change impacts on groundwater resources in other areas of the watershed could determine if similar trends are expected elsewhere and could help prioritize areas for protection.

Future stress to groundwater resources can come from human factors (e.g. development or municipal water takings) or climate change drivers (e.g. increased temperature). Additionally, these factors can work together to further exacerbate stressed aquifers. Understanding how future climate and demographic changes will impact groundwater resources using tools such as water budgets and modelling will help manage this stress moving forward.

Within the watershed, water demand from municipal and non-municipal permitted wells compete for water within the same aquifer resources. Higher temperatures, reduced summer precipitation and extended growing season can contribute to lower groundwater levels. This can impact ESGRAs and lead to decreased discharge to significant ecological features and therefore, increase the vulnerability of ESGRAs to both climate and human pressures. As the climate warms, it will become increasingly important to buffer against changes in climate and non-climate related recharge rates and ensure that groundwater extraction does not negatively impact groundwater dependent ecosystems.

4.2.3 Climate change risk and vulnerabilities

Temperature and precipitation are the biggest climate drivers influencing groundwater levels. The Intergovernmental Panel on Climate Change Water Working Group found that water levels in some aquifers in many temperate regions are influenced by temperature, albeit to a lesser extent than precipitation, which directly impacts water levels (Kundzewicz et al., 2007). However, as temperature increases, its impact on water levels increases, and in shallow aquifers temperature can have a greater influence than precipitation (Chen et al., 2004).

Increased winter groundwater levels

Typically, groundwater levels are lower in the winter and then peak in the spring after the ground thaws and rainfall increases. However, with higher winter temperatures, less frozen ground, more freeze-thaw cycles, and more precipitation falling as rain, recharge and therefore groundwater levels can increase throughout the season. According to the tier 2 water budget and climate change study for Ramara Creeks, Whites Creek and Talbot River (EarthFx, 2014), an increased proportion of rain (compared to snow) and more freeze-thaw cycles during the winter months, are predicted to increase groundwater levels in this period (**Figure 4-8**). Additionally, wells that currently show a seasonal pattern could shift to more constant levels year-round. In contrast, a peak in groundwater levels in the winter could affect the amount of water available during the drier summer season, potentially affecting ecological systems dependant on groundwater discharge.

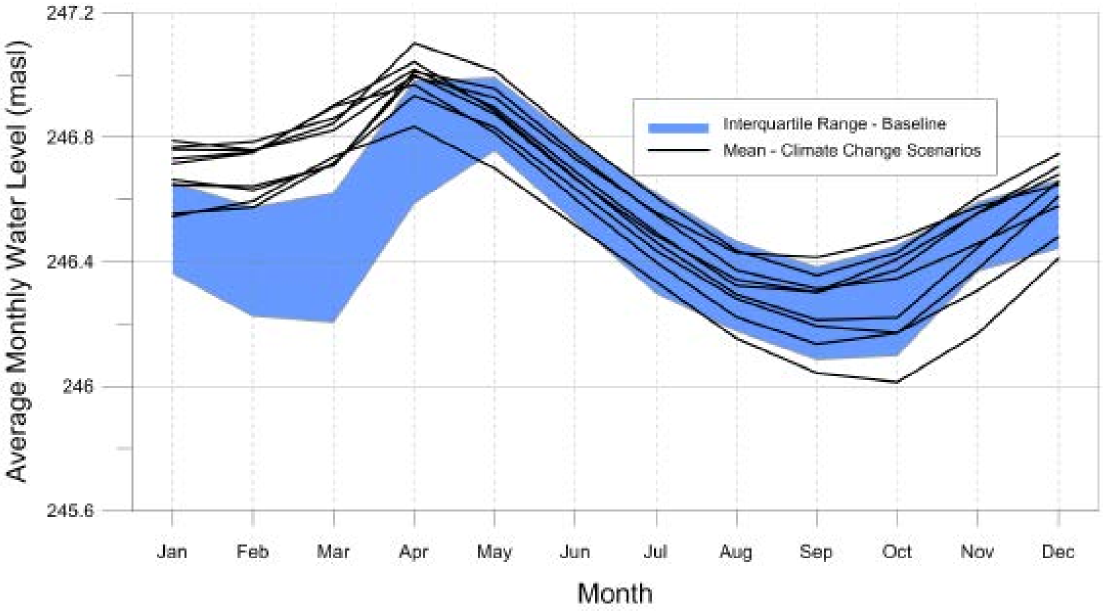


Figure 4-8 Average simulated monthly groundwater levels in the Upper Ramara subwatershed (Earthfx, 2014).

Decreased summer groundwater levels

Shifts in peak recharge, decreased spring recharge, higher summer temperatures, a longer growing season and more infrequent precipitation events all contribute to a decrease in groundwater levels throughout the summer. Longer and more frequent drought periods may result in decreased groundwater levels, which could be further exacerbated by increased human water demand.

Climate change may also impact groundwater quantity through changes to surface water dynamics. For example, increased precipitation intensity and variability will increase the risk of flooding and drought. On the one hand, more frequent heavy precipitation will increase the risk of floods while the risk of drought will increase as drier soils reduce infiltration during the growing season (Bates, et al., 2008). Increased demand for groundwater will further increase the risk of severe drought, especially as the period of low precipitation in summer and late fall extends (Payne et al., 2004). The length and severity of drought may contribute toward lowering the water table and ultimately reducing water quantity.

A longer growing season may also act to decrease groundwater levels through an increase in evapotranspiration. However, these losses will likely be balanced by other water inputs in most areas. Lower groundwater levels in the summer can impact groundwater-maintained wetlands and streams which become vulnerable to drying when droughts are severe. As such, it is important to protect ecologically significant groundwater recharge areas (ESGRAs) from development and other uses incompatible with recharge in order to increase their resiliency to climate change.

Anthropogenic factors can further exacerbate the impacts of climate on the water table. The replacement of natural areas with development can increase water demand while reducing groundwater recharge. Municipalities and other users must plan for future water taking needs and plan for increases in demand with potential lower availability throughout the summer. As a result of both climate and human factors, the demand for water in vulnerable areas could stress the supply available for humans and natural ecosystems. Water conservation programs and public education can help mitigate these impacts. Decreased groundwater levels can also have implications for residents who rely on private well systems, particularly dug wells.

Key Points – Groundwater Levels, Flow and Availability

- Groundwater resources in the East Holland River and Barrie Creeks subwatersheds may be more vulnerable to climate change as water budgets have predicted significant future stress in these areas due to increased water demand.
- Less summer precipitation, along with higher temperatures and more evapotranspiration will decrease summer recharge, lowering the water available in aquifers in this season.
- As a result of the communication between atmospheric conditions and unconfined aquifers, climate-influenced changes in groundwater physical properties and levels are expected to first be observed in these aquifers before confined or significantly deeper aquifers.
- A peak in groundwater levels in the winter could affect the amount of water available during the drier summer season, potentially affecting ecological systems dependant on groundwater discharge.

4.4 Groundwater discharge

4.4.1 Overview

Where the water table meets the ground surface, groundwater can discharge from the subsurface to become surface water. Groundwater discharge areas are often found in low topographic areas and can be observed in and around watercourses in the form of springs and seeps. Groundwater discharge rates can vary throughout the year due to seasonal changes in recharge and groundwater potentials.

The portion of streamflow that is contributed from groundwater is called baseflow. Since groundwater maintains a constant temperature around 11°C, baseflow provides clean, cool water to streams and wetlands. Compared to precipitation inputs, baseflow is relatively constant and supports streams and wetlands between precipitation events. As a result, groundwater discharge is important for preserving the thermal habitat of aquatic ecosystems, and watersheds with high groundwater discharge have been shown to be more resilient to the impacts of climate change (Chu et al., 2008).

The northern flank of the Oak Ridges Moraine is a significant discharge area within the Lake Simcoe Watershed, where groundwater flows downstream to deep river valleys and low-lying tunnel channel valleys (Davies et al., 2008). Nearly 90% of groundwater recharge that occurs on the moraine discharges to stream networks directly adjacent to the moraine (Earthfx, 2006). Groundwater discharge also occurs in other areas of the watershed such as Kempenfelt Bay valley; however, discharge is much weaker nearer to Lake Simcoe (Earthfx, 2006).

Baseflow of a river can be determined with a technique called hydrograph separation, which separates a graph of stream discharge over time (hydrograph) into its baseflow and event flow (i.e. precipitation) components. Applying hydrograph separation to long term surface water flow records is the best method for quantifying the portion of streamflow derived from groundwater discharge to streams, also known as the baseflow index (BFI).

4.4.2 Current status

Hydrograph separation was applied to discharge rates for the seven Environment Canada Water Survey of Canada stream gauge stations from 2007-2017 to determine the average baseflow index in five subwatersheds (Table 4-3). Baseflow indices vary throughout the watershed, ranging from 41.5% in the Schomberg River to 78.9% in Uxbridge Brook.

Table 4-3 Baseflow index for seven stream gauge stations in and near the Lake Simcoe watershed. Data are averaged over a ten-year period (2007-2017).

Station Name	Average Baseflow Index (%)	Dominant Land Type
Beaver River – Beaverton	56.3	Rural
East Holland River – Holland Landing	50.1	Urban
Hawkestone Creek – Hawkestone	42.4	Rural
Pefferlaw Brook - Udora	65.3	Rural
Schomberg River	41.5	Urban
Uxbridge Brook – Davis Drive	78.9	Rural
Black River – near Washago*	67.5	Rural

*station located outside of LSRCA watershed and used for comparison (see Section 4.5.2 below)

The baseflow index is generally higher in rural areas compared to urbanized areas due to the amount of impervious surfaces found in urban regions. Impervious surfaces limit recharge as mentioned in Section 4.1.1 above, which in turn limits the amount of groundwater discharging to streams. The BFI is variable across most streams in the watershed (Figure 4-9) showing similar inter-annual variation which likely reflects regional variability in climate drivers (e.g. increased precipitation vs. drought years). For example, 2008 was a wetter than average year with high streamflows where the annual baseflow index decreased at all stations. In contrast, 2015 was a drier than average year with low streamflows and the annual BFI increased at all stations (O'Connor et al., 2017). Therefore, it is clear that in drier years, groundwater inputs to streams represent a higher proportion of the flow and are important for sustaining aquatic habitats.

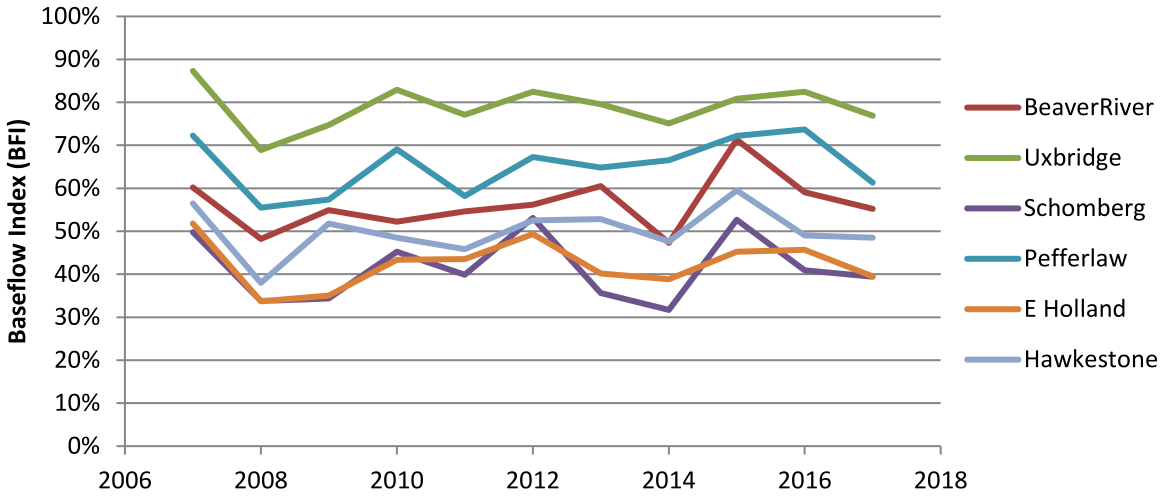


Figure 4-9 Changes in average annual baseflow index for seven stream gauge stations (2007-2017).

Mean monthly baseflow indices were compared between a rural (Beaver River) and urban (East Holland River) subwatershed (**Figure 4-10**). In the Beaver River, baseflow is the main component of streamflow during dry periods and makes up the majority of total streamflow throughout the year. The Beaver River has good groundwater storage capacity as a result of its low gradient system and extensive wetland complex (LSRCA, 2012). In comparison, the East Holland River's mean monthly BFI is significantly lower, having declined by ≈10% between 1970 and 2014.

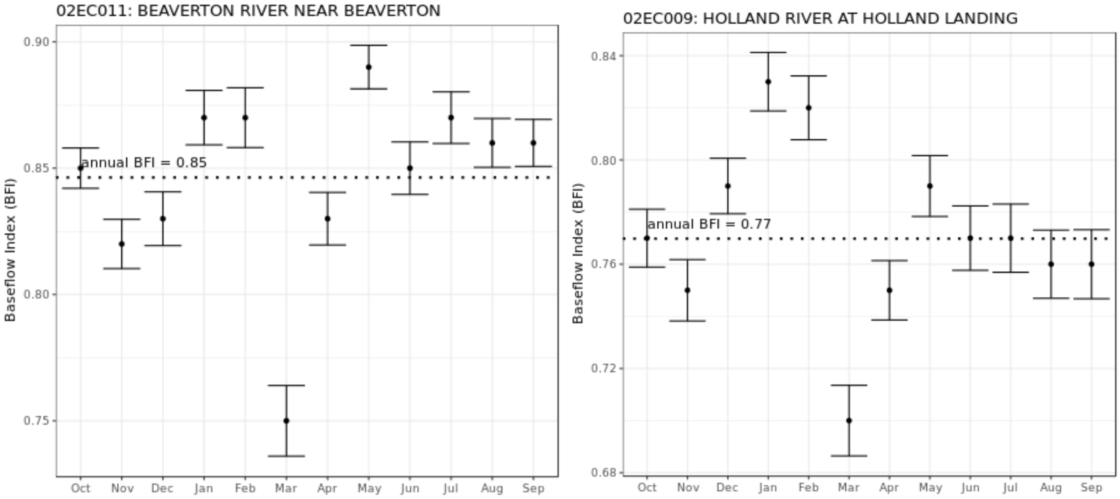


Figure 4-10 Monthly baseflow index (BFI) for the Beaver River and East Holland River (1966-2016). Note: Monthly BFI are obtained from the monthly medians of calculated baseflow (from 14 hydrograph separation methods) and are bounded by the 95% confidence interval.

Stream surveys carried out during periods of low flow found that although few tributaries were dry, the majority of dry tributaries received minimal to no groundwater discharge (**Figure 4-11**). Some of the dry tributaries were actually losing water to the underlying aquifer, and these findings could explain the significantly lower BFI in the East Holland River. Only one reach in the East Holland River was significantly gaining groundwater, but its proximity to the Oak Ridges Moraine may explain the increase in discharge (LSRCA, 2010). As the East Holland catchment is significantly more developed than the Beaver River catchment, this comparison shows that increased development in areas of groundwater recharge can reduce the BFI in these areas over time. This could have further cascading effects on stream ecology, especially in areas with coldwater fisheries.

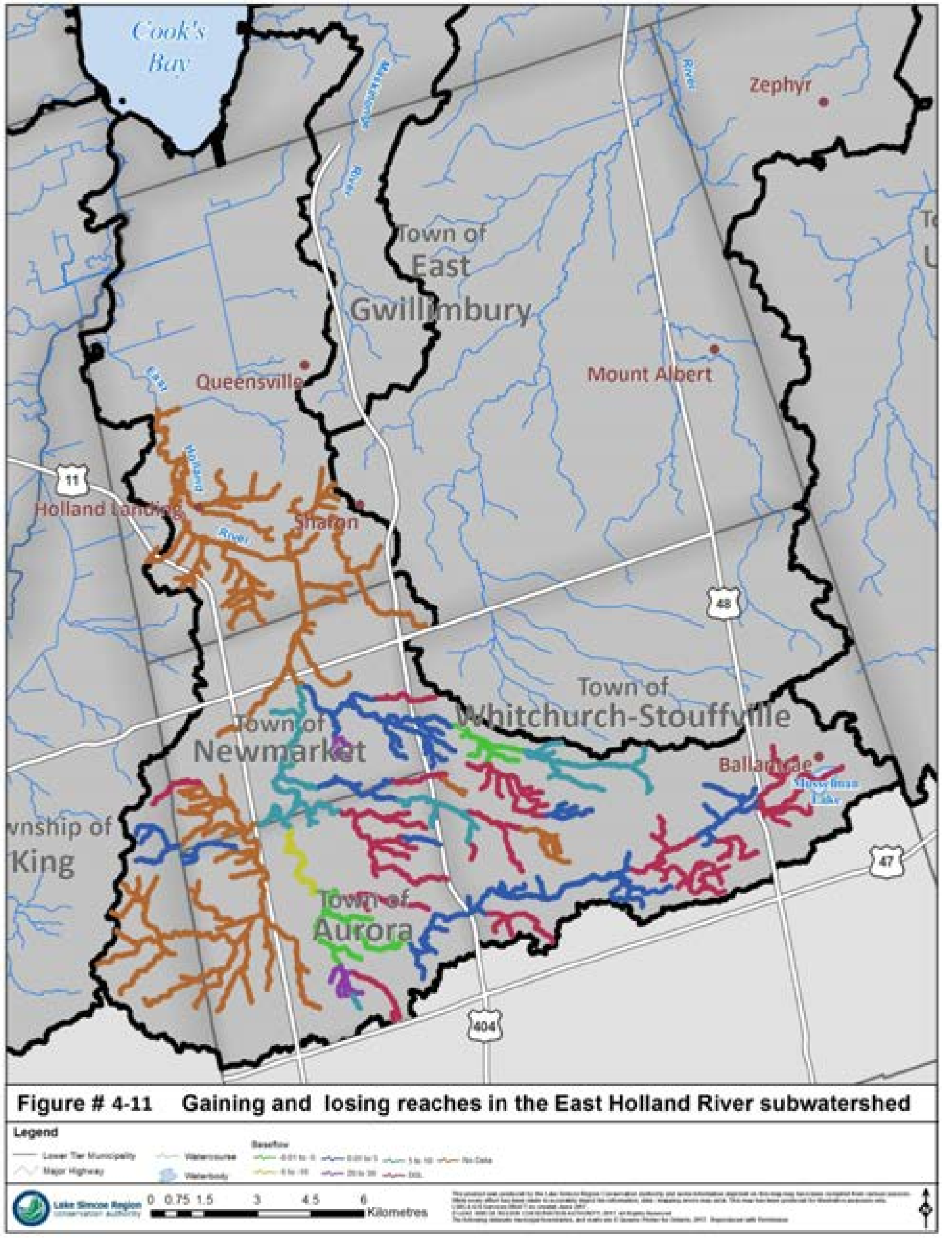


Figure 4-11 Gaining and losing reaches in the East Holland River subwatershed

However, despite these patterns, recent modelling suggests that groundwater discharge in urban areas may not be decreasing as previously thought (Lembcke et al., unpublished data). In the Lover's Creek subwatershed, current (2008) baseflow has actually increased compared to mid-development (1978) conditions, especially in the spring (Figure 4-12). While impervious surfaces do decrease the recharge potential of soils, developed areas also experience reduced evapotranspiration rates from decreased vegetative cover. The groundwater table may also receive inputs from sources such as leaky stormwater infrastructure and lawn/garden irrigation. Together, these inputs may balance the decrease in recharge from impervious surfaces. And while the baseflow index may be lower in urbanized areas, this is more likely due to an increase in runoff than a decrease in groundwater discharge.

This may suggest that urban areas are equally resilient to the impacts of climate change on groundwater discharge as rural areas, since they do not have the previously assumed additional stress on groundwater discharge volume. Further monitoring of both BFI and baseflow volumes may help to clarify these processes and where they occur.

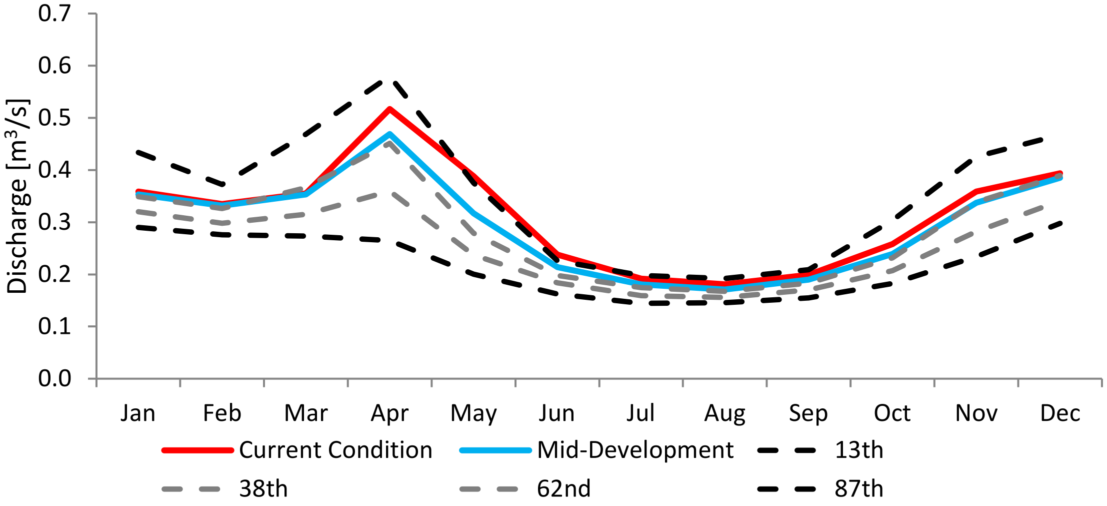


Figure 4-12 Modelled baseflow (groundwater discharge) during current, mid-development (1978), and pre-development (percentiles) conditions in the Lovers Creek subwatershed.

4.4.3 Climate change risk and vulnerabilities

Decreased groundwater discharge impacts on streamflow

Streamflow varies seasonally depending on air temperature, evapotranspiration and precipitation. In the summer, streamflow is lower and groundwater discharge maintains aquatic systems during low flow conditions. Climate change can decrease the amount of groundwater available in aquifers because of reduced summer recharge. Consequently, low flow conditions could occur earlier in the summer and last longer.

Aquatic ecosystems could be significantly impacted if baseflow decreases below a minimum threshold required to sustain those aquatic habitats (subsistence flows). In extreme low flows, there is not enough physical space for aquatic organisms to exist, stream connectivity can be lost, temperatures can increase above an organism’s thermal range, and water quality can quickly degrade as the volume of water becomes insufficient to dilute pollutants.

The shift in recharge from April to March produces a corresponding shift in the rate of discharge to streams and the onset of low flows. As summer low flows occur earlier, their duration and severity can also increase as the growing season lengthens, reducing water availability. As a result, higher temperatures in winter and spring, combined with a shift in spring recharge timing will increase the stress placed on streams during the summer months.

Wegehenkel and Kersebaum (2009) suggest that with the predicted change in climate, the number of days with low-flow conditions will increase and groundwater recharge will decrease, especially in forested areas where evapotranspiration is higher. Urban areas may see an increase in low flow conditions due to decreased baseflow from altered runoff from impervious surfaces and stormwater controls (Bradford et al., 2007). However, some studies suggest that urban areas may be able to buffer the effects of low flows through increases in baseflow from reduced evapotranspiration, interbasin transfers, and leakage from water and wastewater infrastructure (Lembcke et al., unpublished data; Lembcke and Aspden, 2016).

Decreased summer discharge

Because of the projected changes in summer precipitation, temperature and evapotranspiration, groundwater discharge to streams and wetlands is projected to decrease as a result of lower hydraulic gradients.

Low flow models for the Ramara Creeks, Talbot River and Whites Creek subwatersheds predict that summer discharge between July and September in the Upper Talbot River and Rohallion Creek will decrease while Whites Creek will remain stable under climate change scenarios (**Figure 4-13**) (EarthFx, 2014). The variable impacts of climate change on discharge within these subwatersheds are a result of differences in groundwater/stream bank storage between the till and post-glacial sediments of the Whites Creek catchment and the alvar dominated Upper Talbot River catchments (EarthFx, 2014).

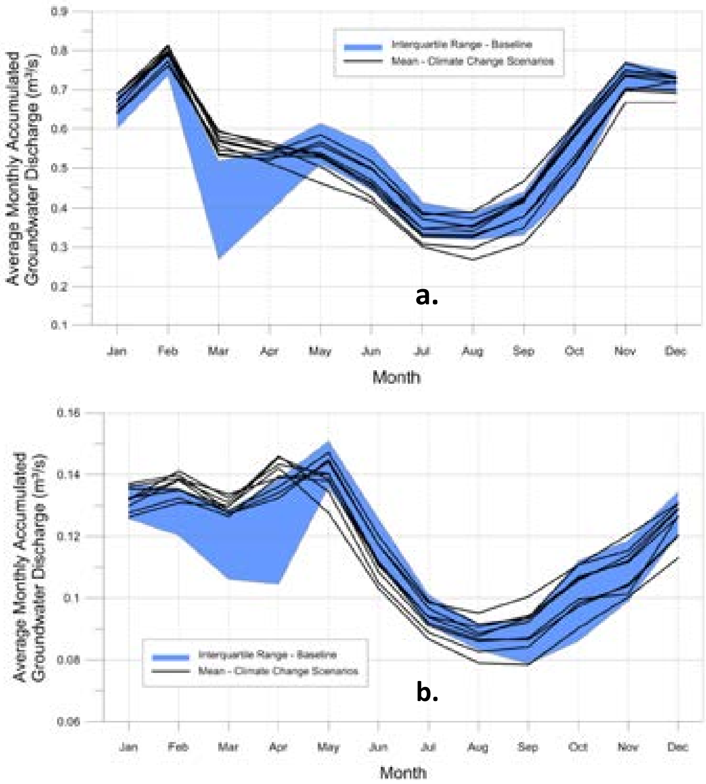


Figure 4-13 Simulated average monthly accumulated groundwater discharge in the (a) Lower Talbot River and (b) Whites Creek subwatersheds

Further differences can be seen between till- and alvar-dominated catchments in terms of overall water storage. Although the Alvar Plain provides high recharge to portions of the study area, the feature has a low storage capacity. As a result, much of the recharge that enters the groundwater system is quickly moved through the subsurface and discharged to local streams and tributaries (Earthfx, 2014). Due to its low storage capacity, streams fed by the alvar are more sensitive to the effects of long-term drought (Earthfx, 2014). Therefore, it may be that catchments containing streambanks with a higher water storage capacity are better able to buffer against climate change impacts on summer discharge.

Decreased groundwater discharge in the summer can impact aquatic habitats that rely on cold water inputs, including streams and wetlands. As mentioned previously in **Section 4.2.2**, ecologically significant groundwater recharge areas (ESGRAs) provide groundwater that sustains ecologically important streams and wetlands. These groundwater-reliant natural features enhance natural heritage (e.g. biodiversity, habitat quality and connectivity), ecosystem services (e.g. erosion control, nutrient cycling and water purification), and provide recreation and cultural opportunities (e.g. hiking, paddling, fishing, bird watching and relaxation). These benefits could be significantly impacted or lost if groundwater discharge originating from ESGRAs decreases and remains low for extended periods. However, where groundwater recharge pathways are long, there could be lag time of many years before observing a response.

Increased winter/spring discharge

The seasonal patterns of groundwater discharge mirror the winter and spring recharge response to climate change (see **Section 4.2.3** above). Winter discharge rates are historically low because ground frost limits infiltration, however due to warming temperatures; winter groundwater discharge to streams is projected to increase (EarthFx, 2014).

As an example, under different climate change scenarios in the Ramara Creeks, Whites Creek and Talbot River study area, the greatest expected change to groundwater discharge will occur in the winter months (December to March), when discharge to streams and lakes will significantly increase. This increased winter discharge could impact other seasons such as the duration and extent of summer low flows. This can impact sensitive ecological features which rely not only on the volume of groundwater discharge but also on its timing.

Key Points – Groundwater Discharge

- Baseflow in urban areas may not be as impacted by development as previously thought, and so urban areas may be equally resilient to the impacts of climate change on groundwater discharge as rural areas.
- Peak groundwater discharge rates are expected to shift earlier in the year as higher winter temperatures and precipitation lead to increased winter recharge.
- Sensitive ecological features like headwater streams and wetlands may be impaired as climate impacts the amount of groundwater discharging to these systems in the summer, decreasing the quality and availability of these habitats for wildlife and plant communities.
- It is likely that catchments containing streambanks with a higher water storage capacity are better able to buffer against climate change impacts on summer discharge.
- Catchments with a lower baseflow index may be more susceptible to climate impacts if they do not have any other water inputs to the system.

4.5 Streamflow and flooding

4.5.1 Overview

During most of the year, streamflow is composed of fluctuating ratios of both groundwater discharge and surface runoff, represented by the baseflow index (BFI). However, during dry periods when runoff is reduced or eliminated, the entire streamflow may be supplied by groundwater discharge, and the BFI increases. Ultimately, sustained groundwater discharge into tributaries maintains water levels and healthy aquatic ecosystems.

Streamflow naturally varies, both spatially and seasonally, due to changes in precipitation inputs and overland flow, and to a lesser extent, changes in groundwater discharge. The annual variability in stream flow produces different flow regimes (**Figure 4-14**) that serve specific ecological purposes (Metcalfe et al., 2013). Rivers and streams usually experience the maximum stream flow (peak flow) during spring thaw periods (or freshet), when relatively high precipitation combines with a melting snowpack. Less precipitation in summer often results in extremely low streamflow that is entirely composed of baseflow (groundwater discharge). During these low flows, the minimum streamflow needed to maintain aquatic ecosystems is called subsistence flows. Low flows can affect surface water availability, water quality and aquatic ecosystems. High flow pulses resulting from low intensity rain events or short winter/spring thaws are important for flushing fine sediments and waste through the system and restoring normal water quality following prolonged low flow periods. Channel-forming flows are those that just overflow riverbanks and are important for producing natural channel structures, including features such as bars, and riffle-pool sequences, which are important for maintaining healthy riverine ecosystems. Riparian flows are those that exceed the banks of the river and can cause erosion and flooding; they are important for laterally connecting streams and floodplain areas but can negatively impact human health and property. A visual summary of these flow regimes is shown in **Figure 4-14**.

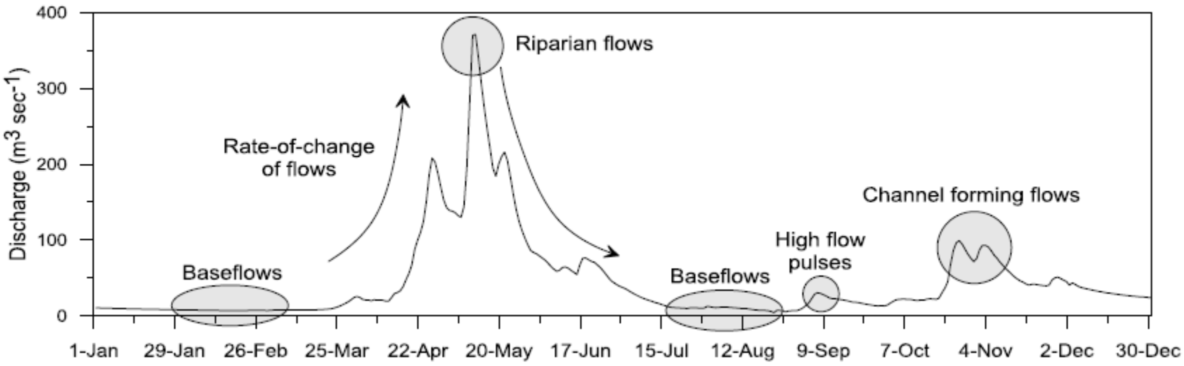
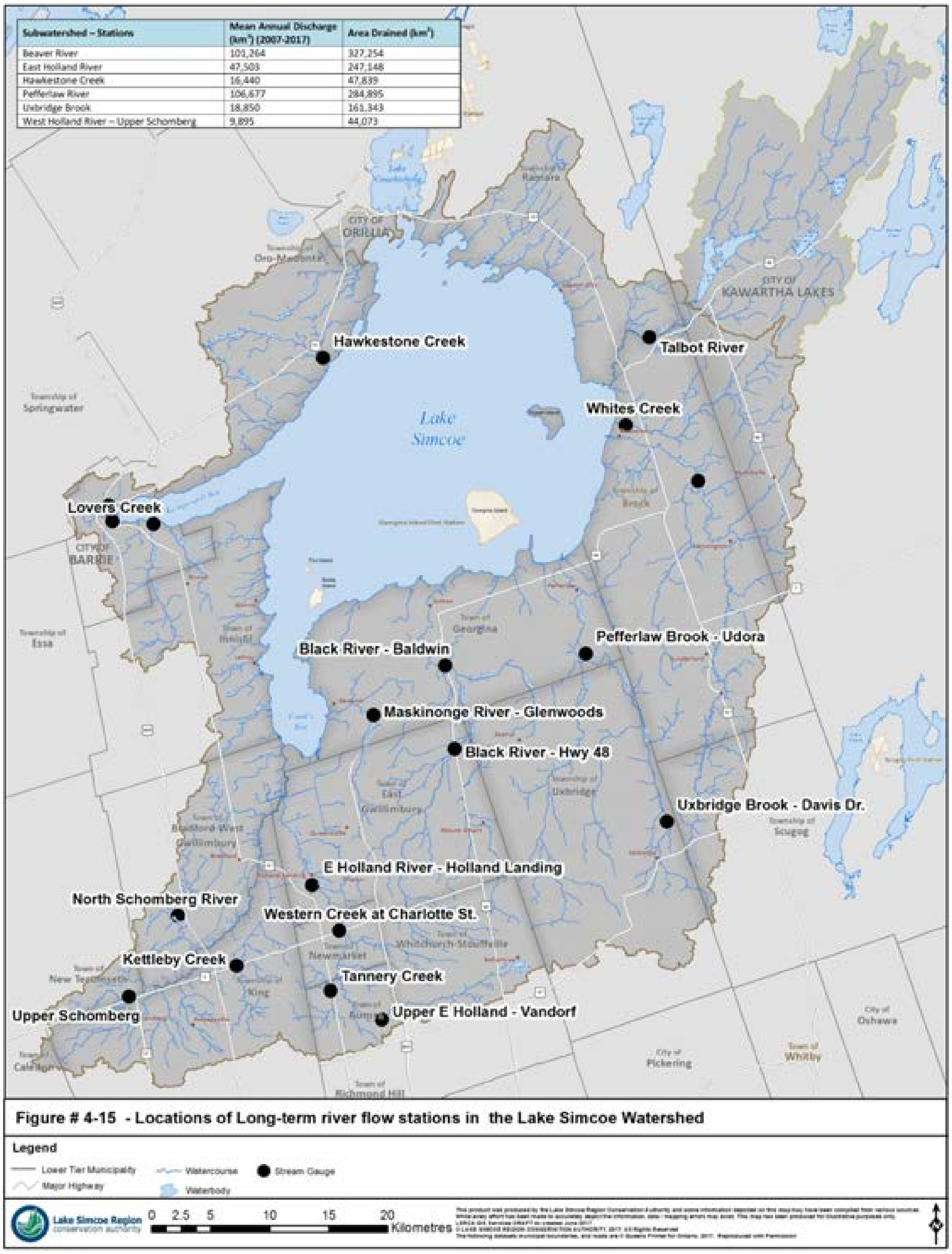


Figure 4-14 Ecologically important flow regimes, used to assess hydrologic alteration, identified on an annual hydrograph. Source: Metcalfe et al., 2013.

Hard engineered features in urban areas, including impervious cover (e.g. roofs and pavement) and traditional storm water management systems stop precipitation from infiltrating directly into the soil and instead commonly divert it directly to watercourses. As a result, urban areas typically have more extreme high flow pulses compared to rural areas. Traditional stormwater management is based on the principle of moving excess water as quickly as possible through the system, resulting in increased erosion and flooding as well as impacts to natural flow regimes. In contrast, low impact development (LID) aims to mimic the natural hydrologic cycle by allowing precipitation to infiltrate into the soil where it falls, thus reducing peak flows, maintaining baseflows, and allowing for more natural flow regimes.

4.5.2 Current status

The LSRCA operates 14 hydrometric stations and another seven are operated by Environment Canada Water Survey of Canada (**Figure 4-15**). These stations continuously measure water level using either a float recorder or pressure sensor and data recorder, which are used to calculate discharge (O'Connor et al., 2012). Additionally, LSRCA staff manually measure stage and discharge at all stations each month, and more often during high flow periods.



Subwatershed – Stations	Mean Annual Discharge (km^3) (2007-2017)	Area Drained (km^2)
Beaver River	101,264	327,254
East Holland River	47,503	247,148
Hawkestone Creek	16,440	47,839
Pefferlaw River	106,677	284,895
Uxbridge Brook	18,850	161,343
West Holland River – Upper Schomberg	9,895	44,073

Figure 4-15 The locations of long-term river flow stations in the Lake Simcoe watershed

Hydrometric measurements were used to calculate monthly streamflow volume between 1965 and 2018 at the six long-term gauged stations. During this period, mean annual streamflow rates ranged from 0.3 – 3.2 m^3/s. The highest monthly average for gauged stations historically occurs in March and April, during the spring freshet (**Figure 4-16**). In contrast, the lowest flows occurred in August and September. Streamflow values tended to rise slightly in late autumn and lower slightly in winter months. In the watershed, spring thaw has typically resulted in the highest surface water flow rates. The highest evapotranspiration rates and lowest amounts of precipitation have historically been in the summer, resulting in a negligible water surplus and lower average streamflow during the hottest months.

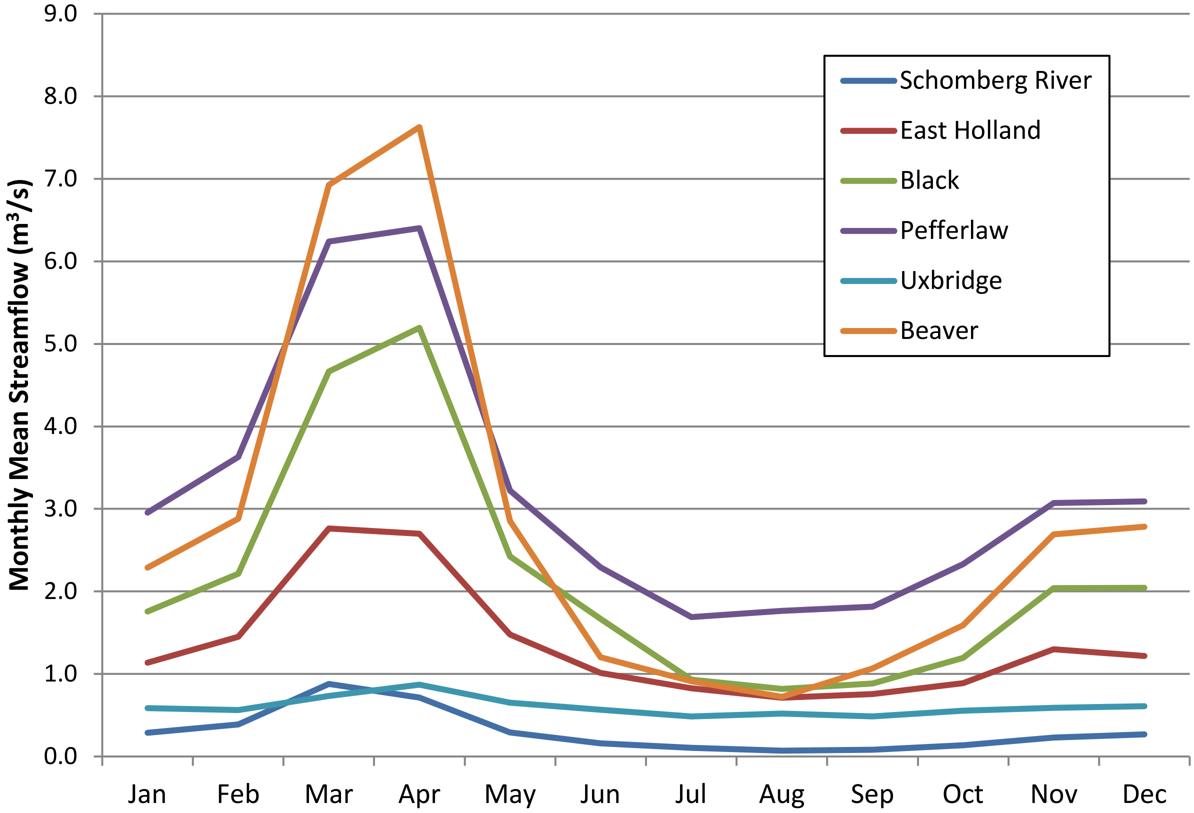


Figure 4-16 Monthly mean streamflow measurements at six gauged stations (1965-2018)

Long-term annual streamflow has increased but remains spatially and seasonally variable. Streamflow measurements at the Beaver River station show an increase in winter stream discharge and a reduction in spring stream discharge (**Figure 4-17**), indicating a shift in the timing of spring snowmelt. This data is supported by a previous study which showed that streamflows in eastern North America have increased in winter and peak flows are expected to occur up to a month earlier by the mid-21st century (Milly et al., 2005). The seasonal shift in flow variability potentially reflects increased precipitation variability over that same period. Winter low flows and summer high flows are higher overall in the Beaver River, but total flow is significantly declining. This is because while the magnitude of spring peak flows is increasing, the duration is decreasing over time.

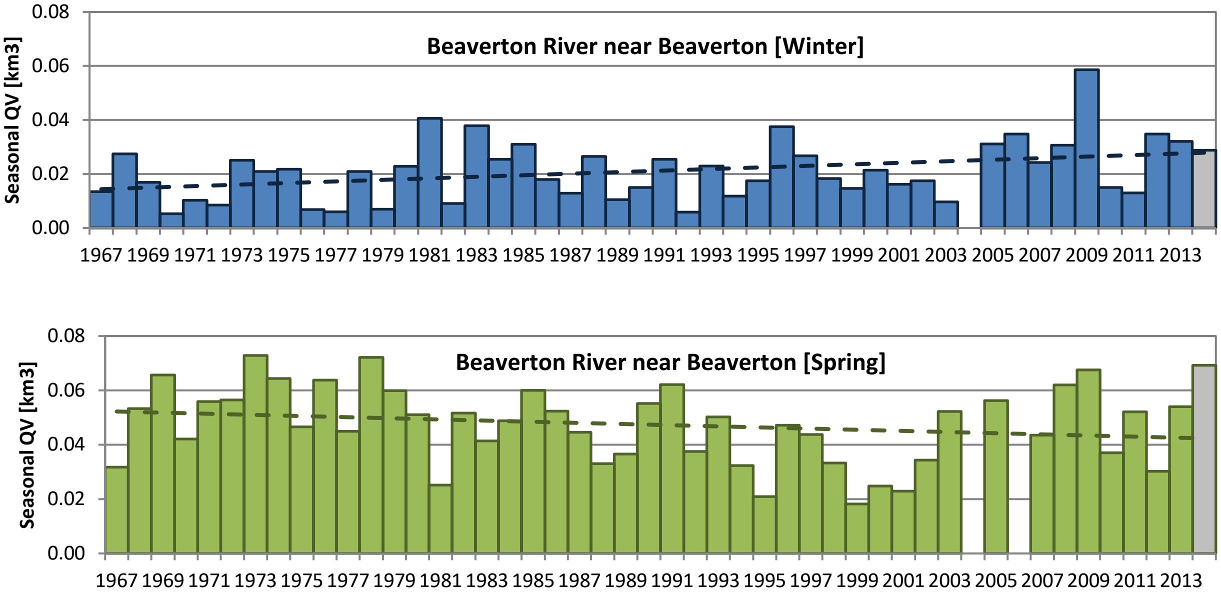


Figure 4-17 Seasonal changes in stream discharge (QV) in the Beaver River.

In order to isolate the impact of climate change from land use change on stream flow, the Black River immediately north of the Lake Simcoe watershed (not to be confused with the Black River within the Lake Simcoe watershed, and herein referred to as Black River – near Washago) was assessed due to long dataset and minimal land use change. Therefore, changes to streamflow regimes in the Black River-near Washago catchment are attributable to climate change and can be used to help infer factors impacting flow within the Lake Simcoe watershed.

Trends in seasonal stream discharge at the Black River-near Washago station show similar changes to those observed in Lake Simcoe tributaries. A comparison between time periods before (1916-1979) and after (1980-2013), climate impacts on temperature show that peaks in spring stream discharge have shifted earlier in the year (**Figure 4-18**). As there has been minimal land use change within the watershed it can be concluded that observed changes are due to climate change and therefore observed changes in the Lake Simcoe watershed are also likely the result of climate.

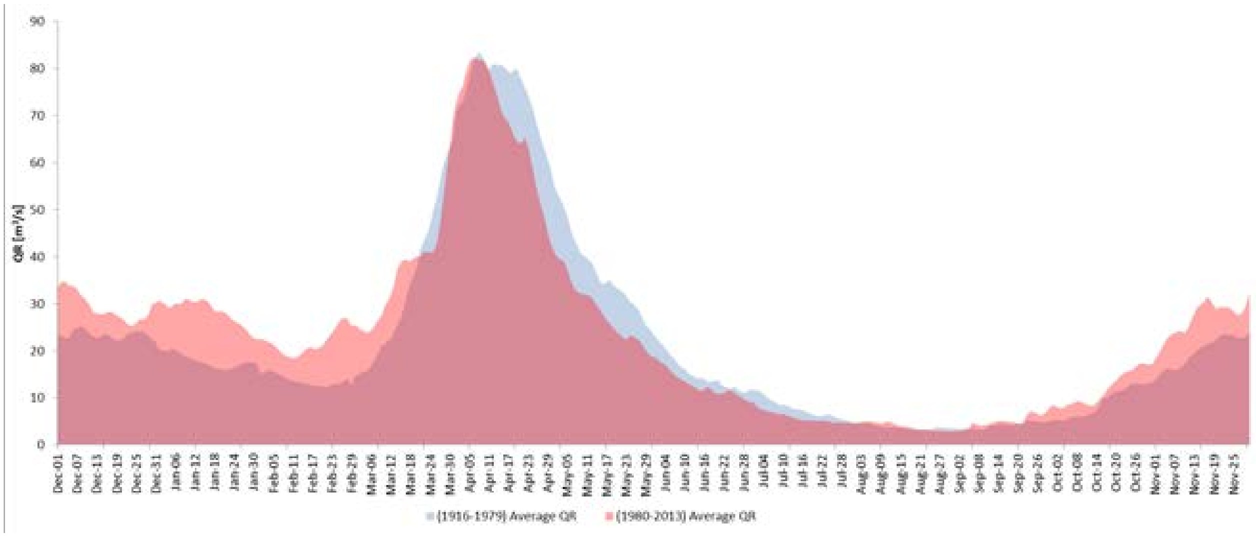


Figure 4-18 Climate change impacts on flow regime between a pre-development (1916-1979) and post-development (1980-2013) period in the Black River – near Washago.

Extreme flows have also been examined at this station and they also reflect changes in climate. The magnitude of flows in both winter and spring has increased over the period of record (**Figure 4-19**). Total streamflow in the spring is decreasing due to a shorter duration of peak flows, although the magnitude remains stable. Additionally, the highest magnitude flows are occurring in March instead of April or May, reflecting a shift in the timing of the freshet, as was suggested by both modelling and theory. Conversely, looking at low flows, summer and autumn minimum flows have both been decreasing over the period of record (**Figure 4-20**).

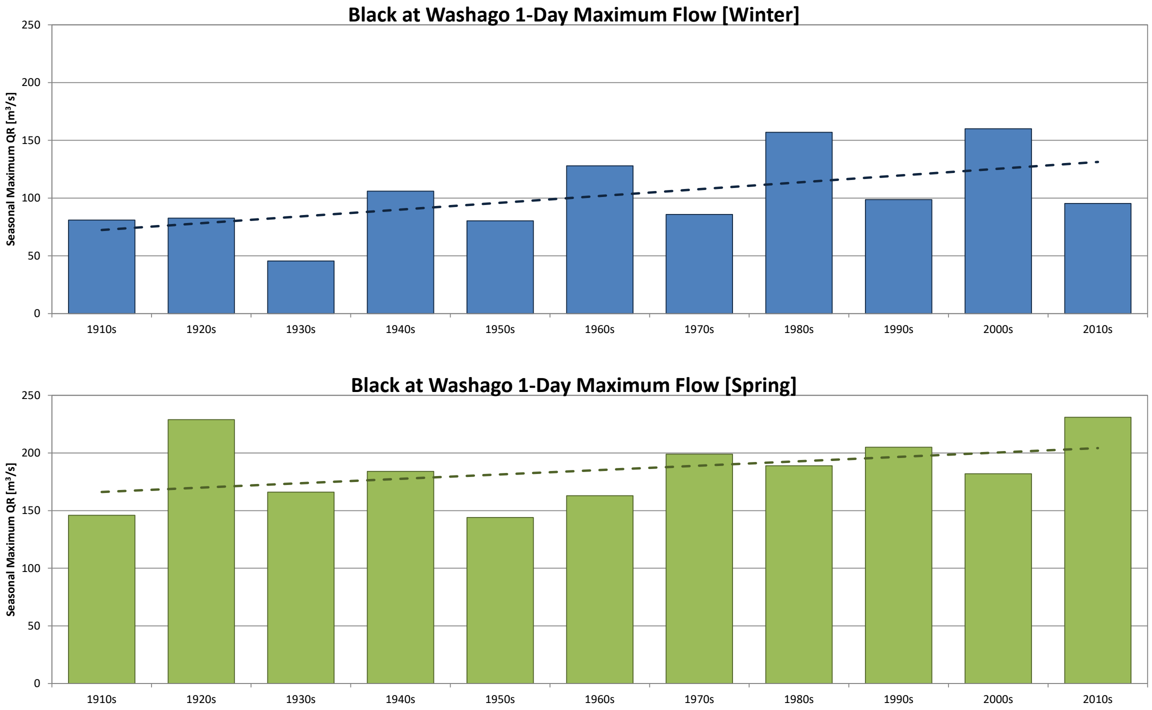


Figure 4-19 Single-day maximum flow in winter (a) and spring (b) at the Black River - near Washago station (1915-2015) (Aspden, 2014).

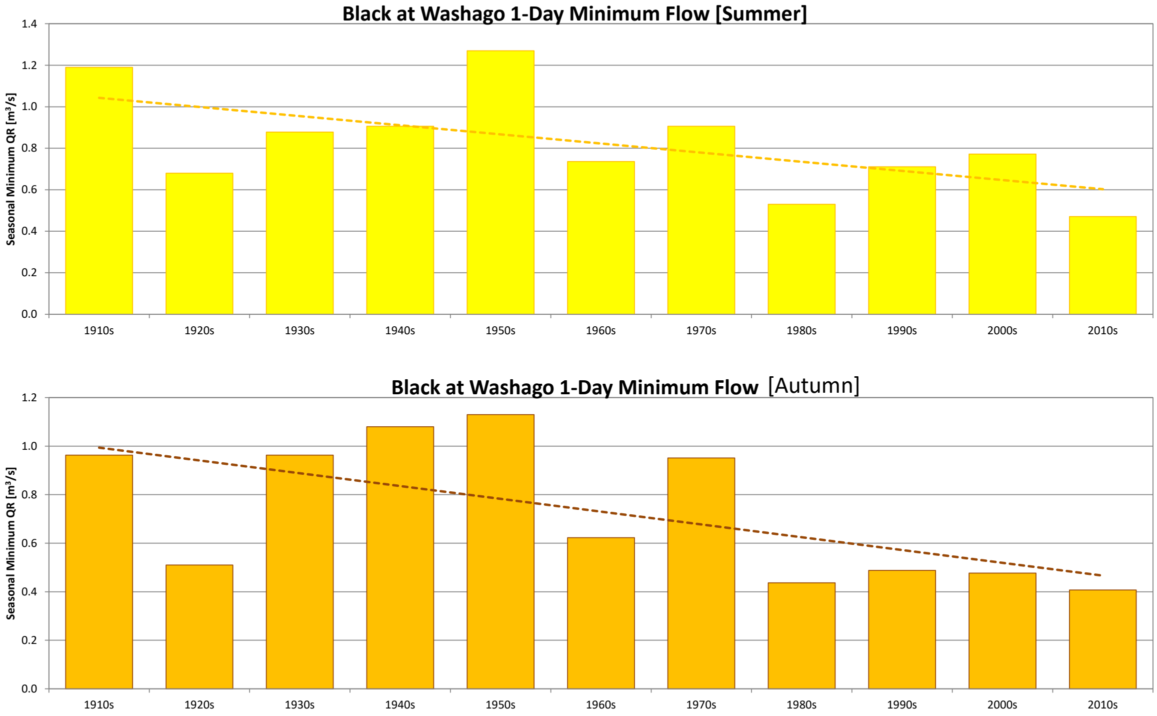


Figure 4-20 Single-day minimum flow in summer (a) and autumn (b) at the Black River - near Washago station (1915-2015) (Aspden, 2014).

4.5.3 Climate change risk and vulnerabilities

Climate derived changes in precipitation can impact streamflow by changing the volume and seasonality of flow. A warmer climate and increased climate variability will increase the risk of both floods and droughts (Kundzewicz et al., 2007; Aspden, 2014). Some studies suggest that even modest increases in temperature predicted under scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) may substantially alter the winter hydrological cycle and impact streamflow. The period of snow melt continues to occur earlier in the season as winter temperatures warm, resulting in changes to streamflow throughout the year (Cayan et al., 2001; Stewart et al., 2004; Mote et al., 2005 Tague et al., 2008; Marchildon et al., 2015; Golmohammadi et al., 2017).

Changes in the streamflow regime can impact aquatic ecosystems by influencing various processes, as discussed in **Chapter 5 – Tributary Ecosystems**. For example, the spring freshet provides spawning cues for some fish species, shifts in sediment flushing can impact food availability and quality of spawning grounds, and increased low flows can degrade or remove aquatic habitats. Hydrologic changes can also impact water availability for human use (e.g. drinking water, recreation or industrial purposes).

Shifts in spring freshet

With climate change, winter temperatures are increasing and fluctuating more drastically, leading to an increased frequency of mid-winter thaws. These thaws, in addition to more winter precipitation falling as rain instead of snow, lead to a decrease in snow accumulation. Additionally, with increased and fluctuating winter temperatures, the ground fluctuates through more freeze-thaw cycles, and melting snow and rain is able to infiltrate the soils. All of these factors can combine to shift the spring freshet earlier, or reduce its magnitude and/or duration, affecting total yield. This can impact stream hydrology as peak flows are necessary for channel formation and flushing sediment out of the system.

Modelling of the future hydrologic impacts of climate change on the East Holland River predicted that the timing of the snowmelt and the spring freshet will occur earlier than baseline conditions (EarthFx, 2018). Depending on the stream hydrology, some areas may be more impacted than others.

Spring freshets are not only important for hydrologic systems, but they also provide essential life history cues to fish species, such as spawning, hatching or migrating (as discussed in **Chapter 5 – Tributary Ecosystems**). Shifts in the timing of the freshet could affect the synchrony of spawning, hatching and food availability, and a decrease or loss of spring freshet could eliminate these cues altogether.

Increased frequency of summer low and subsistence flows

As the spring freshet shifts earlier in the year, the drier summer and period of low flows may begin earlier. Coupled with decreased summer precipitation and a longer growing season, low flows may also be lower and last longer than they have historically. This would also be exacerbated by an increased water demand in the summer season by both humans and vegetation. However, streams that are sustained by groundwater inputs may be buffered against these effects, although summer discharge is also vulnerable to climate change, as discussed above.

It is possible that some streams may dry up in areas where the water table is at risk of lowering and/or in streams with already low summer water levels (e.g. some reaches in the East Holland River – see **Figure 4-1**). Chen et al. (2004) suggest that climate change may result in less surface water availability. For example, climate change may extend the season of low to no flows in some tributaries, potentially impacting the overall water resources.

Where water availability is high, changes in surface water may actually impact the climate system. For example, when more water is available in soils and surface water, this leads to more evaporation in warmer weather, which could potentially feedback into the atmosphere and vegetation rather than infiltrating into the soil, and thus impacting the water cycle (Field et al., 2007). This recycling reduces the amount of water available for runoff, potentially lowering streamflow over time.

Historically, river management has focussed largely on setting a single low flow target to maintain baseflow volumes. In contrast, environmental flows aim to manage systems to maintain the various natural flow regimes necessary to protect aquatic habitats. Lovers Creek flows have been modelled under urban growth scenarios: pre-development, mid-development (1978) and current conditions to determine what impact development has on flow regime (Matrix Solutions Inc., 2017). The modelled data generally shows reduced spring melt timing occurring earlier in the year and that low flows have increased overall in the Lovers Creek subwatershed (**Figure 4-21**).

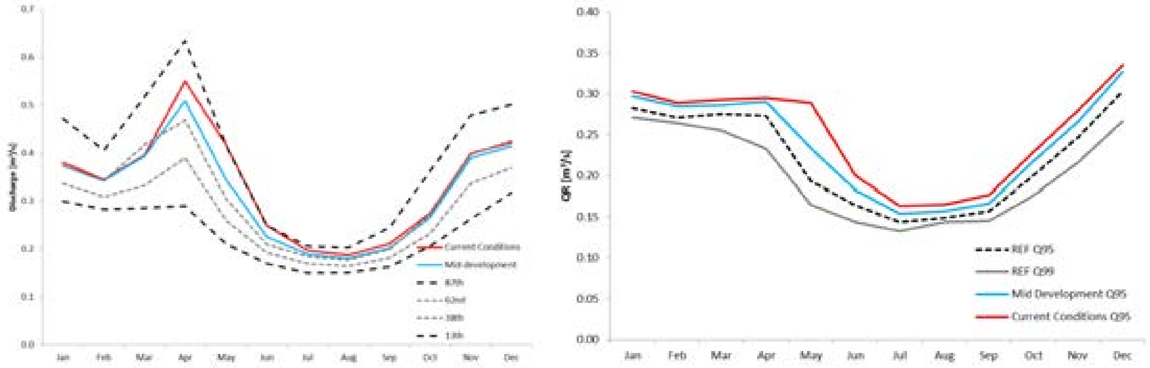


Figure 4-21 Modelled baseflow (left) and subsistence flows (right) for the Lovers Creek subwatershed.

Within the Ramara Creeks, Talbot River and Whites Creek Subwatersheds, modelled scenarios predicted that the scale and the severity of drought and extreme low flow periods will increase (EarthFx, 2014). These results are likely to also be observed in other subwatersheds, however further research is needed to assess the exact impacts in other areas. Groundwater storage within aquifers may be important for offsetting this water loss, particularly where high levels of shallow aquifer extractions (e.g. water takings or evapotranspiration) are dominant. In addition, new policies and planning to avoid localized water shortages may be required to mitigate changes in flow timing and magnitude.

Persistent low or subsistence flows in streams and rivers can impact aquatic ecosystems by reducing the amount of physical habitat available, potentially fragmenting stream reaches and degrading the water quality since there is less volume to dilute pollutants (see **Chapter 3 – Water Quality**). Additionally, lower water levels increase water temperature, which is further exacerbated by warmer air temperatures. More summer low flows can also increase the number and length of stream reaches that dry up, reducing habitat availability and potentially fragmenting stream reaches. Reduced habitat availability can increase competition for food and the prevalence of disease as aquatic species are forced into smaller areas.

Increased stream temperatures resulting from climate change (i.e. from warmer air temperatures and longer low flow regimes) affects aquatic species differently. For example, warmwater fishes (e.g. sunfish, perch) will benefit from increased stream temperature, but cool and coldwater fish species (e.g. brook trout, mottled sculpin) will suffer. As streams warm over time, coldwater fish species will be forced into headwater areas where cooler groundwater can sustain their thermal requirements. However, these habitats are threatened by decreases in groundwater discharge and migration barriers (e.g. dams, perched culverts) which may not allow the fish to access the headwaters.

Increased summer flood frequency and magnitude

Climate change has increased the intensity of short duration rain and snow events throughout the year (see **Chapter 2 – Climate Change Trends and Projections**), which can result in increased frequency and magnitude of summer floods. These effects will be further exacerbated by increased development and areas with more impermeable surfaces and/or altered streams (e.g. hardened banks, straightened channels) will be more impacted than more natural areas. Incorporating low impact development, re-naturalizing streams, and other flood mitigation measures can help to minimize the impacts of these intense summer storms.

The intensity, duration and frequency of historic and current storm events in the Black River – near Washago catchment were compared to determine any changes that result from climate drivers. Despite the appearance of stable streamflow regimes in the watershed, the analysis found evidence of climate driven increases in the magnitude and frequency of flooding (**Figure 4-22**). As mentioned in **Section 4.5.2** above, this watershed has remained relatively undeveloped, and so these observed changes are likely to be attributable to climate change.

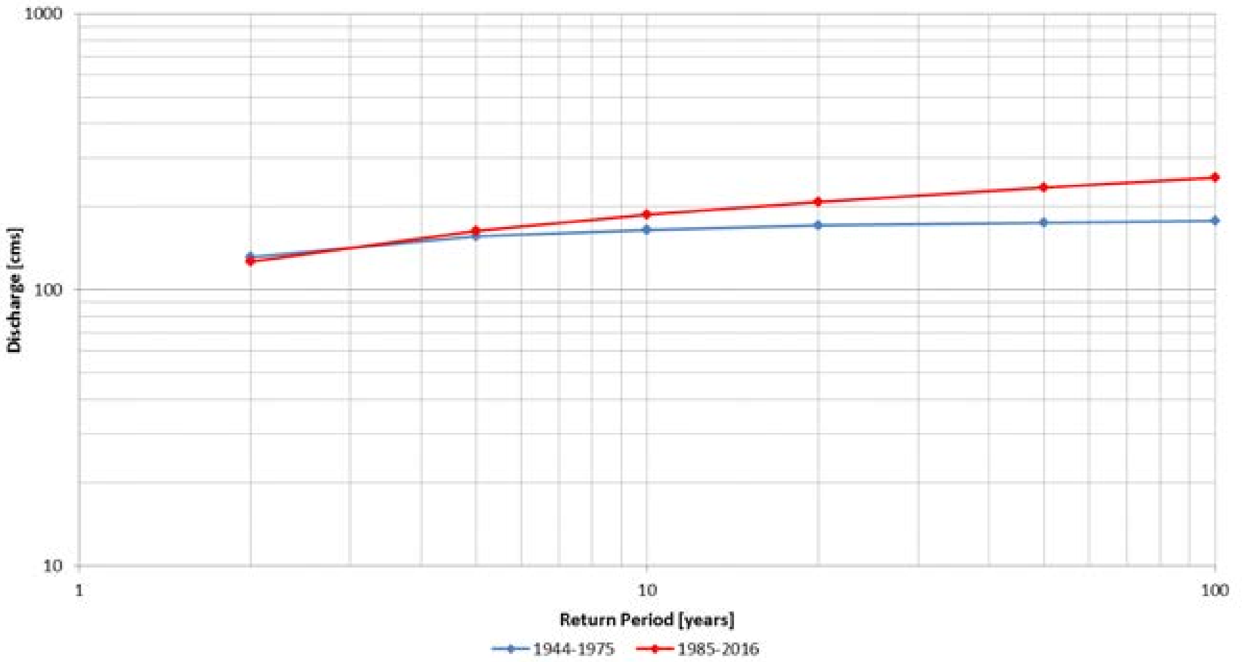


Figure 4-22 Streamflow magnitude and frequency has increased in the Black River – near Washago catchment in recent decades, compared to historical trends

More summer high-flow pulses

More extreme weather events are predicted under projected climate change scenarios, including an increase in intense, short-duration precipitation events (see **Chapter 2 – Climate Change Trends and Projections**). This will have a serious impact on streamflow as isolated high-intensity storms can cause stream levels to quickly rise, especially in urban areas and managed systems, leading to flood events.

Comparing annual hydrographs for pre-settlement and current conditions, more high pulse flows are now occurring throughout the year, and especially in the summer season **Figure 4-23**. This is a time when stream levels are typically low, and streams exhibit baseflow or subsistence flow conditions. However, under projected climate change scenarios, these low flows are expected to be punctuated even more frequently by high flow pulses.

Increased summer high flow pulses can have some negative impacts on stream ecosystems, including increased erosion, flushing of nutrients and pollutants into the stream, and increased turbidity affecting aquatic organisms. Conversely, these high flow pulses could help to mobilize and sort gravels and prevent vegetation encroachment.

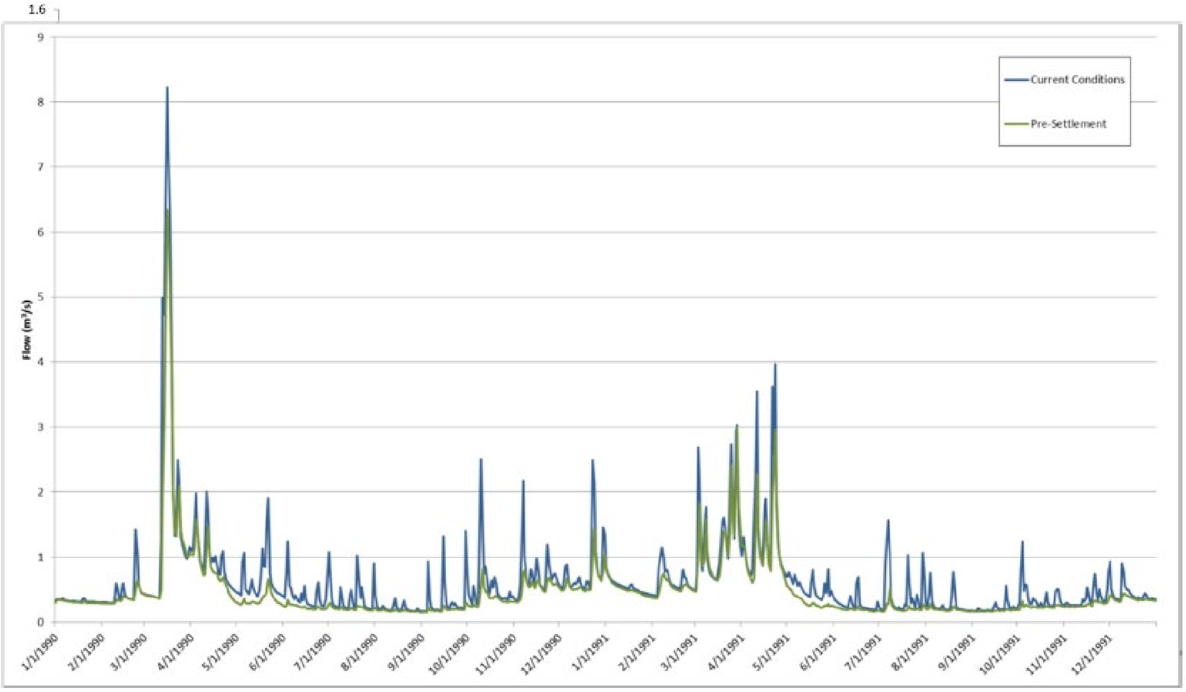
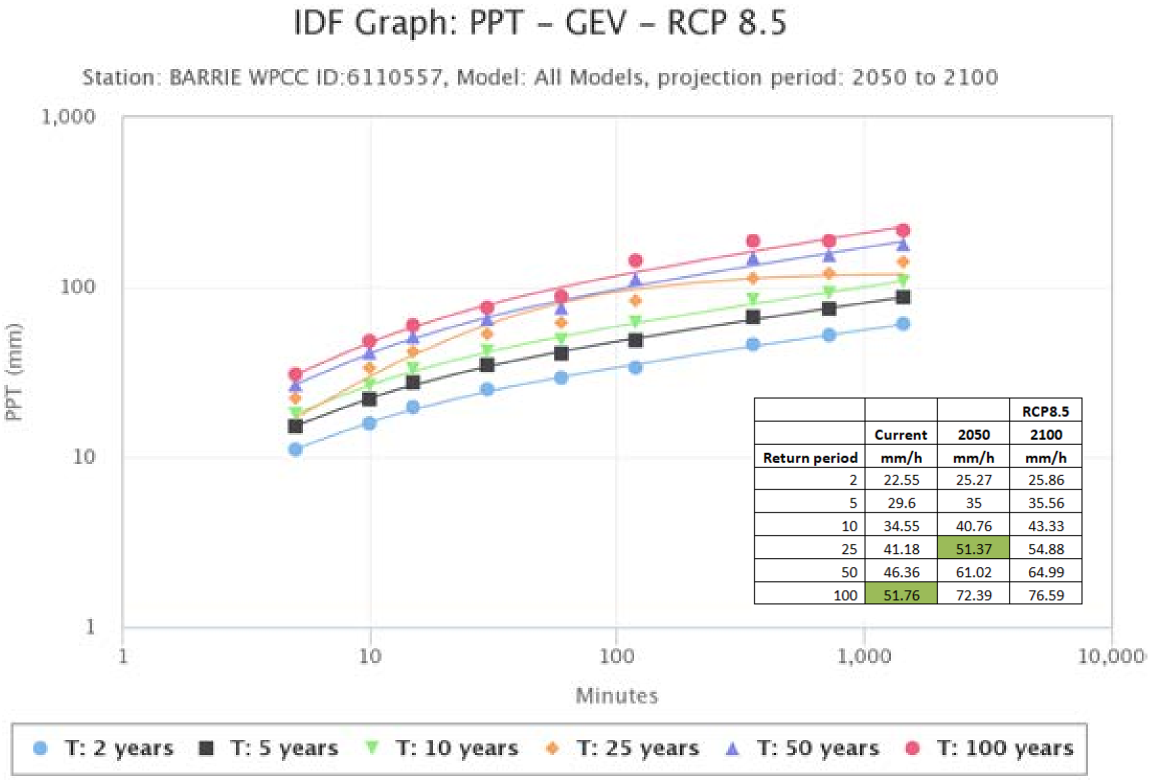


Figure 4-23 Annual hydrograph showing an increase in high flow pulses under modelled current conditions compared to pre-settlement conditions for Lovers Creek.

Climate impacts on streamflow variability over two climate normal periods (1944–1975; 1985-2016) were analyzed at Black River near Washago. The data shows that the magnitude of 10-year flood events in the current climate period is very similar to 100-year flood events in the previous climate period. In other words, climate change has increased the likelihood of flooding by more than ten times over the past 75 years (see **Figure 4-22**).

Similarly, the projected intensity-duration-frequency (IDF) curve analysis for Barrie predicts that 25-year floods in 2050 will be similar to the 100-year flood in the current climate period (**Figure 4-24**) (Simonovic et al., 2018). The extreme Precipitation Index (EPI) assessment of observational two-day precipitation events showed that 5-, 10- and 20-year precipitation events have all become substantially more frequent since the 1960s (Janssen et al., 2014). The frequency of heavy precipitation days (total precipitation of 10mm or more) is expected to continue in the coming decades as a result of climate change (**Chapter 2 – Climate Trends and Projections**).



			RCP8.5
	Current	**2050**	**2100**
Return period	**mm/h**	**mm/h**	**mm/h**
2	22.55	25.27	25.86
5	29.6	35	35.56
10	34.55	40.76	43.33
25	41.18	51.37	54.88
50	46.36	61.02	64.99
100	51.76	72.39	76.59

Figure 4-24 Intensity-Duration-Frequency curve for the Barrie station showing the projected intensity of 2 – 100 year storm events between 2050 and 2100, RCP8.5

As flood frequency, intensity and duration increases, this can have significant impacts on infrastructure and human health, especially in urban areas. A 100-year storm event will impact more buildings and infrastructure than a 10-year storm event (Figure 4-25), and as storms of this size occur more often the economic losses increase. Approximately 19% of Canada's population is at risk of riverine and/or overland flooding, which can cause financial, mental and health stress, especially in areas that flood year after year (Mandrak and Feltmate, 2019). This highlights the importance of building climate resilient communities which minimize the risk and/or impacts of flooding.

Figure 4-25 The difference in floodplain inundation between a 10-year and 100-year storm event

Changes in the seasonality of high flows and flooding along with seasonal changes to temperature and precipitation, climate projections expect a shift in the seasonality of high flows and flooding. Increased winter temperatures, combined with more precipitation falling as rain than snow will result in an increase in both winter streamflow and the potential for more winter flooding events (Figure 4-26).

Figure 4-26 Climate change is expected to increase the occurrence of winter flooding.

An increase in median monthly streamflow for winter (December through March), and decreases in all other months (Figure 4-27) was projected for the Ramara Creeks, Talbot River and Whites Creek subwatersheds (Earthfx, 2014). This pattern of change was predicted in streams across the study area, with median winter stream flow increasing by as much as 50%. These predicted changes to the hydrologic regime will undoubtedly have impacts on stream ecology and geomorphology. Similar patterns are expected in the East Holland River subwatershed (Earthfx, 20418) and are likely to be observed in other catchments within the watershed.

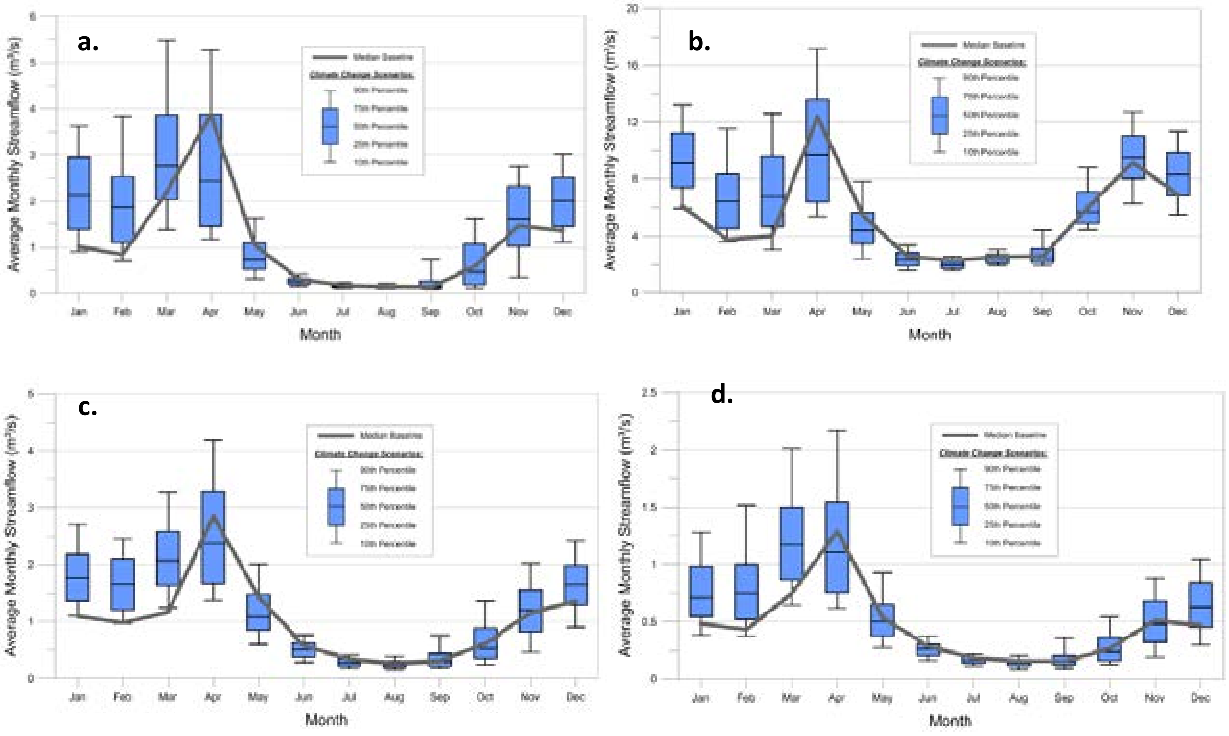
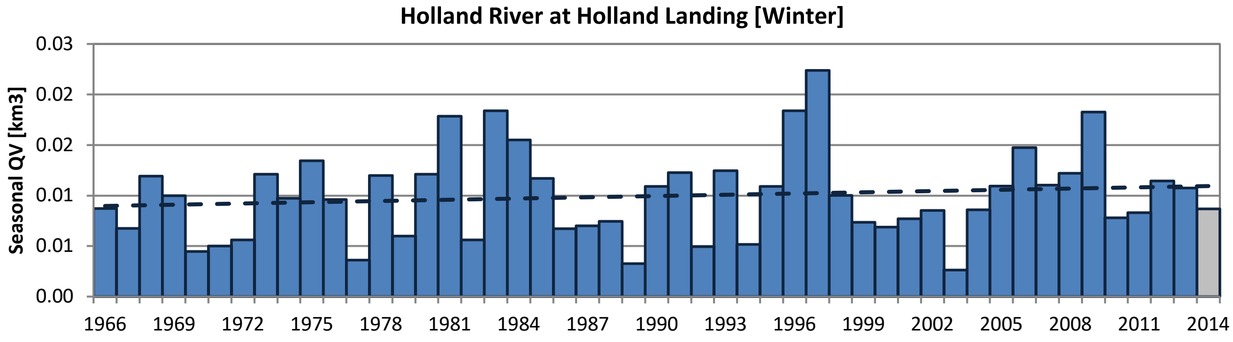


Figure 4-27 Monthly simulated streamflow statistics for Whites Creek (a), Lower Talbot River (b), Upper Talbot River (c), and Rohallion Creek (d) (Earthfx, 2014).

Total snow accumulation and the volume of spring peak flow have declined over the last 40 years. These changes are likely to increase the risk of winter floods as precipitation and streamflow increase throughout the winter season (Eckhardt and Ulbrich, 2003). A feedback loop may exist during the winter and spring thaw periods. On one hand, snowmelt, high soil moisture content and low evapotranspiration may increase infiltration and recharge potential during the winter (Barnett et al., 2008). However, as air temperature increases into the spring, soils lose moisture and evapotranspiration resistance increases. As a result, runoff could increase during rainfall events, reducing infiltration and recharge rates.

The magnitude of flood events is influenced by the volume and intensity of upstream water influxes whereas the frequency of flooding depends on the frequency of precipitation events. Intense short-duration precipitation may be increasing the frequency of riverine flooding as well as increasing winter snow accumulation, leading to higher winter streamflow. Modelled flows for Lovers Creek found that the magnitude of large winter floods has increased (**Figure 4-28**). It also found that small floods are occurring earlier in the spring whereas smaller late summer floods are occurring later in the year, and that high flows have become less predictable as the timing of events have become more variable (Matrix Solutions, 2017). Precipitation variability in the watershed is seasonal, with the most changes observed in the winter and spring. Winter streamflow has increased as more winter precipitation is falling as rain and rain-on-snow events have become more common.



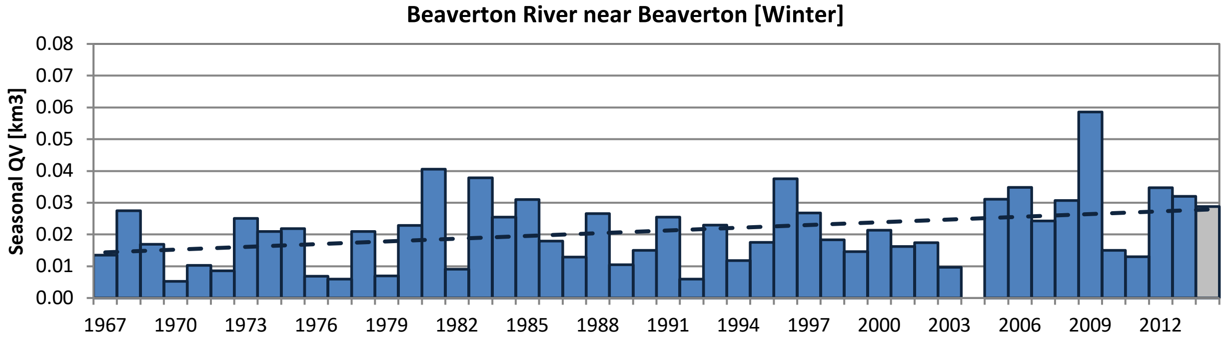


Figure 4-28 Increasing winter streamflow (QV) at the Holland River and Beaver River stations over the period of record. Grey bars indicate an incomplete data year.

Winter flooding can be further exacerbated by ice jams, which can occur as high flows break up river ice and carry it downstream where it can accumulate, block the river flow and cause significant flooding (**Figure 4-29**). A flood of this type occurred in the Grand River in February 2018, causing the evacuation of approximately 2,200 properties and one fatality. A shift in flooding from spring to winter may affect the way flooding events are predicted and managed. Hydrologic and hydraulic modelling as well as floodplain and inundation mapping should consider the effects of climate change, including increased winter flooding.

Figure 4-29 Ice jams in the Lake Simcoe watershed (Beaverton [left] and Newmarket [right])

Key Points – Streamflow and Flooding

- Due to warmer winters, the timing of snowmelt and the spring freshet will continue to shift earlier in the year, impacting not only the hydrology but also ecology of the system.
- The volume of winter streamflow is expected to rise as temperatures and precipitation increase in this season.
- Winter high flows can be exacerbated by ice jams which occur when high flows break up river ice and carry it downstream where it can accumulate, block the river flow and cause significant flooding.
- Extreme precipitation events are expected to become more frequent and more intense, increasing the magnitude and frequency of floods, which can negatively affect communities.
- Climate change may extend the season of low to no flows in some tributaries, potentially impacting the surface water resources
- Current flow regimes may be altered by changes to temperature and precipitation patterns due to climate change.

4.6 Stormwater management

Stormwater management (SWM) features are designed to control runoff volume and associated peak flows via detention and/or retention. As climate change impacts precipitation patterns and the volume and magnitude of flow regimes, stormwater infrastructure needs to be designed to adapt to these impacts.

4.6.1 Quantity control

In order to reduce peak flows, stormwater should be infiltrated on-site as much as possible. Low impact development (LID) features can be used to manage stormwater as close to its source as possible (**Figure 4-30**). Alternatively, on-site storage above and/or below ground may be used where feasible opportunities exist to gradually release stormwater to the downstream receiving water body or infiltrate from the storage device.

Figure 4-30 Bioswales, a type of low impact development (LID) feature

4.6.2 Design input

Intensity-duration-frequency (IDF) curves are used extensively in the design of stormwater infrastructure. IDF projections are region-specific and the best projection for one area might be different than in other regions (see **Figure 4-24**) (Coulibaly et al., 2015). The current statistical representation of the magnitude and frequency of extreme events via IDF curves may not hold true into the future, based on recently observed and projected trends in North America’s climate (Coulibaly et al., 2015). In order to help municipalities update and adapt their IDF curves for future climate scenarios, the Ontario Ministry of Environment, Conservation and Parks has completed a project to develop IDF curves for all 25-km grid points across the entire province through an **online climate data portal**. The updated IDF curves have significant changes including more frequent high intensity rainfall events and substantial spatial variations between locations (Wang & Huang, 2014).

Swales and ditches must also be designed to convey the flow from the required design storm, which is typically the 5-year storm. Appropriate adjustments to IDF curves should account for the adaptation needed for conveyance capacity. Velocities analyzed throughout SWM systems, including swales, inlets, and outlets will result in appropriate energy dissipation measures specified and will also be addressed through IDF curve adaptation.

In a climate change scenario with more intense rainfall events, stormwater volume reduction requirements may also become more difficult to achieve. Climate change projections show a modest increase in total annual precipitation, with increases predicted in winter and spring in particular (as discussed in **Chapter 2 – Climate Change Trends and Projections**). Similar to mitigating peak flow increases, volume reduction can be accomplished by a variety of techniques including infiltration, reuse and rainwater harvesting, canopy interception, and evapotranspiration. The use of LID features that include volume reduction should be encouraged. The projected changes in groundwater recharge and seasonal increases in groundwater levels may reduce retention volumes for SWM features, including LID. If the site characteristics do not allow the use of LID or volume reduction, retention and filtration techniques including rate control practices should be used to mitigate the impact on receiving watercourses by offsetting the cumulative effects of runoff volume increases.

Key Points – Stormwater Management

- Current intensity-duration-frequency (IDF) curves will need to be adapted to future climate conditions as precipitation patterns change.
- As climate change increases the frequency of intense rainfall events, stormwater volume reduction requirements may also become more difficult to achieve
- Low impact development (LID) features may help in achieving volume reduction.

4.7 Current and future vulnerability assessment

The current and future vulnerability of each watershed indicator for water quantity (**Table 4-4**) was developed based on the methodologies described in **Chapter 1 – Introduction**. In summary, the current vulnerability score is a combination of an indicator’s degree of sensitivity and exposure to climate change in the present. The future vulnerability combines climate model projections and the degree of confidence to an indicator’s current vulnerability score to provide the overall vulnerability score for each indicator.

Table 4-4 Current and future vulnerability of water quantity to climate change in the Lake Simcoe watershed

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
Recharge volume - summer	Precipitation, air temperature ET	Decreased soil moisture, increased runoff, decreased recharge	H	M	M	H	M
Recharge volume - spring	precipitation, ET	Decreased snowmelt, decreased recharge	H	M	M	M	M
Recharge volume - winter	precipitation, air temperature, freeze-thaw cycles	Increased frequency and length of winter thaw, increased infiltration, increased recharge	VH	M	H	M	M
Discharge to wetlands	precipitation, air temp, ET	Decreased summer soil moisture, decreased summer precipitation, increased drying of ecologically significant wetland features	H	M	M	H	M
Recharge timing	precipitation, air temp, ET	Significant recharge occurring earlier	VH	VH	VH	H	VH
Low flows	precipitation, air temp, ET	Extension of the low flow season, decreased streamflow volume	M	M	M	H	M
Discharge volume - summer	Precipitation	Decreased precipitation, increased frequency and persistence of dry periods, decreased discharge, increased duration of low and subsistence flows	M	M	M	H	M
	Precipitation, air temp, ET	Decreased precipitation, increased frequency and persistence of dry periods, decreased availability of subsistence flow to wetlands	M	M	M	H	M
Discharge volume - winter and spring	Precipitation, air temp, free-thaw cycles	Increased freeze-thaw cycles, increased period of ground thaw, increased soil moisture and infiltration potential, increased discharge	H	M	M	M	M
Water table level - summer	Precipitation, air temperature, ET	Decreased soil moisture, increased runoff, decreased recharge, decreased water table	L	L	L	H	M
Streamflow - spring flows	precipitation, air temperature, freeze-thaw cycles	Earlier freshet, decreased freshet volume, decreased spring peak flow	VH	H	VH	VH	VH
Streamflow - winter flows	precipitation, air temperature, freeze-thaw cycles	Increased snowmelt, increased rain on snow, increased frequency and duration of winter thaw, increased winter freshets pulses	VH	H	VH	VH	VH
	precipitation, air temperature, freeze-thaw cycles	Increased rain on snow, increased runoff, increased winter streamflow and increased frequency and duration of thaw, increased snowmelt, increased winter streamflow	VH	H	VH	VH	VH
Streamflow - summer flows	Precipitation, air temp, ET	Increased short-duration intense precipitation, increased high flow pulses	VH	M	H	VH	VH
Streamflow - Low flows	Precipitation, air temperature	Decreased total precipitation, increased winter recharge and increased short-	M	M	M	M	M

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future
		duration intense precipitation in summer = increased low and subsistence flows					
Floods - summer	Precipitation, air temperature, ET	Decreased total precipitation & decreased soil moisture + increased short-duration intense precipitation, increased runoff = increased flood frequency and magnitude, increased flow pulses	VH	M	H	M	M
Floods - winter	precipitation, air temperature, freeze-thaw cycles	Increased snow melt, increased soil moisture, increased rain on snow, increased runoff, increased flood frequency and magnitude. Floods occurring earlier	VH	H	H	M	H
Floods - spring	precipitation, air temperature, freeze-thaw cycles	Decreased winter snow accumulation, increased winter recharge, decreased overall spring flood frequency and magnitude	VH	H	H	M	H
Groundwater level	Precipitation, air temperature, ET	Longer more frequent drought, decreased water levels in unconfined aquifers	L	H	L	H	M
	Precipitation, air temperature, ET	Drought causing increasing water demand (habitat and people) leading to further reductions in water level	H	M	M	H	M
	Precipitation, air temperature, ET	Increased drought, lower water table leading to reduced water available for surface water features	H	H	M	H	M
Groundwater level - winter	Precipitation, temperature, freeze-thaw	Increased winter recharge, increased water table leading to higher groundwater level in winter	M	VH	H	H	H
	Precipitation, temperature, freeze-thaw	Increased winter recharge, increased water table, increased vadose freeze-thaw leading to increased flooding (runoff) and infrastructure damage (heaving)	H	H	H	H	H
Groundwater quality - chloride	Precipitation, ice formation, freeze-thaw	Increased recharge in winter, increased cl concentration in vadose, heightened risk of dissolved cl in groundwater system	H	H	H	H	H

Recommended actions were developed to address these vulnerabilities as the climate changes and they are summarized in **Chapter 8**.

Chapter 5

Tributary Ecosystems

5.1 Introduction

The Lake Simcoe watershed encompasses 18 major river systems, comprised of streams, creeks, and tributaries, that flow into the lake. The varying flow and thermal regimes within these systems support unique wildlife assemblages that rely on the watershed's aquatic natural heritage features for spawning, nursery and overwintering habitat, as well as migration routes (LSRCA, 2018). The watercourses themselves provide important functions to residents, such as flood protection, while their rich diversity of wildlife contributes towards the watershed's booming recreation industry. Most notably, local and visiting anglers are attracted to the diversified fisheries afforded by Lake Simcoe and its tributaries. However, the populations of the 58 species of fish known to reside in Lake Simcoe's tributaries are stressed by the continual expansion of industrial, urban, and agricultural activities, which are negatively impacting the watershed's water quality and supply. Recent analyses of LSRCA's monitoring data suggest that the health of fish populations and the benthic communities that underpin them may be deteriorating (LSRCA, 2015). The impacts of climate change will only exacerbate the existing anthropogenic pressures imposed on these systems.

5.1.1 Aquatic natural heritage vulnerabilities

Warming water temperatures, reduced snowpacks, more frequent drought, and more extreme precipitation patterns will all cause a shift in the suitability of aquatic habitats for resident species. However, the magnitude of these impacts on individual species will vary, and the degree to which climate change will impact a particular aquatic species depends on the resilience of their habitat or of the species in question (Williams et al., 2015). At the ecosystem level, disturbance, degradation, fragmentation, reduced biodiversity, and invasion by alien species can all enhance a system's vulnerability to climate change. However, whether individuals fare better or worse under new conditions will depend on (Adams, 2011):

- Their preferred temperature range;
- Their ability to disperse (which may be limited by biological, geological, or human constraints);
- The length of time it takes them to grow and reproduce; and,
- Their specific habitat requirements.

Therefore, some species may be able to cope or even thrive under new conditions, while others may struggle. The notion that the impacts of climate change may be felt disproportionately among species can also be applied at the biome level, where certain ecosystems may display greater vulnerability than others. In this regard, aquatic ecosystems stand out as being particularly vulnerable to climate change because of the dependence of water temperature and availability on climate; the fact that aquatic species are limited in their ability to move along changing temperature gradients; and because they are already exposed and weakened by existing anthropogenic stressors (Woodward et al., 2010). Aquatic systems are also unique in that they are heavily influenced by the status of groundwater and of the landscapes that surround them. By integrating climatic, terrestrial, hydrologic, and geologic processes, aquatic natural heritage systems can serve as valuable early indicators of climate change.

5.1.2 Fish and benthic invertebrates as indicators of aquatic health

Traditionally, techniques aimed at monitoring aquatic ecosystem health have focused on the use of physical and chemical parameters as indicators of water quality. While these parameters are useful in determining changes in the water's physiochemical composition, they don't provide information on the biological responses to changing conditions. In order to accurately account for the real impacts that physicochemical changes have on freshwater ecosystems, LSRCA routinely monitors the biological communities within the Lake Simcoe watercourses. In particular, LSRCA uses data on the composition of fish and benthic communities as indicators of changes in water quality, temperature, flows, and instream habitat (LSRCA, 2013).

Among fauna, fish and macroinvertebrate assemblages have been highlighted as good bio-indicators for monitoring ecosystem degradation. Not only are these species relatively easy to capture and sample, but there are also unique advantages associated with the use of each of these groups. Fish are located within the top of the aquatic food chain and can thus help to provide an integrated view of watershed's environments (Fierro et al., 2017). Their ability to move quickly renders them strong indicators of prolonged stresses rather than sudden changes in conditions (LSRCA, 2013). Furthermore, changes in fish assemblages can be used as a relatable means to communicate statements about aquatic conditions to the general public.

On the other hand, benthic invertebrates are not able to move quickly and are extremely sensitive to changing conditions, meaning that they are strong indicators of more rapid changes. In being at the bottom of the food web, benthic invertebrates are especially useful in providing early warnings about other environmental stressors. Since fish and benthic assemblages are each sensitive to different stressors, using compositional changes in the populations of these groups in combination can provide hints to changes in a wide array of conditions (Li and Li, 2007; Fierro et al., 2017). In both instances, prolonged stresses will eventually cause a shift in the fish and benthic communities from ones that are sensitive and require clean, cool water to survive to ones that are more tolerant of degraded conditions.

5.2 Fisheries

5.2.1 Fisheries trends in the Lake Simcoe tributaries

One of the tools used by LSRCA to assess the changes in the composition of fish communities is the Index of Biotic Integrity (IBI). This index uses ten measures of fish community composition, sorted into four general categories of community health: species richness, local indicator species, trophic composition, and fish abundance (Steedman, 1988). Each of these metrics is given a score, and when aggregated, provide an IBI score that is used to derive the overall health of the fish community (**Table 5-1**).

Table 5-1 Modified Index of Biotic Integrity Scores for Fish Assemblage Health (Steedman, 1988)

IBI Score	Heath of Fish Community
9 – 20	Poor
21 – 27	Fair
28 – 37	Good
38 – 50	Very Good

Figure 5-1 Brook trout (Salvelinus fontinalis) captured in the Lake Simcoe watershed.

The majority of metrics used in the calculation of IBI scores are assessed based on the presence of indicator species. These species are especially indicative of community health for the habitat they are suited for. Species are generally characterized as cold-, cool-, or warm-water, depending on their overall habitat requirements (MDNRC, 2010). In assessing the overall health of the Lake Simcoe watershed's fish populations, brook trout (*Salvelinus fontinalis*) (**Figure 5-1**) are used as a surrogate for the health of cold and cool water sites, and sunfish species (Centrarchidae) are used for warm-water sites. Brook trout are only found on a regular basis where the streams are cold, clean, and have well vegetated buffers. As a result, brook trout populations tend to be found in headwaters along the Oak Ridges and Oro Moraines, where groundwater inputs contribute towards colder water temperatures (**Figure 5-2**). Mottled sculpin, another species requiring cold water stream habitat, are also indicative of brook trout habitat. Conversely, sunfish species are usually found in lower stream reaches where the water is warmer, and the streams are wider. This group of species indicates where there is good water quality, warm temperatures, sufficient habitat and adequate forage fish populations. Furthermore, as top-level predator fish species, the presence of these piscivores serves as evidence of different trophic levels within the community and is therefore an indication of good health.

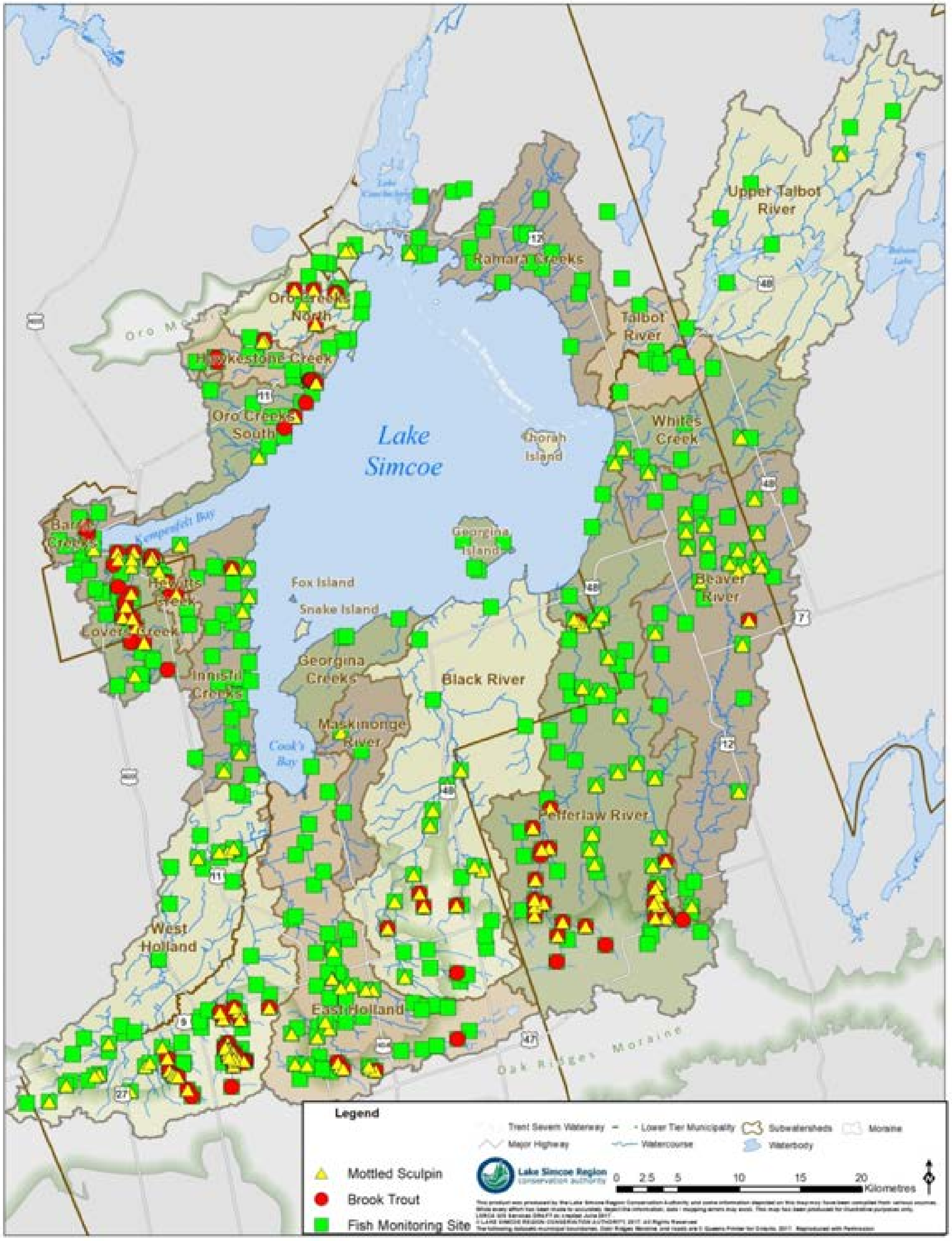


Figure 5-2 Sites with coldwater fish captures in the Lake Simcoe watershed, 2002-2016

Based on the IBI scores, the health of the fish population in the Lake Simcoe tributaries is fairly good with 79% of the sites being categorized as Very Good, Good or Fair. Only 21% of the sites were rated Poor or didn't have any fish captured. Given that IBI scores are highly influenced by the presence of indicator species, high scoring sites can be interpreted as having high diversity and a high abundance of indicator species. Sites that are rated poor or that contained no fish tend to be located in highly urbanized subwatersheds (**Figure 5-3**). Here, a lack of stormwater controls and riparian vegetation, flashy flows, and non-natural stream modifications have likely degraded the health of fish communities. Of the routine monitoring sites that have a period of record sufficient to support long term trends, most are showing stable IBI trends, while 9% are showing decreasing trends and only 5% are showing increasing trends. Since monitoring began in 2003, brook trout and sunfish biomass has remained relatively stable at the watershed scale (**Figure 5-4**).

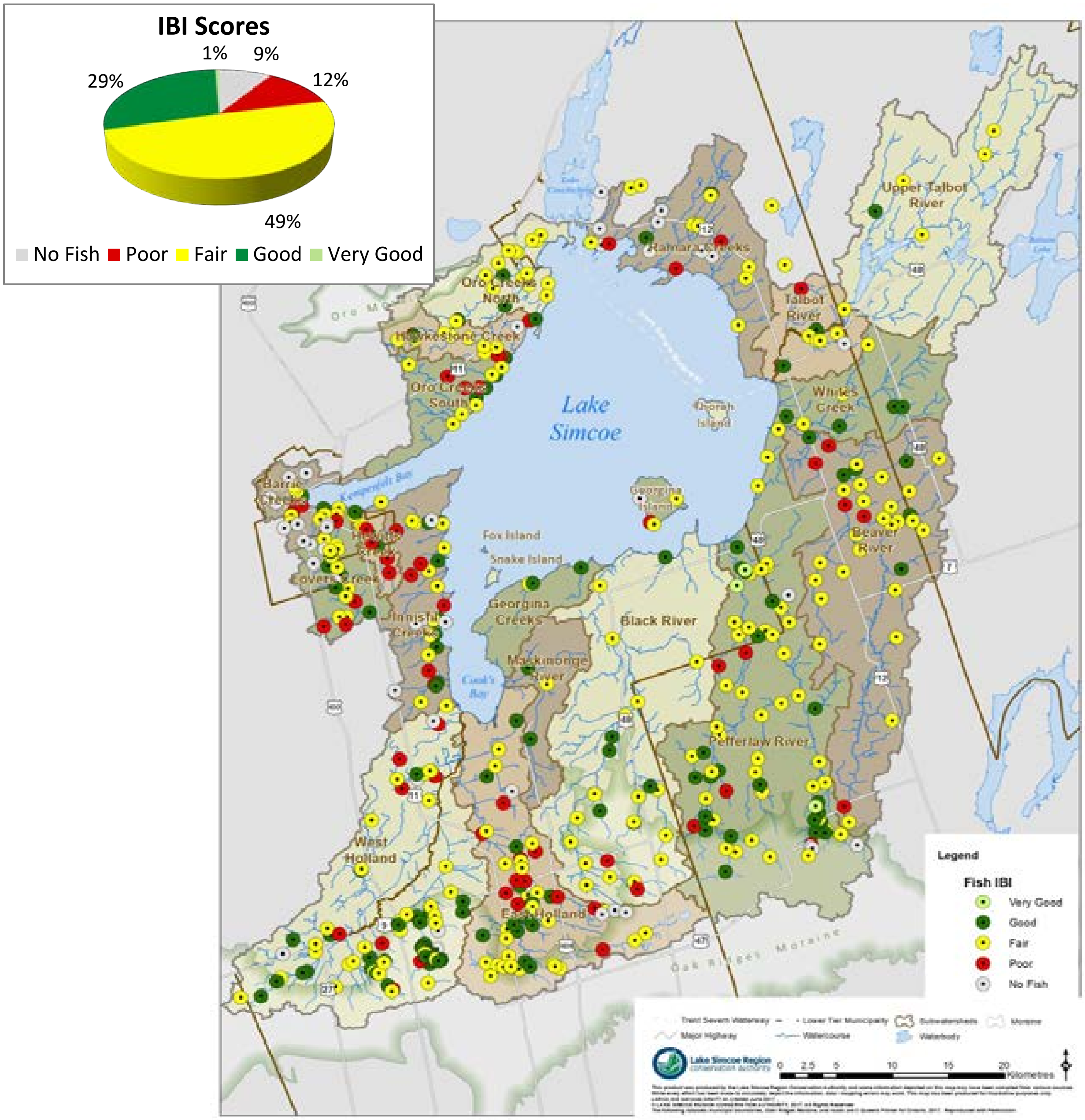


Figure 5-3 IBI scores for fish sampling sites in the Lake Simcoe watershed that were sampled between 2002 and 2016

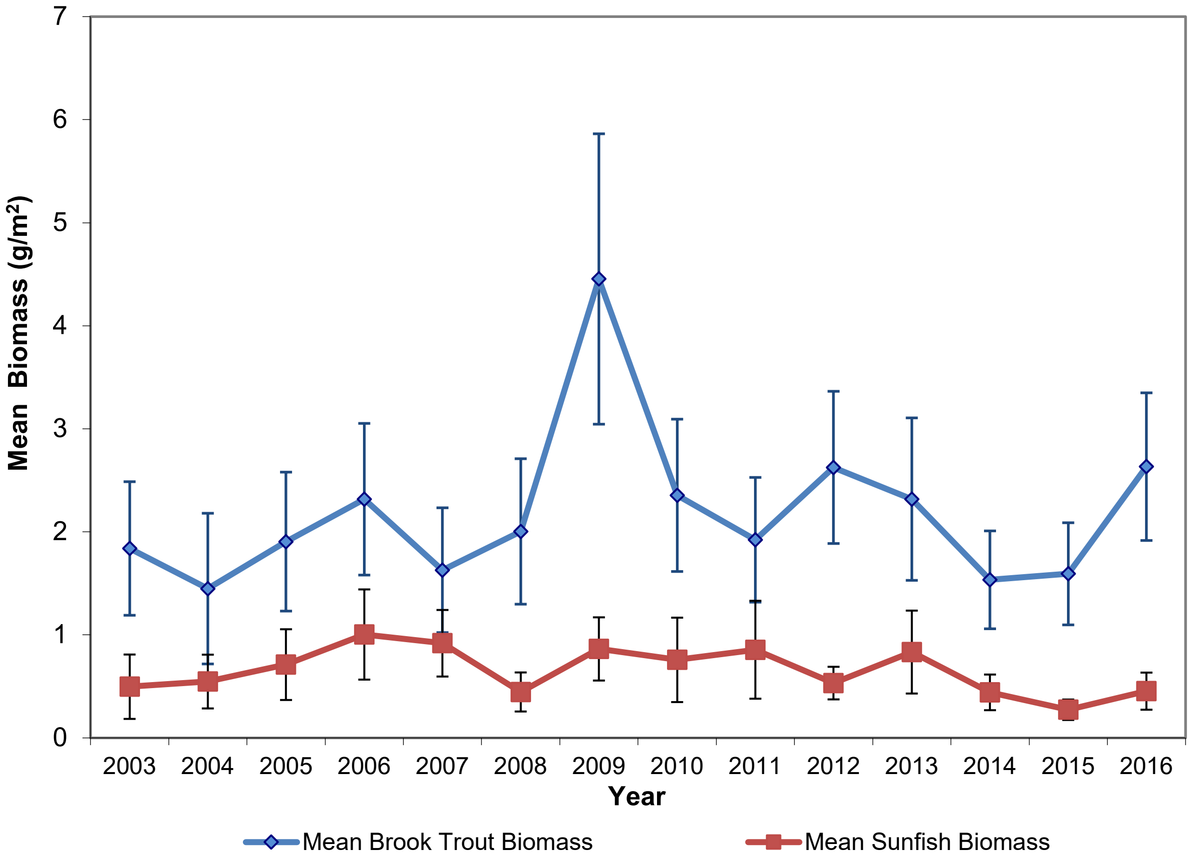


Figure 5-4 Mean brook trout and sunfish biomass showing standard error between 2003 and 2016 for the tributaries in the Lake Simcoe watershed. Both brook trout and sunfish biomass has remained relatively stable at the watershed scale.

Similar to biomass, IBI scores for each of the thermal habitat regimes have also remained relatively stable (**Figure 5-5**). However, this stability may be a reflection of the short time period in which fish monitoring has occurred. Based on the data, the IBI scores of cool-, cold-, and warm-water fish assemblages are all displaying slightly decreasing trends, although they are not significant. These trends have remained relatively stable despite rapid changes in the landscapes surrounding the tributaries. Traditionally, the intensification of agricultural activities and urban development, which have been accompanied by the removal of natural features, water quality degradation, habitat loss and fragmentation, and the introduction of invasive species, have altered the physical, chemical, and biological conditions of aquatic communities. Warming temperatures and more variable precipitation patterns will compound these stressors and increase their cumulative impacts, ultimately altering the availability of cool, cold and warm water habitat and the fitness of the fish assemblages that inhabit them.

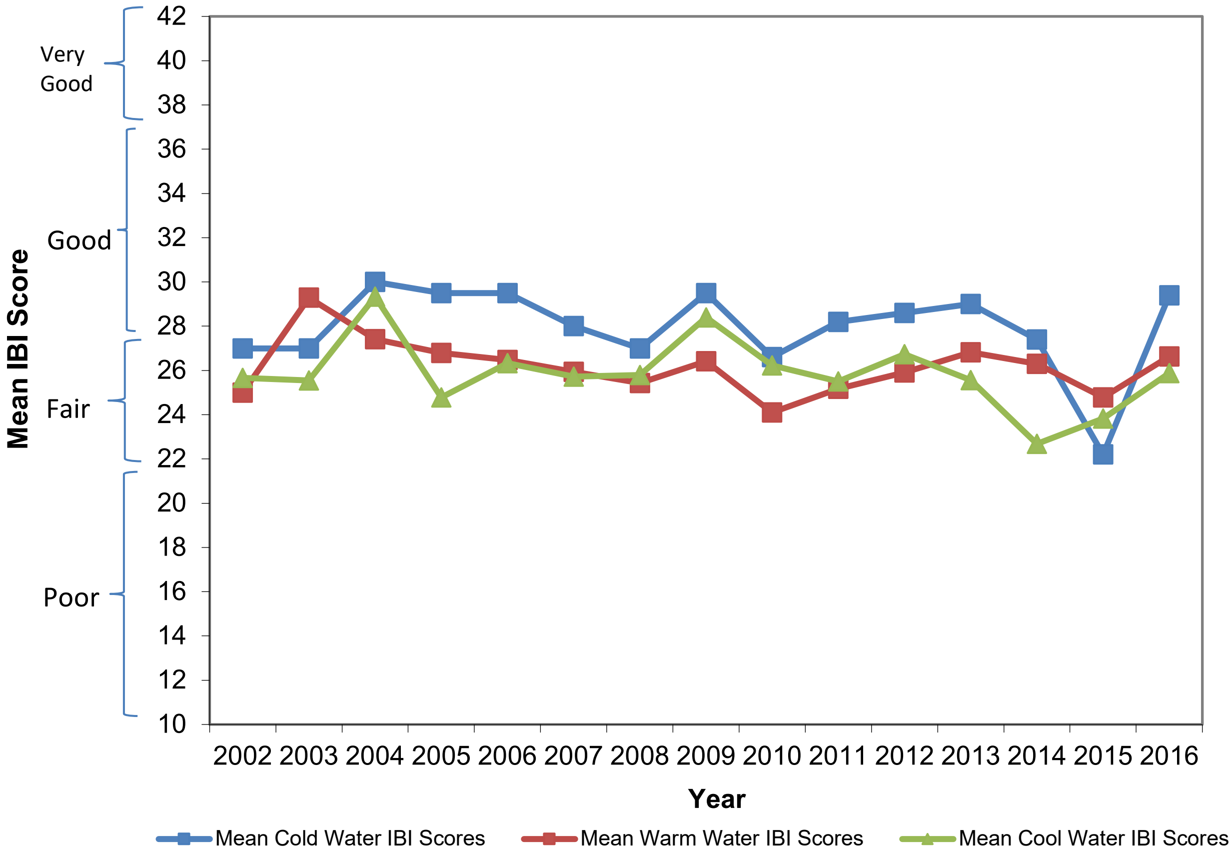


Figure 5-5 Mean IBI score for cold-, cool-, and warm-water habitat in Lake Simcoe's tributaries. IBI scores have remained relatively stable since 2002, showing a slight non-significant declining trend.

5.2.2 Climate change impacts on fish assemblages

Habitat Availability

Each individual fish species has a specific range of habitat conditions that it can tolerate. Within these conditions, temperature stands out as a parameter for which fish have strict preferences. As such, stream temperature is an important factor in determining the distribution and abundance of fish. It can affect important physiological functions, such as energy budgets and growth, as well as life history characteristics, recruitment, and population growth rates (Al-Chokhachy et al., 2013). Because of their sensitivity to temperature, fish species select habitat of a temperature at which they can carry out these functions with high efficiency. However, fish species must ensure that they stay below a certain temperature threshold since exposure to overly warm temperatures can reduce growth, lower sperm mobility, inhibit ovulation, and reduce egg viability (Hokanson et al., 1973). The preferred temperature of a given species is referred to as its thermal niche. Coldwater fish, including brook trout, generally seek temperatures below 19°C, and require colder water for reproduction (Scott and Crossman 1998). However, they are able to survive in water that is warmer than their preferred range as long as temperatures remain within their tolerable range. Meanwhile, cool-water fish seek habitat that lies between 19-22°C and warmwater fish can live in streams warmer than 22°C (Allan and Castillo, 2007).

Disparities in habitat preferences are also present in regard to the levels of dissolved oxygen (DO) each species requires. Coldwater fish require higher DO levels, especially for reproduction and for the survival of their offspring, while warmwater fish tend to tolerate lower DO levels (Fondriest Environmental Inc., 2013). If fish are unable to access habitat that lie within their temperature and DO tolerance range, their survival, growth, or reproductive success will likely be impaired.

Across the Lake Simcoe watershed, urbanization has led to changes in the landscape that contribute to the warming of streams. These changes include the loss of riparian habitat, which typically provides shade to streams from the hot summer sun, and an increase in impervious land cover, which increases the temperature of runoff entering the stream during rain events. In addition, the construction of dams for recreation, flood control, water supply, or hydropower, and the construction of stormwater management ponds can also enhance warming of water. Climate change is now expected to produce interacting stresses that will exacerbate the impacts that these stressors have on stream temperatures.

Surface water temperatures are in close equilibrium with air temperature; as air temperatures rise, so will water temperatures (Mohseni et al, 1998). However, based on LSRCA's monitoring data, water temperatures at cool and warm water sites follow the yearly fluctuations in air temperature more closely than coldwater sites (LSRCA, 2015). Water temperatures at coldwater sites may not be as sensitive to changes in air temperature due to the heavy influence of colder groundwater inputs. These inputs are important for providing coldwater refugia to cool- and coldwater fish during summer (Dove-Thompson at al., 2011). However, as outlined in **Chapter 4 – Water Quantity,** changes in the timing of snow and rainfall events, , reduced soil moisture, and higher evaporation rates have the potential to reduce summer groundwater discharge. In addition, as atmospheric temperatures continue to increase it is expected that groundwater temperatures may also warm, which would reduce the groundwater's ability to buffer air temperature changes. Although increases to groundwater temperature are likely to occur at a slower rate than in surface waters, studies have found that this warming may already be occurring (Gunawardhana and Kazama, 2011; Menberg et al., 2014). As groundwater levels fall and as groundwater temperatures increase, its ability to moderate the effect of rising air temperatures on surface waters may decline and coldwater streams may subsequently warm at faster rates.

In the same way that groundwater is expected to change, surface water quantity will likely experience similar flow variations. It is anticipated that under future climate change, more extreme low flows are expected during the summer months (see **Chapter 4 – Water Quantity**). As streams become shallower, they become more sensitive to changes in air temperatures and prone to greater thermal fluxes. Warmer streams will increase evaporation rates, further reducing streamflow (Delpla et al., 2009). Hence, climate change can intensify the feedback cycle in which rising evaporation rates caused by warmer water promote further water warming. Conversely, the occurrence of more frequent intense rainfall events will drive more frequent high-flow periods. While this may offer some temperature relief from rising stream temperatures, these events are highly variable and are often short-lived.

Rising air temperatures, declining groundwater inputs, and reduced flows will all contribute to increased water temperatures and a reduction in cold- and coolwater habitat across the the watershed (Chu, undated). Since dissolved oxygen (DO) concentrations tend to decrease with rising water temperatures, the amount of habitat with DO levels suitable for cold- and coolwater species will also decline. The loss of suitable habitat for cold- and coolwater fish species will place stress on these populations as they face longer periods in summer confined to ever-smaller suitable habitat spaces (McDermid et al., 2015).

Based on LSRCA's monitoring data, air temperature changes have influenced water temperature in all thermal regimes. Surprisingly, the temperature of monitoring sites where brook trout have been caught every year , intermittently, and never do not display significant trends over time (**Figure 5-6**). However, each of these sites is significantly correlated with the mean daily maximum air temperature recorded at the Baldwin station. Historically, the water temperatures at sites where brook trout have been caught every year or intermittently have been within their optimal or tolerable temperature range. While water temperature at these sites have remained relatively stable, projected rises in air temperatures and its subsequent impact on water temperature could eventually render these sites too warm for brook trout. Even if streams remain within brook trout's tolerable range, exposure to sub-optimal temperatures can affect individuals' growth rates, incubation times, competitive ability, and synchrony with prey, even if temperatures never reach their lethal range (Wenger et al., 2011).

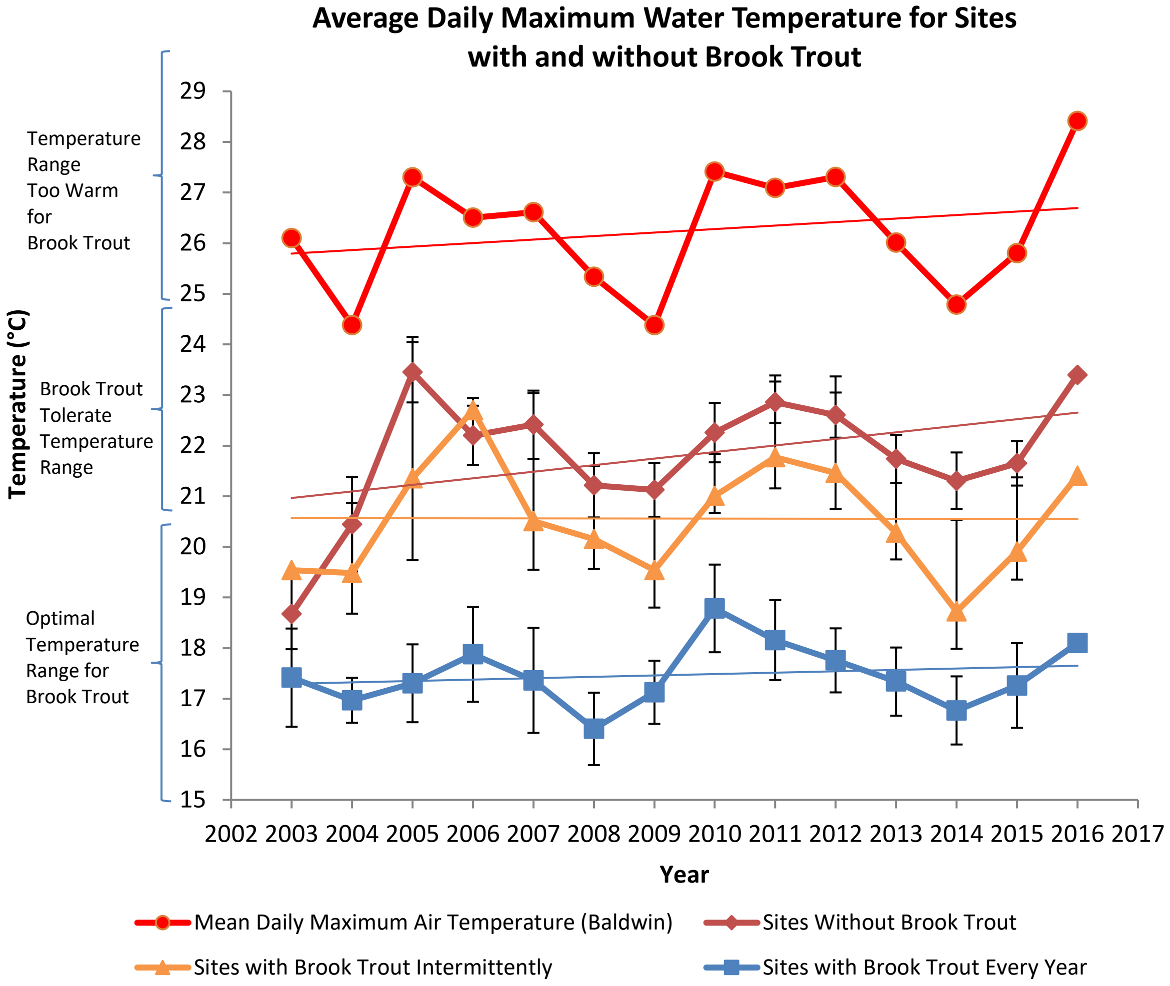


Figure 5-6 Trends (2003-2016) in average daily max air temperatures and water temperatures at sites in the Lake Simcoe watershed with brook trout captured every year, occasionally, or never. While all three sites fail to display significant temperature trends over time, they are each significantly correlated with mean daily maximum air temperature.

The observed trend in rising stream temperature across the Lake Simcoe watershed is validated by modelled projections, which predict past, present, and future stream temperatures based on changes in air temperatures (di Rocco et al., 2016) (**Figure 5-7**). According to the model, coldwater habitat has decreased and coolwater habitat has increased considerably since pre-European development. These trends are expected to continue well into the 21st century. By 2065, the Lake Simcoe watershed will experience a substantial decrease in coldwater streams. Presently, most of the watershed's headwater streams are coldwater, but under future climate change it is expected that only 12% of the watershed's streams will remain cold by 2065. Streams that are expected to remain cold are headwaters on the Oak Ridges Moraine and in the Lover's Creek subwatershed south of Barrie.

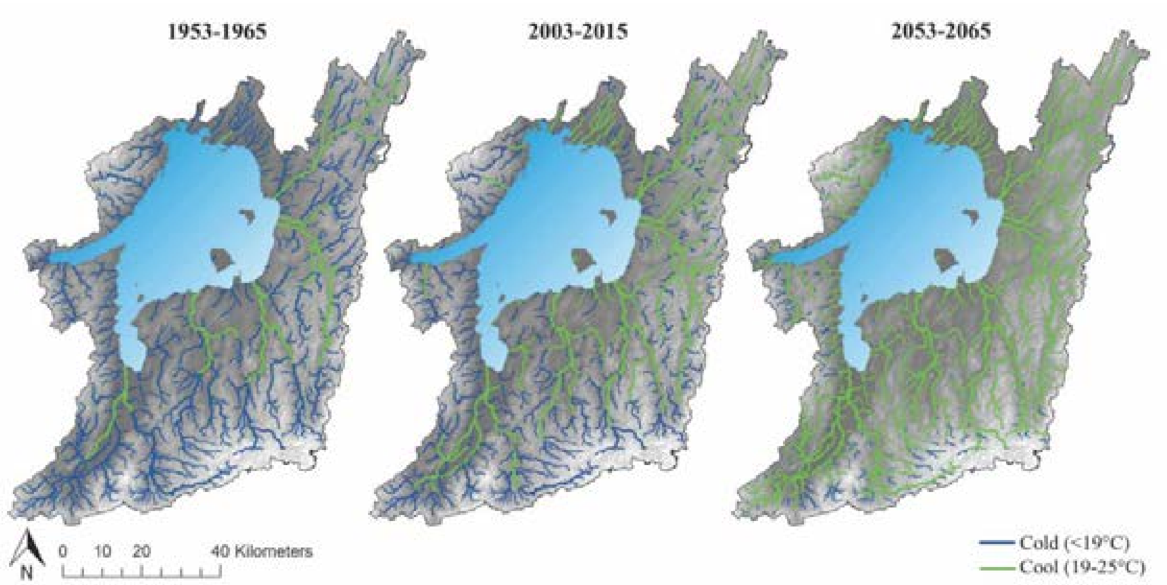


Figure 5-8 Shifting thermal regimes in Lake Simcoe watershed tributaries. The left map is the hindcasted stream temperature based on mean July air temperature during 1953-1965 and land cover largely forested pre-European settlement. The centre map is the predicted stream temperature for 2003-2015. The right map shows the stream temperatures based on air temperature predicted for 2053-2065. The width of the streams increases with reach contributing area. The land is shaded based on elevation (di Rocco et al., 2016)

In response to warming stream temperatures, coldwater fish, including brook trout, will have to seek refuge in either deeper, more northerly, or groundwater-fed streams. In the Lake Simcoe watershed, observations and models suggest that brook trout will congregate around cooler headwaters and groundwater seeps. Confined to ever-shrinking habitat, coldwater fish populations may become stressed from crowding conditions, which can increase their susceptibility to disease and place them at increased competition for resources. Also of concern is the possibility of increased intraspecific predation. Warmer and shallower streams mean that adult and juvenile fish will be occupying space closer together, both in geographic distribution and within the water column as the zone of warm surface water and the anoxic zone near the bottom of the water column expand (Ficke et al., 2007) (**Figure 5-8**). This will increase the chance

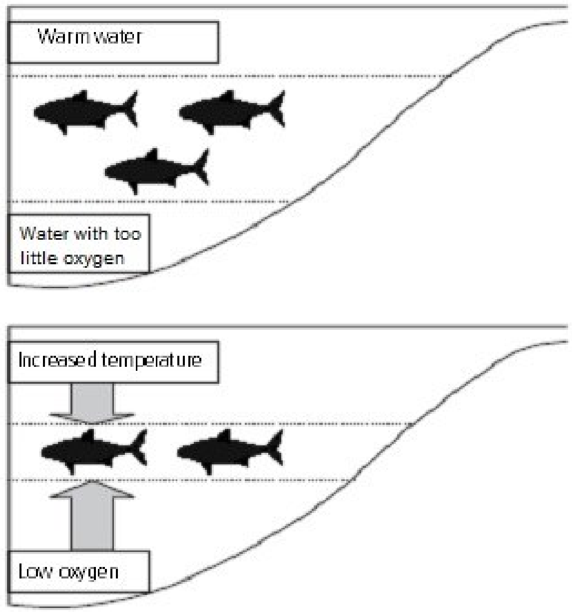


Figure 5-7 The potential impact of climate change on coldwater habitat availability. Increased solar radiation will expand the zone of warm surface water, while metabolic processes will eliminate oxygen in a larger portion near the bottom of the water column, decreasing habitat suitable for coldwater fish. Adapted from Ficke et al. 2007

of adult individuals preying on juveniles (Dove-Thompson et al. 2011). Intraspecific predation is already believed to be occurring within Barrie's streams, where brook trout have been the only species caught. Young brook trout can get away with eating only invertebrates, but as trout get bigger, they need to feed on small fish to survive. If brook trout are the only fish species present in the stream, adult brook trout are likely forced to feed on their young. The occurrence of adult brook trout feeding on juveniles will likely become more common as brook trout populations become increasingly confined to shrinking habitat space and competition for resources intensify (R. Wilson, pers. comm.).

While it is expected that the Lake Simcoe tributaries will continue to contain coldwater habitat under future climate change –albeit limited to a select number of groundwater-fed headwaters- the success of coldwater species will be contingent on their ability to reach these cold water refuge tributaries. The presence of barriers, however, can impede movement throughout aquatic systems and can ultimately limit an individuals' ability to effectively migrate to more environmentally suitable habitat. Without access to this habitat, fish can be faced with physiologically burdensome conditions, such as low flows, high temperatures, or low dissolved oxygen, which can cause stress. Where conditions exceed the adaptive capability of the fish, death of individuals, and eventually local species extirpations can occur.

Migratory barriers in the form of dams, weirs, perched culverts, and enclosed watercourses are common throughout Lake Simcoe's tributaries, and have been known to occur near and within cold- and coolwater sites. For example, one of the sites in Hawkstone Creek is known to be thermally tolerable for brook trout, yet the site contains low brook trout biomass (LSRCA, 2015). Low brook trout densities are attributed, in part, to the presence of dams upstream and downstream of this site, which make it difficult for fish to reach the area. The removal of anthropogenic barriers, such as these dams, can help increase resilience of fish of all thermal regimes and other aquatic biota to climate change by facilitating migration and allowing individuals to access and move freely between important habitats.

Key Points – Fish habitat availability

- Coldwater species are especially vulnerable to increasing water temperature associated with climate change because they have lower thermal and higher dissolved oxygen ranges than cool- and warmwater species.
- Groundwater inputs provide coldwater refuges as the influence of air temperature on water temperature is reduced at these sites.
- Climate change is likely to decrease stream flow in some tributaries during the summer and water temperature will increase during low flows.
- Increased water temperature is almost certain to decrease dissolved oxygen concentration in many tributaries, resulting in fewer suitable cold- and coolwater habitats.
- Where brook trout are caught every year, the water temperature remains within their optimum thermal range (15°C to 20°C). At higher temperatures, brook trout are either intermittently caught or not caught at all.
- The majority of the watersheds headwaters streams are currently coldwater habitats. By 2065, climate models predict that 12% of these habitats will remain and will be limited to the headwaters in the Oak Ridges Moraine and in the Lover's Creek subwatershed.
- Coldwater fish species are likely to become crowded within shrinking habitats as the depth of warm waters at the surface and the depth of low dissolved oxygen concentration at the bottom increase. Crowding increases competition for resources, disease susceptibility and intraspecific predation.
- Fish migratory barriers such as dams, weirs and culverts common throughout the watershed will almost certainly limit the ability of coldwater species to reach coldwater habitats and refuges in the future unless they are removed.

Reproduction

Spawning phenology is a key fish life history trait that has substantial implications for the survival of eggs and juveniles. Fish have evolved to reproduce under environmental conditions that are favorable to the survival of the young. The general timing of spawning for most fish species is seasonally consistent, mainly occurring either in the spring or the fall, and broadly established by photoperiod (Warren et al., 2012). In the Lake Simcoe watershed, most fish, including sunfish, spawn in the spring, while most Salmonids, including brook trout and lake whitefish (*Coregonus clupeaformis*) spawn in the fall. However, local factors can control the specific timing of spawning within a species' broader seasonal window (Holcombe et al., 2000). Processes such as spawning and egg development require specific thermal conditions and are timed to coincide with food availability (Warren et al., 2012; Hasnain, 2010).

In order to ensure that spawning takes place within the appropriate time window, fish rely on spawning triggers, or environmental cues, that indicate the arrival of optimal conditions. Moreover, these cues allow species to synchronize their breeding, which is important in ensuring that individual fish will find a mate and for enhancing brood survivorship (Blanchfield, 1998). Most commonly, spawning cues involve sudden changes in the environment, such as changes in flow and water temperature. However, climate change is affecting the timing and magnitude by which these changes occur, resulting in altered spawning phenology. This could have major consequences for fish reproduction across all stages of the reproductive process.

Temperature is a fundamental physical regulatory factor in the lives of fish and has been identified as one of the most important environmental cues for spawning (Bye, 1990). Changes in water temperature can trigger a range of reproductive processes, including gamete development, spawning, hatching, and larval and juvenile development and survival (Pankhurst and Munday, 2011). For spring spawners, rising water temperatures are required to cue maturation. Therefore, a general increase in water temperature, driven by climate change, may result in waters reaching minimum temperature thresholds sooner and the subsequent advancement of the onset on reproductive processes. This raises concerns for the survival of young, who are more sensitive to temperature fluctuations than are adults (Rombough, 1997). Eggs must pass a certain developmental stage before embryos can survive hatching (Luczynski, 1984), but if parental and offspring reproductive and developmental processes advance at different rates in response to warmer temperatures, then eggs may be underdeveloped at hatching. Furthermore, rising temperatures could play a role in the truncating of spawning periods in spring spawners. Each species has a maximum thermal threshold above which breeding may be inhibited (Pankhurst and Munday, 2011). Thus, depending on the rate of the spring temperature increase, thermal thresholds may be reached earlier, and the spring spawning window may be reduced.

In addition to temperature, the spring freshet has increasingly gained attention as an environmental cue used in reproduction. While research on this topic is limited, particularly with regards to the species present in the Lake Simcoe tributaries, it is believed that high stream flows cue migration and spawning in some fish species. Additionally, in a study by Næsje et al. (1995), high spring flows induced hatching of the river-spawned eggs of lake whitefish (*C. clupeaformis*). Importantly, the study found that the length of the hatching period depended on the rise in water discharge during the spring flood. A fast increase in water discharge and high water flow led to synchronous hatching. A small or varying flood gave longer hatching periods with less synchrony. While the mechanisms by which flows stimulate hatching remain unclear, one proposed explanation is that the increased water discharge agitates the eggs, which induces hatching (Næsje et al., 1995).

By using the spring flood as a cue for the start of migration, spawning, and hatching, fish become vulnerable to changes in the timing and magnitude of the freshet. As discussed in **Chapter 4 – Water Quantity**, historical and projected data are all pointing to more rain events throughout winter and a gradual disappearance in the spring freshet following warming winter temperatures. High flow periods, caused by heavy rain events or pre-mature thaws during early spring, may induce reproductive processes at an earlier date, when conditions are not optimal and food is scarce. On the other hand, the gradual disappearance of the freshet may result in the loss of this environmental trigger as a spawning cue, and reproduction and growth may be delayed, which may also negatively influence fish survival.

Fall spawners are vulnerable to changes in their environmental spawning cues in much the same ways as spring spawners. Like spring spawners, fish that spawn in the fall use changes in temperature to trigger reproduction. However, in contrast to spring spawners, waters must cool down in order for reproduction to be triggered (Pankhurst and Munday, 2011). In the case of brook trout, ovulation and spawning occur once water temperatures drop to at least 16°C (Hokanson et al., 1973). Low flows and rising temperatures are now threatening to alter the suitability of this parameter as a spawning cue. Elevated water temperatures throughout the summer have been found to delay fall spawning (Warren et al., 2012). This is believed to be caused by delayed or diminished gonad development in adult fish, which is a consequence of prolonged exposure to elevated summer temperatures (Luksiene and Svedang, 1997; Pankhurst and Munday, 2011).

Delayed spawning could lead to large deviations between the time of emergence and food availability. Broadly speaking, warmer temperatures in spring will likely lead to earlier phytoplankton blooms and associated successional dynamics in zooplankton populations (Warren et al., 2012), and also lead to delayed fry emergence among fall spawners. With anticipated increases in temperatures, trends toward earlier peaks in prey availability and later fry emergence are expected, thereby increasing the potential for asynchrony between fry and their prey. Moreover, fish size has been linked to temperature and salinity tolerance, with larger fish generally being more robust (Watanabe, 1985; Hurst, 2007). In delaying spawning, juveniles may not undergo adequate growth to withstand the higher temperatures and high salt levels that are typical of spring.

Figure 5-9 A female brook trout builds a redd by using her swimming body motion as well the sideways movement of her tail to form a depression in the gravel. Source: Sean Landsman

In addition to changes in the timing of reproduction, reduced productivity among fall spawners has also be identified as a possible impact of climate change. As part of their reproductive behaviour, many fish, including brook trout, typically form spawning nests known as redds in the gravel of streams and along the shores of lakes (Scott and Crossman, 1998; Figure 5-9). These redds are where they deposit their eggs. One indication of reproductive effort, or the proportion of energy that fish devote to reproduction, is the abundance and density of these redds (Warren et al., 2012). Warmer water temperatures have been found to reduce redd density among brook trout, likely resulting from the diminished gonad development associated with high water temperatures (Warren et al., 2012). Fewer redds could be an indication of reduced spawning activity. If this is this case, then warming temperatures could contribute to declining brook trout populations, which could have major implications for survival of populations for years to come.

Fall spawning is also heavily influenced by the availability of spawning and incubation habitats. For brook trout, these habitats are characterized by the presence of groundwater discharge (Curry and Noakes, 1995). There remains some uncertainty as to why brook trout prefer to spawn in sites with upwelling groundwater, but it is believed to be attributed, at least in part, to the more stable thermal regimes afforded by groundwater inputs throughout the incubation period (Baxter and McPhail, 1999). It is also believed that brook trout use the physical (flowing water), chemical, or temperature gradients produced by upwelling groundwater to locate suitable spawning habitat. Clearly the ability to detect these gradients will be a function of their intensity, as determined by the rate of groundwater discharge (Næsje et al., 1995). A lowering of the groundwater table, particularly during the summer months, has the potential to reduce groundwater inputs, which will affect the number of suitable spawning sites. As a result, brook trout will have fewer options in terms of spawning habitat and may face increased intraspecific competition as they congregate around the suitable areas that will remain. Alternatively, failure to locate groundwater-fed sites may force some individuals to construct redds in sites with sub-optimal conditions. The increased thermal variability that their eggs will be exposed to may hinder their growth and survival.

The importance of stabile conditions for egg development pertains not-only to the thermal regime, but to a range of parameters that characterize the stream channel. While large spring flows may be used by some fish to stimulate spawning, lower, stable flows during the rest of the year are crucial for maintaining nursery habitat. In fact, it is believed that fish choose to spawn in sites that are less likely to be destabilized by large velocity variations (Gebrekiros, 2016). The use of redds during spawning has evolved, in part, as a precaution against these flow variations, since redds can help protect eggs from agitation and bed scour (Buxton et al., 2015). Yet, these redds have been known to be ineffective against floods, which scour redds and dislodge or smother eggs (Wald, 2009). Moreover, these high-flow events are capable of washing away newly emerged fry. These impacts are relevant for both spring and fall spawning, with fall-spawners being sensitive to winter floods, and spring-spawners being sensitive to summer floods. With climate change expected to contribute to an increase in large runoff events through more frequent and intense storms during the summer months and more rainfall events during the winter months, eggs and fry face greater exposure to high flows. These high-flow events, which may occur more frequently and at greater magnitudes, can directly affect fish populations by causing damage and mortality to fish and their eggs as they are scoured, buried or displaced into unsuitable habitats.

Key Points – Fish reproduction

- The timing of spawning has a substantial influence on fish egg and juvenile survival.
- Most of the fish species in the watershed spawn in the spring, although Salmonid species such as Brook Trout and Lake Whitefish spawn in the autumn.
- Fish spawning is triggered by environmental cues that indicate the arrival of optimal spawning conditions. Climate change is affecting the timing and magnitude of the spawning cues which resulting in altered spawning phenology.
- The optimal spawning temperatures are occuring earlier in spring and later in autumn and the timing of spawning is altering as a result. Young fish are more sensitive to fluctuating water temperature and therefore earlier spawning in the spring may reduce recruitment and survival.
- In spring, the timing and magnitude of the spring freshet is changing in response to climate change, and the spawning timing and reproductive success of fish species triggered by high streamflows is likely to be impacted by these changes.
- In autumn, spawning occurs when water temperatures fall below 16C. The reproductive success and survival of young fish is likely to be impacted as this threshold is reached later in the season when flows are typically lower.
- Altered spawning times are likely to lead to an increasing divergence between the time of emergence of young fish and their phytoplankton prey.
- Many fish species in Lake Simcoe tributaries form redds (spawning nests) in the gravel of streams along the shores of lakes to deposit eggs. The density of redds among Brook trout has declined in response to warming water temperature. Fewer redds could indicate reduced spawning activity.

Overwintering Survival


Figure 5-10 In March, 2011, Investigations into a reported fish die-off in a pond located in Toronto's Sam Smith Park revealed that that it was likely a result of winter kill. Source: Friends of Sam Smith Park

In the Lake Simcoe watershed, mean temperatures are expected to increase more during winter than during other seasons, suggesting that the impacts of climate change may be more pronounced during winter. The winter period is of importance for fish population dynamics due to increased mortality risk (**Figure 5-10**). Among juvenile fish especially, a large part of the annual mortality occurs during this period (Byström et al., 2006; Hurst, 2007). This mortality may result from a range of possible stressors, including hypothermia, predation, displacement by flooding, inadequate lipid reserves leading to eventual starvation, and physical damage from anchor ice and frazil ice (Seelbach, 1987). However, vulnerability to these stressors is not equal among all fish, with large fish having been known to exhibit higher winter survivorship (Garvey et al., 1998). For larval and juvenile fish, large size confers a host of advantages during a time when mortality is typically high, including reduced risk of predation and starvation. Winter stressors may be especially important during the first winter, when rapid growth and large size prior to the winter season are necessary for overwintering survival. Hence, the first winter is often viewed as a critical period in which interacting stressors influence survival of larval and juvenile fishes, recruitment to later life stages, and, ultimately, year class strength of fishes.

Body size is strongly linked to growth during early life stages. Growth rate is heavily influenced by temperature, although the relationship between these two parameters differs between species and seasons. In general, warm-water species undergo rapid increases in growth rate as temperatures rise, passing through a peak at optimum temperature and falling rapidly as temperatures become adverse (Árnason et al., 2009). Brook trout, on the other hand, benefit from warming temperatures during the winter and spring, but experience reduced growth rates with rising temperatures during the summer and fall (Xu et al., 2010). Given that size can affect the survival rate of the young of many fish species, changing water temperatures could affect the relative survival and recruitment rates of fishes of all temperature regimes. The opposing influence of temperature on the growth rates of sunfish and brook trout will likely result in contrasting overwintering survival trends in response to future rises in water temperatures and subsequent changes in spawning phenology.

As temperatures increase, many warmwater species will benefit from more favorable growth conditions and a significant decrease of winterkill. Young-of-the-year fish will be able to thrive in the warmer conditions and will subsequently be able to grow larger by their first winter; leading to enhanced overwinter viability (Jackson and Mandrak, 2002). In addition, this enhanced growth rate will be accompanied by a prolonged growing period prior to their first winter as rising temperatures trigger earlier spawning in the spring. The earlier onset of reproduction can result in the production of larger eggs, potentially leading to a larger body size prior to the first winter (Zięba et al., 2015). As a result, higher over-winter survivorship would be expected relative to that which occurs under the present climatic regime. In contrast, delayed breeding among fall-spawners will reduce the length of time individuals have to grow before the onset of winter, although growth gains achieved as a result of rising winter temperatures may offset the losses resulting from warmer fall temperatures (Meyer and Griffith, 1997). The overall outcome will ultimately depend on the juvenile's ability to withstand winter stressors until the benefits from warming winter temperatures can be realized. Hence, from purely a size standpoint, warmer temperatures will provide conditions that could potentially enhance growth among fish of all thermal regimes, leading to improved winter survivorship.

While growth can certainly contribute towards increasing an individual's chance of overwintering survival, fish of all sizes may remain vulnerable to the onslaught of winter stressors if they are unable to access a proper food source, both before and during the winter months. Fish use a number of strategies to survive the winter period and avoid starvation, including building up energy stores in autumn, as well as reducing activity during winter (Casselman et al., 1987). However, fish must continue to consume resources to maintain energy stores. A study by Brodersen et al. (2011) investigated the overwintering biology of juvenile fish and found that temperature does not influence overwintering survival in isolation, but rather, it is directed strongly by resource availability. The study found that increases in winter temperatures that occur when the fish's main food source, zooplankton, is present results in reduced fish biomass loss. In contrast, the same temperature increases that occur when zooplankton is absent results in enhanced fish biomass loss. To complicate the matter, however, zooplankton response to rising temperatures is complex, and not directly coupled to temperature (Brodersen et al., 2011; Vadadi-Fülöp et al., 2012). These findings reinforce the notion that future changes in temperature may significantly alter fish overwintering survival. In order to fully understand how survival of the Lake Simcoe watershed's fish populations will be impacted, more regional work will be needed to explore the complex relationship between temperature and zooplankton dynamics.

Key Points – Fish overwintering survival

- Air temperatures are projected to increase significantly in the winter. At present, fish mortality is highest in the winter, especially among young fish. As winter water temperatures increase in response to warmer air temperatures, water temperature-related fish mortality may decline.
- Fish body size is strongly linked to water temperature, especially in young fish. Warmwater fish grow more rapidly in the summer up to their thermal optimum while cool- and coldwater fish grow more rapidly in the winter and early spring.
- Fish survival rates are strongly linked to body size and increased water temperatures could impact the growth and recruitment rates of warmwater species and overwintering survival of fishes of all thermal regimes.

Water Quality

Acceptable water quality is an essential prerequisite for fish habitat, and each species has different tolerance levels to different water quality parameters (Koehn, 1993). Although tolerance thresholds exist, it is important to note that fish have mechanisms that can allow them to adapt to small fluctuations in water quality.

These mechanisms, however, are only effective in mitigating stress if fluctuations occur within natural limits and rates (Svobodová, 1993). If changes in water quality occur too quickly or for too long, then fish will become stressed. This stress can lead to hindered growth, reproduction, and digestion. It can also lower the ability of the immune system to respond effectively and fully, placing individuals at greater vulnerability to parasites and disease. If chronic stress persists, or if fish are exposed to repeated acute stress or to a single acute event of substantial magnitude, mortality will likely ensue.

Figure 5-11 Pollution in a pond located in Newmarket, Ontario

Human activities have altered water quality across the Lake Simcoe watershed, particularly following rapid development towards the end of the 20th century. Water quality degradation has been closely associated with stormwater runoff and agricultural drainage that can wash contaminants into surrounding streams. Climate change is expected to exacerbate water quality degradation, raising serious concerns regarding the ability of fish to withstand future conditions (**Figure 5-11**). Changes in precipitation and temperature regimes are expected to intensify existing contaminants pathways, both in terms of the magnitude and frequency of contamination. In addition, a new climate will allow for the creation of new pathways for pollutants and nutrients to enter streams. A detailed overview of the anticipated changes to water quality resulting from climate change has been provided in **Chapter 3 – Water Quality.** Overall, fish will face more frequent and prolonged exposure to potentially harmful levels of contaminants and nutrients. The following is a list of water quality parameters that are expected to increase in concentration, either acutely or chronically, along with a brief summary of their potential impact on fish.

a) **Nutrients (phosphorus and nitrogen)**: While nutrients are an important factor in stream production, excessive nutrient loads are a major contributing factor in eutrophication. Algal blooms can reduce dissolved oxygen concentrations, thereby reducing the amount of suitable habitat for fish and potentially leading to suffocation.

b) **Chloride**: In general, prolonged exposure to high chlorine concentrations is considered to be toxic to the majority of freshwater fish species. Exposure can result in damage to nerves that can ultimately lead to suffocation (Svobodová, 1993).

c) **Suspended sediment**: Suspended sediment can kill fish at high levels by smothering eggs, and affecting feeding, predator avoidance, and reproduction (Birtwell, 1999).

d) **Pesticides**: Since pesticides are designed and used to kill living organisms, acute pesticide poisoning among fish often leads to mortality. When excessive quantities of aquatic plants and algae are killed by pesticides, their decomposition can lead to low DO concentrations. The food that fish prey upon are often more sensitive to pesticides than the fish themselves. Therefore, increasing pesticide concentrations may also reduce their food supply (Svobodová, 1993).

e) **Dissolved organic carbon (DOC)**: High DOC concentrations can alter fish habitat availability via changes in light, water temperature, and oxygen. DOC can also reduce foraging efficiency and food availability for fish (Lamka, 2017).

As climate change further contributes to water quality deterioration, the changes in water chemistry will become increasingly sudden and severe. Fish can expect to find themselves in environments with conditions beyond their normal tolerance levels more frequently, leading to increased levels of stress. By enhancing mortality rates and reducing reproductive success, the impacts of climate change will extend beyond the individual level and affect entire population dynamics. Of particular concern are the implications of changes in water chemistry on brook trout, which are sensitive to even small changes in their environment. Given their observed and projected declines, preserving the health and integrity of brook trout habitat by identifying and mitigating localized sources of water quality degradation will be crucial in minimizing the amount of stress that will be placed on the species.

Key Points – Water quality impacts on aquatic communities

- Fish are adapted to tolerate small fluctuations in water quality but can become impacted if water quality changes too quickly, making them more vulnerable to parasites and disease.
- Repeated acute or chronic stress from reduced water quality is likely to increase fish mortality.
- Tributary water quality in the Lake Simcoe watershed has historically been impacted by human activities such as development, and climate change has exacerbated these impacts.
- Changes in air temperature and precipitation are likely to affect existing contaminant pathways by increase the magnitude and frequency of contamination, and new pathways are likely to form. As a result, fish are likely to face more frequent and prolonged exposure to contaminants, resulting in increased stress and mortality.

Interspecific competition

In any biological community, organisms compete for the habitat and resources they need to survive. If they are unsuccessful and are unable to move to another habitat, they will likely die. In order to reduce this competition, each fish species has evolved to occupy a distinct niche that allow them to partition resources and coexist. However, changing climatic conditions will impact the availability and distribution of these resources and force the species that depend on them to alter their range accordingly. The extent and rate at which each species will expand or contract its range will differ. As a result, ecological communities will be reshuffled, newly overlapping ranges will form, and interactions among fish species that have occurred for centuries will be transformed (Alexander et al., 2016). The abundance and range of populations may change, but their resource and habitat requirements will not; leading to intensified competition within these novel community assemblages as certain species struggle more-so than others and species with similar resource and habitat requirements face-off in their newly overlapping ranges.

Changing competitive environments can manifest as altered interactions among existing competitors or as altered interactions among novel competitors; both of which are likely to occur within the Lake Simcoe watershed's fish communities. As discussed previously, climate change is expected to increase the availability of suitable habitat for warm and coolwater species and reduce the availability of habitat for coldwater species in Lake Simcoe's tributaries. This raises concerns considering that coldwater species will likely be unable to migrate at the same pace or to the same extent as warm and coolwater species. While these species have always co-existed within the watershed's aquatic ecosystems, thermal constraints have minimized habitat overlap between their ranges, thus minimizing competition for habitat and resources. However, as warm and coolwater species encroach into coldwater habitat and coldwater species are left with nowhere to go, these species will increasingly face direct competition.

Competition between species can devastate entire populations when one species has a competitive advantage over the other. Unfortunately, in the case of brook trout, populations can be be displaced or eradicated when faced with strong competition by warmwater species such as smallmouth bass (*Micropterus dolomieu*) (Lasenby, 2000). Both species compete for similar habitat and prey. However, when pinned against one-another, smallmouth bass can out-compete brook trout for resources (DFO, 2009). Research on the vulnerability of Ontario's fish species to predators under future climate change shows that there is a tipping point before which smallmouth bass struggle to compete with brook trout. Once smallmouth bass populations increase in abundance, they can easily gain a toehold in the ecosystem and out-compete brook trout for food (Alofs and Jackson, 2015). Even in cases where they do not overlap spatially, a growing smallmouth bass population in areas previously inhabited by brook trout can reduce prey abundance and diversity, negatively affecting food resources for remaining fish species (Jackson, 2009). As warm and cool water species, such as brown bullheads (*Ameiurus nebulosus*), pumpkinseed (*Lepomis gibbosus*) and bluegill (*Lepomis macrochirus*), colonize former coldwater habitats, competition between species can intensify. Competitive species have the greatest chance of surviving, while those that are subordinate will have to either adapt or face extirpation.

Climate change may also increase the availability of suitable habitat for species that are currently restricted to more southern regions. The traits possessed by invasive species, including aggressive feeding, rapid growth, prolific reproduction, and the ability to tolerate and adapt to a wide range of habitat conditions, enable them to outcompete native species for food, nutrients, and space. For these species, warming waters and altered stream flow may form the catalyst and the means for invasion into the Lake Simcoe watershed. An invasion is especially likely where waterbodies are connected, such as Lake Simcoe and the Great Lakes, which are connected by the Trent-Severn Waterway. As a result, the Great Lakes have been a main source of invasive species. Once established, invasive species can dramatically alter food web structures, decreasing food availability for native species. This direct competition can lead to population decline and biodiversity loss in the watershed.

Figure 5-12 The round goby is a small, bottom-dwelling invasive fish with significant economic and ecological impact.

The impacts of invasive species are already being felt within the Lake Simcoe watershed's aquatic communities, where recent introductions have significantly altered native population abundance and dynamics. One of the best-known examples of an invasive species that is disrupting native populations is the round goby (*Neogobius melanostomus*) (**Figure 5-12**). The round goby is an aggressive species that reproduces quickly and decreases the levels of native fish by eating eggs and young and by out-competing them for space and food. It is believed that the presence of these invaders could lead to reduced diversity and health of warmwater fish communities in the Lake Simcoe watershed. The majority of these sites are in the lower sections of the subwatersheds where these invasive species have access from Lake Simcoe. This is merely one of many invasive species that are competing with native populations for food and space. With the introduction of new species on the horizon, the stress of climate change on native fish may render them more vulnerable to the impacts of invasive species. This is particularly concerning for species such as brook trout, which is sensitive to change and already showing signs of decline. These species are least likely to withstand the cumulative effects of climate change and will be at greatest risk of extirpation.

Key Points – Interspecific competition

- Fish occupy distinct niches as a result of competition for habitat and resources. Climate change alters habitats and resources availability in aquatic systems and as fish may be impacted as they alter their range in response. The extent to which each species will expand or contract will differ, and is likely to lead to changes in fish communities.
- While the abundance and range of fish populations may change, their resource and habitat requirements will not. As a result, competition within novel community assemblages may increase.
- Increased water temperature increases warmwater habitat while decreasing coldwater habitat. While warm- and coldwater fish species co-exist within the Lake Simcoe, climate change is likely to increase the overlap between their ranges leading to increased competition.
- Warmwater fish species such as Smallmouth bass could gain a competitive advantage over cool-, and coldwater species due to increased water temperature. Some cool- and coldwater species may become displaced or eradicated when competing or similar resources with warmwater species. In some aquatic ecosystems in Ontario, smallmouth bass have been known to out-compete and displace Brook trout.
- Non-native species typically become invasive due to competitive advantages such as aggressive feeding, rapid growth, prolific reproduction and stress tolerance. Increased water temperature due to climate change may provide novel habitat for southern invasive species to migrate northward via the Trent-Severn Waterway or accidental transportation.

5.3 Benthic invertebrates

5.3.1 Introduction

Benthic invertebrates are organisms that live in or on the bottom sediments of rivers, streams, and lakes. Although generally small, their size can range from microscopic to a few tens of centimeters or more in length (Heip, 1995). Benthic invertebrates live either on the surface or under substrates, such as rocks and logs, or within sedimentary deposits, and comprise several types of feeding groups, including deposit-feeders, filter-feeders, grazers and predators. Each species has evolved to live within a specific range of conditions. These conditions are determined by the abiotic and biotic factors present at a given site, such as the direction and rates of flows, temperature, sediment grain sizes, the deposition of organic matter, and the concentration of various chemicals, including dissolved oxygen, hydrogen sulfide, ammonia, and phosphorus. Where benthic invertebrates live and what they eat represents their niche. The great diversity of benthic species can be attributed to the various physical, chemical, and biological processes that affect the bottom of freshwater systems and create sufficient heterogeneity within the benthic habitat to support a variety of niches (Hutchinson, 1993).

Benthic invertebrates play a central role in several major ecological processes. The following are some of the essential functions they perform in freshwater food webs (Covich et al., 1999):

- They accelerate detrital decomposition by relying on dead organic matter as one of their main sources of energy. They process riparian leaf-litter inputs to headwater streams.
- They release bound nutrients into solution by their feeding activities, excretion, and burrowing into sediments. These nutrients accelerate microbial and plant growth, which in turn is consumed by herbivorous and omnivorous benthic invertebrates.
- They serve as predators that control the numbers, locations, and sizes of their prey.
- They supply food for both aquatic and terrestrial vertebrate consumers (e.g., fishes, turtles, birds).
- They accelerate nutrient transfer to overlying open waters of lakes as well as to adjacent riparian zones of streams.

By each functioning under distinct conditions, each benthic species exhibits many specializations. As a result, each species is of different relative importance to each ecological process. Changes in the distributions and abundances of one species can therefore result in disproportionate and unexpected responses by other species as they attempt to compensate for the changes in the associated species.

5.3.2 Benthic invertebrates in the Lake Simcoe watershed

The presence of different benthic species in a watercourse can be used as an indication of the health of that watercourse. Certain species are able to tolerate degraded water quality better than others. If numerous individuals of highly tolerant species are collected at a site, it is usually an indication of poor water quality (Mandaville, 2002). In contrast, collecting high numbers of species that are sensitive to pollution can serve as an indicator of good water quality. If these organisms were once abundant, but subsequent sampling shows a decline in numbers, it may indicate that water quality is deteriorating.

LSRCA uses two main approaches to evaluate tributary health based on benthic invertebrate communities. The first is the Hilsenhoff Biotic Index (HBI). The HBI uses indicator organism and their designated values, ranging from 1 to 10, to come up with an overall score for the site being sampled (Hilsenhoff, 1977). An organism's value is based on their known sensitivity to organic pollutants; 0 being most sensitive, 10 being most tolerant. Hence, a site's overall score is used as an indication of the degree of organic pollution; with higher values indicating more polluted systems (**Table 5-2**).

Table 5-2 Pollution levels according to the Hilsenhoff Biotic Index (HBI) (Hilsenhoff, 1977)

HBI Value	Water Quality	Degree of Organic Pollution
0.00 – 3.50	Excellend	No apparent organic pollution
3.51 – 4.50	Very Good	Slight organic pollution
4.51 – 5.50	Good	Some organic pollution
5.51 – 6.50	Fair	Fairly significant organic pollution
6.51 – 7.50	Fairly Poor	Significant organic pollution
7.51 – 8.50	Poor	Very significant organic pollution
8.51 – 10.00	Very Poor	Severe organic pollution

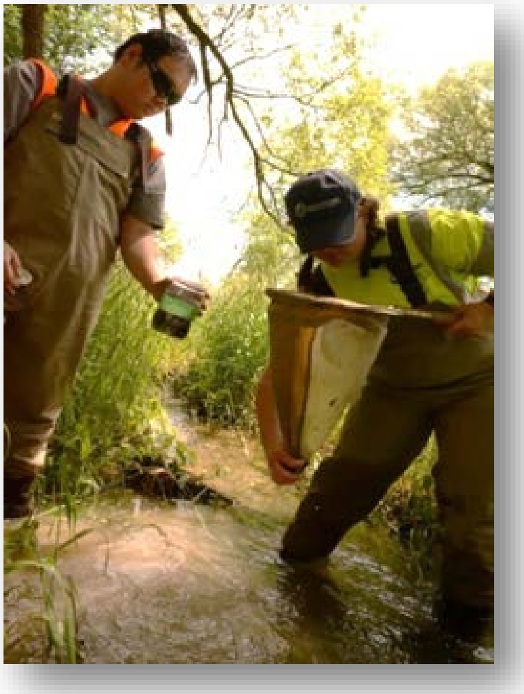


Figure 5-13 Staff members collect benthic invertebrates at one of LSRCA's benthic monitoring sites

The second tool used to infer water quality from benthic assemblages is the EPT index, which is named for three orders of aquatic insects that are considered to be sensitive to pollution: Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies). The EPT index itself is a measure of the total number of distinct taxa within the three groups. The EPT Index increases with improving water quality, therefore a high abundance and diversity of these organisms can indicate good environmental conditions (Lenat and Crawford, 1994).

LSRCA routinely monitors 55 sites for benthic invertebrates (**Figure 5-13, Figure 5-14**). Although these sites are unevenly distributed among the subwatersheds, Hawkstone Creek and Hewitt's Creek subwatersheds show the highest percentage of high-quality sites. The Barrie Creeks and Maskinonge River subwatersheds, which have undergone substantial urbanization, have the lowest rankings.

Despite existing pressures, benthic samples indicate that the majority of the routinely monitored sites are stable, showing neither improvement nor degradation. A total of eight long-term monitoring sites show a trend, two of which are improving trends and six of which are degrading trends (**Table 5-3**). The degrading trends are driven by increases in pollutant-tolerant species, such as worms and crustaceans. In contrast the improving trends are being driven by increases in the abundance of sensitive species, specifically within EPT taxa, and a reduction in the number of pollution tolerant species, indicating improvements in water quality and habitat conditions.

When assessed at the watershed scale, the benthic data suggests that there may be hotspots of degraded water quality. Generally, the subwatersheds that are faring the worst based on their Hilsenhoff Biotic Index values and trends are those that are among the most highly urbanized and agricultural in the watershed. The impermeable surfaces and intensive agricultural activities that characterize these regions allow for high levels of chemicals, nutrients, and contaminants to enter nearby watercourses as surface waters travel along the landscape. These same characteristics make the tributaries surrounding these regions the most vulnerable to climate change; further exacerbating water quality degradation and subsequent changes to benthic communities.

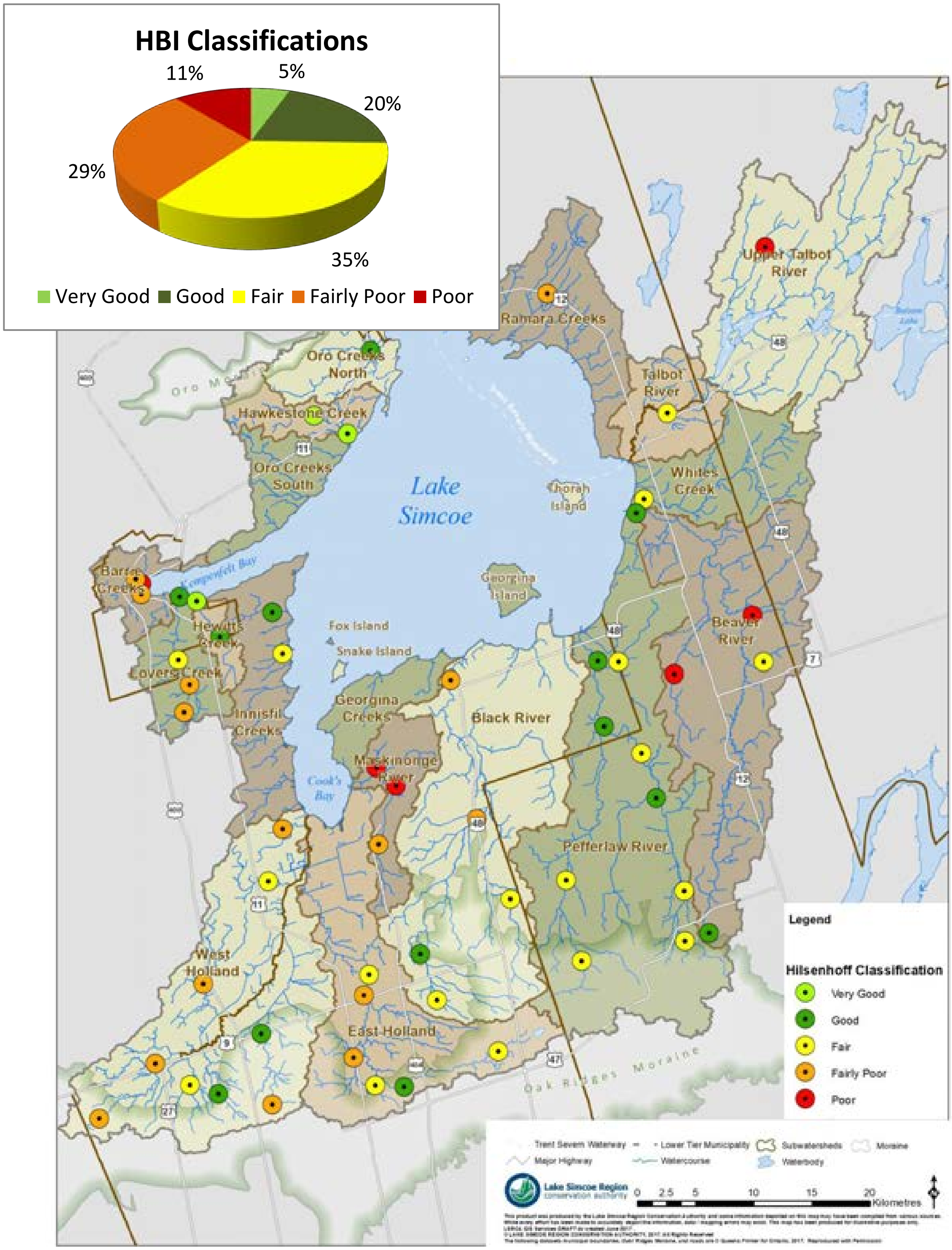


Figure 5-14 Hilsenhoff Biotic Index (HBI) scores for long-term benthic invertebrate monitoring sites

Table 5-3 Long term benthic invertebrate monitoring sites showing trends (2005-2016)

Subwatershed	Site	Trend	Cause	Years of Data
Black River	Mid Reach	Increasing	More EPT	6
Beaver River	Mid Reach	Decreasing	More Tolerant Families	11
Maskinonge River	Headwater Tributary	Decreasing	More Tolerant Families, Fewer Caddisflies	7
Pefferlaw River	Headwater Tributary	Decreasing	More Amphipods, Fewer Caddisflies, Fewer Mayflies	6
Pefferlaw River	Headwater Tributary	Decreasing	Fewer Intolerant Families, Fewer Mayflies	6
Pefferlaw River	Mid Reach	Increasing	Fewer Amphipods, More Caddisflies	7
West Holland River	Headwater Tributary	Decreasing	Fewer bivalves	8
West Holland River	Headwater Tributary	Decreasing	Fewer EPT, More Amphipods	11

5.3.3 Influence of physical and biological parameters on benthic invertebrates

Although it is well known that benthic invertebrates are very sensitive to changes in the quantity and quality of water, essential information on species-specific responses to changes in these parameters is lacking. Moreover, there is insufficient information about how individual benthic invertebrate species interact with one another under different conditions. Without this knowledge, it becomes impossible to make specific predictions about how community assemblages will change in composition and abundance in response to climate change. We do, however, have a comprehensive understanding of the ways in which the pattern of delivery and concentrations of nutrients, contaminants, and sediment will shift in response to climate change. In addition, for many of these parameters there is general information available regarding their impact on the overall health and productivity of benthic communities. In a few instances, studies have successfully identified vulnerabilities among specific groups or species. The following is a synthesis of this information as it relates to the water quality parameters that are expected to be altered by climate change.

a) **Nutrients:** The effects of nutrients on benthic invertebrates are mainly indirect. Nutrients may initially stimulate benthic communities because more food is supplied in the form of plant material and organic detritus. However, as sediment organic matter increases, the sediment can become deoxygenated, which can be lethal for some benthic organisms. If anoxic periods persist, it is expected that mobile organisms will leave the affected area and sessile species will die. Once recolonized, these areas tend to be dominated by a less diverse range of species tolerant of low oxygen conditions or those better at first exploiting open spaces left after all the original animals have died or migrated (e.g. small polychaete worms, nematodes and clams) (Nielsen and Jernakoff, 1997). The Hilsenhoff Biotic Index categorizes macroinvertebrates based on their response to organic pollution. Hence, more comprehensive and readily available information exists regarding species-specific tolerance levels to parameters associated with organic pollution, such as phosphorus, nitrogen, and dissolved oxygen, compared to other, less well-studied parameters.

b) **Sediment:** Excessive fine sediments can blanket the stream bed, filling the interstitial space between particles. This can significantly alter the range and size of the bottom sediment particles, which can in turn directly affect the diversity of the benthic species that inhabit the affected site (Lake et al., 2000). By reducing the interstitial spaces, habitat availability is reduced, and there is a substantial change in substrate type. In streams, cobble beds may become covered in silt, decreasing the diversity of benthic invertebrates and favoring a more limited diversity of burrowing species, such as oligochaetes and chironomids. High sediment concentrations have also been shown to increase drift and enhance dragging of benthic invertebrates from where they are attached to further downstream, as well as affect the propensity of larval insects to complete their life history and emerge as adults (Magbanua et al., 2016). In general, high sediment concentrations are believed to contribute to a decreased abundance and diversity of species within the EPT orders (Magbanua et al., 2016; Lake et al., 2000; Hoy 2001).

c) **Chloride:** Benthic invertebrates seem to be less sensitive to elevated chloride concentrations compared to other freshwater species, although there is significant variation among benthic macroinvertebrates in terms of their salinity tolerances (Blasius and Merritt, 2002). Toxicity also depends on length of exposure. Long-term exposure tends to be more harmful than acute exposure. As with many of the water quality parameters, the most salt-sensitive groups are the mayflies, stoneflies, and caddisflies (Stranko et al., 2013). The most salt-tolerant are certain dragonflies, crustaceans, beetles, and true flies. A study conducted in the Toronto region found that increases in mean chloride concentrations were correlated with a decrease in the number of sensitive benthic taxa and an increase in the number of tolerant benthic taxa (Wallace and Biastoch, 2016). It is largely believed that a chloride concentration threshold exists; before which benthic species richness increases and beyond which species richness decreases. However, the level at which this threshold occurs remains unclear, and will likely vary between watercourses and benthic community structures.

d) **Temperature:** Benthic invertebrates have evolved to live within a specific temperature range, which limits their distribution and affects the community structure. Temperature affects their emergence patterns, growth rates, metabolism, reproduction, and body size (Hussain, 2012). Species vary in their tolerance to temperature ranges, but few are able to tolerate temperatures beyond their upper tolerance limit. Rising temperatures can result in decreases in richness or relative abundance of coldwater-preference benthic species and increases in warmwater-preference species (Hamilton, 2013). Other widespread responses include declining richness with temperature over time or of EPT species and total taxa.

e) **Flow:** Flow variability and predictability can affect benthic invertebrate communities by dictating the kinds, numbers, and life history strategies of the species present (Hussain, 2012). Extremely variable and/or unpredictable flow regimes lead to environments in which abiotic processes determine community organization, compared to more predictable regimes in which biotic factors, such as competition or predation, controls the community structure (Gasith and Resh, 1999). Streams that experience more sporadic heavy flows have less abundant and less diverse invertebrate communities than those that have more consistent flows. Much of this reduction is because of losses caused by wash-out of the invertebrates themselves, as well as scouring of the substrates under which some benthic invertebrates typically live. Low flows during drought can also affect the composition of invertebrate species by leading to thermal stress and/or low dissolved oxygen levels (Hussain, 2012). The species that are believed to be most tolerant to low flow conditions are those that can creep down into the habitat to find sufficient moisture, or even water, to allow them to survive, such as some flat worms, oligochaetes, harpacticoid copepods, Elminthidae and their larvae, some chironomid larvae, and Hydrocarina.

The impacts of climate change could include either exposure to higher concentrations of these parameters, longer exposure periods, or both. Existing research on the responses of benthic communities to changes in physical parameters makes it clear that the altered pattern of nutrient, sediment, and contaminant delivery associated with climate change will likely prompt shifts in benthic community structures. Given the role of benthic invertebrates in maintaining energy flow and nutrient cycling, as well as acting as a food source, major ecosystem processes could be affected as communities shift towards assemblages that are better suited for the more extreme and unpredictable conditions of the future. This is especially concerning since benthic species within communities are known to lack redundancy in their ecological roles (Covich et al., 1999). Hence, the loss of some species will likely alter or degrade critical ecosystem processes due to the absence of species that can functionally replace them. Although the exact consequences of each species' loss cannot be predicted, if one species after another were lost, then at some point the ecosystem would change drastically.

Key Points – Benthic invertebrates

- Increased nutrient inputs (e.g., phosphorus) associated with changes in air temperature and precipitation could initially stimulate benthic communities due to increased food availability (e.g., phytoplankton). However, prolonged productivity increases associated with nutrients could also deplete dissolved oxygen and increase benthic community mortality.
- Bank erosion and surface runoff deposits fine sediments on the stream bed that settle into the interstitial spaces, and reduces habitat quality for certain benthic species. Increased siltation associated with changes in air temperature and precipitation could decrease benthic species diversity in favour of burrowing species.
- In general, benthic invertebrates are less sensitive to elevated chloride levels than other aquatic organisms. Long term exposure to chloride tends to be more harmful to benthic invertebrates than acute exposure. In the Toronto region, streams with elevated chloride levels have been shown to contain more tolerant species and fewer sensitive species.
- Water temperature affects emergence timing, growth rate, body size, metabolism and reproduction in benthic invertebrates. Increased water temperature due to climate change is likely to impact benthic species with a lower thermal range and benefit those with a higher thermal range, altering the benthic community structure.
- The stability and predictability of streamflow influences benthic community structure as streams with more variable and unpredictable flows have lower benthic species diversity. The increased variability and unpredictability in streamflow due to climate change is likely to result in reduced benthic species diversity in some streams.

5.3.4 Using benthic invertebrates as climate change indicators

Although there remain uncertainties regarding individual and community responses to various changes in water quality parameters, the notion that climate change will act as a driver of compositional change among benthic invertebrate communities is undoubted. Traditional bioassessment tools, such as the EPT index, are based on the premise that high-quality streams usually have the greatest richness of sensitive species, while low-quality sites have the lowest richness of sensitive species and will instead be dominated by more tolerant species. While these tools have proven to be effective in recognizing sites with degraded water quality, field observations alone are not sufficient to determine the cause of degradation. By acting as a compounding pressure, climate change will increasingly act as a contributor to degradation. There will therefore be a need to modify traditional bioassessment tools to help characterize the contribution of climate change to changes in metrics so that effective management and regulatory actions can be developed.

As previously mentioned, the challenge with using benthic invertebrates as indicators of climate change lies primarily in the lack of experimental studies on individual sensitivities to changes in water quality parameters, which, in some cases, are driven by climate change. These sensitivities have received little consideration because climate change was not considered a stressor of concern until recently, yet they could be of immense value in monitoring the effects of progressive changes in water quality parameters and hydrological regimes. A better understanding of the sensitivity levels of specific benthic invertebrates – whether at the species, genus, or family level – could allow them to be used as metrics that can help distinguish between responses to distinct climate change impacts, such as rising temperatures, higher chloride concentrations, and higher sediment loads.

One approach towards the use of benthic invertebrates as climate indicators would be the creation of an index that is exclusive to a particular water quality parameter associated with climate change and that is based on benthic invertebrate sensitivities to the parameter in question. This would be similar to the Hilsenhoff Biotic Index, which uses the presence and abundance of species with known tolerances to organic pollutants as an indication of the degree of organic pollution at a given site. Like the Hilsenhoff Biotic Index, the new biotic index would require that each species be assigned tolerance numbers for the water quality parameter under investigation, and a method for deriving the level of water quality impairment based on the abundance and tolerance of the species present.

Another approach would be to modify existing metrics, such as HBI and EPT, so that the components can be partitioned based on sensitivity to certain parameters. The effectiveness of this approach in detecting climate change-related temperature trends was investigated in a study by Hamilton (2013). In this study, the changes in benthic community composition resulting from rising temperatures could be distinguished from the changes stemming from other causes by examining the ratio of cold- or warmwater-preference taxa to total invertebrate taxa richness and the ratio of cold- or warmwater-preference EPT taxa to total EPT taxa. In this case, the partitioning of taxa was appropriate because the species that were sensitive to disturbance or to conventional pollutants (e.g. the species used in HBI and EPT assessments) were also sensitive to changes in temperature. If these species are also found to be sensitive to other abiotic factors that are influenced by climate change, then a similar partitioning approach could be used to support a shift from a presumption of pollution as the cause of the reduction in the EPT or HBI metric to consideration of climate change-related effects.

While the development and modification of bioassessments show promise in detecting climate-related effects on benthic communities, the synergistic effects of climate change, land-use, and development will continue to make it difficult at best, to distinguish the effects of climate change from the effects of other anthropogenic stressors. Even as bioassessments progress to the point where they can be used to infer changes in climate change-related parameters, climate change could only be regarded as a contributing factor acting alongside existing anthropogenic stressors, rather than an exclusive driver. Hence, the protection of water resources and aquatic natural heritage systems need to encompass broad adaptation strategies that address interactions between climate change and other stressors.

5.4 Current and future vulnerability assessment

The current and future vulnerability of each watershed indicator for tributary ecosystems (**Table 5-4**) was developed based on the methodologies described in **Chapter 1 – Introduction**. In summary, the current vulnerability score is a combination of an indicator's degree of sensitivity and exposure to climate change in the present. The future vulnerability combines climate model projections and the degree of confidence to an indicator's current vulnerability score to provide the overall vulnerability score for each indicator.

Table 5-4 Current and future vulnerability of tributary ecosystems to climate change in the Lake Simcoe watershed

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
Loss of cool- and coldwater habitat	Rising temperatures	Surface water temperatures are in close equilibrium with air temperature. As air temperatures rise, water will warm and cold/coolwater habitat will be lost.	VH	VH	VH	H	VH
Overcrowded brook trout habitat, leading to stress and intraspecific predation	Less summer precipitation (lower groundwater levels)	Groundwater inputs buffer rises in water temp. Less groundwater input = more rapid warming of water	VH	M	H	H	H
Earlier spawning among spring spawners	Rising temperatures	Loss of coldwater habitat via warming water temperatures will force brook trout to occupy space closer together, leading to more stress and intraspecific predation as competition for resources intensify	H	M	M	H	M
Truncated spring spawning period	Less summer precipitation (lower groundwater levels)	Loss of coldwater habitat via reduced groundwater inputs will force brook trout to occupy space closer together, leading to more stress and intraspecific predation as competition for resources intensify	H	M	M	H	M
Altered timing of spring reproduction	Rising temperatures	A general increase in water temperature may result in waters reaching minimum temperature thresholds sooner and the subsequent advancement of spawning	M	H	M	H	M
Delayed spawning among fall spawners	Rising temperatures	Each species has a maximum thermal threshold above which breeding may be inhibited. Depending on the rate of the spring temperature increase, thermal thresholds may be reached earlier, leading to a reduced spring spawning window	L	H	M	H	M
Reduced reproductive success among fall spawners	Greater proportion of winter precipitation falling as rain (earlier and less defined freshet)	Earlier freshet can induce earlier reproductive events. On the other hand, the gradual disappearance of the freshet may result in the loss of this environmental trigger as a spawning cue, and reproduction and growth may be delayed.	L	H	M	M	M
Reduction in suitable spawning sites for brook trout	Rising temperatures	Brook trout require a drop in temperature to cue spawning. Warming waters will delay the timing that temperature thresholds are reached.	M	H	M	H	M
Reduced recruitment as a result of scouring	Rising temperatures	Higher temperatures reduce gonad development	L	H	M	H	M

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
of redds, dislodging or smothering of eggs, or washing away of fry by high-flow events							
Enhanced overwintering survival	Less summer precipitation (lower groundwater levels)	Brook trout prefer to spawn in sites with groundwater inputs and use upwelling groundwater as an indication of suitable habitat	VH	M	H	H	H
Greater exposure to poor water quality, leading to reduced fitness and reproductive success	More extreme precipitation	High-flow events are capable of washing away newly emerged fry and disturbing redds	M	H	M	VH	H
Range expansion and population increase among cool and warmwater species	Rising temperatures	Warm-water species undergo rapid increases in growth rate as temperatures rise. Brook trout benefit from warming temperatures during the winter and spring but experience reduced growth rates with rising temperatures during the summer and fall. Depends heavily on the availability of zooplankton	M	VH	H	H	H
Invasion by newly introduced species	More extreme rainfall	Sediment, contaminants, and nutrients are washing into tributaries following heavy precipitation events	VH	H	H	VH	VH
Shifts in benthic communities towards a greater abundance of tolerant species	More drought	The concentration of sediment, contaminants, and nutrients increases during low flow periods	VH	H	H	H	H

Recommended actions were developed to address these vulnerabilities as the climate changes and they are summarized in **Chapter 8**.

Chapter 6

The Lake Ecosystem

6.1 Introduction

Lakes are sentinels of climate change as many of their physical, chemical, and biological processes are highly sensitive to changes in the surrounding landscape and atmosphere (see overview by Adrian et al., 2009). Lakes can provide an early indication of climate-related changes, some of which are highly visible and easily measurable. For example, shifts in the timing of ice formation and thawing typically reflect changes in atmospheric warming (Magnusson et al., 2000). Other climate signals are more complex but equally informative. For example, indicators from lake sediment cores form a record through time (i.e. the past few decades to over 12,000 years ago) and can be used to reconstruct past environmental changes, and put current environmental changes, such as those due to climate, into a long-term context (Smol 2008). Sediment cores have also been used to predict that future climate conditions are expected to mirror those of the mid-Holocene, ~8600-4500 years BP (Moos et al., 2009).

Lake ecosystem indicators reflect climate change effects directly or indirectly through the influence of climate on both the catchment and the lake itself. These indicators are measurable response variables such as water temperature, dissolved oxygen concentration, and plankton community composition that allow us to track changes in ecosystem function. Because the lake ecosystem responds to environmental changes in the catchment, such as phosphorus loading (**Chapter 3 – Water Quality**) or land use changes (**Chapter 7 – Terrestrial Natural Heritage**), and many climate signals act in synergy with multiple other environmental stressors (see Keller, 2007), it can be difficult to separate the climate response from other environmental responses in some indicators. However, adopting an integrated approach to the interpretation of changes occurring in the response variables can indicate the overall effects of climate as part of the broader changes occurring in the watershed.

6.1.1 Lake Simcoe

Lake Simcoe is the largest lake in south-central Ontario (surface area 722 km^2; maximum water depth 42 m). The lake is typically divided into a main basin and two bays: Kempenfelt Bay is located to the west of the main basin and Cook's Bay extends southward (**Figure 6-1**). Lake Simcoe is part of the Trent-Severn Waterway; a historic transportation corridor connecting Lake Ontario to Lake Huron, which is now maintained for recreational travel (see 'Lake Simcoe Water Levels' info box below). Water flows into Lake Simcoe from the surrounding watershed and exits the lake through a single outlet at Atherley Narrows, located at the north end of the lake, eventually flowing into Lake Huron.

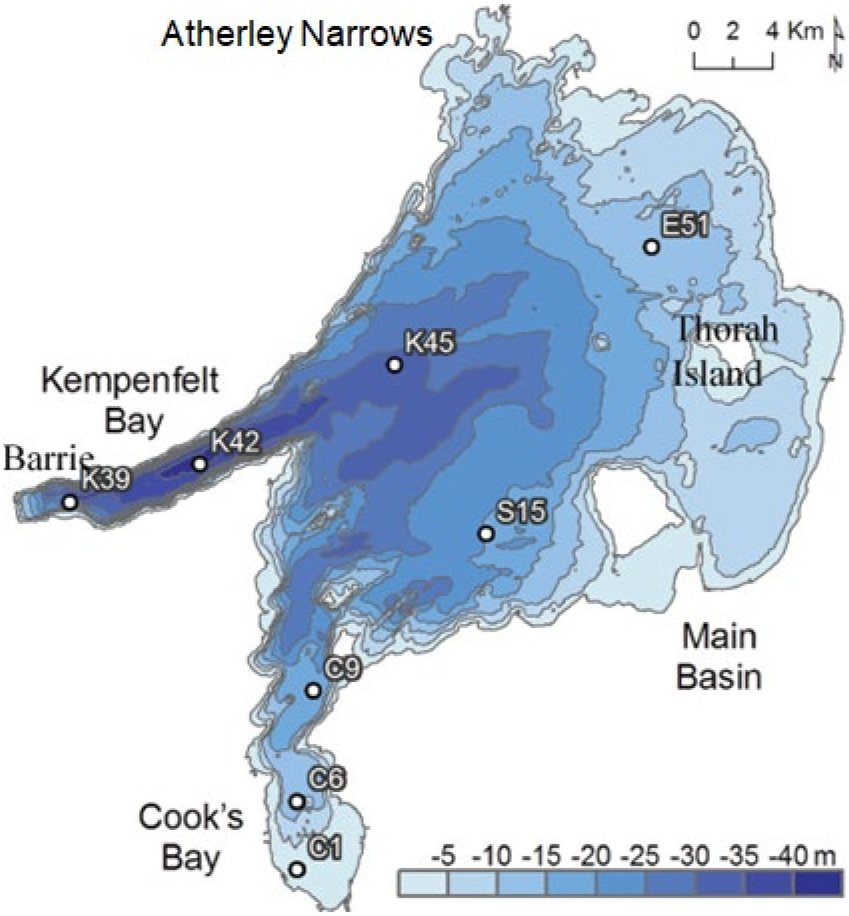


Figure 6-1 Bathymetric map of Lake Simcoe including some Provincial lake monitoring stations locations.

Located approximately 80 km north of Toronto, the lake is a popular destination for tourism and recreation throughout the year. Lake Simcoe provides watershed residents with many valuable socioeconomic and ecosystem services, such as drinking water for eight communities; wastewater assimilation; and supports tourism, recreation, and agricultural activities. Together, these services contribute an estimated $922.7 million annually to Ontario's economy (Wilson, 2017).

Temperature and precipitation anomalies associated with climate change (Chapter 2 – Climate Trends and Projections) will affect many aspects of Lake Simcoe. Climate change indicators in the Lake Simcoe Protection Plan (LSPP) include meteorological trends (e.g. air temperature, precipitation), lake thermal trends (e.g. timing and duration of water column stratification), and the timing of seasonal processes such as fish spawning and ice cover. Since routine monitoring began in 1980, the trends of many key environmental variables indicate that several lake processes are already showing the effects of climate change. In addition to climate change, other anthropogenic stressors impact the lake's ecological health. For example, historical water quality issues associated with excess phosphorus loading resulted in recruitment failures in the recreational coldwater fishery (e.g. lake trout and lake whitefish) and can cause excessive growth of algae and shoreline macrophytes (Winter et al., 2007). In response, the Lake Simcoe Environmental Management Strategy (LSEMS, 1979 - 2008) and the Lake Simcoe Protection Plan (since 2009) identify and measure a suite of response variables and recommend remedial measures to reduce water quality impacts.

Lake Simcoe Water Levels

The water level in Lake Simcoe is managed as part of the Trent-Severn Waterway system. Lake water level management is complex and considers the varying needs and impacts that each action will have on the wider system (Parks Canada, 2019). As a result, the annual average water level in Lake Simcoe is relatively constant (**Figure 6-2**), varying by approximately 0.5 metres over the course of the year. The highest levels usually occur between April and June. As the summer progresses, the levels begin to drop because of increased evaporation, reduced inflows and a hydrological rule curve for management. The lowest water levels are reached in late fall and winter. Summer water levels are lowered gradually (known as drawdown) to make room for fall precipitation, as well as precipitation and runoff in winter and spring. Climate change could impact water levels in the future as precipitation and evaporation become more variable (**Chapter 2 – Climate Trends and Projections**), especially in the summer and fall. Management of the water levels in the Trent-Severn Waterway system is balanced between flood prevention and the human need for water across much of south-central Ontario.

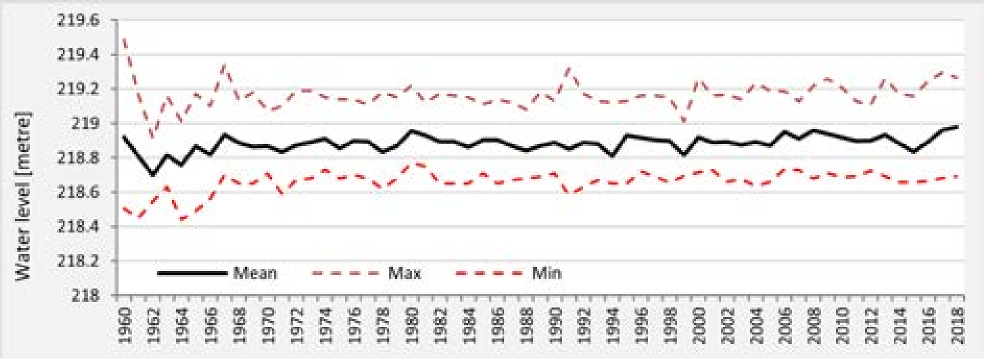


Figure 6-2 The minimum, maximum and average water levels in Lake Simcoe between 1960 and 2018.

6.2 Physical processes

The water column of many lakes can stratify (or form layers of water) with different temperatures. Thermal stratification follows seasonal patterns and occurs when the difference in water density (i.e. weight) between warm and cold waters is sufficient to separate the water column into layers. Water is most dense (i.e. heaviest) at 3.98°C. On either side of this temperature, water is less dense (i.e. lighter) and forms layers in a water column based on temperature. During most of the year, warmer (less dense) water lies on top of denser, cooler water with the bottom waters of a lake being closer to 3.98°C than the water above it (**Figure 6-3**). In the fall, cooler air temperatures decrease the surface water temperature, and surface water becomes denser and sinks downward, mixing surface and bottom waters. This process is known as fall turnover. As air temperatures decline further, the less dense surface water forms into lake ice at 0°C (ice is 8.5% less dense than liquid water at 0°C), while the denser water beneath the ice remains liquid at temperatures closer to 3.98°C. Lake Simcoe is covered by a layer of ice during the winter and this period is known as the ice-on season. Lake ice is directly affected by air temperature and therefore highly sensitive to climate change. For example, the timing of surface freezing (i.e. ice-on) and thawing (i.e. ice-off) is directly affected by air temperatures (Yao et al., 2013).

Higher air temperatures during the summer lead to increased surface water temperatures, which in turn postpone the date of freezing. Between 1980 and 2012, air temperature increased by 1.6°C, with significant increases occurring in June (0.07°C per year, or 2.2°C in total) and September (0.06°C/year or 1.9°C overall) (MOECC, 2015).

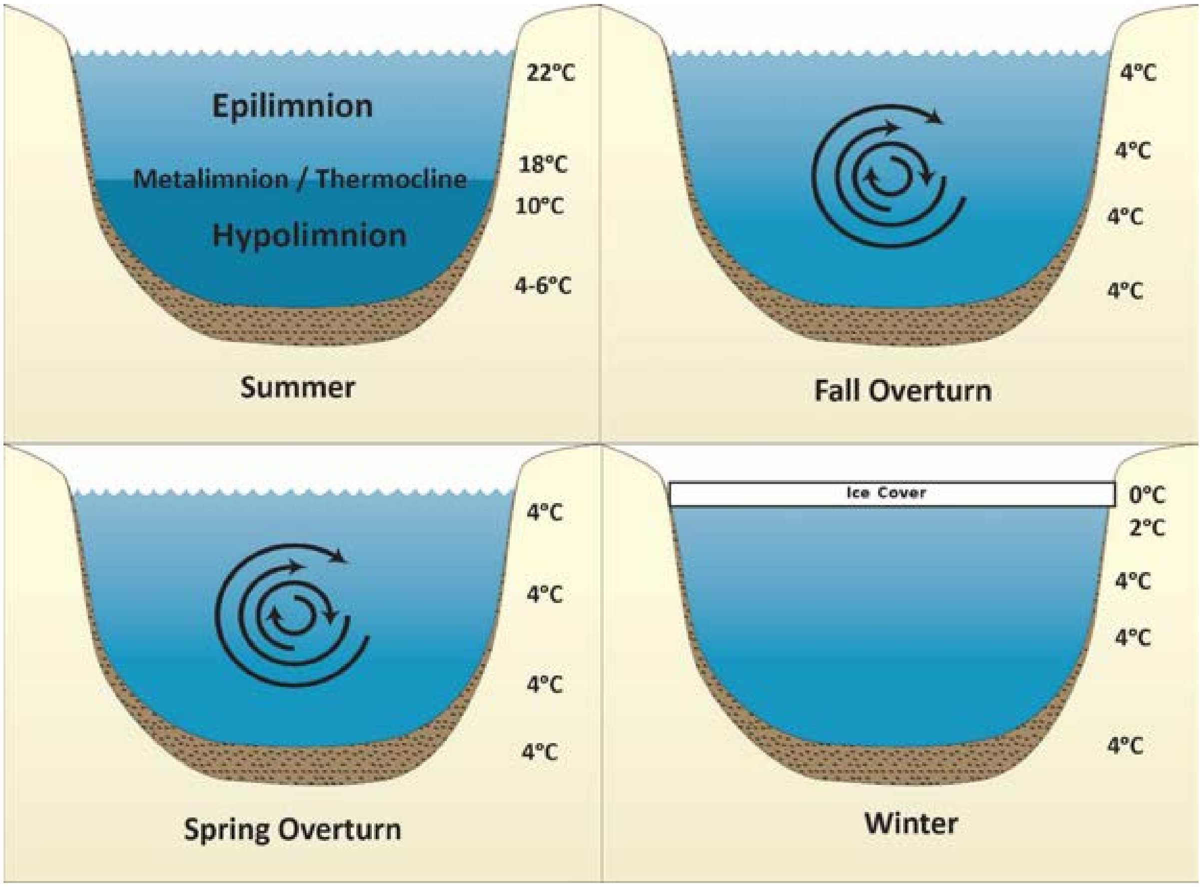


Figure 6-3 Diagram showing stratification and water column mixing throughout the year in a dimictic temperate lake.

As air temperature increases in spring, lake ice melts and the surface water temperature (and density) increases. With the water column of the lake isothermal, full mixing occurs distributing nutrients and oxygen; a process known as spring turnover. In late spring and early summer, surface water temperature further increases, becomes less dense and the water column separates into two layers: the warmer, shallower, epilimnion at the surface (in Lake Simcoe this layer is ~15 m deep) and the cooler hypolimnion below. Between these layers is a zone of rapid water temperature change (defined as >1°C per 1 m of depth) known as the thermocline, or metalimnion (Figure 6-3). The temperature / density difference between the epilimnion and hypolimnion creates resistance to mixing by wind inputs. As a result, in a well-stratified water column (such as Kempenfelt Bay), there is no mixing between the epi- and hypolimnion, which leads to oxygen depletion in the hypolimnion during the stratified period. In the eastern half of the main basin of Lake Simcoe, a relatively shallower water depth (~20-25 m), a large surface area, and strong winds can result in the water column being mixed during the summer due to the strength of wind energy overcoming the resistance to mixing by the density difference of the water column.

6.2.1 Climate impacts to thermal stratification

Water temperature is most strongly affected by solar energy, air temperature, and water clarity. Solar energy warms the overlying air and surface water. Water clarity determines the maximum depth of sunlight penetration and, as such, the depth of the epilimnion. In Lake Simcoe, the average water temperature in the upper epilimnion (0-5 m water depth) during the April – November ice-free period, has increased by approximately 2°C between 1980 and 2017, while the maximum summer (July-September) water temperatures have increased by ~1°C (**Figure 6-4**). The sharp water temperature decrease in 1992 (**Figure 6-4**) is likely related to a global cooling event following the 1991 eruption of Mount Pinatubo in the Philippines (Soden et al., 2002).

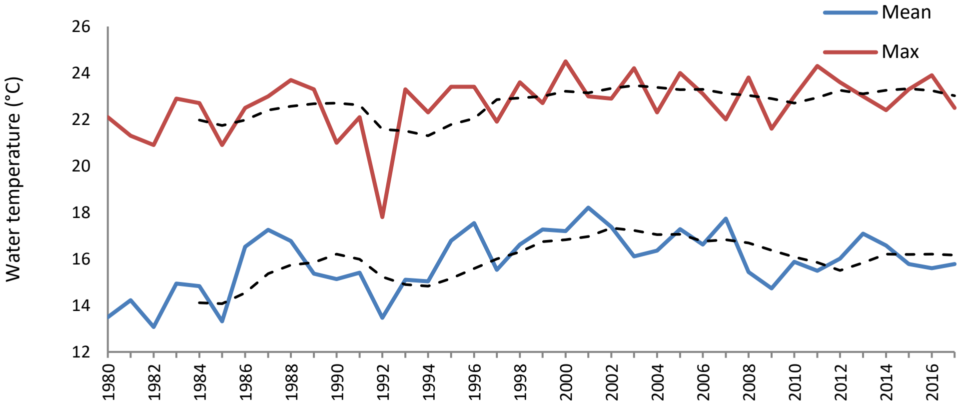
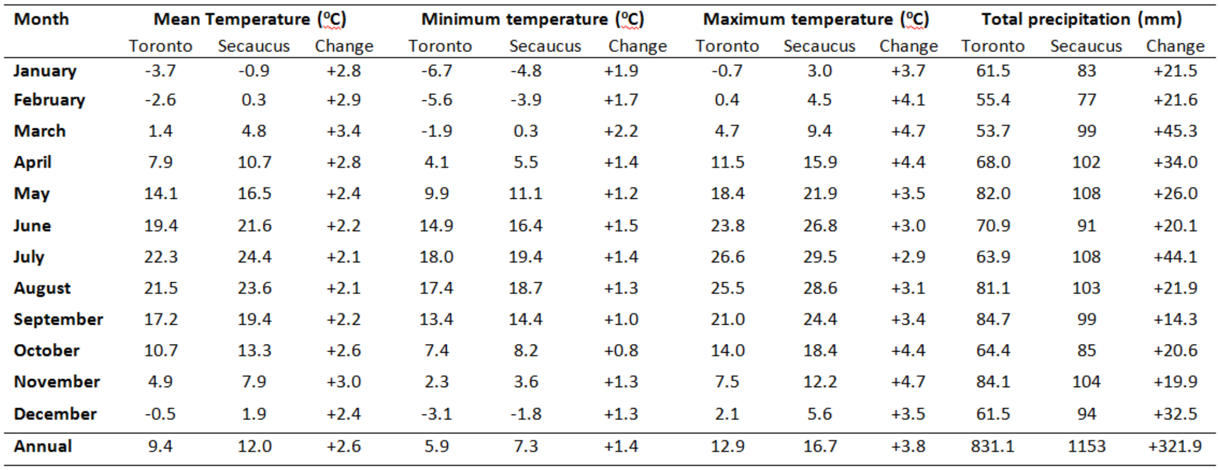


Figure 6-4 Long term (1980 to 2017) water temperature in the Lake Simcoe epilimnion (0 to 5 m depth) showing mean annual (April-November) and maximum summer (July – September) water temperatures. Dashed lines are the 5-year moving average.

Measurement of the timing and duration of water column stratification since the 1980s shows that the onset of water column stratification in Lake Simcoe is occurring earlier in spring, ending later in fall, and extending the duration of water column stratification (Stainsby et al., 2011). In Kempenfelt Bay, the duration of water column stratification was approximately 28 days longer in 2012 compared with 1980. This correlated with increases in air temperature, especially in June and September, as well as increases in water clarity (MOECC, 2015) from phosphorus reduction strategies and filter feeding by invasive dreissenid mussels. Since 1980, the onset of thermal stratification is occurring an average of 18 days earlier with fall overturn occurring 12 days later (MOECC, 2015). In addition, the period of ice cover on Lake Simcoe, described in detail below, has also declined since the start of record-keeping in 1852. A longer period of water column stratification, along with a shorter ice-on season, and warmer water temperatures, could have significant implications for physical processes such as evaporation and lake effect snow. In addition, shifting patterns in the annual cycle of temperate lakes may impact the survivability of lake biota, and the timing of life cycle processes such as fish spawning.

Climate warming is likely to continue to impact Lake Simcoe's thermal profile in the coming decades. Hydrological modeling in the business-as-usual climate forcing scenario (A2) projects that water temperature in Lake Simcoe will increase between 2.2°C and 3.4°C by the end of the century, further extending the duration of water column stratification by up to three months (Bolkhari, 2014). As such, this extended period between spring and fall turn-over could threaten the coldwater fish community and dissolved oxygen targets set by the LSPP. Warmer water, a trend currently seen in the hypolimnion, holds less dissolved oxygen than cooler water and a longer period between lake mixing means a higher risk of oxygen depletion in the hypolimnion. A recent study by Fitzpatrick and Dunn (2019a) matched urban analogs to illustrate projected climatic conditions by 2080. In this study, Toronto, the closest Canadian study site to Lake Simcoe, had predicted 2080 conditions that most closely matched Secaucus, New Jersey, which is up to 5°C warmer and 45.4% wetter than current Toronto climate normals (Fitzpatrick and Dunn, 2019b). As shown in **Table 6-1**, much of the climate warming will occur in late fall, over winter, and in early spring. Although northern New Jersey and central Pennsylvania do not have any lakes similar in size to Lake Simcoe, the changes to air temperature and precipitation (both amount and type, i.e. snow vs rain), and air temperature being highly correlated to water temperature, can be used to infer changes to lake stratification. Warmer temperatures and increased precipitation from late fall to early spring will have a large impact on extending the period of lake thermal stratification, force water column mixing later in fall and earlier in spring, and change tributary inputs to the lake as winter rainfall events on saturated surfaces become more common. Increased winter rainfall is predicted to increase phosphorus loading to Lake Simcoe due to increased tributary flow (Crossman et al., 2013). This changing climate trend is likely already occurring with precipitation showing an increasing trend (1948-2015), lake water temperatures increasing (1980-2014), and ice cover decreasing (1973-2015) across the Great Lakes Region (ECCC and USEPA, 2017).

Table 6-1 Monthly and annual climate normals (1981-2010) for Toronto (Ontario) and Secaucus (New Jersey) (Data from ECCC 2019 and NOAA 2019)



Month	**Mean Temperature (ºC)**			**Minimum temperature (ºC)**			**Maximum temperature (ºC)**			**Total precipitation (mm)**		
	Toronto	Secaucus	Change	Toronto	Secaucus	Change	Toronto	Secaucus	Change	Toronto	Secaucus	Change
January	-3.7	-0.9	+2.8	-6.7	-4.8	+1.9	-0.7	3.0	+3.7	61.5	83	+21.5
February	-2.6	0.3	+2.9	-5.6	-3.9	+1.7	0.4	4.5	+4.1	55.4	77	+21.6
March	1.4	4.8	+3.4	-1.9	0.3	+2.2	4.7	9.4	+4.7	53.7	99	+45.3
April	7.9	10.7	+2.8	4.1	5.5	+1.4	11.5	15.9	+4.4	68.0	102	+34.0
May	14.1	16.5	+2.4	9.9	11.1	+1.2	18.4	21.9	+3.5	82.0	108	+26.0
June	19.4	21.6	+2.2	14.9	16.4	+1.5	23.8	26.8	+3.0	70.9	91	+20.1
July	22.3	24.4	+2.1	18.0	19.4	+1.4	26.6	29.5	+2.9	63.9	108	+44.1
August	21.5	23.6	+2.1	17.4	18.7	+1.3	25.5	28.6	+3.1	81.1	103	+21.9
September	17.2	19.4	+2.2	13.4	14.4	+1.0	21.0	24.4	+3.4	84.7	99	+14.3
October	10.7	13.3	+2.6	7.4	8.2	+0.8	14.0	18.4	+4.4	64.4	85	+20.6
November	4.9	7.9	+3.0	2.3	3.6	+1.3	7.5	12.2	+4.7	84.1	104	+19.9
December	-0.5	1.9	+2.4	-3.1	-1.8	+1.3	2.1	5.6	+3.5	61.5	94	+32.5
Annual	9.4	12.0	+2.6	5.9	7.3	+1.4	12.9	16.7	+3.8	831.1	1153	+321.9

Key Points – Climate change impacts on the ice-off season

- The maximum annual water temperature in the epilimnion in Lake Simcoe has increased by approximately 1.9°C since 1980. Modelling predicts that temperature could rise by an additional 3.4°C by the end of the century.
- An increased difference in temperature between surface layers and bottom layers in Lake Simcoe water will cause increased resistance to mixing, and an extended period of stratification.
- Stratification in Kempenfelt Bay currently occurs earlier in the spring and lasts approximately 28 days longer than it did in 1980. Modelling predicts that stratification could be extended up to an additional three months by the end of the century.

6.2.2 Climate impacts to ice cover

Ice cover is not only critical to limnological aspects of the Lake Simcoe ecosystem, but also the winter recreational economy, cultural heritage, and winter transportation to the residents of the lake's islands. Lake Simcoe has one of the longest periods of ice records in Canada with ice-on and ice-off dates recorded since 1852 in Kempenfelt Bay. These data show that fall freeze-up is occurring later and spring thaw is occurring earlier, resulting in a shorter period of ice cover (**Figure 6-5**). From the Kempenfelt Bay record, the mean (1852-1873) ice cover was 126 days with average ice-on date of December 17th and an average ice-off date of April 24th. From 1998-2017, the mean period of ice cover was 93 days, with the average ice-on date being January 9th and the average ice-off date being April 13th.

Water column stratification is sensitive to the duration of ice cover (Titze and Austin, 2014) in that an earlier ice-off date can have subsequent effects on lake processes because of earlier exposure to light, warmer air temperature and wind. For example, the spring algal bloom timing shifts in alignment with an earlier ice-off date, affecting the availability of food for other organisms such as zooplankton, and planktivorous fish. In addition, the development of fall-spawning fish species (such as lake trout) is tied to water temperature and ice dynamics, as discussed later.

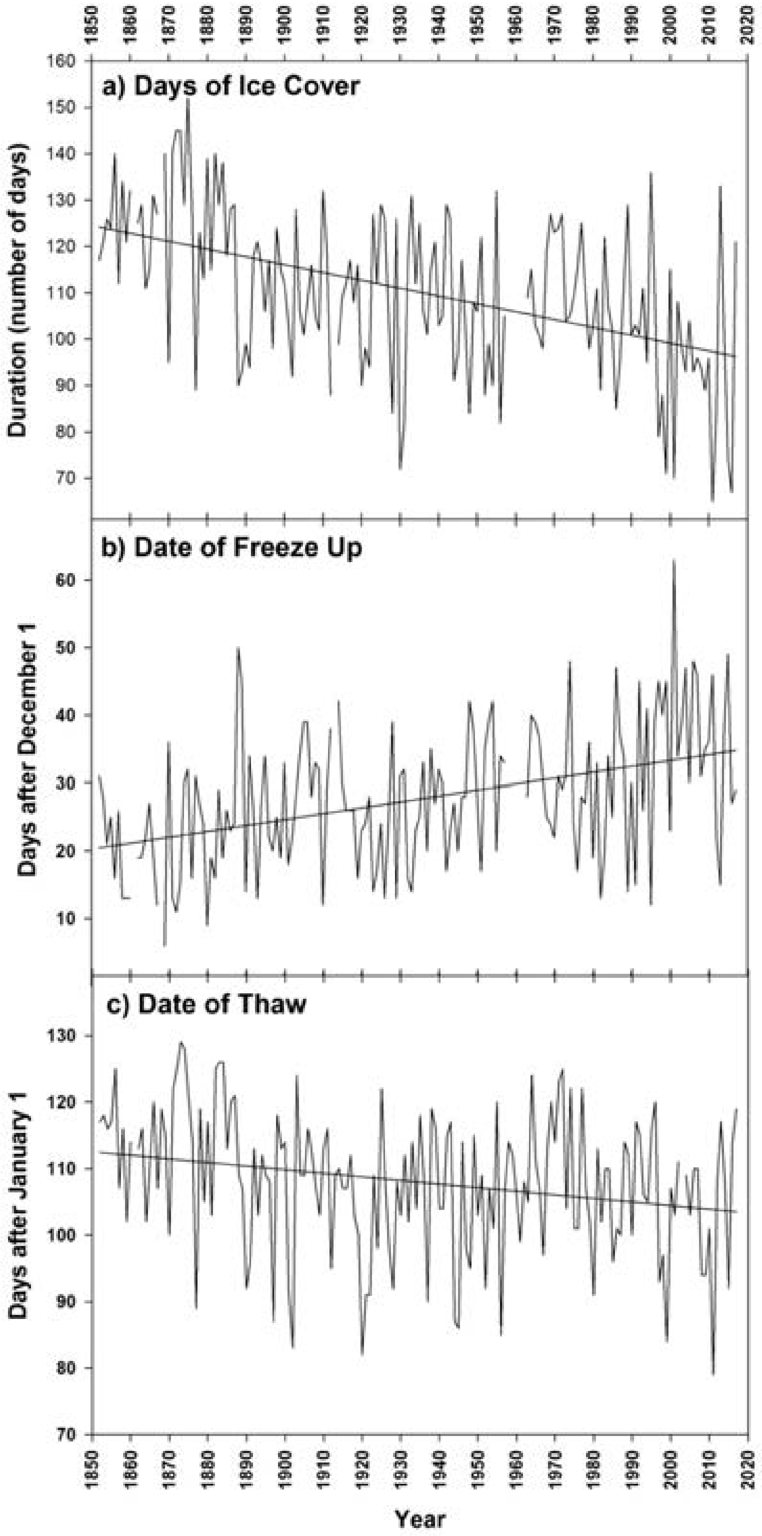


Figure 6-5 Long-term (1852-2017) ice cover trends for Kempenfelt Bay: a) duration of ice cover; b) date of freeze-up as number of days after December 1; c) date of thaw as number if days after January 1. Solid line is linear regression trend line (data courtesy of Alex Mills, pers. comm.).

Figure 6-6 MODIS satellite image of Lake Simcoe on February 20th 2012 showing open water areas that are not identified by previous methods.

Although the historical record of ice cover (Figure 6-5) suggests that Kempenfelt Bay froze every year, these data do not indicate if lake ice covered the entire surface of Lake Simcoe. More recently, daily satellite imaging recorded since 2000 clearly shows open water throughout the winter in 2001-2002 and 2011-2012 (**Figure 6-6**), even though the Kempenfelt Bay record reports full ice cover for 70 days in 2001-02 (Feb. 2nd – Apr. 13th, 2002) and 65 days in 2011-2012 (Jan. 15th – Mar. 30th, 2012) (Alex Mills, pers. comm.). Although the Kempenfelt Bay ice records give an indication of ice cover duration, they may not accurately reflect ice cover over all of Lake Simcoe. Ice dynamics respond to changing winter conditions and these changes can result in thinner, poorer quality ice. There are no long-term records of ice thickness or ice quality for Lake Simcoe. Thinner ice and open water will affect lake stratification in winter (described below) and impact the winter recreation economy, particularly ice-fishing.

Numerical modeling produced simulations of future ice conditions under the business-as-usual (A2) climate scenario for the Fisheries Management Zone 16 (FMZ 16), which extends across Southern Ontario from Windsor to Lake Simcoe. Under this scenario, ice-off is expected to occur up to 32.2 days earlier, and ice-on to occur up to 27.6 days later by 2100 (Minns et al., 2014). The model predicts that warming will increase the duration of open water by up to 47.0 days (Minns et al., 2014). Vertical mixing of the water column is crucial for circulating oxygen and nutrients from shallow to deeper water (Mironov et al., 2002) and changes to mixing dynamics associated with the duration and thickness of ice cover will likely influence other physio-chemical (e.g. dissolved oxygen concentration) and biological processes (e.g. algal blooms) during the winter.

6.2.3 Winter lake stratification

Winter water column stratification forms a weaker (relative to the ice-off period) thermal gradient between the cooler upper layer (0 – 2°C) and the relatively warmer and denser layer (~4°C) in the lake. Once ice forms on a lake, water circulation is mainly driven by heat fluxes, and to a lesser extent by wind energy (Kirillin et al., 2012). Conventional winter lake stratification forms a stable gradient with little active water movement because ice and snow form a barrier between water and the atmosphere (**Figure 6-7a**). Heat fluxes from the sediment create convection in the warmer water at the bottom of the lake that can create some water circulation. In winters with reduced snow accumulation, clear (i.e. blue) ice and open water can allow light to penetrate into the lake, where it stimulates algal growth that produces dissolved oxygen through photosynthesis (Figure 6-7**b**). Thermal convection nearer to the surface can mix this photosynthetic dissolved oxygen through the water column during the ice-on season. One or both of these processes can occur during the ice-on season depending on climate variation. A review of 101 ice-covered lakes found that algal blooms occur frequently under ice-covered lakes (Hampton et al., 2017).

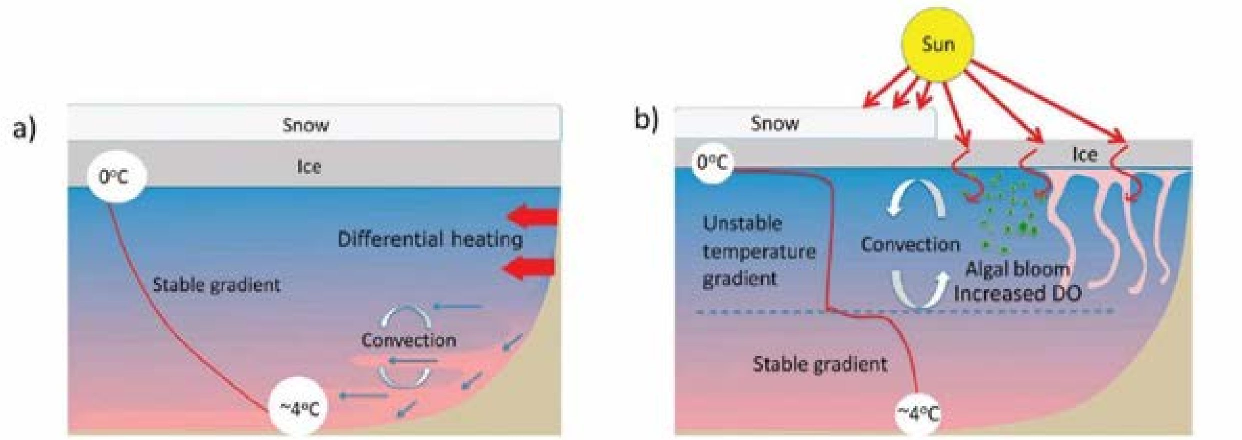


Figure 6-7 Winter lake stratification under two snow cover conditions. The conceptual diagram depicts the circulation patterns and stratification that occur during (a) Winter I with full snow coverage on ice, so heat fluxes from differential heating dominate resulting in an inverse stratification, and (b) in Winter II when the snow partially melts, allowing solar radiation to warm the upper water column and drive a deepening convective layer together with a possible algal bloom that produces oxygen. (Yang et al., 2017).

The 2014/15 winter water column stratification was measured in Lake Simcoe and the results suggest that active water movements are an important process during the ice-on season (Yang et al., 2017). The study observed conventional winter stratification early in the ice-on season from January to mid-March, followed by thermal solar convection from mid-March to ice-off in mid-April. This ice-on solar convection allowed algal growth that increased the concentration of dissolved oxygen by 2 mg/L at the surface. The 2014/15 winter season was the third coldest in the last 100 years in Southern Ontario (ECCC, 2019). If solar convection is occurring even in cold winters, it is likely that warmer winters will experience even more solar convection, further increasing the spring concentration of dissolved oxygen over the coming decades. More ice-on solar convection and increased dissolved oxygen accumulation from warmer winters could have important implications for other lake chemical and biological processes, including implications for the recreational winter fishery for lake trout and lake whitefish.

Key Points – Climate change impacts to winter stratification in the lake

- Warmer winters are increasing the length of the ice-off season. Lake freeze and thaw dates show that freeze-up is occurring later and thaw is occurring earlier, extending the ice-off season by an average of 33 days since 1852-1873. Models predict that this could extend by a further 47 days by 2100.
- More open water and thinner ice resulting from warming winters may alter winter stratification. Active water movement has been detected during winter stratification in Lake Simcoe, suggesting that solar energy is warming surface water under the ice and creating surface convection. Increased light penetration encourages algal growth and could increase the circulation of dissolved oxygen during the ice-on season.

6.3 Chemical processes

6.3.1 Dissolved oxygen

Lakes and other freshwater ecosystems require dissolved oxygen to support the abundance and diversity of species living within them. Factors that influence the concentration of dissolved oxygen include water column stratification (i.e. the separation of the different water depths into distinct layers), water temperature, aquatic plants, and the amount of organic matter floating in the water column.

Water temperature strongly influences the availability of dissolved oxygen as cooler water can hold more dissolved oxygen than warmer water (Wetzel, 2001). Wind also influences the concentration of dissolved oxygen as turbulence provides more surface area for oxygen to transfer across the air-water boundary. Temperature and wind-driven turbulence interact to create convection currents that circulate warmer water downward and cooler water upward (as previously described). The influence of these climate drivers differs during the ice-on and ice-off season because of normal seasonal variability.

Immediately after ice-off in the spring, the concentration of dissolved oxygen in Lake Simcoe surface waters (0-2 m depth) is highest (~10-13 mg/L) and more or less evenly distributed through the water column (LSRCA, unpublished data). Upon thermal stratification of the water column, the concentration of dissolved oxygen in the hypolimnion (i.e. the bottom layer) begins to decrease due to respiration by consumers and the decomposition of organic matter. By late summer / early fall, dissolved oxygen is at its lowest concentration as stratification prevents oxygen from the epilimnion (i.e. the lake's surface layer) from replenishing the depleted dissolved oxygen. The rate of dissolved oxygen depletion depends on several factors such as temperature, the decomposition of organic matter, how many organisms consume oxygen, their particular oxygen demands, and other complex physiochemical processes.

The end-of-summer dissolved oxygen concentration in the hypolimnion provides a measure of the changes in habitat quality of the lake that affect the coldwater fish. To address adverse impacts on the coldwater fishery, the Lake Simcoe Protection Plan (LSPP) established a target of 7 mg/L of dissolved oxygen as the optimum end-of-summer concentration (MOE, 2009). In Kempenfelt Bay, the minimum end-of-summer concentration of dissolved oxygen in the hypolimnion increased from 3.1 mg/L in 1980-1990 to 5.5 mg/L in 2008-2017 (**Figure 6-8a**) (MECP, 2019). However, the minimum end-of-summer dissolved oxygen concentration remains slightly below the LSPP target of 7 mg/L.

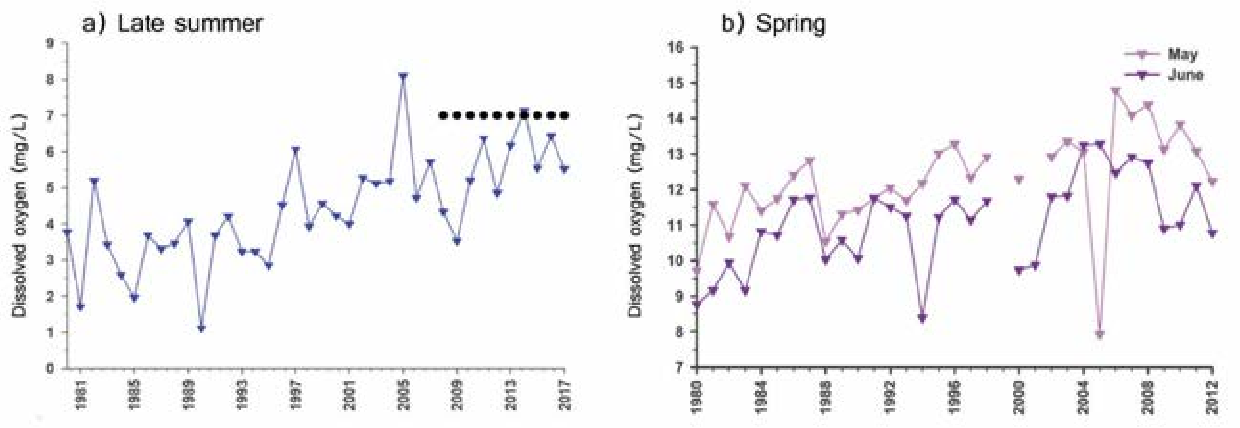


Figure 6-8 Long-term dissolved oxygen trends in Lake Simcoe in late summer and spring: (a) minimum late summer volume-weighted deep-water dissolved oxygen concentration between 1980 and 2017 (MECP, 2019), the dotted line denotes the LSPP target of 7 mg/L; (b) mean spring volume-weighted dissolved oxygen concentration (MOECC, 2015).

As dissolved oxygen is consumed by biological processes, such as respiration and the decomposition of organic matter as described below, any changes in climate affecting these processes will also impact dissolved oxygen. Hydrological modeling of dissolved oxygen in Kempenfelt Bay found that oxygen deficiency, or hypoxia, may last up to 40 days longer and reduce the end-of-summer dissolved oxygen by up to 1 mg/L by 2100 under the business-as-usual (A2) scenario (Bolkhari, 2014; **Figure 6-9**). This extended period of below-target dissolved oxygen concentration could have serious impacts to the health of the cold-water fish community in Lake Simcoe. An earlier model in Lake Erie found similar results where atmospheric warming of 4°C correlated to a 1-2 mg/L decrease in hypolimnetic dissolved oxygen (Blumberg and DiToro, 1990). However, recent studies suggest that other climate factors could mitigate declining oxygen levels.

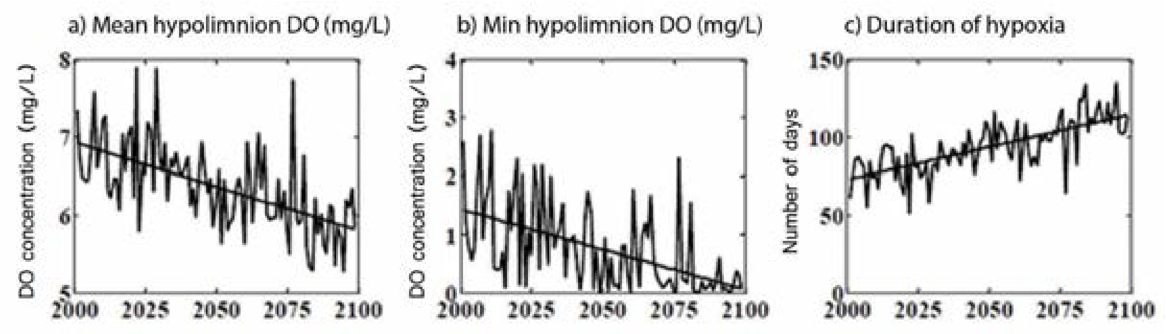


Figure 6-9 Downscaled end-of-century projections for mean (a) and minimum (b) hypolimnetic oxygen, and (c) the duration (days) of hypoxia under the business-as-usual carbon emission scenario (A2) (Bolkhari, 2014). Model simulations were compared against observed data from eight MOECC monitoring stations across Lake Simcoe (C1, C6, C9, K39, K42, K45, E51 and S15).

The increasing springtime concentration of dissolved oxygen in Lake Simcoe (**Figure 6-8b**) suggests that one or several processes may be facilitating oxygen accumulation during the ice-on season. One possible explanation is the relationship between ice thicknesses and the concentration of dissolved oxygen described previously. Full ice coverage of a lake's surface would act as a barrier that oxygen would not penetrate, preventing flux between water and air. Thus, the sources of dissolved oxygen under a layer of ice are likely from algal production (i.e. photosynthesis). Warmer winters with thinner or clearer ice would allow more light to penetrate the ice enabling more photosynthesis to occur (than under a snow-covered lake), increasing the concentration of dissolved oxygen. In Lake Erie, winter and spring diatom populations have been increasing since about 2000 (Reavie et al., 2016). Although few detailed studies have been carried out on winter algae, in Lake Erie there appears to be a causal relationship between increased algal biomass and decreasing dissolved oxygen in the hypolimnion, likely caused by decomposition of algae during the period of thermal stratification (Reavie et al., 2016). In Lake Simcoe, ice-on photosynthesis increased the concentration of dissolved oxygen by 2 mg/L during the winter of 2014/15 (Yang et al., 2017). As well as increasing algal growth under the ice, thermal convection under the ice allows dissolved oxygen to circulate throughout the weakly stratified water column.

Over the coming decades, unfrozen open water areas over Lake Simcoe could also contribute to increases in over-winter dissolved oxygen concentrations. In the absence of an ice barrier, dissolved oxygen continues to transfer across the air-water boundary throughout the year. And, as oxygen-saturated cold water can hold more dissolved oxygen (0°C, DO = 14.6 mg/L) than oxygen-saturated warm water (22°C, DO = 8.7 mg/L; Wetzel, 2001), more dissolved oxygen can accumulate in winter than in summer. In sum, warmer winters could increase the total ice-on accumulation of dissolved oxygen due to increased algal dissolved oxygen production and increased dissolved oxygen holding capacity.

Key Points – Climate impacts on dissolved oxygen

- Nutrient reduction efforts have resulted in an increase in the concentration of dissolved oxygen in Lake Simcoe at the end of summer from an average of 3 mg/L in the 1980s to 5 mg/L in the past decade.
- However, warmer water contains less dissolved oxygen at saturation, suggesting that climate change could offset some of these gains achieved.
- Modeling suggests that Lake Simcoe could experience a decrease of 1 mg/L of dissolved oxygen, with low-oxygen events lasting up to 40 days longer by the end of the century.

6.3.2 Phosphorus

Phosphorus is one of the most significant threats to water quality in Lake Simcoe and reduction strategies for this nutrient are a target of the LSPP. Historically, human activities such as altering natural landscapes for development, industry and agriculture led to significant increases in the concentration of phosphorus in the lake. As the concentration of phosphorus increases in the water column, plant and algal growth also increase due to excess nutrient availability. The increased plant and algal biomass eventually dies, sinks to the lake bottom, and microbial decomposition consumes the dissolved oxygen present in the hypolimnion, depleting the concentration of dissolved oxygen over time. As the primary goal of the LSPP is to have a sustainable coldwater fish community, end-of-summer hypolimnetic dissolved oxygen, and reductions to phosphorus loading are critical targets of this lake management strategy.

Phosphorus loading from human activities is the main driver of the increased phosphorus concentration in Lake Simcoe. External phosphorus inputs represent the main source of phosphorus entering the lake and strategies to reduce phosphorus loading have resulted in a decline in the phosphorus concentration in the lake since the 1980s (**Figure 6-10**). However, climate effects may be impacting the success of the LSPP. Phosphorus loading from tributary sources currently account for ~60% of the total phosphorus load to the lake, and tributary sources are driven by the volume of flow, which is, in turn, driven by the amount and type of precipitation and surface run-off. In addition, surface run-off from urban areas is a major component of phosphorus loading. Currently, ~31% of total phosphorus loading is from urban areas, despite these areas only comprising 12% of the total watershed surface area (LSRCA, unpublished data). For a full assessment of tributary phosphorus loading, please refer to **Chapter 3 – Water Quality.**

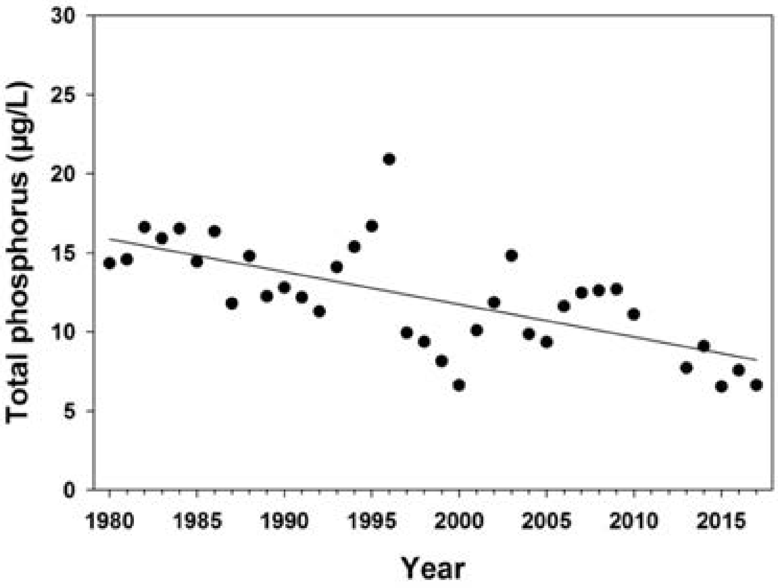


Figure 6-10 Long-term (1980 to 2017) volume-weighted spring total phosphorus concentration in Lake Simcoe (MECP, 2019).

Lake Simcoe is a net phosphorus sink and retains the majority (91%) of the total annual phosphorus load within the lake sediment, the water column and aquatic biota of the lake. Under low (DO < 2 mg/L) oxygen conditions, the sediment can then become a source of phosphorus through microbial action and redox reactions by releasing phosphorus that was bound to metals such as iron, aluminum, and magnesium. This sediment-bound phosphorus could serve as an important contributor of phosphorus to Lake Simcoe if there are extended periods of low deepwater dissolved oxygen due to a longer period of water column stratification. In a laboratory test of Lake Simcoe sediment by Nürnberg et al. (2013), samples incubated in anoxic (DO = 0 mg/L) water at 10°C released 4.3 mg/m^2/day of phosphorus, whereas samples incubated at 24°C released 12.5 mg/m^2/day of phosphorus. Further research is needed to fully understand the effect of dissolved oxygen and water temperature on internal phosphorus loading.

Key Points – Climate change impacts on phosphorus

- The phosphorus load to Lake Simcoe has declined from an average of over 100 tonnes per year in the 1990s to approximately 86 tonnes per year in the 2010s as a result of extensive effort by watershed stakeholders.
- As described in the Water Quality chapter however, loading is variable and highly impacted by climate-driven factors such as precipitation and tributary flow. As such, climate change may lead to increases in phosphorus loading in the coming decades.
- Under the extended periods of low oxygen conditions projected with climate models, phosphorus bound in lake sediments can be released to the water column, further affecting lake ecosystem function.

6.3.3 Chloride

The chloride concentration in many aquatic ecosystems in North America has increased over the past few decades (Dugan et al., 2017). There are several sources of chloride within a watershed, but winter road salt is the primary source of concern. Road salt lowers the freezing point of ice so that water remains in a liquid state for longer, making winter maintenance easier. Road accidents are significantly reduced as a result of de-icing (Trenouth et al., 2015); however, chloride is harmful to aquatic ecosystems when present in high concentrations. The Canadian Council of Ministers of the Environment established a guideline for chloride of 120 mg/L, above which impacts to native freshwater organisms are expected to occur (CCME, 2011).

Water quality monitoring at Atherley Narrows gives an indication of water quality in the lake, as the Narrows is the lake's only outflow. A significant increase in chloride is evident over the 48-year period of record at that station (**Figure 6-11**). When monitoring began, concentrations averaged less than 10 mg/L, which is similar to what would be found in un-impacted lakes on the Canadian Shield. Over time however, concentrations have increased at a rate of about 0.8 mg/L per year. If this trend continues, the Canadian Water Quality Guideline could be exceeded in 85 years.

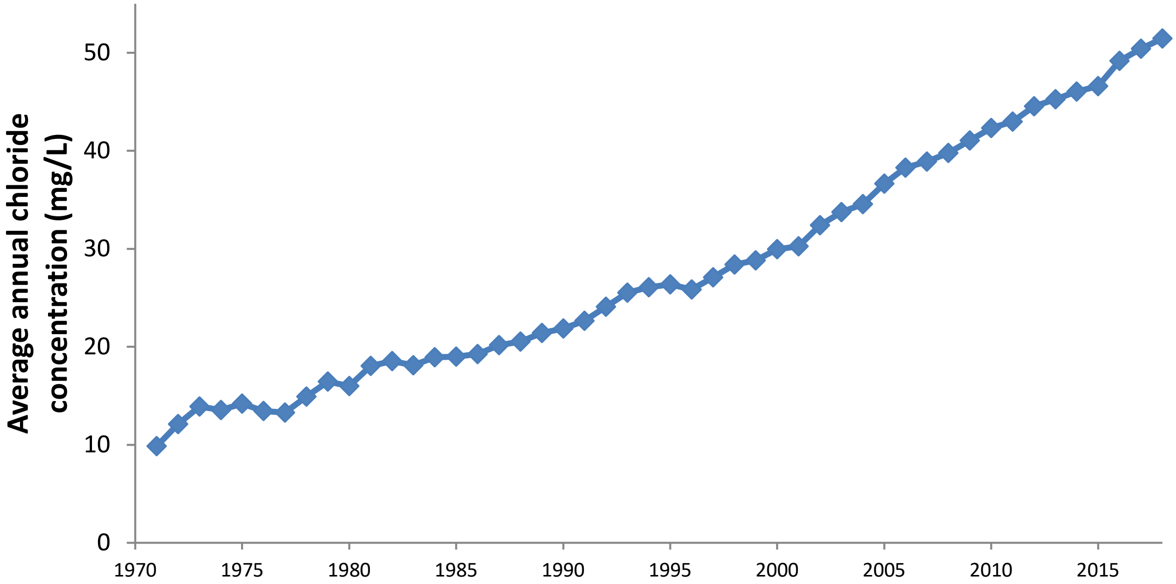


Figure 6-11 Trends in chloride concentration at the Atherley Narrows outflow station, Lake Simcoe, 1971 - 2018

With climate change, this trend may in fact become even more pronounced. As freeze-thaw cycles and freezing rain events become more frequent, the application of salt to manage ice on roads, sidewalks, and parking lots will become more frequent as well. This increasing frequency in events, coupled with projected increases in roads and parking lots to support a growing population, is expected to lead to an increase in the use of winter salt, and an increase in the rate to which concentrations increase in the lake. As much of the direct impact of chloride on aquatic ecosystems is first felt in Lake Simcoe's tributaries, chloride is discussed in greater detail in **Chapter 3 – Water Quality**.

6.4 Biological processes

Climate change is a critical environmental stressor for freshwater ecosystems. Lakes are mostly closed systems and, as such, they may be more vulnerable to climatic variation than terrestrial ecosystems. Even small alterations to biological processes can have significant cascading effects along the levels of biological organization (**Figure 6-12**). The ecological fitness of organisms, and therefore their resilience to environmental change depends on life history traits (e.g. growth rate, recruitment, body size). Interactions between and among species influence trophic dynamics (e.g. predation, herbivory, omnivory), and intraspecific / interspecific competition influences community interactions (e.g. species richness and community composition). Changes in the structure of communities can alter ecosystem functioning (e.g. production and trophic dynamics) and alter the flow of energy through the food web.

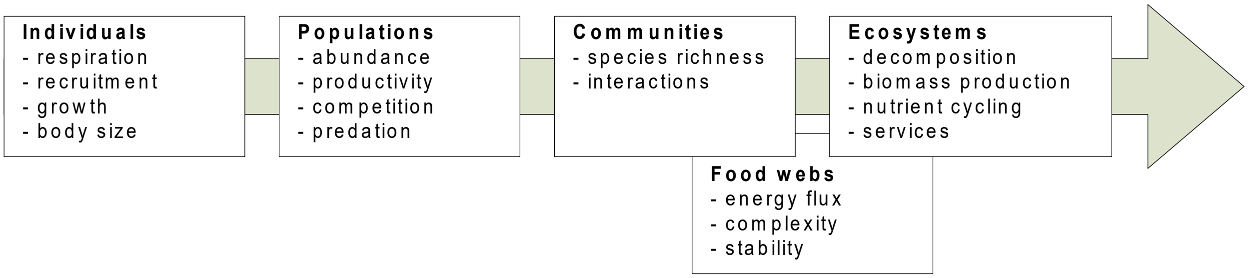


Figure 6-12 Diagram describing the levels of biological organization from individuals to ecosystems.

The survival of some recreationally important native species in Lake Simcoe depends on coldwater habitats that are vulnerable to warming water temperature and competition from species that are better adapted to warmer water. The loss of these native species would reduce the diversity of species in Lake Simcoe. Aquatic ecosystems with relatively low diversity are typically dominated by generalists and invasive species and can be become highly stressed in these environments. Highly stressed aquatic ecosystems may require intensive management efforts to recover. Therefore, understanding the impacts of climate change on the Lake Simcoe ecosystem will support effective management actions to promote resilience and a healthy lake for watershed residents.

6.4.1 Phytoplankton

Phytoplankton (i.e. free-floating algae) form the base of the aquatic food web and support higher trophic organisms in a lake, including invertebrate (e.g. zooplankton and benthos) and vertebrate (e.g. fish) consumers. The abundance of phytoplankton can be controlled from the bottom-up (e.g. temperature, light and nutrients) or the top-down (e.g. herbivory by zooplankton or fish). Changes to phytoplankton abundance and species diversity associated with climate change and other anthropogenic stressors can alter food web dynamics and structure.

Phytoplankton are excellent water quality indicators due to their dominance and diversity in aquatic ecosystems, and a relatively short life cycle that responds rapidly to environmental changes (Smol, 2008). Phytoplankton species assemblages are closely linked to climatic and environmental conditions such as nutrient concentrations, water clarity, pH, and water column mixing; with different species having environmental optima and tolerances under different environmental conditions. Diatoms (Bacillariophyta) make up the largest component in the Lake Simcoe phytoplankton community (**Figure 6-13),** but green algae (Chlorophyta), cryptomonads (Cryptophyta), and blue-green algae (Cyanophyta) are significant at different times of the year. Due to relatively high phosphorus inputs from the Holland River, Cook's Bay (**Figure 6-13**, sites C1, C6, C9) has a higher amount (biovolume) of phytoplankton compared to Kempenfelt Bay (K39, K42) or the main basin (K45, E51, S15). Phosphorus loading is typically cited as the main driver of primary production (Kovalenko et al., 2017; Pilcher et al., 2017) but the fossil record suggests that climate warming is impacting algal communities in Lake Simcoe (Hawryshyn et al., 2012) and across the northern hemisphere (Rühland et al., 2008; 2015), although in Lake Simcoe grazing by invasive dreissenid mussels has obscured the recent part of the climate signal.

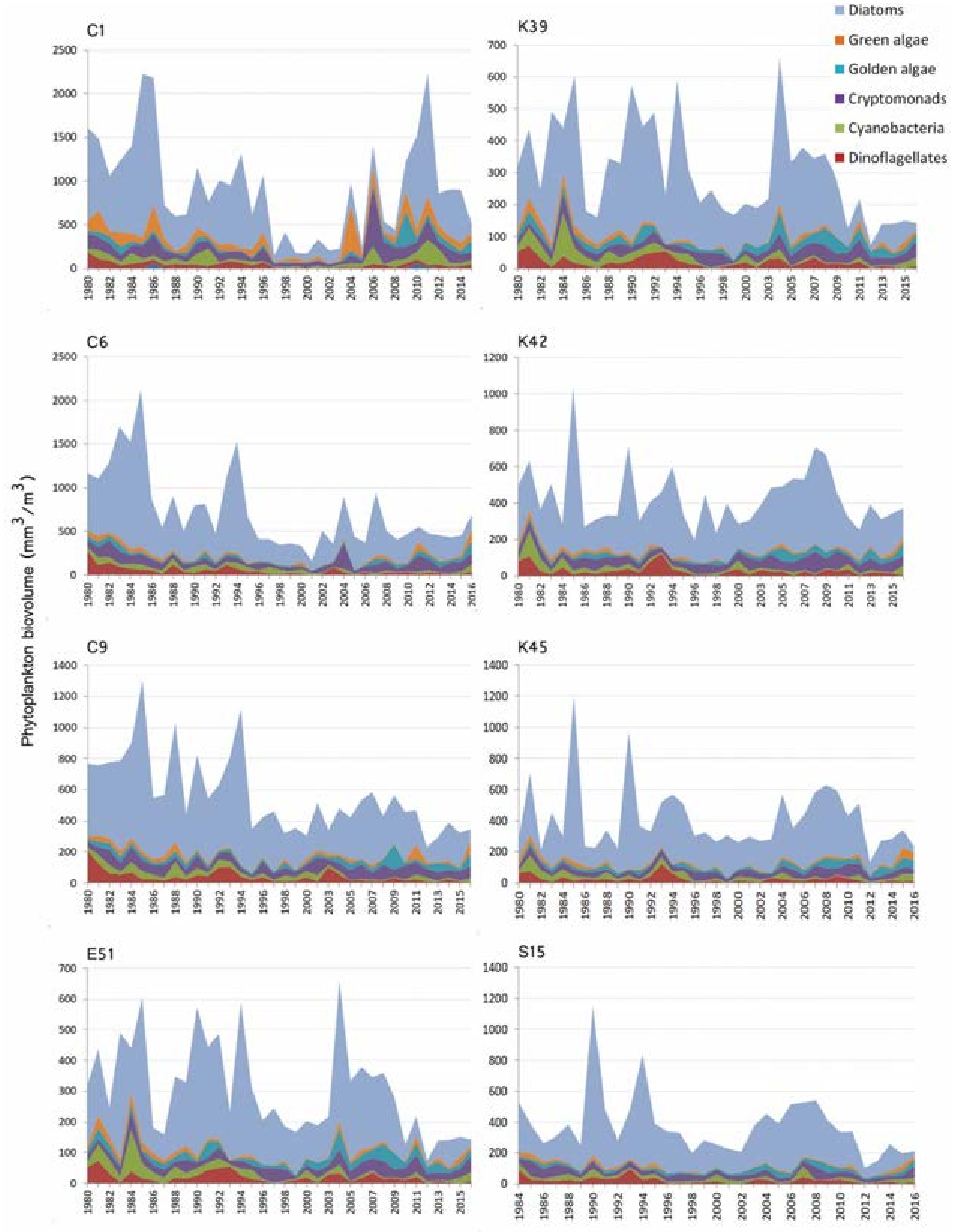


Figure 6-13 The biovolume of major phytoplankton groups at the Lake Simcoe monitoring stations from 1980 to 2016 showing dominance by diatoms (MOECC, 2015 and unpublished data).

Climate change impacts

Increased water temperatures and the length of water column stratification are two of the primary climate drivers of phytoplankton growth. Climate change alters the size structure of phytoplankton communities as warming favours smaller, lighter planktonic species (Winder et al., 2009; Beall et al., 2016) over heavier forms that need frequent water column mixing to remain in the photic zone. Typically, warmer water temperatures coincide with less wind and a more stable water column that favours algae that sink slowly in the water column (e.g. lightly silicified, disk-shaped *Cyclotella* and *Discostella* spp.). More heavily silicified diatoms (such as barrel-shaped *Aulacoseria* spp. and heavier forms of *Fragilaria* spp.) need a mixed water column where vertical currents keep these diatoms in relatively well-lit areas. In a synthesis of paleolimnological sediment core studies from over 200 lakes from across the Northern Hemisphere, Rühland et al (2008) found that increases in *Cyclotella* taxa, at the expense of *Aulacoseira* taxa, occurred in conjunction with changes to freshwater habitat structure and quality that was linked to climate warming trends. This species change occurred significantly earlier in sensitive Arctic lakes (~1870) compared to lakes in temperate regions (~1970).

In Lake Simcoe, this climate-related shift in the diatom community occurred in the 1970s but is muted by other environmental stressors (Hawryshyn et al., 2012). Heavily-silicified *Aulacoseria* dominated the early part of the sediment core record, increasing after land clearance by European settlers, construction of the Trent-Severn Waterway, and increased phosphorus loading. Lightly-silicified, disk-shaped taxa increased with climate warming in the 1970s, but these taxa were typical of nutrient-enriched systems (*Stephanodiscus* spp.). Grazing by invasive dreissenid mussels further muted this climate signal by selectively feeding on centric diatoms, driving the diatom community toward the current domination by lightly-silicified, but pennate, *Fragilaria* and *Asterionella* (Hawryshyn et al., 2012).

In addition to climate-related changes in phytoplankton community composition, further changes are taking place due to physical changes in lakes. During winter, changing ice conditions associated with warming can affect the growth of phytoplankton under the ice. Pronounced changes in ice dynamics (as discussed previously) are accompanied by equally pronounced shifts in phytoplankton assemblages in the Great Lakes Region (Reavie et al., 2016; Beall et al., 2016). Significantly more chlorophyll-*a*, indicating higher algal biovolume, and therefore more photosynthetic oxygen is produced under snow-free ice, thin ice and open water (Twiss et al., 2012), although wind-driven sediment turbulence also plays a role (Chowdhury et al., 2015). The over-winter and spring diatom blooms in Lake Erie have been linked to late-summer deepwater hypoxia as decomposition of this biomass uses hypolimnetic oxygen, and this may be more severe in years with lower than average ice cover and relatively high diatom biovolume (Reavie et al. 2016; Wilhelm et al., 2014; Zhou et al., 2015). Further restructuring of the phytoplankton community has been linked to the intensity and duration of water column stratification. In studies on all five Great Lakes, Bramburger et al. (2017) reported that a deep chlorophyll layer forms during the ice-free period with an algal community distinctly different from the overlying epilimetic phytoplankton. The summer phytoplankton of the epilimnion is dominated by *Cyclotella* diatoms and cyanophytes, whereas the deep chlorophyll layer contains mostly heavier diatoms, likely remnants of the winter-spring phytoplankton bloom. A ten-year study of phytoplankton in all five Great Lakes concluded that a thicker epilimnion favours diatoms such as *Cyclotella*, and a changing pelagic food web is due to an epilimnion warming faster than atmosphere, changing stratification patterns, and a longer time between ice-out and summer conditions (Reavie et al., 2014).

In the Great Lakes Region, earlier ice-off results in earlier spring phytoplankton blooms (Smol et al., 2005; Hampton et al., 2017). As zooplankton emergence has historically coincided with phytoplankton bloom timing, earlier blooms could result in mismatched bloom-grazing phenology. Shifting phytoplankton blooms and assemblages could, in turn, have cascading trophic impacts as earlier zooplankton population increases are out of sync for use by juvenile fish predators. Zooplankton are a critical food source for young lake trout after the alevin stage (i.e. once the yolk sac is absorbed). Warmer winter water temperature can accelerate trout development and reduced zooplankton abundance, or mismatched timing, in spring could impact the survival of young fish. Further research and monitoring are necessary to better understand the impact of ice dynamics on phytoplankton emergence and assemblages, and associated water quality and trophic impacts.

Harmful algal blooms

A trend toward warmer surface waters, and a longer period of water column stratification, may be shifting a competitive advantage in the phytoplankton toward cyanobacteria (blue-green algae; Cyanophyta). In addition to more favourable environmental conditions, dreissenid mussels have selective feeding that may reject cyanobacteria while ingesting other algal groups that outcompeted and kept cyanobacteria biovolume in check (Pearl and Huisman, 2008; Kerfoot et al., 2010).

These competitive advantages could enhance cyanobacterial population growth in warmer water. In a study of phytoplankton in the Great Lakes (2001-2011), climate warming was reported as a cause of changes in pelagic food webs with a trend toward higher cyanobacteria biovolumes, particularly in summer in lakes Superior, Erie, and Ontario (Reavie et al., 2014). In a longer study of Lake Ontario, Estepp and Reavie (2015) found that between 1975 and 2000, abundance of cyanobacteria and green algae increased, likely coinciding with increased water clarity. From 2001-2014, the total biovolume of phytoplankton did not change, but the community was restructured with high densities of centric diatoms (due to the climate signal described above) and higher abundances of cryptophytes and cyanobacteria.

Hydrological modeling using the predictions under the business-as-usual (A2) climate scenario, have predicted that total phytoplankton biovolume may decrease, but conditions favouring an increased proportion of cyanobacteria in the phytoplankton community increased from 2070 onwards (Bolkhari, 2014). As cyanobacteria abundance increases, so does the risk of harmful cyanobacteria blooms. From 1994-2009 there has been a significant increase in reports of algal blooms in Ontario lakes (**Figure 6-14**) with over 50% of these reports due to cyanobacteria (Winter et al., 2011). Although this increase may be related to climate, it may also be a result of increased human activity on cottage lakes and more reports being made where algal blooms were unrecognized in the past. At present, harmful algal blooms have not occurred in Lake Simcoe itself during the period of monitoring (i.e. 1980 to present) but a few harmful algal blooms have occurred in recent years in nearby lakes (e.g. Musselman Lake, Wagner Lake, and Lake St. John), and one harbour attached to Lake Simcoe (Lagoon City, July - August 2013). In addition to harmful effects to human health from cyanobacterial hepto- and neurotoxins, increasing abundances of cyanobacteria could counteract lake restoration strategies. Climate change impacts exacerbate increased phosphorus loading on lakes, creating a positive feedback for cyanobacteria and the presence of harmful algal blooms (Paterson et al., 2017). The success of cyanobacteria relative to other algal groups under climate warming scenarios is the result of many synergistic environmental variables. Total phosphorus concentrations, internal loading, and length of stratification favour cyanobacteria in warm weather conditions, with highest biovolume being the potentially toxin-producing taxa *Aphanizomenon*, *Anabaena*, and *Microcystis* (Wagner and Adrian, 2009). Climate-related changes must be factored into lake management strategies.

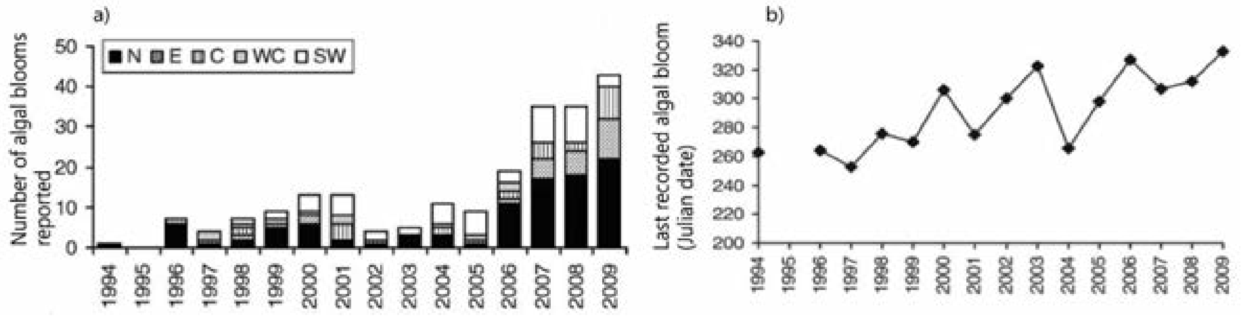


Figure 6-14 Algal blooms in Ontario. (a) The number of algal bloom reports broken down by Ontario region - N) Northern; E) Eastern; C) Central; WC) West Central; and SW) South West; (b) The latest day of the year where an algal bloom was reported to the Ontario Ministry of the Environment each year from 1994 to 2009 (Winter et al., 2011).

Key Points – Climate change impacts on phytoplankton

- Water temperature increases and wind-driven mixing alter the size, structure, and composition of phytoplankton communities. Warmer water favours smaller algal forms whereas cooler, more mixed, water favours larger algal forms.
- The sediment core record shows climate-related shifts in the diatom assemblage of Lake Simcoe since the 1980s.
- The spring phytoplankton bloom is occurring earlier due to earlier ice-off. Because zooplankton and young fish emergence and feeding is aligned with the spring phytoplankton bloom, their growth and survival may be impacted by earlier blooms.
- Modelling projects that the total phytoplankton biovolume will decline but that the proportion of cyanobacteria will increase from 2070 onward due to climate change.

6.4.2 Pathogens

Swimming advisories and recreational beach closures can occur during the ice-free season on Lake Simcoe due to higher than allowed concentrations of bacteria in the water. Sources of these bacteria can be wash ups from wave action on the lake; imports of suspended material from nearby tributaries; overflow from stormwater facilities during storm events; surface run-off following rainfall events (particularly from urban areas and agriculture with grazing livestock); and feces from birds such as gulls and geese (Nevers et al., 2018). Monitoring for bacteria, and posting swimming advisories, in the Lake Simcoe Watershed is currently under the jurisdiction of the Regional Health Units, who typically use fecal indicator bacteria (*Escherichia coli* or *Enterococcus* spp.) to assess contamination. In Ontario, guidelines for posted swimming advisories are *E. coli* concentrations exceeding 100 colony forming units (CFUs) per 100 ml of water (MOE, 1994). Although *E. coli* and coliform bacteria are used as indicators, there are more than 100 taxa of bacteria, viruses, and parasites that can cause water-borne illness. Most illnesses are ear, nose, and throat; respiratory; or gastrointestinal infections, although more severe illnesses (e.g. hepatitis, giardiasis, or acute and chronic toxic effects from algal blooms) also pose a public health threat (Patz et al., 2008). The most at-risk groups are frequent water users (e.g. lifeguards, in-water recreation), young children, the elderly, pregnant women, and people with compromised immune systems.

Pathogens and human health risks have been identified as a primary concern in the LSPP. The frequency, and duration, of beach closures was reported to have increased between 2003 and 2009 (MOE, 2009), but were reported as mostly "no change" trend in 2014 (MOECC, 2015). Khan et al. (2013) investigated the occurrence of *Campylobacter* (a cause of gastrointestinal infections in humans) at five Lake Simcoe beaches and found that although these bacteria were found infrequently, sources of contamination included beach sand, bird feces, and nearby tributaries. Additionally, beaches on the south and eastern shorelines had a higher frequency, and longer duration, of advisory postings, likely due to greater exposure to on-shore winds and waves (MOECC, 2015).

In a study of 12 Great Lakes cities in the US, extreme precipitation events were associated with beach closures the following day. Between 1948 and 2004, 51% of waterborne disease outbreaks in the US were preceded by an extreme precipitation event (Bush et al., 2014). In urban areas, more than 60% of the annual contaminant load is transported during storm events, with increased turbidity in receiving waters correlating with increased bacterial concentrations (Patz et al., 2008). In Milwaukee, the 1993 outbreak of the parasite *Cryptosporidium* was preceded by the heaviest rainfall in 50 years (Patz et al., 2008). Further, in Wisconsin, the summertime bacterial concentration in lakes shows a positive correlation with not only the mean daily precipitation, but also the duration between rainfall events, suggesting that an extended dry spell, followed by an intense precipitation event leads to bacterial contamination in water (Patz et al., 2008).

Unfortunately, climate change projections for the Lake Simcoe watershed predict more frequent and intense precipitation events, interspersed by extended dry periods, which suggest that pathogen outbreaks and beach closures will become more common occurrences in the future.

6.4.3 Aquatic plants

Aquatic plants, or macrophytes, are vascular plants, bryophytes (non-vascular plants) and macro-algae (plant-like, multicellular algae) that live in aquatic environments. In Lake Simcoe, macrophytes form an important part of the littoral zone community and are one of the key autotrophic communities in the lake. Many ecological functions are assigned to freshwater macrophytes, including habitat creation for fish and invertebrates; reducing erosion, stabilizing soft sediments, reducing suspended particles; nutrient cycling; and primary production (Jeppesen et al., 2014; Kotta et al., 2014; Short et al., 2016).

In Lake Simcoe, aquatic plant surveys conducted in Cook's Bay between 1984 and 2013 suggest that the submerged aquatic plant species diversity is changing, and aquatic plant biomass has increased in the study area (**Figure 6-15**), likely as a result of increased water clarity between the 1980s and present. Also of note is that warmer years within comparable studies (e.g. 1987 vs 1984, and 2013 vs 2008 where water clarity was constant between studies using similar sampling methods) had a higher biomass of aquatic plants (**Table 6-2**). Three invasive aquatic plants species (out of 21 total submersed plant species) have been recorded in Lake Simcoe: Eurasian watermilfoil (*Myriophyllum spicatum*; first reported 1984), curly-leaf pondweed (*Potamogeton crispus*; first reported 1984), and starry stonewort (*Nitellopsis obtusa*, first reported 2009). These invaders are fast-growing in comparison to many native species, particularly at warmer water temperatures, and currently account for a large portion of the shallow-water biomass. In 2008, *M. spicatum* comprised 24.4% of the total recorded plant biomass and was reported at 61% of the 215 sample stations (Ginn, 2011; LSRCA, unpublished data). Since 1984 (**Table 6-2**), increases have be recorded in maximum wet weight biomass (1.2 to 4.5 kg (wet)/m^2) and the maximum depth of plant colonization (from 6.0 to 10.5 m), mainly due to increased water clarity resulting from phosphorus abatement strategies and filter-feeding by invasive dreissenid mussels.

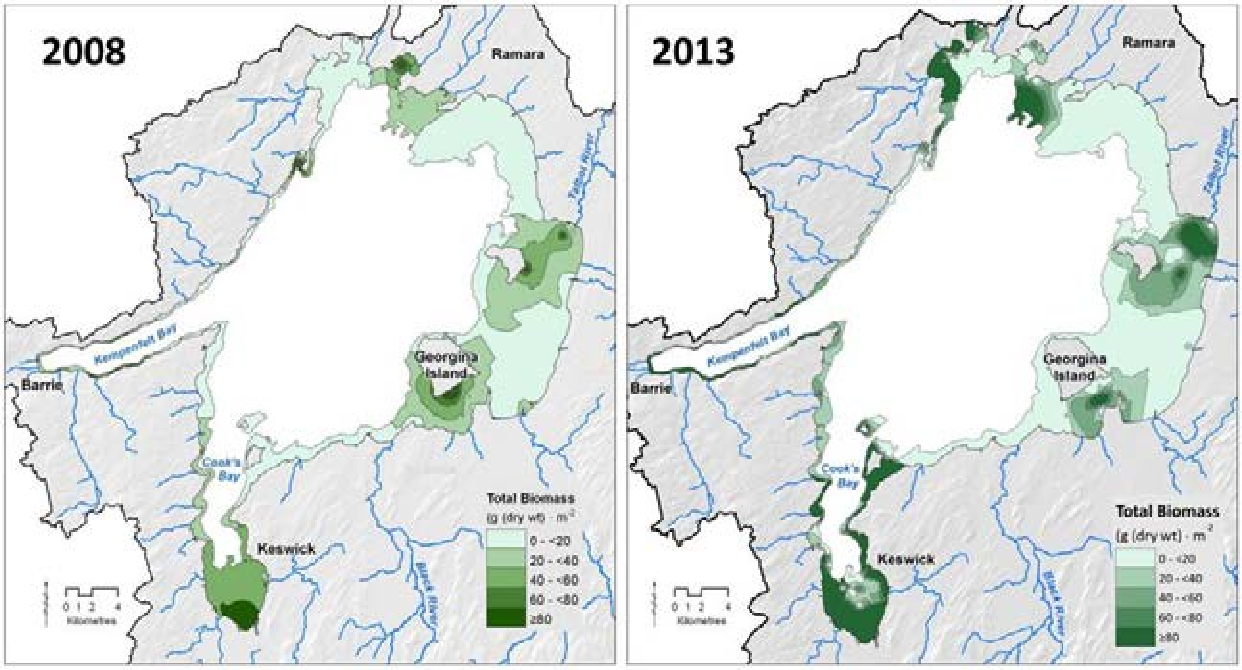


Figure 6-15 Aquatic plant distribution and dry weight biomass from Lake Simcoe, 2008 and 2013 (Ginn 2011 and LSRCA unpublished data)

Table 6-2 Aquatic plant and key environmental variables recorded for 1984, 1987, 2006, 2008, 2013). Plant data is from Neil et al., 1985 & 1991; Stantec, 2007; Ginn, 2011; and LSRCA unpublished data. Secchi disk data from Lake Simcoe station K-42 (MOECC, 2015). Mean air temperature, total precipitation, and cooling degrees days were recorded at the Barrie-Oro reporting station (ECCC, 2019).

Variable	1984	1987	2008	2013
Number aquatic plant species recorded	11	14	13	19
Max. wet weight biomass (kg (wet)/m^2)	1.2	2.4	3.1	4.5
Max. depth plant colonization (m)	6.0	6.0	10.5	10.5
Mean Secchi disk transparency (m)	4.1	4.4	7.2	6.8
Mean air temperature (°C ; May-Sept)	16.1	17.8	15.3	16.2
Cooling degree days (>18°C; May-Sept)	180.8	279.0	101.7	163.0
Total precipitation (mm; May-Sept)	382.2	478.0	470.9	414.3

Years with relatively warmer air temperatures tend have higher plant biomass than comparable, relatively cooler years (e.g. 1987 vs 1984, and 2013 vs 2008; Table 6-2). In comparison between 2008 and 2013, the maximum recorded aquatic plant biomass was higher in 2013, which had higher mean temperature (from May to September) and 60 more cooling degree days (i.e. days with temperatures above 18°C) than 2008. The highest number of cooling degree days and the highest mean May-September air temperature were in 1987, which also had a relatively large maximum plant biomass. In 1987 however, plant growth was likely limited by poorer water clarity, and less available habitat space in

Cook’s Bay. With projected warming in air temperature, and our observed higher plant biomass during warmer years, it can be assumed that climate warming will likely lead to increases in aquatic plant biomass if water clarity, and aquatic plant habitat space, remain in their current state.

Climate change impacts

Water temperature affects the growth rate of aquatic plants. In general, net photosynthesis increases with temperature up to a species thermal optimum, after which growth and survival of a species sharply decline (Kotta et al., 2014; Jeppesen et al., 2010). Different macrophyte species respond differently to changes in water temperature (Netten et al., 2010), and species-specific responses to water temperature directly influences macrophyte community structure and species diversity. Although many studies show a relationship between warming water and increased macrophyte cover (Rooney and Kalff, 2000; Kotta et al., 2014), others show a reduction in macrophyte cover associated with warmer winters in nutrient rich systems (Hargeby et al., 2004; Kosten et al., 2009).

Anecdotal observations made during ten years of field monitoring on Lake Simcoe suggest that macrophyte and littoral algae community season succession patterns may be straying from a “classic” temperate lake scenario to more variation, likely caused by cooler La Niña (2015) and warmer El Niño (2016) events (**Figure 6-16**; LSRCA unpublished data). In a classic temperate lake, cool water temperatures after ice-off correspond with plant communities dominated by diatoms and littoral green algae. As the water warms, macrophytes become more prominent, increasing in biomass until cooler temperatures and shorter days trigger senescence and diatoms become dominant again before ice on. In recent years on Lake Simcoe, this pattern has been changing. In 2015, cooler, relatively wet weather, likely related to a La Niña event, led to an extended period of dominance by green algae (such as *Spirogyra*) in shallow water, delayed growth in aquatic plants, and complaints of algal blooms from lake users. A rapid change to hot and dry (El Niño-driven) conditions in mid-summer, 2015, was likely responsible for a sudden increase in aquatic plant biomass, but observations indicate the amount of plants was below average. The winter of 2015-16 was relatively mild in southern Ontario, followed by an early and rapid onset of hot, dry weather conditions. The persistence of these weather conditions, likely related to the El Niño event, created ideal conditions for plant growth, at the expense of algae in the classical temperate lake pattern. This resulted in observations of higher than average aquatic plant biomass, and complaints of “too many plants” from lake users. Rapid shifts between higher plant biomass and lower plant biomass, likely driven by changing seasonal weather patterns, seem to be occurring with more frequency and are upsetting what would be considered a “typical” or “classic” seasonal pattern for aquatic plants in temperate lakes.

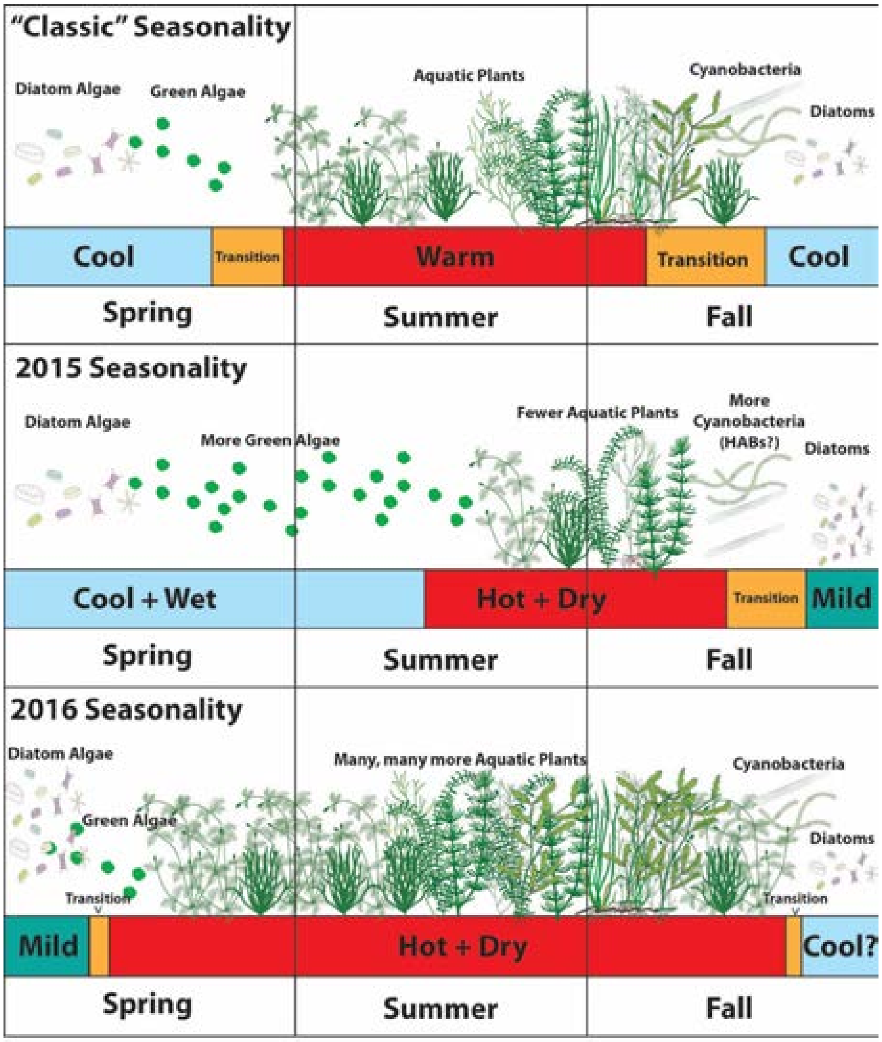


Figure 6-16 Observed differences in macrophyte and littoral algae amounts during a "classic" or typical year on a temperate lake, compared to the 2015 La Niña and 2016 El Niño ocean oscillations.

Filamentous, attached, green algal species (e.g. *Cladophora*) can also "bloom" in shallow waters near the shoreline, causing foul-smelling mats as they detach, wash up on shorelines, and decay. Excessive growth and biomass of these algae is typically associated with phosphorus loading and allelopathy (i.e. the production of secondary metabolites that enable *Cladophora* to suppress the growth of other algae) (Trochine et al., 2011). Although Lake Simcoe does not currently have the comparable biomass of *Cladophora*, nor the shoreline wash-ups reported from the northern shoreline of Lake Ontario (Howell, 2018), underwater video observations show extensive amounts on shallow water, hard-to-sample, rocky substrates where large amounts of dreissenid mussels are also found (LSRCA, unpublished data). Potential trajectories for *Cladophora* in Lake Simcoe, under a warming climate scenario, may include an increased biomass and larger shoreline wash-ups. In studies from Lake Ontario near Rochester, NY, Vodacek (2012) found that elevated phosphorus concentrations created conditions favourable for *Cladophora* growth, as did the presence of dreissenid mussels, which convert particulate phosphorus into a much more bioavailable soluble form (Higgins et al., 2012).

Key Points – Climate impacts on aquatic plants

- Generally speaking, the rate of photosynthesis increases with temperature up to a species thermal optimum, then declines. Different species have different thermal optimums and therefore, increased water temperature enhances the growth of species with a higher thermal optimum, possibly at the expense of those with lower optima.
- Invasive species often have higher thermal optima than native species, providing them a competitive advantage. In Lake Simcoe, some invasive species begin growing earlier (e.g. Eurasian water-milfoil) and some grow faster (e.g. starry stonewort) than native species.
- The lake tends to have higher plant biomass in warmer years, which is expected to continue, particularly if water clarity remains high.
- Years with atypical weather patterns have atypical plant growth patterns. Cool springs can lead to extended periods when filamentous green algae is dominant in the lake, whereas early and hot springs can lead to rapid plant growth. In both cases, this can lead to frustration of lake users.

6.4.4 Zooplankton

Zooplankton are small animals that migrate in the water column, nearing the surface to find food (typically phytoplankton) and avoiding predators at deeper depth. They are some of the primary consumers in the food chain, transferring energy from phytoplankton to planktivorous fish. Water temperature affects zooplankton species differently, depending on a species' thermal tolerance. Climate can indirectly affect zooplankton by bottom-up effects that alter food availability (i.e. changes in phytoplankton biovolume and diversity) and top-down effects due to trophic interactions such as predation from planktivorous fish.

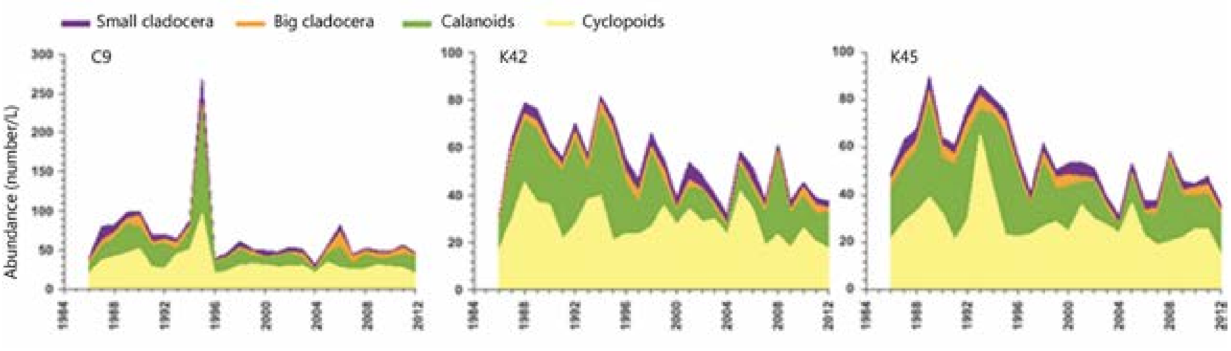


Figure 6-17 Zooplankton abundance (number of individuals per litre of lake water) at three lake stations (MOECC, 2015); C9 is located in outer Cooks Bay, K42 in Kempenfelt Bay and K45 in western main basin. Note difference in vertical axis scaling on C9 graph.

The Lake Simcoe zooplankton community is currently dominated by copepods (i.e. calanoids and cyclopoids) and cladocerans. Total abundance of zooplankton is similar at all lake stations, and declined after 1994 following the invasion by spiny water flea (*Bythotrephes longimanus*) (Figure 6-17). This invader was reported in Lake Simcoe in 1993, however after an initial increase the population declined and has remained low since 2006, possibly due to predation by fish such as cisco and the invasive round goby (MOECC, 2015).

Climate change impacts

In recent years, the effect of climate change has likely been an important factor for zooplankton abundance and community composition in Lake Simcoe. The coldwater cladoceran *Daphnia longiremis* and coldwater calanoid *Leptodiaptomus sicilis* were rarely recorded after 2000 (MOECC, 2015). This trend could indicate that warmer water temperatures and a longer ice-off season may be impacting coldwater zooplankton species. Further research is necessary to fully understand the impacts of water temperature on the growth and survival of different zooplankton species and its effects on the zooplankton community.

Indirectly, water temperature affects zooplankton dynamics through higher and lower trophic levels. Pan-European mesocosm experiments found that the increased phytoplankton biomass and increased fish predation associated with warming affected zooplankton abundance (Moss et al., 2010) but that these effects are highly species dependent. More research is necessary to examine how climate change and other factors are affecting the zooplankton community, and the potential cascading trophic effects these changes may have.

Key Points – Climate change impacts on zooplankton

- Climate change can influence zooplankton populations either through affecting food availability (i.e., phytoplankton abundance) or predation (i.e., small fish abundance).
- Evidence suggests that coldwater-adapted zooplankton are becoming less common in Lake Simcoe.
- A reduction in zooplankton could have a cascading trophic impact on the survival of young fish as they rely on zooplankton for food once they've passed the alevin stage (i.e., once the yolk sac is absorbed).

6.4.5 Fish

Fish are ectothermic, meaning that their body temperature closely matches the surrounding water temperature and, as such, they may be particularly sensitive to the warming effects of climate change. Individual species are adapted to specific ecological conditions that optimize their growth and survival (**Table 6-3**). Typically, the fish community is divided into three main groupings: warmwater species, which survive a wide range of temperatures but prefer water temperatures above 25^{o}C (e.g. largemouth bass, bluegill, crappie); coolwater species, preferring water temperatures around 19-25^{o}C (e.g. yellow perch, walleye, muskellunge); and coldwater fish, preferring temperatures less than 19^{o}C (lake trout, lake whitefish, cisco) (Holm et al., 2009). As a sustainable, coldwater fish community is the main, underlying goal of the Lake Simcoe Protection Plan, the fact that warmer water holds less dissolved oxygen at saturation puts these fish species, their habitat, and our lake management strategy in jeopardy as a result of climate change.

Table 6-3 Ecological temperature metrics for example fish species in Lake Simcoe (data from Hasnain et al., 2010)

Species	Temperature (ºC) Preferred	Growth optimum	Upper lethal	Spawning optimum	Egg development optimum
Lake herring (cisco)	12.4	18.1	23.9	3.3	5.6
Lake trout	11.8	10.0	24.3		
Lake whitefish	12.7	14.7	23.9	3.0	5.0
Yellow perch	17.6	25.4	25.6	9.1	15.0
Smallmouth bass	25.0	26.0	36.0	18.0	21.0
Largemouth bass	28.6	26.6	31.9	19.2	20.0

Climate change will impact each fish species differently and may result in a shift in the community structure of fishes from one adapted to colder water temperature to one adapted to warmer water (Chu et al., 2005). To illustrate some of the visible climate related impacts, we will draw examples from two important recreational fish in Lake Simcoe. Lake trout (*Salvelinus namaycush*) are an important recreational fish in the Lake Simcoe coldwater fishery. Water temperature directly affects lake trout metabolic processes with both growth and adult survival rates being lower in warmer water (Casselman, 2002). In addition, studies of lake trout on Lake Simcoe have shown that arrival of mature adults at spawning shoals was occurring about five days later in 2000-2004 compared to 1978-1982, a change that positively correlated to increased water and air temperatures (MOECC, 2015). Conversely, smallmouth bass (*Micropterus dolomieu*) are an important recreational fish in the Lake Simcoe warmwater fishery. Earlier ice-out can increase prey availability and extend the growing season which could increase the survival of young smallmouth bass in the winter (Casselman, 2002). However, high spring flows can increase fry and egg displacement downstream which could decrease the survival of young smallmouth bass (Lorantas and Kristine, 2004).

Warming waters may also permit the migration of fish species (both native and invasive) into new habitats that will disrupt the existing community structure. For example, by removing cold temperatures as a migration barrier, 19 warmwater fish species from the Mississippi or Atlantic Coastal basins could invade lower Great Lakes, and eight warmwater fish species from lower Great Lakes could invade lakes Huron, Michigan, and Superior (Mandrak, 1989). In addition to direct competition and species displacement, these 27 fish species are expected to carry 83 species of parasite that are currently not in the Great Lakes and which could have devastating impacts to the existing fish communities (Mandrak, 1989).

Assessing the full climate impacts on the Lake Simcoe fishery is out of the scope of this report and full details are available in Dove-Thompson et al. (2011).

Key Points – Climate impacts on fish in Lake Simcoe

- The projected increases in water temperature and decreases in dissolved oxygen associated with climate change put the lake's coldwater fish community at risk.
- Coldwater fish like lake trout may experience delayed spawning, reduced growth rates, and reduced survival in warming temperatures.
- Warmwater fish like smallmouth bass may benefit from warming temperatures, however, the projected increase in flow in the spring may negatively affect spawning beds and fry development.
- Warming waters may also allow new invasive species to colonize the lake.

6.4.6 Invasive species

Since the 19th century, the Great Lakes Region has been invaded by at least 182 non-native species, 65% of which have arrived since the opening of the St. Lawrence Seaway in 1959 (Ricciardi, 2006). Of these, 51 alien species have been recorded in the Lake Simcoe Watershed with 17 species and two fish diseases present (MOECC, 2015; LSRCA, unpublished data). Several of these (e.g. dreissenid mussels, round goby, starry stonewort, Eurasian watermilfoil, rusty crayfish) are classed as "invasive" in that they can spread rapidly and dominate over native species (Kernan, 2015). Impacts of invasive species include outcompeting native species for resources (e.g. dreissenid mussels, starry stonewort), predation on native species (e.g. rusty crayfish, round goby), introduction of pathogens, hybridization with native species (e.g. Eurasian watermilfoil), and changes to food webs (e.g. dreissenid mussels, round goby) (Kernan, 2015). In addition, invasive "ecosystem engineers" (e.g. dreissenid mussels) can transform a lake to make the habitat more suitable to future introduced species (e.g. round goby).

Although there are currently knowledge gaps in this area, climate change has been highlighted as a synergistic stressor with invasive species, as increased temperatures and other conditions may enhance the survival of introduced species or increase their ability to spread and survive in new areas. Many of the current invasive species are from the Ponto-Caspian Region of Eastern Europe, which has a climate similar to the warmer conditions predicted for the future of the Great Lakes Region. In Lake Simcoe, ice cover and coldwater temperatures likely limit the expansion and survival of these invaders. However, warming water temperatures and a decrease in ice cover will create more favourable conditions for them, as well as thermally stress, thus reduce the survival of key native species (Rahel and Olden, 2008). Another interesting scenario may be the resurgence of invasive species that have already declined. For example, zebra mussels have been largely replaced in Lake Simcoe by their congener, quagga mussels (Ginn et al., 2018). Quagga mussels are adapted to cooler water (~4°C) and low food conditions, whereas zebra mussels rely on large concentrations and relatively warmer water temperatures. With warmer water conditions under climate change, and assuming an increase in algal biovolume, the zebra mussel population may be able to rebound in Lake Simcoe, or there could be a partitioning of habitats with zebra mussels returning to dominate the shallow water and quagga mussels continuing to occupy the cooler water and silty substrate of the profundal zone.

6.5 Current and future vulnerability assessment

The current and future vulnerability of each watershed indicator for the lake ecosystem (**Table 6-4**) was developed based on the methodologies described in **Chapter 1 – Introduction**. In summary, the current vulnerability score is a combination of an indicator's degree of sensitivity and exposure to climate change in the present. The future vulnerability combines climate model projections and the degree of confidence to an indicator's current vulnerability score to provide the overall vulnerability score for each indicator.

Table 6-4 Current and future vulnerability of the lake ecosystem to climate change in the Lake Simcoe watershed

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
Water temperature	↑ air temp	↑ water temperature	VH	VH	VH	H	VH
Thermal stability	↑ air temp	↑ water temperature, ↑ thermal stability	VH	VH	VH	H	VH
Duration and timing of stratification	↑ air temp, ↑ thermal stability	Earlier onset, ↑ period of stratification, shallower thermocline, ↓ surface layer nutrient concentration	VH	VH	VH	VH	VH
Ice duration	↑ air temp	later ice-on, lengthening the ice-free period	VH	VH	VH	H	VH
Ice thickness	↑ air temp, snowfall variability	earlier ice out, ↓ ice thickness	VH	VH	VH	H	VH
Phosphorus loading - atmospheric	↑ wind, precipitation	↑ wind transports P into lake, precipitation trapping dust particles, drought increasing wind deposition	VH	M	M	M	M
Phosphorus concentrations - late summer, early fall	↑ air temp, ↑ thermal stability	↑ stratification and ↓ DO concentration leading to ↑ sedimentary P release	VH	VH	VH	H	VH
DOC transport - summer	↑ air temperature, ↑ drought and ↑ heavy rainfall events	↑ concentration of organic carbon in rivers and streams, ↑ potential for high levels of DOC to intermittently flush into Lake Simcoe	VH	M	H	H	H
DOC transport - winter	↑ air temperature, ↑ precipitation	↑ rain on snow, ↑ C in percolate, ↑ potential of C transport to the lake	H	L	M	H	H
DOC concentration - summer	↑ air temperature, ↑ water temperature	↑ lake DOC concentration, ↑ microbial decay, ↓ DO from microbial respiration	H	H	H	H	H
	↑ air temperature, ↑ water temperature	Increased microbial response DOC may lead to anaerobic respiration and ↑ CH4 emissions	L	M	M	L	M
DOC concentration	seasonal precipitation anomalies	↓ water clarity from ↑ DOC transport into the lake	H	M	H	H	H
Dissolved oxygen - summer	↑ water temperature	↓ DO, ↑ duration of hypoxia	VH	VH	VH	H	VH

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
	↑ water temperature	↑ P in water column, ↑ primary productivity in water column, ↑ lake-bed bacterial productivity, ↓ DO, ↑ anoxia	VH	H	VH	H	VH
Dissolved oxygen - winter	↑ water temperature	Improved water quality as earlier ice-out = ↑ O2 concentration	VH	VH	VH	H	VH
Light penetration	↑ water temperature	↑ clarity from dreissenid filtration = ↑ light penetration and, leading to ↑ water temperature, deepening of photic zone, ↑ SAV growth	VH	VH	VH	H	VH
	↑ water temperature	reduced ice cover and thickness, ↑ photosynthetic opportunity leading to ↑ SAV expansion	VH	VH	VH	H	VH
Turbidity	↑ precipitation intensity	↑ suspended solids from fluvial erosion, ↑ suspended solids	VH	M	H	M	M
Aquatic biodiversity	↑ water temperature >20°C	↑ anoxia in deeper cold water, ↑ cold-water and deep-water benthic species extinctions	VH	VH	VH	H	VH
Fisheries	↑ water temperature	↑ abundance of warm water fish, ↓ abundance cold water fish	VH	VH	VH	H	VH
	↑ water temperature	↓ cold water spawning habitat leading to recruitment failures in cold water species.	VH	VH	VH	H	VH
	↑ water temperature	↓ larvae survival	VH	VH	VH	H	VH
Cold-water habitats and refuges	↑ water temperature	Direct impact: ↓ cold water refuges.	VH	VH	VH	H	VH
Cold-water habitats and refuges	↑ water temperature	Indirect impact: ↑ climate driven anoxia + groundwater input = ↓ deep, cold-water refuges	VH	L	H	H	H
Primary productivity	↑ thermal stability,	↑ water clarity from dreissenid filtration = ↑ primary productivity, ↓ hypolimnetic oxygen	VH	VH	VH	H	VH
Phytoplankton	↑ water temperature, longer growing season	↑ algal biomass	VH	VH	VH	VH	VH
	↑ thermal stability, ↓ P loading	Favouring of species that prefer warmer water and are better P utilizers (i.e. *F. crotonensis*)	VH	H	H	H	H
Harmful algal blooms	↑ thermal stability, ↑ wind (kicking up nutrients) leading to ↑ hypoxia	↑ P availability during mixing leading to ↑ cyanobacteria in surface water	VH	L	H	H	H
Invasive species	↑ water temperature	↑ freshwater growing season, ↑ range for invasive species	H	H	H	H	H

Recommended actions were developed to address these vulnerabilities as the climate changes and they are summarized in **Chapter 8**.

Chapter 7

Terrestrial Natural Heritage

7.1 Introduction

7.1.1 Ecosystem services

Natural heritage refers generally to the plants, animals, and terrestrial features that make up natural communities. More specifically, the Provincial Policy Statement recognizes woodlands, wetlands, valleylands, Areas of Natural and Scientific Interest (ANSI), habitat of endangered and threatened species, fish habitat, and significant wildlife habitat as natural heritage features to be protected for the long term (MMAH, 2014). When these natural communities are healthy, resilient, and connected, they can form a robust natural heritage system that can effectively provide the functions and services upon which the natural environment and humans depend. These systems are vital in creating habitat, enabling the movement of species, maintaining biological diversity, and sustaining threatened communities (Haddad et al., 2015). These ecological functions, in turn, provide valuable ecosystem services that contribute to human wellbeing. Ecosystem services are generally divided into four categories: provisioning, regulating, supporting, and cultural services (Millennium Ecosystem Assessment, 2005) (**Table 7-1**). At over $922 million annually, the value of these services to habitants of the Lake Simcoe Watershed is substantial (Wilson, 2017). The preservation of natural heritage systems ensures that communities are saved the expense of replacing these services if the integrity and functioning of the watershed is diminished. Hence, communities have a vested interest in protecting these systems.

Table 7-1 Examples of ecosystem services, adapted from the Millennium Ecosystem Assessment report (2003).

Indirect Benefits to Humans		Direct Benefits to Humans	
Supporting	Regulating	Provisioning	Cultural
Primary production Nutrient cycling Soil formation Hydrological cycle Habitat formation Pollination Seed dispersal	Gas regulation Climate regulation Disturbance regulation Biological regulation Water regulation Waste regulation Nutrient regulation Soil retention Disease regulation Flood regulation Water purification	Food Fresh water Raw materials Genetic resources Medicinal resources Ornamental resources	Aesthetic Recreational Spiritual Historic Scientific Educational

The benefits derived from ecosystem services have become increasingly valuable as concerns regarding the impacts of climate change heighten. Ecosystems are unique in that their protection and enhancement can be used as a tool that provides synergies between climate change mitigation and adaptation. By pulling carbon from the atmosphere and storing it in biomass and soil, wetlands, forests, and grasslands are able to function as large terrestrial carbon sinks that prevent increases in the level of greenhouse gases in the atmosphere (Grace, 2004). The latest report on natural carbon sequestration in the Lake Simcoe watershed indicated that carbon uptake by the region's natural capital translates into an annual value of $35.9 million in avoided social costs of climate change (Wilson, 2017).

Meanwhile, the presence of natural heritage features can help communities adapt to climate change by regulating environmental processes and buffering them against climate change impacts. For example, healthy ecosystems can mitigate flooding and increase groundwater recharge by enhancing infiltration during heavy and/or prolonged precipitation events (Villarreal and Bengtsson, 2005). Vegetation can act as a natural water purifier during these events by slowing the transport of water and filtering it before entering surface and groundwater (Millennium Ecosystem Assessment, 2005). Vegetation further safeguards water quality by preventing soil erosion and subsequently reducing damage to built infrastructure during high-runoff events. Such services have been interpreted as providing 'insurance' by maintaining the capacity of the system to continue to function over a range of conditions (Loreau et al., 2002). Therefore, through the provision of regulatory services, natural heritage features can contribute to reducing societal and ecological vulnerability to climatic risks.

The province defines a **natural heritage system** as "a system made up of natural heritage features and areas, and linkages intended to provide connectivity (at the regional or site level) and support natural processes which are necessary to maintain biological and geological diversity, natural functions, viable populations of indigenous species, and ecosystems. These systems can include natural heritage features and areas, federal and provincial parks and conservation reserves, other natural heritage features, lands that have been restored or have the potential to be restored to a natural state, areas that support hydrologic functions, and working landscapes that enable ecological functions to continue." (MMAH, 2014)

7.1.2 Ecosystem resilience

The degree to which an ecosystem can maintain its structural and functional characteristics under different pressures, including climate change, is dependent on its resilience. Ecosystem resilience reflects the ability of an ecosystem to withstand shocks and disturbances and to revitalize itself if damaged (Yan, 2011). Each ecosystem varies in its response to disturbances and stressors; hence, they each display different levels of resilience. Whether or not an ecosystem can withstand and recover from pressures and disturbance is dependent on several influencing factors, including the biology and condition of its component species or habitats; the nature, severity and duration of the impacts; and the degree to which potential impacts have been mitigated (Great Barrier Reef Marine Park Authority, 2009). If the function of an ecosystem is impaired, the capacity of that ecosystem to absorb or recover from impacts will be reduced. Generally speaking, the literature has identified the following correlations between characteristics of ecosystems and ecosystem resilience (Epple and Dunning, 2014):

- Ecosystems composed of naturally occurring species are likely to be more resilient to climate change than ecosystems whose vegetation is made up of non-native species.
- Ecosystem degradation and past disturbances may lead to decreased resilience to a wide range of impacts from climate change.
- Fragmentation decreases ecosystem resilience to climate change.
- Biodiversity increases resilience to climate change.

Based on these factors, climate change may lead to certain species, communities, and ecosystems being more susceptible to degradation, or they may be lost entirely from the landscape.

Within the Lake Simcoe watershed, the resilience of natural heritage systems is threatened by the impacts of urban growth, agricultural activities, and recreational use. These stressors have contributed to the loss, degradation, and fragmentation of habitat, rendering ecosystems more vulnerable to disturbances (Walpole and Bowman, 2011b). Climate change has the potential to further weaken natural systems by altering ecosystem dynamics through changes in ecosystem composition and species' behavior. Habitat fragmentation can further magnify these impacts by hindering the ability of species to move or adapt to changing conditions. As an ecosystem's integrity is reduced, so is its ability to provide derived services. Understanding how climate change will impact the demand for these services and the Lake Simcoe watershed's capacity to provide them will be crucial in developing adaptive management actions that enhance resilience.

7.2 Wetlands

7.2.1 Wetlands in the Lake Simcoe watershed

A wetland is land that is seasonally or permanently covered by shallow water, as well as land where the water table is close to or at the surface. In either case, the presence of abundant water has caused the formation of hydric soils and has favoured the dominance of either hydrophytic or water-tolerant plants (MMAH, 2014). There are four types of wetlands represented in the Lake Simcoe Watershed: marshes, fens, bogs and swamps (Beacon Environmental & LSRCA, 2007). Swamps are the most common type in the watershed, followed by marshes. Bogs and fens are rare communities in the watershed.

Wetlands provide habitat for a diverse assortment of wildlife species, including birds, mammals, amphibians, fish, invertebrates, and plants. These species rely on wetlands for food, water, spawning, and nursery areas. Wetlands are associated with many wetland-dependent species that are vulnerable to changing conditions (Gibbs, 1993). This includes various species of amphibians and birds, whose sensitivity to environmental influences make them effective bioindicators of wetland health (Waddle, 2006; Berardi et al., 2008).

Globally, anthropogenic and natural threats have resulted in significant wetland loss (Davidson, 2014). As a region that has experienced both intensive agriculture and rapid urban development, the Lake Simcoe watershed has lost 45% - 65% and 65% - 85% of wetlands in its northern and southern sections, respectively, since pre-settlement days (MNRF, 2017). Today, approximately 18% of the Lake Simcoe watershed is comprised of wetlands. These are identified as core features in the natural heritage system (**Figure 7-1**) and represent only 20-25% of historic wetland habitat (LSRCA, 2018a). In recognizing the value and importance of wetland features, the LSRCA is striving to achieve 40% of historic watershed wetland coverage and to maintain a minimum of 20% watershed coverage (LSRCA, 2018a). Understanding the impacts of climate change on these features is crucial in informing restoration and conservation efforts and ensuring that these targets remain attainable.

Wetland Types

Swamp: A swamp is a wetland with standing or slowly moving water on a seasonal or permanent basis. Swamps are normally nutrient-rich areas where trees and shrubs thrive.

Marsh: A marsh is a nutrient-rich wetland that is periodically inundated with water. Water remains within the rooting zone of plants for most of the growing season. Characteristic vegetation includes reeds, rushes, and sedges.

Bogs: Bogs are peatlands covered with mosses, low shrubs, and in some areas, trees.

Fens: A fen is a peatland with a high water table where drainage is slow and that is generally less acidic and richer in nutrients than a bog.

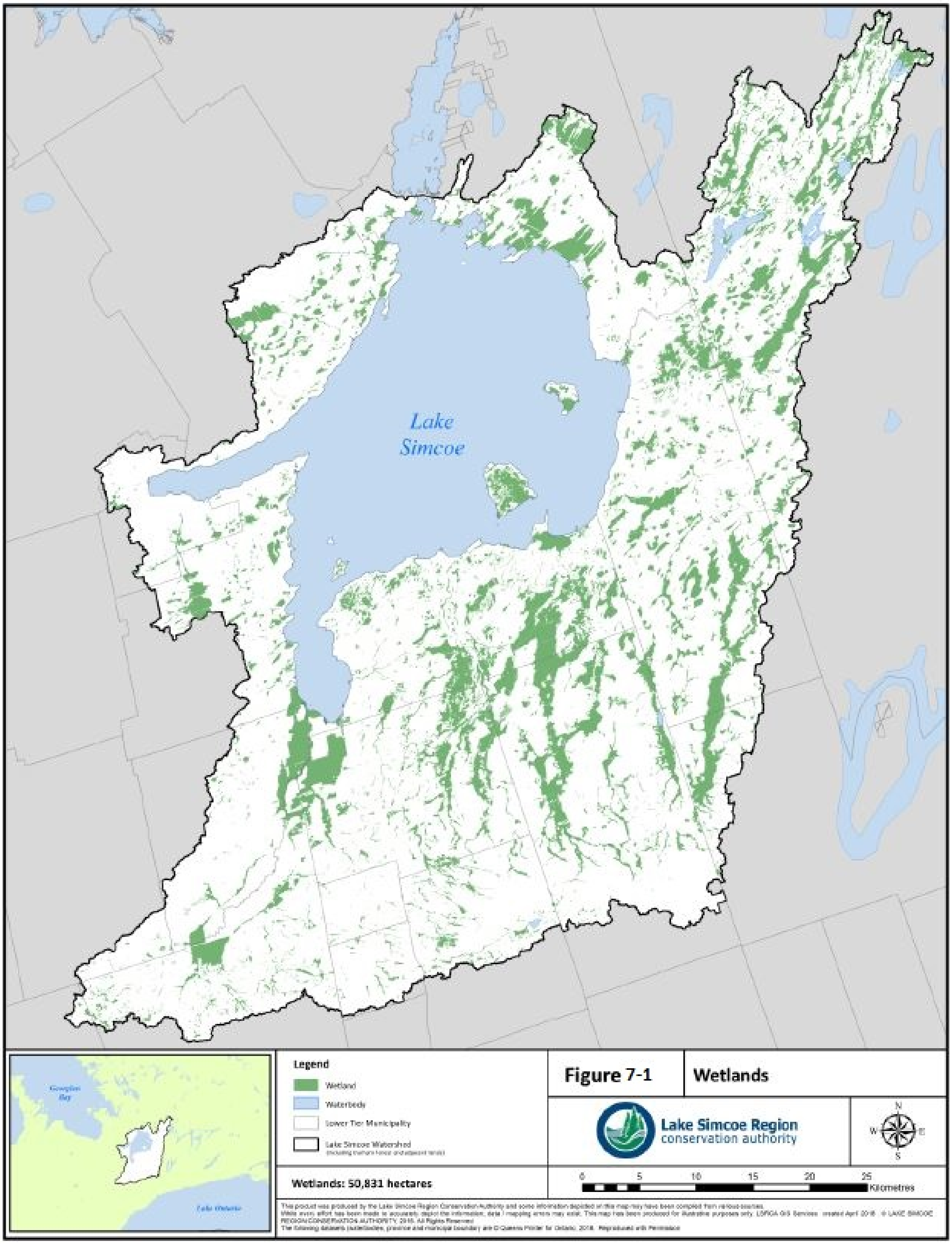


Figure 7-1 Wetland coverage in the Lake Simcoe watershed (LSRCA, 2018a)

7.2.2 Wetland hydrology

Wetlands are particularly vulnerable to changes in the quantity and quality of water supply. Changes in the timing, duration, and magnitude of annual and seasonal flows, along with changes in temperatures and atmospheric CO_2, will alter the natural succession of wetland plants in a way that may ultimately change the distribution and abundance of vegetation found within wetland types (Dove-Thompson, 2011). For example, studies suggest that wetland plants that use the C_3 photosynthetic pathway may be enhanced more by atmospheric CO_2 enrichment than those with C_4 systems (Burkett and Kusler, 2000). Meanwhile, projected changes in seasonal water availability will also influence the nature and function of specific wetlands by changing the suitability of habitats for certain plant species.

Wetland hydrology fluctuates over time, depending on the balance between inflow (e.g. precipitation, groundwater flow, surface water) and outflow (e.g. evaporation, infiltration, surface water). Based on these interactions, projected changes in winter precipitation and temperature patterns will likely contribute to wetland drying (Woo, 1992). One of the climate drivers behind the drying of wetlands is the anticipated reduction in snow accumulation in the Lake Simcoe watershed, which will reduce the amount of meltwater available in the spring. Without this meltwater, the flood period for many of the region's wetlands may be shortened. Furthermore, milder winters will reduce the severity of frost. Typically, hard, frozen surfaces throughout the winter enhance surface runoff by preventing infiltration. This runoff can pool and contribute to wetland recharge. As soils thaw in conjunction with warming winters, more rain and meltwater will be able to seep into the ground throughout the winter months rather than pool at the surface.

In combination, it is expected that more winter rainfall and reduced soil frost will lead to a gradual shift towards enhanced winter groundwater recharge. While groundwater-fed wetlands may benefit from elevated water tables – at least until water levels decline in the summer months – (see **Chapter 4 Water Quantity**) wetlands that rely more-so on precipitation inputs will continue to suffer from reduced surface flows. If the balance between water inflow and outflow becomes skewed towards enhanced outflow, then wetlands will begin to shrink as they dry out. In response, wetland vegetation communities requiring less water such as sedges, grasses, wet meadows, and trees may replace emergent and submergent vegetation (Dove-Thompson, 2011). It is likely that some marshes may become more swamp-like as woody plant species move into marsh areas. Eventually, wetlands may dry out entirely and progress to terrestrial ecosystems comprised of less diverse vegetation and wildlife (Mortsch, 1998).

Given their sensitivity to climate, vernal or ephemeral pools are likely to be early victims to the effects of climate change and can therefore be used as early climate change indicators. These pools collect and depend on rainwater during winter and spring, changing in volume in response to varying weather patterns. As a result, their hydrologic regime is governed by the balance between precipitation rates and evaporation rates and can fluctuate dramatically from year-to-year and even within single seasons (Keeley, 1998). This unique environment provides habitat for numerous rare plants and animals that spend the dry season as seeds, eggs, or cysts, and then grow and reproduce when the ponds are again filled with water (Sasamoto, 2010). These features are also ideal habitats for invertebrates and important breeding grounds for many birds and amphibians; some of which are obligate vernal pool species.

As temperatures rise and the number of consecutive dry days increases, vernal pools in the Lake Simcoe watershed may experience a net water deficit, driven by enhanced evaporation and reduced precipitation inputs.

Figure 7-2 Without groundwater inputs, vernal pools depend on runoff of winter and spring snow and rain, making them particularly vulnerable to drying as a result of climate change. Credit: Noah Cole

The hydrological conditions of vernal pools will be altered such that these features will experience more frequent and longer periods of drying out, with some pools potentially not filling at all (Brooks, 2009) (**Figure 7-2**). Based on a report by the MNRF, wetlands in southern Ontario have been identified as being among the most vulnerable to drying under the B2 and A1 emissions scenarios, which are comparable to the newer standard RCP 4.5 and RCP 8.5 scenarios, respectively (Chu, 2015) (**Figure 7-3)**. In the Lake Simcoe watershed, 90% of the swamps, 84% of the marshes, 50% of the fens and 100% of the bogs may be highly vulnerable to drying (Chu, 2011). Generally, wetlands that depend on precipitation and surface runoff rather than groundwater are particularly at risk of drying (MNRF, 2017). However, even wetlands that depend more on groundwater flows, such as those located along the Oak Ridges Moraine, can be affected as water tables are drawn down by a drying climate (Flournoy, and Fischman, 2013).

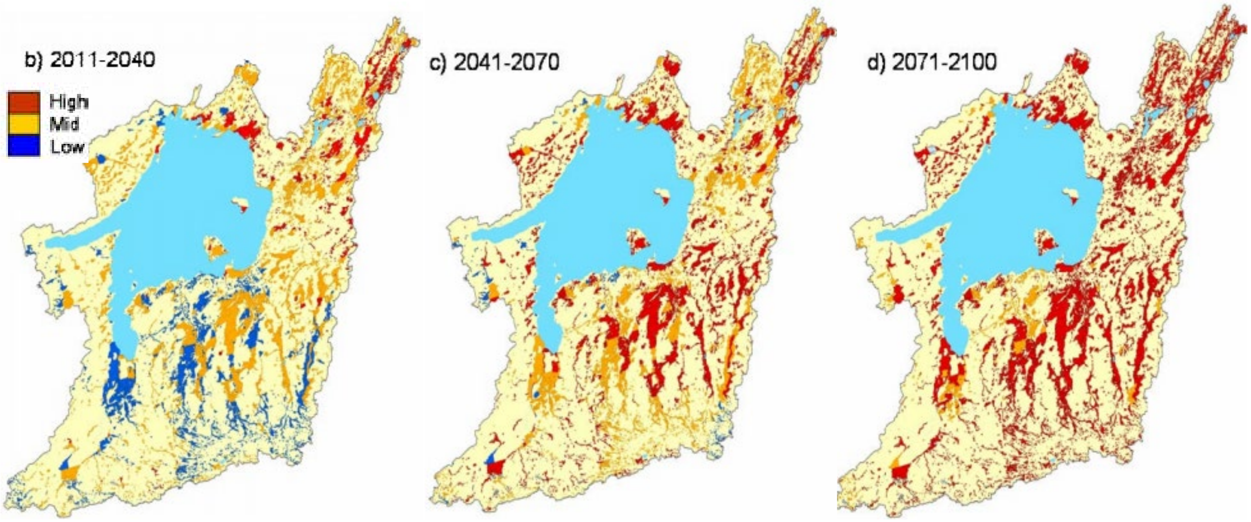


Figure 7-3 The vulnerability of LSRCA's wetlands to groundwater discharge potential and changes in air temperature and precipitation associated with climate change under the Canadian Global Climate Model 2 A2 scenarios (Chu, 2011)

7.2.3 Water quality

Changes to water quality represent another driver of wetland degradation stemming from climate change. As outlined in the Water Quality chapter, the pattern of delivery of many nutrients, sediment, and pollutants may shift or become more extreme, with the highest concentrations occurring during low flow periods or following extreme rain events. Often referred to as the kidneys of the landscape, the role wetlands play in capturing and filtering water, along with their role in providing habitat for a variety of migratory, endangered, and commercially important species, render them vulnerable to these changes in water quality.

An oversupply of nutrients can result in rapid and unpredictable growth of plants and algae that block out light and, in the case of blue-green algal blooms, can produce toxins that affect wildlife and humans. Erosion can cause sediment to block out light to aquatic plants and smothers aquatic animals. Contaminants such as pesticides and chloride can severely affect wetland species by changing their behavior, growth, and development (Jones et al., 2017). The species at greatest risk will be those that are particularly sensitive to changes in environmental conditions, such as migratory birds and amphibians. Several characteristics, including permeable skin and reliance on both aquatic and terrestrial habitats, render amphibians among the most environmentally sensitive species (Hopkins, 2007). A study by Sadowski (2002) examined amphibian distribution in the Toronto region and found that amphibian abundance and diversity were consistently low in wetlands with elevated chloride concentrations, while a study by Johnson and Chase (2004) identified eutrophication in North American wetlands as a driver behind frog deformities. With nutrient and sediment concentrations expected to rise and guideline exceedances expected to occur more frequently following changing climatic conditions, it is likely that wetland biota will experience greater stress that will result in more pronounced changes in ecosystem composition and function.

7.2.4 Wetland wildlife

Just as certain plants are associated with wetland habitats, so are certain animals. As the composition of plants in a wetland transition and the quality of wetlands is degraded, wetland animals will have to adapt, migrate, or face extirpation. Hence, the presence or absence of a particular wetland-dependent species can serve as an indication of wetland health and integrity (Siddig et al., 2016). Migratory birds are often used as wetland indicator species due to their reliance on wetlands for food, shelter, and/or breeding (Stewart, 1996). One such species is the pied-billed grebe (*Podilymbus podiceps*), a climate change-sensitive wetland bird present in the Lake Simcoe watershed (Mortsch et al., 2006). A study by Chu (2011) found that the distribution of the pied-billed grebe (**Figure 7-4**) in the Lake Simcoe watershed may be reduced by 84% by 2100 as most of the wetlands that it currently inhabits will become degraded or lost with climate change (**Figure 7-5**). Unfortunately, reduced distributions will likely be the case not-only for birds, but for many wetland-dependent species that will need to search for more suitable habitat as the wetlands they have traditionally relied on change in composition, become degraded, or are lost entirely.

Figure 7-4 The pied-billed grebe is a wetland-dependent species who will likely become threatened as wetland habitat is degraded or lost.

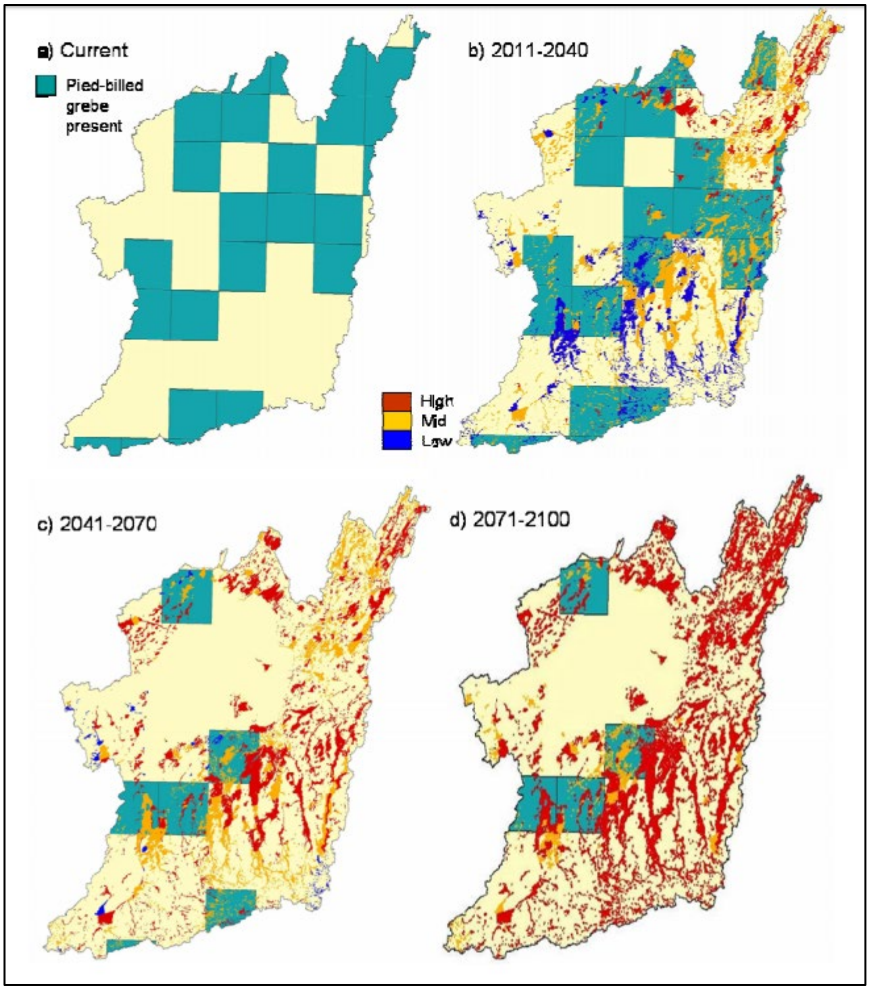


Figure 7-5 Current and predicted future distribution of pied-billed grebes within the Lake Simcoe watershed as a result of the vulnerability of suitable wetland habitat to climate change under the Canadian Global Climate Model 2 A2 (Chu, 2011)

7.2.5 Loss of wetland ecosystem services

In reducing the health of wetland ecosystems, the risk of losing their accompanying services increases. Wetlands provide important services such as water storage, groundwater recharge, storm protection, flood mitigation, shoreline stabilization, erosion control, and retention of carbon, nutrients, sediments and pollutants. Many of these services will only increase in importance as climate change exacerbates droughts, floods, and water quality impairment. For example, wetlands can act as hydrological buffers by maintaining stream flow and replenishing groundwater during dry periods. They can reduce flood damage by collecting and distributing water during high flow periods. They also buffer against water quality impairment by intercepting surface runoff and removing or retaining sediment and contaminants before they reach open water. The value of these services can be substantial. For example, flood protection from wetlands in the Lake Simcoe watershed has been valued at approximately $169 million per year (Wilson, 2017). As wetlands become damaged or lost, they lose their capacity to provide these services. Changes in the abundance and health of wetlands will hinder the watershed's ability to regulate flows, remove excess sediment and pollutants, and provide habitat for fish and wildlife.

The loss or degradation of wetlands can also have significant impacts on the watershed's carbon budget. A recent study that examined carbon sequestration in both drained and restored wetlands at sites across southern Ontario demonstrated that restored wetlands increase the amount of carbon stored in the landscape (Enanga et al., 2014). Based on the most recent report, carbon uptake by wetlands in the Lake Simcoe watershed is valued at over $25 million (Wilson, 2017). Wetland losses or shifts in wetland composition may not only result in reduced carbon uptake and storage, but it may ultimately convert some wetland habitat from a carbon sink to a carbon source; further enhancing climate change (Burkett and Kusler, 2000). Given the ecologic and economic benefits they provide, the costs associated with the loss of wetlands warrant attention. Recognizing the impacts of climate change will be crucial in protecting critical wetlands and the services they offer.

Key Points – Wetlands

- Reduced snow accumulation and fewer freeze thaw cycles in the winter are likely to contribute to wetland drying.
- Increased rainfall and reduced soil frost is likely to increase groundwater recharge in winter. Groundwater-fed wetland will benefit from increased winter recharge while rain-fed wetland will be impacted by reduced surface flows.
- Approximately 90% of the swamps, 84% of the marshes, 50% of the fens and 100% of the bogs in the Lake Simcoe watershed are highly vulnerable to drying. Precipitation and surface runoff dependent wetlands are most at risk of drying.
- Wetlands play an important water purification role, capturing and filtering the nutrients and contaminants from the water.
- Nutrient and sediment inputs above guideline exceedances are likely to occur more frequently due to climate change, putting greater stress on sensitive wetland biota and resulting in pronounced changes in ecosystem composition and function.
- The distribution of the pied-billed grebe (a wetland species sensitive to climate change) is likely to reduce by up to 84% by the end of the century due to climate related habitat degradation or loss.
- Wetlands within the Lake Simcoe watershed provide flood protection services valued at $169 million, which is very likely to reduce as wetlands become degraded or lost due to climate change.
- Fewer high-quality wetlands will impact flow regulation, water filtration and reduce the fish and wildlife habitat.
- Loss or degradation of wetlands is likely to impact the watershed’s carbon budget by reducing wetland carbon sequestration.

7.3 Woodlands

7.3.1 Woodlands in the Lake Simcoe watershed

At approximately 35%, woodland cover accounts for a substantial portion of the Lake Simcoe watershed (LSRCA, 2018a). Of these features, 44% are swamp, 36% are upland forest, and 20% are cultural woodland (plantations, thickets, savannahs and woodlands) (LSRCA, 2018a). Importantly, the Lake

Simcoe watershed is located in the transitional zone of the deciduous-dominated forests to the south and the predominantly coniferous boreal forest to the north. As a result, the majority of woodland cover in the watershed is deciduous, followed by mixed and coniferous (Beacon Environmental and LSRCA, 2007) (**Figure 7-6**). The ownership of these forests is complex, with forests contained within LSRCA, provincial, or municipal conservation areas, protected areas, and on private land. Equally challenging is the management of urban forests, which rely on a strong collective stewardship ethic between residents, businesses, and environmental groups to ensure their growth and long-term health.

Woodlands provide environmental and economic benefits to both private landowners and the general public, including erosion prevention, water quality improvements, hydrological and nutrient cycling, carbon storage and sequestration, wildlife habitat, outdoor recreational opportunities, and the sustainable harvest of woodland products (OMNR, 2010). Many of these services play an important role in reducing the risks of climate change, such as reducing flooding, helping to maintain lower water temperature along riverbanks, and mitigating heat island effects. The services provided by the Lake Simcoe watershed's forests have been valued at $5,272 per ha/year, rendering them among the watershed's most highly valued natural assets (Wilson, 2017).

A woodland's capacity to provide ecosystem services is dependent on several factors including the degree of fragmentation, patch size, woodland quality, and total woodland cover. A general guideline of 30 to 40% cover of a planning area has been cited as a minimum threshold for woodland ecosystems to remain viable in terms of functions and attributes (Gartner Lee Limited, 2002). Although total woodland cover within the Lake Simcoe watershed is within this range, it remains below the 40% target established by LSRCA's Natural Heritage System and Restoration Strategy and below the 50% low-risk target established by ECCC's AOC Guideline for maintaining viable populations (2013). In addition, many of the Lake Simcoe watershed's woodlands are highly fragmented and are unevenly distributed across the subwatersheds; a reflection of the high levels of urbanization and agricultural conversion that the watershed has been subject to. Alone and in combination, the impacts of fragmentation, isolation, and disturbances render these woodlands more vulnerable to the impacts of climate change.

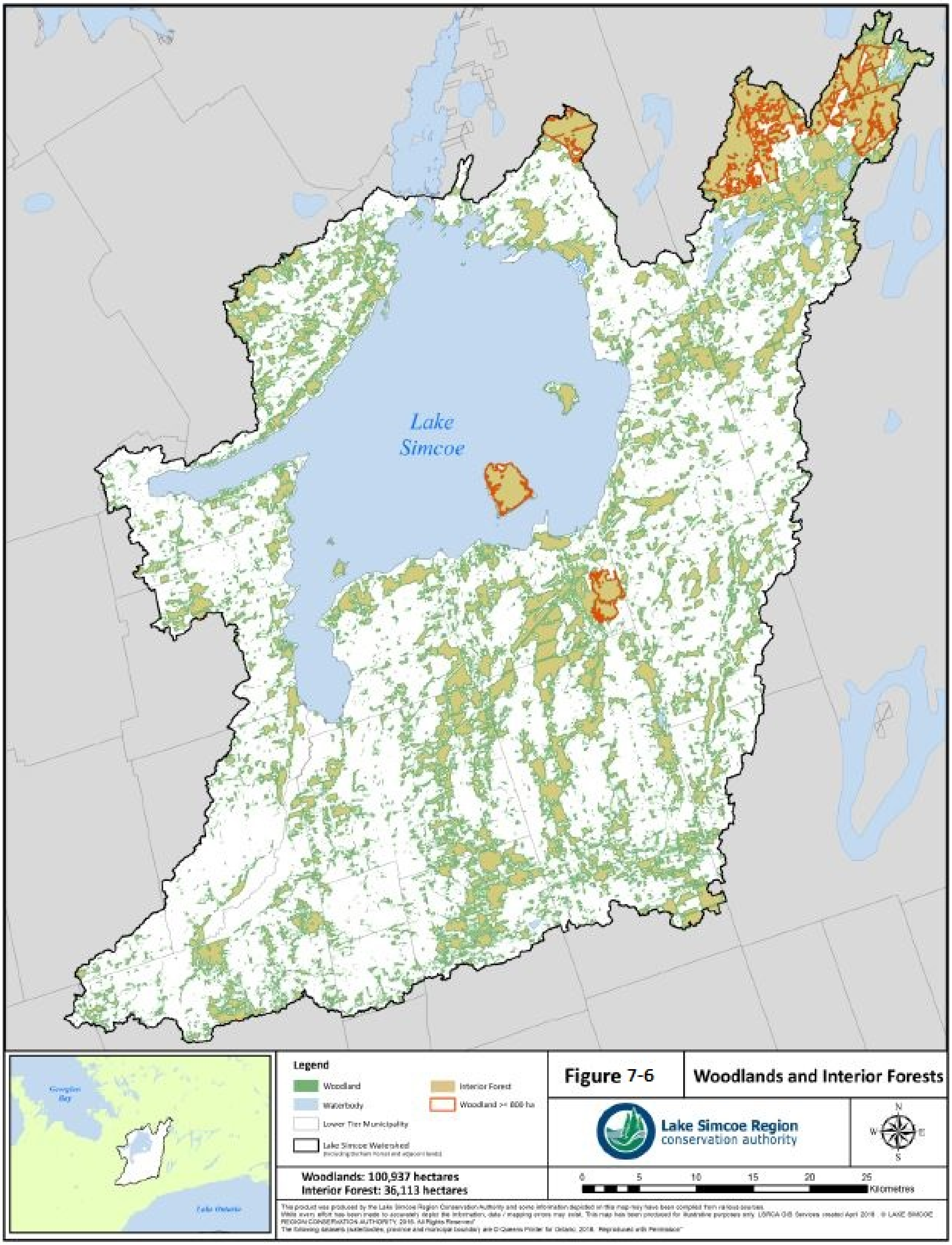


Figure 7-6 Forest coverage in the Lake Simcoe watershed (LSRCA, 2018a).

Climate change is projected to have significant impacts on the health and composition of the Lake Simcoe watershed's forests. Warming temperatures, drought, extreme events, and freeze-thaw cycles will place stress on existing woodland species, which are suited for local conditions and may be unable to migrate to keep pace with their climate envelope. LSRCA has been proactive in modifying its approach to tree planting and forest management to ensure that these activities remain effective and adaptive under future climate conditions. The '*Adapting Forestry Programs for Climate Change'* report (LSRCA, 2018b) investigates the range of pressures climate change will place on forests in the Lake Simcoe watershed and provides a series of recommended response options in order to adapt current forestry programs to these expected pressures. This section provides a summary of the climate change impacts identified by the '*Adapting Forestry Programs for Climate Change'* report (LSRCA, 2018b) and explores the overarching changes in health, composition, and productivity that the Lake Simcoe watershed's woodland habitats may experience.

7.3.2 Persistence, migration, extirpation

A fundamental effect of climate change on regional forests will be potential shifts in the distribution of vegetation. Temperature, precipitation, wind, and radiation patterns must be within a plant's physiological tolerances in order for it to survive, grow, and reproduce (Pearson and Dawson, 2003; Williamson et al, 2009). The species that are currently present in the Lake Simcoe watershed are suited for the current climate. However, as temperatures rise, climatically suitable habitats for most species will move northward yet the actual movement of species will lag behind the rate of movement of their climate envelopes (Williamson et al., 2009). In other instances, climate envelopes will decrease or be lost entirely due to the spatial complexity of future climate patterns, while new climate niches allowing for novel species combinations may form (McKenney et al, 2015).

Tree species have three possible fates in this rapidly changing environment: persistence in current locations through adaptation to new conditions, migration to track changing habitats, or extirpation (LSRCA, 2018b). In order to persist, species will have to be able to tolerate new environmental conditions or undergo long-term evolutionary changes (Aubin, 2014). Unfortunately, most tree species in eastern North America, especially those that are typical of boreal forests, are considered vulnerable to climate change due to a lack of adaptive capacity to cope with the rapid rate of climate change (Johnston et al, 2009; Rogers et al, 2017). Fragmentation, which is characteristic of the Lake Simcoe watershed's woodlands, further enhances this vulnerability.

Species that are unable to acclimate or evolve may be able to migrate, although for most species, migration rates will lag behind a rapidly warming climate. In general, species that reach maturity quickly have the best migration potential. This is because they produce large amounts of easily-dispersed seeds that are able to survive and grow in significantly different climate conditions than the parent plant and are able to spread asexually in new habitat (Johnston et al, 2009; Aubin, 2014). On the other hand, long-lived species with low dispersal potential and low genetic variation will be particularly threatened (Kilkenny et al, 2013). The temperate-boreal forest transition, which is present in the watershed, may be particularly sensitive to climate change and species composition may shift dramatically as the boreal forest recedes and temperate species migrate northwards (Parker et al, 2000; Boulanger et al, 2016). The temperate-boreal ecotone in the northern United States has shown evidence of temperate species regeneration and reduced boreal species regeneration; suggesting that temperate species may replace boreal species as they inch northward (Fisichelli et al, 2014a).

Figure 7-7 The Canada warbler (*Cardellina canadensis*) is one of many species that may be impacted by the loss of boreal habitat. This species relies on southern boreal forests for breeding habitat.

As trees struggle to regenerate and become replaced by more climatically suitable species, it is anticipated that the resulting woodland landscape will be increasingly dominated by temperate, rather than boreal ecosystems. Although the remaining boreal forests in Ontario, including those in the Lake Simcoe watershed, are smaller and more fragmented than those further north, the southern areas are biologically rich, containing the most diverse assemblages of species (Vucetich et al., 2000). A loss of boreal habitat would distress a number of bird and mammal species as they reach their northern limit in the southern Boreal Forest, intermingling with boreal species that are at their southern limit (Ferguson et al., 2008) (**Figure 7-7**). This can lead to new species' interactions, as novel species' assemblages are created.

Tree species that can't acclimate, evolve, or migrate will be forced to persist in a site with conditions for which they may not be suited. Under these conditions, trees may experience impaired growth and reproduction, and may subsequently be more vulnerable to pests and diseases. Eventually, trees are likely to experience decline and reduced regeneration, leading to extirpation from climatically unsuitable regions (Aitken et al., 2008). As occupying species fail to regenerate under unsuitable climates, migrants, likely moving northerly, will take their place (Colombo, 2008).

In the context of southern Ontario, the northward migration of southerly species will be hindered by physical barriers, such as the Great Lakes, large regions dominated by farms or cities, a fragmented forest landscape, and expanding urbanization (Colombo, 2008; Puric-Mladenovic et al., 2011; Douglas et al., 2014). Moreover, Lake Simcoe and the fragmented nature of the watershed's woodlands may pose similar challenges for species that must migrate across the watershed in conjunction with their climate envelopes. It is therefore uncertain whether southern tree species will be able to effectively spread to and across the Lake Simcoe watershed without assisted migration (Puric-Mladenovic et al., 2011).

7.3.3 Extreme weather events

Whether trees migrate or remian, they will need to endure the more frequent and intense extreme weather events, such as drought, wind gusts, and ice storms that are associated with climate change (Dale et al., 2001). The stress imposed by these conditions has the potential to exceed a tree's tolerance threshold and render them more vulnerable to the cumulative impacts of disturbance, resulting in damage, mortality, and widespread forest change (Allen et al., 2010). For example, as outlined in the **Section 7.8**, climate change is expected to change the frequency, severity, duration, and distribution of pests and disease outbreaks. As extreme climate events amplify tree stress, they become more susceptible to the impacts of these pests and diseases (Johnston et al., 2009; Aubin, 2014). Generally, the average age of forests may decrease as disturbances favor the establishment of early successional species (Williamson et al., 2009). In weakening woodlands at the stand and individual scales, climate-disturbances reduce their long-term resilience to acute and chronic climate trends and set the stage for more dramatic ecosystem impacts over time.

Figure 7-8 It is expected that climate change will drive more frequent ice storms, which may increase the risk of hazards as ice builds up on trees and branches.

Climate change will influence the characteristics of cold-weather tree damage through increased incidences of ice storms caused by freezing rain and freeze-thaw cycles, during both winter and in the early stages of spring. Ice storms can be immensely destructive (**Figure 7-8**). Frozen limbs, dragged down by the weight of ice, can break, bend to the ground, or cause outright breakage of the trunk (Irland, 2000; Hauer et al., 2006). Of particular concern is the potential for falling limbs and trees to land on cars, power lines, homes and people. The frequency and severity of ice storms may increase as temperature rise and hover around the freezing mark, and unfrozen ground throughout the winter may increase the chance of trees uprooting entirely.

Figure 7-9 Extreme weather events and winter warming will drive browning of conifers.

More frequent winter freeze -thaw cycles and an earlier start to the growing season may present several problems for plant growth as the earlier onset of spring bud burst increases the risk of damage by late spring frosts (McKenney et al., 2014). Repeated frost damage can hinder trees by delaying hardening and reducing freeze tolerance (Gu et al., 2008). Moreover, freeze-thaw events can cause winter browning on conifers, otherwise known as winterburn. During periods of increased sunlight, strong winds, and warm temperatures, conifers lose water from their needles faster than it can be replaced. The damage to needles worsens when warm temperatures in early spring are followed by the sudden return of cold temperatures. These freeze-thaw cycles can once again cause needles to dry out, freeze, and die. Winter browning occurs more severely in young conifers and those on the edges of forests (DeHayes, 1990) (**Figure 7-10**). In cases where winter browning does not result in tree mortality, damaged trees may experience abnormal bud development and may take several years to fully recover; during this time trees are weaker and are more vulnerable to pests and disease. As winter temperatures rise, conifers may face heightened rates of water loss. Coupled with the increase in freeze thaw cycles, the result is an increased risk of winter browning that, at best, causes temporary tree damage, and at worst, results in large-scale conifer die-back.

Figure 7-10 Salt applied to a sidewalk in the Lake Simcoe watershed. Salt applied in anticipation of freezing rain and freeze-thaw events can be harmful to nearby trees and shrubs.

Also associated with freeze-thaw events is the potential for more road salt applications (**Figure 7-10**), and subsequent rises in the chloride concentration of stormwater that trees may become exposed to. Trees and shrubs can be injured by salt spray and drift, by salt that leaches into the soil or by a combination of both (Equiza et al., 2017). Most species have a very limited tolerance to salt, and while urban trees are at the greatest risk of stormwater exposure, trees along woodland edges that are adjacent to roads can also face high levels of salt exposure. However, there remains uncertainty regarding the impacts of road salt on trees. One study in particular, conducted at an LID in Toronto, found that trees that were not isolated from winter runoff fared better than those that were isolated, suggesting perhaps that trees may be more tolerant to road salt than previously thought (STEP, undated). As a cautionary approach, LSRCA has made attempts to safeguard urban trees from salt exposure by installing trees adjacent to LID stormwater features, rather than as a component of it.

As the climate changes, rising temperatures and more frequent and intense droughts will be another source of stress on trees. Increasing rates of drought-induced tree mortality are already being recorded worldwide (Luo and Chen, 2015), driven primarily by chronic increases in evaporative demand and reduced soil water availability (McDowell et al., 2016). Trees that are drought-stressed may display reduced productivity and reproduction and may be more susceptible to pests and disease (Haliburton Land Trust, 2012). Prolonged or intense droughts pose an increased risk of tree mortality, which could ultimately prompt changes in woodland composition as individual trees are replaced by more resistant species. However, the relative influence of drought-stress is not spread evenly among species. The small size and shallow root systems of seedlings render them more vulnerable to heat-stress (Colombo, 2008; Fisichelli et al., 2014b). Because of reduced seedling survival, young forests may be particularly sensitive to the increased occurrence of droughts associated with climate change.

7.3.4 Ecosystem services

Predicting the impact of climate change on specific tree species can be extremely challenging when thresholds are involved. Moreover, there is a potential that other landscape processes, themselves linked to climate, will magnify the impact of extreme climate events on woodland populations (Edwards and Batley, 2016). For example, the loss of vegetative cover, whether a result of deforestation or of climate change-induced stress can destabilize the soil, resulting in excessive wind erosion and soil drift. As roots of nearby trees become exposed, they will be less able to withstand the added weight of ice accumulation during ice storms, resulting in more trees being uprooted and enhanced hazards to public safety. Erosion control is merely one of the many services that may be lost if woodlands and their associated ecosystems are degraded. Flow regimes and water and soil quality are among some of the other regulating services that will be significantly affected by a change in forest composition. Given the role that woodlands play in mitigating climate change, changes to woodland productivity are of particular concern as we reach the tipping point beyond which warmer temperatures become detrimental to woodland productivity.

The net effects of climate change on productivity remains unclear, but it will undoubtedly vary between locations and individuals over time. Temperature, moisture, nutrient availability, and atmospheric CO_2 concentrations affect rates of photosynthesis and respiration, phenology, reproduction, growth, and mortality (Williamson et al., 2009). Generally, productivity is more likely to decrease in areas that are now or will become moisture limited; it is more likely to increase in northern areas that are currently temperature limited. However, productivity gains will be restricted by several counteracting factors. A longer growing season and a higher atmospheric concentration of carbon dioxide provide opportunities for improved productivity if conditions remain favourable. However, these gains may be outweighed by exponentially increasing respiratory losses with rising temperatures, causing a decline in net productivity (Parker et al., 2000; Johnston et al., 2009; Mohan et al., 2009). Furthermore, research indicates that the positive effects of climate change on productivity may be offset by growth losses and mortality related to heat stress and drought, more frequent disturbance, pests and diseases, changes in suitable habitat, and continued problems with air pollution (Parker et al., 2000; Rustad et al., 2012).

At the individual scale, carbon uptake rate is dependent on species, stand density and tree age, but large trees consistently provide a considerably greater benefit than smaller trees (Stephenson et al., 2014). In extreme cases, a single large tree can sequester the same amount of carbon in one year as is contained in an entire mid-sized tree (Stephenson et al., 2014). Carbon sequestration by the Lake Simcoe watershed's forests has been valued at over $23 million (Wilson, 2017), and while future changes in the magnitude of this carbon flux remain unclear, the enhanced storage and sequestration potential of old-growth forests further justifies their preservation in the Lake Simcoe watershed.

Key Points – Woodlands

- The temperate-boreal forest transition that runs through the watershed is particularly vulnerable to climate change as most boreal tree species lack the adaptive capacity to cope with the rapid rate of climate change, and fragmentation enhances this vulnerability.
- The remaining boreal forests in the Lake Simcoe watershed are fragmented and biologically rich. Loss of these forests will impact many bird and mammal species which is likely to lead to novel species interactions and assemblages.
- Tree species with poor adaptive capacity are likely to experience impaired growth and reproduction, increasing their susceptibility to pests and disease.
- The northward migration of southern species is likely to be hindered by barriers such as the Great Lakes and large areas dominated by agricultural and urban land use, and fragmented forest landscape.
- More frequent extreme weather events such as drought, sustained high winds, and ice storms associated with climate change have the potential to exceed a tree's tolerance threshold and increase its vulnerability to climate change.
- Increased disturbance from extreme weather events is likely to decrease the average age of trees within a forest, weakening woodlands at the strand and individual scales.
- Younger woodlands are less resilient to acute and chronic climate related disturbances.
- More ice storms and freeze-thaw cycles in winter and early spring impacts forests by causing tree branches and trunks to bend or under the weight of the ice. Falling limbs can land on cars, power lines, homes and people.
- Earlier bud bursts in spring coupled with increased freeze-thaw cycles increase the risk of damage from late spring frost.
- Increased freeze-thaw events can cause winter browning of conifers known as winterburn. Conifers that survive winterburn are weaker and more vulnerable to pests and disease.
- More freeze-thaw cycles may increase road salt exposure for trees.
- More frequent and intense droughts are likely to impact tree growth, reproduction and pest and disease susceptibility. Prolonged drought is likely to increase tree mortality.
- Loss of vegetative cover will destabilize the soil, resulting in increased erosion.
- Carbon sequestration from forests in the Lake Simcoe watershed is valued at over $4.5 million / year.
- Larger trees sequester more carbon. Woodlands composed of younger trees are likely to sequester less carbon and result in a reduction in the value of carbon sequestration for the watershed.

7.5 Wildlife range shifts

7.5.1 Climate and species distribution

The Lake Simcoe watershed is home to thousands of different species, including numerous species that are regionally rare, as well as species that are considered provincially or nationally at risk (LSRCA, 2018a). The geographic ranges of many of these species are limited by climatic factors, including temperature, precipitation, moisture, humidity, and wind. Therefore, any regional shift in the magnitude or variability of these factors will influence the ability of these species to continue to live within the watershed. While the response to warming is generally understood, there remains uncertainty regarding the impact of changes in other climatic factors on species distributions. Despite the uncertainties, it is predicted that the distribution and size of plant and animal populations will be affected by climate change through changes in the composition and location of particular habitats that species depend on.

As air temperatures warm, species at their northern range boundary that are limited by climate are poised to benefit due to changes in the quality of their habitat from increasing annual temperatures (Myers et al., 2009). Populations at the southern edge of their range, however, may encounter increased biotic and physiological stresses, such as competition from their southern counterparts, which will result in range contractions. Therefore, populations of species at the northern limit of their range may become more abundant or colonize new habitat, whereas those species at the southern limit of their range may be threatened (MNRF, 2015). Given that ecosystems are complex assemblages of species, range and abundance shifts that occur independently of shifts of other species could create new interactions that could dramatically alter entire ecosystems (McDermid et al., 2015).

7.5.2 Regional evidence of wildlife range shifts

Evidence of range and abundance changes among species has been identified by regional studies in the Great Lakes Basin. Based on these studies, southern flying squirrels (*Glaucomys volansin*) have shifted northward into Ontario during years with relatively warm winters and higher availability of food, and have contracted their range to its historical limit after a very cold winter and mast failure (Bowman et al., 2005). Birds have been found to be shifting their ranges in several directions, although these shifts are predominantly northward (McDermid et al., 2015). In some cases, ranges are also showing contractions. Langham et al. (2014) projected an average loss of 76% in summer range and a 45% loss in winter range for 90 climate-threatened bird species in the Great Lakes Basin. The conservation of these species will be complicated by changes in the size and distribution of habitats used for breeding, stop over rests, and wintering (Bairlein and Hüppop, 2004). In some cases, species may alter their migratory routes in order to adapt to these changing conditions.

More localized studies in the Lake Simcoe watershed have found analogous trends to those in the Great Lakes Basin. Southern birds and mammals have shown northerly range expansions into the watershed in response to climate change (Myers et al., 2009; Melles et al., 2010). Mammal species richness in the region is predicted to increase by 20% by the year 2100 in response to changes in annual temperature. This reflects the increase in the number of species whose geographic range will shift or expand to include the Lake Simcoe watershed. Among these species are the common grey fox (*Urocyon cinereoargenteus*) and eastern fox squirrel (*Sciurus niger*), whose ranges currently reach southern Ontario and may expand into the watershed as temperatures warm (**Figure 7-11**). Similarly, the range of

Figure 7-11 The Lake Simcoe watershed will likely experience an increase in mammal species richness as species expand and shift their range to include the watershed. Among incoming species are the common grey fox (top), and the eastern fox squirrel (bottom).

the Virginia opossum (*Didelphis virginiana*), which is historically just south of the Lake Simcoe watershed, is predicted to fully encompass the watershed by 2040 (**Figure 7-12**) (Walpole and Bowman, 2010). The increased species richness not only raises concerns for unknowns regarding novel species assemblages and interactions, but also for the potential for species listed under the provincial *Endangered Species Act* to colonize the Lake Simcoe watershed, which will have implications for the land-use and development restrictions being enforced by LSRCA.

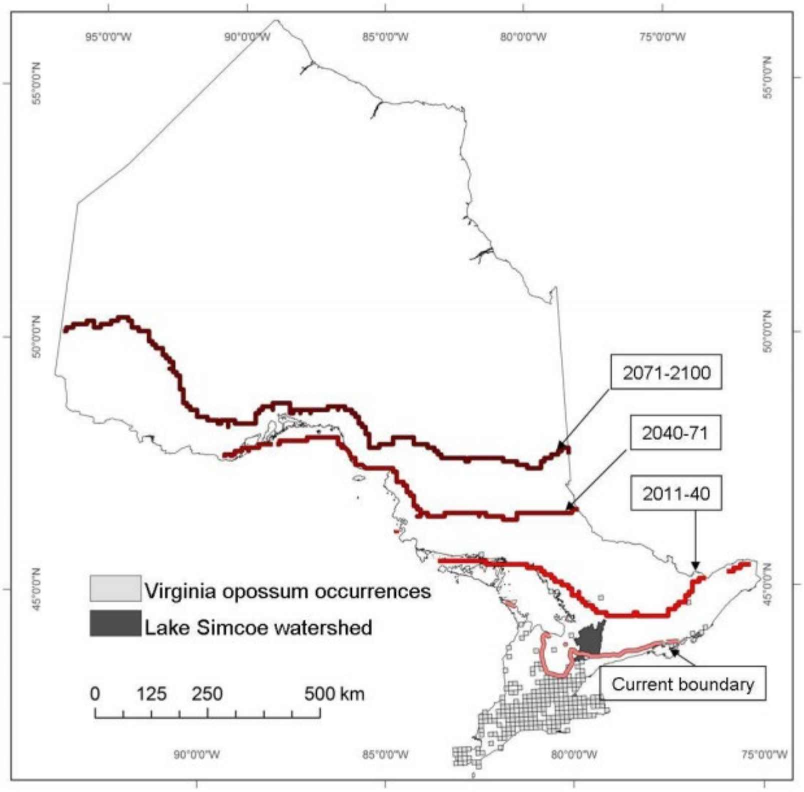


Figure 7-12 Future projections of the Virginia opossum northern range boundary in Ontario (Walpole and Bowman, 2010). Virginia opossum occurrences area is based on the 1970-1993 Ontario Atlas of Mammals data.

7.5.3 Barriers to migration

Although the distribution of suitable habitat for any given species within the watershed will likely shift in response to climate change, each species will vary in its ability to alter its range accordingly. With regards to migration potential, it is generally expected that there will be selection for species with good dispersal ability over those with poor dispersal ability (Nituch and Bowman, 2013). For example, birds and butterflies tend to be highly mobile, while plants are immobile and may therefore struggle to adjust their ranges based on changing climate conditions (McDermid et al., 2015). Small species with shorter life cycles are also more likely to adapt to climate change. Meanwhile, species with a narrow range of temperature, precipitation, or habitat requirements may be less capable of adapting, and may subsequently experience declines or local extirpation. Hence, climate change may promote an increase in 'generalist' species and a decrease in 'specialist' species within the watershed (Walpole and Bowman, 2011a).

The ability of species to adapt to climate-related threats will also be heavily impacted by habitat fragmentation. Landscape connectivity, or the degree to which the landscape facilitates or impairs movement among resource patches, affects dispersal success and colonization rates (Kang et al., 2016). Specifically, the presence of human-made barriers such as roads, cities, fences, or agricultural zones hinders the ability of many species to move across the landscape to locate more suitable habitat, breeding grounds, and alternative food sources (David Suzuki Foundation & Ontario Nature, 2011). Roads in particular can be especially devastating to migrating populations. These features not only fragment and degrade the natural landscape, but they also impede access to resources and habitat for species that avoid roads and lead to high rates of road mortality. By hindering their ability to move freely along changing climate gradients, roads can prevent populations from colonizing new habitat and instead force them to live within environments that become increasingly unsuitable. The ecological effects of roads are already known to be particularly damaging for amphibian and reptile populations (**Figure 7-13**). Presently, road mortality is a number one threat for five of Ontario's at-risk turtle species (Ministry of Transportation, 2016). Unfortunately, the ecological impacts of roads will become amplified as species relocate in response to intensifying anthropogenic and climatic stressors. Across southern Ontario, road networks are growing to support the human population. Without landscape permeability, migrating wildlife will be limited in their ability to redistribute as their environment changes.

In acknowledging the importance of ecological linkages and the growing threats from agricultural, urban, and industrial land in the watershed, the Lake Simcoe Region Conservation Authority's '*Natural Heritage System and Restoration Strategy'* has assessed linkage potential within the watershed in order to optimize connectivity between core features. Based on the report, approximately 1,657 opportunities for local proximity linkages and 32 opportunities for regional linkages were identified (LSRCA, 2018a) (**Figure 7-14**). Local linkages connect isolated core features within 60 m of each other and are of great importance within a subwatershed. Regional linkages provide connections between subwatersheds and are crucial in promoting large-scale gene flow and diversity. However, even with the restoration of identified linkages, there may still be insufficient connectivity between subwatersheds. In addition, given its size, Lake Simcoe itself could pose as a physical barrier to migration for terrestrial animals that are looking to travel northward across the watershed, especially since northward connectivity adjacent to the lake is lacking.

Figure 7-13 A snapping turtle (*Chelydra serpentina*) attempts to cross the road in the Lake Simcoe watershed's Brock Township

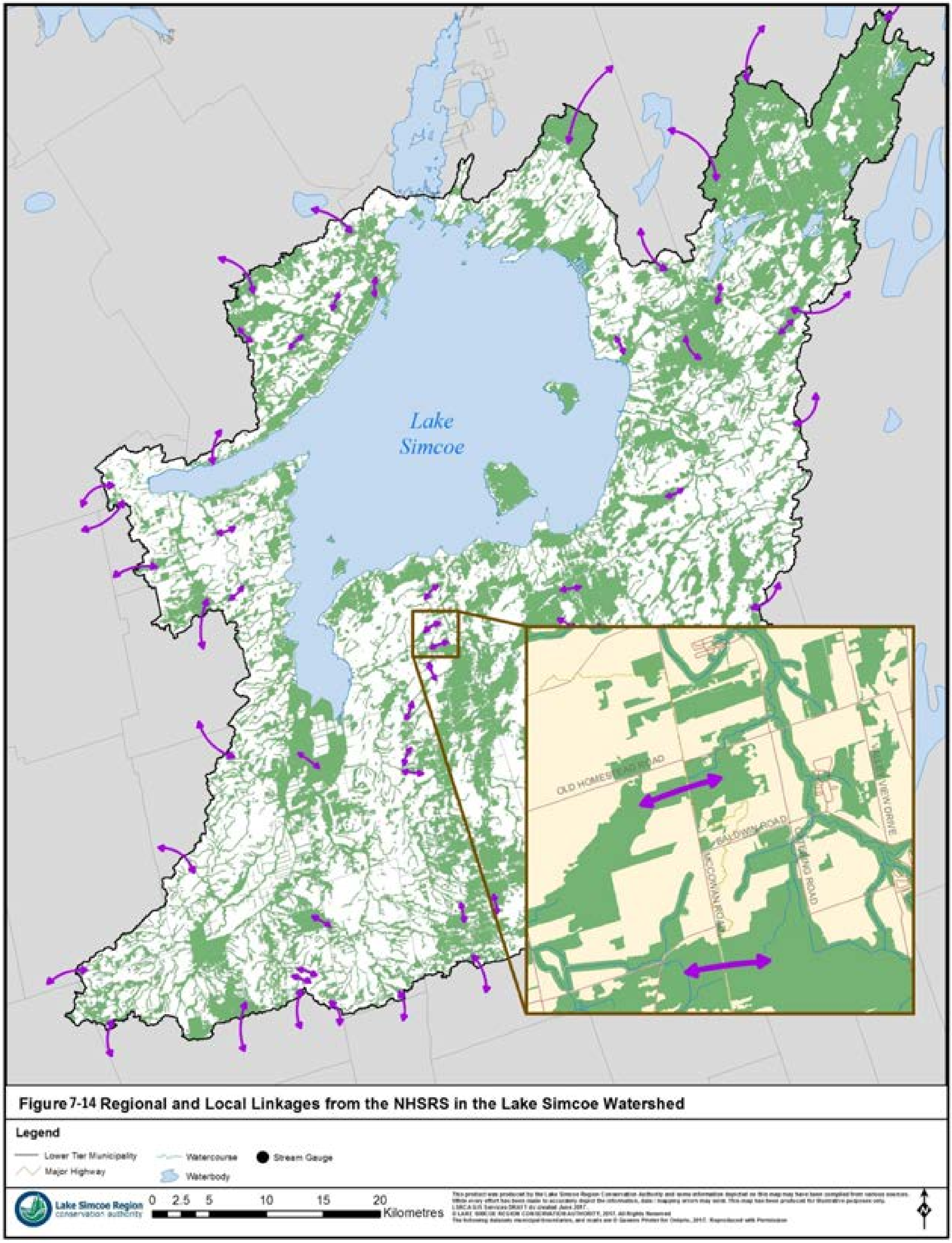


Figure 7-14 Local and regional linages identified across the watershed (LSRCA, 2018a).

When species are mobile and suitable habitat is present in the right location, range shifts may represent a viable response to changing climatic conditions (McDermid et al., 2015). However, the Lake Simcoe watershed will likely be subject to a growing number of migration barriers in the matrix between natural areas as urbanization, agricultural development, and economic activities intensify. These activities will render migration barriers a worsening problem. Hence, many species will struggle to disperse to suitable climates and will therefore be challenged with coping with the environment to which they are bound.

Figure 7-15 The Jefferson salamander, which is already considered to be a species at risk, will need to migrate as climate change threatens to degrade and shift the habitat on which it relies.

Some species, particularly those already at-risk, may be unable to cope with the stress associated with living in an unsuitable climate. One such species is the Jefferson salamander (*Ambystoma jeffersonianum*) (**Figure 7-15**), which has been ranked as threatened under Ontario's Endangered Species Act (2007). Because the northern range limit of the Jefferson salamander lies within the Lake Simcoe watershed, and the breeding ponds on which it relies are threatened, the species is considered vulnerable to climate change (Brinker and Jones, 2012). Also concerning are the natural and anthropogenic barriers, such as major highways, urban centres, and Lake Simcoe, which border the species' current distribution. These barriers will impair the ability of the salamanders to migrate to more hospitable habitat and will ultimately place added stress onto this already disappearing species. As a region that is vulnerable to the synergistic effects of climate change and fragmentation, the development of ecological connectivity networks in the Lake Simcoe watershed will be crucial in enhancing mobility among species that have no choice but to alter their ranges in response to climate change. There will thus be a growing need for consideration of ecosystem connectivity in conservation and landscape planning, as well as a need to actively employ or remove specific features that can either enhance or hinder movement, such as wildlife passage sites and fences, in order to reduce isolation between habitats and enhance population connectivity.

Key Points – Wildlife range shifts

- Species at the northern boundary of their range are likely to benefit from increased air temperature while species at southern boundary of their range are likely to become stressed.
- Mammal species richness in the Lake Simcoe watershed is predicted to increase by 20% by the end of the century due to increased air temperature.
- The range of Virginia opossum (a northward migrating species) will fully encompass the watershed by 2040. Other northward migrating species include the common grey fox and eastern fox squirrel.
- Generalist species with greater a greater ability to disperse and wider environmental tolerance range are likely to adapt and migrate more easily than specialist species with poor dispersal and narrower tolerance range.
- Man-made barriers such as roads, cities, fences or agricultural zones impact the ability of many species to move across the landscape.
- Roads represent the largest threat for five turtle species at risk in Ontario.
- Due to its large size, Lake Simcoe may also pose a physical barrier to migration to terrestrial species moving northward, particularly where northward connectivity adjacent to the lake is lacking.
- The Lake Simcoe watershed lies within the northern boundary of the Jefferson salamander's range and its breeding ponds are threatened. Barriers such as highways, urban centres and the lake itself hinder the salamander's ability to migrate northward, making it vulnerable to climate change.

7.6 Invasive species

The devastating impacts associated with invasive species have rendered them among the five major threats to ecosystem integrity, according to the 2005 Millennium ecosystem assessment. In fact, the report highlights climate change and the introduction of invasive species as the two anthropogenic drivers of biodiversity change that are most difficult to reverse. These species are non-native to their new environment and, once established, can cause damage to local biodiversity, human development, recreation, and human health. The economic implications of these impacts can be substantial, with growing investments continuously being made towards their management and control.

The presence of invasive alien species has been exploding across Canada; particularly in Ontario where hundreds of invasive plants have thrived. It is therefore not surprising that invasive species represent one of the largest threats to Lake Simcoe's waters, wetlands and woodlands (LSRCA, 2018a). There are 48 known species in the Lake Simcoe watershed that are considered invasive, with 32 generally living above water or on land (Table 7-2) and the rest (16) in the water (Table 7-3) (MOECC, 2015). While these species may spread through natural pathways, terrestrial species are also introduced and moved through human transport, horticultural planting, accidental release, and the movement of firewood. For aquatic invasions, the proximity of Lake Simcoe to the Great Lakes, as well as the Trent-Severn Waterway that connects these water bodies, results in the Great Lakes being a principal source (MOECC, 2015). Unfortunately, the management of these species is becoming increasingly difficult and costly as populations continue to grow and spread across the watershed. Meanwhile, the threat of new invaders is raising concerns given the suite of novel impacts they may have on existing ecosystems and the investments that may be required in order to prevent or control their establishment.

Table 7-2 Terrestrial invasive species present in the Lake Simcoe watershed (MOECC, 2015).

Scientific Name	Common Name	Taxonomic Group
Acer negundo	Manitoba maple	Vascular Plants
Acer platanoides	Norway maple	Vascular Plants
Alliaria petiolata	Garlic mustard	Vascular Plants
Berberis vulgaris	European barberry	Vascular Plants
Cynanchum rossicum	Dog strangling vine	Vascular Plants
Cynanchum louiseae	Black dog strangling vine	Vascular Plants
Elaeagnus umbellata	Autumn olive	Vascular Plants
Fallopia japonica	Japanese knotweed	Vascular Plants
Heracleum mantegazzianum	Giant hogweed	Vascular Plants
Impatiens glandulifera	Purple jewelweed	Vascular Plants
Iris pseudacorus	Yellow iris	Vascular Plants
Lonicera tatarica	Tartarian honeysuckle	Vascular Plants
Lonicera spp	Exotic bush honeysuckles	Vascular Plants
Lythrum salicaria	Purple loosestrife	Vascular Plants, Aquatic
Miscanthus sacchariflorus	Japanese silver grass	Vascular Plants
Pastinaca sativa	Wild parsnip	Vascular Plants
Phragmites australis ssp. australis	European common reed	Vascular Plants, Aquatic
Pinus sylvestris	Scotch pine	Vascular Plants
Pistia stratiotes	Water lettuce	Vascular Plants, Aquatic
Rhamnus cathartica	Common (European) buckthorn	Vascular Plants
Frangula alnus	Glossy buckthorn	Vascular Plants
Robinia pseudoacacia	Black locust	Vascular Plants
Aegopodium podagraria	Goutweed	Vascular Plants
Alnus glutinosa	European alder	Vascular Plants
Hemerocallis	Daylily	Vascular Plants
Vicia cracca	Tufted vetch	Vascular Plants
Sirex noctilio	Sirex wood wasp	Insects, Forest pest
Agrilus planipennis	Emerald ash borer	Insects, Forest pest
Sirococcus clavigignenti-juglandacearum	Butternut canker	Forest Disease
Myrmica rubra	European fire ant	Insects
Trachemys scripta elegans	Red-eared slider	Reptiles
Cygnus olor	Mute swan	Birds

Table 7-3 Aquatic Invasive species present in the Lake Simcoe watershed (MOECC, 2015)

Scientific Name	Common Name	Taxonomic Group
Neogobius melanostomus	Round goby	Fish
Osmerus mordax	Rainbow smelt	Fish
Cyprinus carpio	Common carp	Fish
Pomoxis nigromaculatus	Black crappie	Fish
Carassius auratus	Goldfish	Fish
Pimephales promelas	Rosey red minnow	Fish
Bythotrephes longimanus	Spiny water flea	Invertebrates (Non-insects)
Dreissena rostriformis bugensis	Quagga mussel	Invertebrates (Non-insects)
Dreissena polymorpha	Zebra mussel	Invertebrates (Non-insects)
Orconectes rusticus	Rusty crayfish	Invertebrates (Non-insects)
Echinogammarus ischnus	Eurasian amphipod	Invertebrates (Non-insects)
Hydrocharis morsus-ranae	European frogbit	Vascular Plants, Aquatic
Myriophyllum spicatum	Eurasian watermilfoil	Vascular Plants, Aquatic
Potamogeton crispus	Curly-leaf pondweed	Vascular Plants, Aquatic
Stratiotes aloides	Water soldier	Vascular Plants, Aquatic
Novirhabdovirus sp	Viral hemorrhagic septicemia	Fish Disease
Cyprinid herpesvirus 3	Koi herpes virus	Fish Disease

Figure 7-16 Dog-strangling vine being removed from one of LSRCA's conservation areas. This invasive plant can have devastating impacts on native communities and can form dense mats that hinder or prevent access by forestry workers and equipment.

Invasive species can have devastating impacts on the diversity of natural areas and the services they provide. They can radically change community composition and structure by out-competing or preying upon key native species (Mainka and Howard, 2010). Since invasive alien species have been introduced from other regions, the absence of competitors or predators means that they are able to outgrow and replace many native plant species, especially understory species and young trees. These changes in species composition may affect wildlife that are adapted to native plant communities and may reduce the ecosystem's capacity to provide services. For example, preliminary research by the University of Toronto's Cadotte Urban Biodiversity & Ecosystem Services Lab is showing that dog-strangling vine (DSV) (Figure 7-16), which has gained a strong foothold in the Lake Simcoe watershed, is reducing native plant species richness, pollinator diversity, and nutrient availability in the meadow ecosystems of Toronto's Rouge Park (Ontario Nature, 2015). These changes can threaten the provision of services relating to water infiltration, soil erosion, and even food security. Through impacts such as these, DSV and other invasive species can disrupt the linkages that make ecosystems healthy, strong, and resilient.

In order for a species to become invasive, it must arrive, survive, and thrive in its new environment. Climate change will act on all three components of this invasive pathway. Ultimately, climate change will increase the extent, frequency, and severity of invasive species, as well as facilitate the introduction of species that have not historically been invasive. One of the most significant ways in which this will likely occur is through the enhancement of pathways for invasive introductions. Invasive species tend to have rapid dispersal characteristics, which allow them to shift ranges quickly in response to changing conditions (Masters and Norgrove, 2010). Typically, terrestrial species use wind or rain to transport seeds to new locations. Aquatic species rely on high water events, such as the spring freshet and storm events, to provide temporary links between aquatic environments (Sager and Hicks, 2011). Projected increases in wind gusts, temperature, and precipitation may help disperse seeds of invading terrestrial species, while potential increases in the number of high-water events enable the spread of aquatic invasive species.

Figure 7-17 A patch of European common read, otherwise known as Invasive *Phragmites*, in the Town of Aurora. Changes in resource availability will enable this invasive plant to more aggressively push out native plants and take over natural habitats.

Changes in resource availability predicted under climate change may be disadvantageous for certain native plants relative to faster growing invasive species. Invasive species are inherently well suited to succeed in environments with high resource availability, while many native - and often slow growing - plant species are well adapted to nutrient-poor conditions (Duthie, 2016). In the Lake Simcoe watershed, climate change will likely lead to a future of warmer temperatures, increased CO_2 availability, and increased soil nitrogen availability. Unique adaptive features and differential plant responses will likely render invasive species more successful in these resource-rich environments. For example, European common reed (*Phragmites australis subsp. australis*), an invasive perennial grass that is spreading rapidly throughout the watershed and choking out native vegetation (**Figure 7-17**), can switch from a C_3 to a C_4 photosynthetic pathway, and vice versa (Srivastava et al., 2014). This allows it to trap atmospheric carbon dioxide more efficiently and tolerate more extreme environmental conditions, such as elevated CO_2 and higher temperatures. Similarly, higher nitrogen concentrations could assist invasive species in proliferating, especially grasses, by favoring fast-growing plant species (Parker and Schimel, 2010). In either case, the rapid-growth and competitive traits of invasive plants will allow them to monopolize resources as they become more readily available, at the expense of native plants.

Just as with native species, changes in precipitation and temperature will alter the boundary within which an invasive species can survive. Rising temperatures may allow the northward spread of some invasive species that are currently restricted in their northern ranges. Hotter and dryer conditions may cause drought-tolerant invasive species, such as common (European) buckthorn, to thrive in new environments (Simberloff, 2000). Rising water temperatures could expand suitable habitat for invasive aquatic species that favour warm waters. This may be particularly true for species that can also tolerate low-oxygen conditions; such as the round goby, which has been steadily expanding its geographic range since it was first spotted in the watershed in 2004 (Cross and Rawding, 2009; MOECC, 2015). Species range shifts will also lead to native species moving out of their current distribution or becoming rarer.

This creates ecological space for other, potentially invasive species to move in. Hence, range shifts create the potential for new invasive species to move in as their boundaries shift into the watershed and the boundaries of native species shift out.

Another impact of climate change on invasive species may arise from changes in the frequency and intensity of extreme climatic events that disturb ecosystems. Observational and experimental studies have repeatedly shown that ecological disturbance is often a precursor to biological invasion (Hierro et al., 2006; Hobbs and Huenneke, 1992). This is due, at least in part, to their short generation times, strong dispersal abilities, and broad environmental tolerances which allow invasive species to cope with rapid changes. In addition, invasions generally have two distinct phases: a quiescent phase, during which ranges shift only slightly, followed by a growth phase, during which rapid expansion occurs (Masters and Norgrove, 2010). By disturbing the landscape, climate change may create niches that quiescent invasive species can exploit. Landscapes that have been disturbed by fragmentation, such as the Lake Simcoe watershed, may be particularly vulnerable to invasions due to edge effects, which promote invasive species establishment (McDonald and Urban, 2006).

Predicting the precise effects of climate change on the introduction and spread of invasive species in the Lake Simcoe watershed remains a challenge due to limited monitoring and reporting, as well as uncertainties in understanding species-specific responses to anticipated changes. Nevertheless, it is widely accepted that climate change will likely facilitate the expansion of invasive populations into the watershed. In this regard, one of the greatest concerns is the spread of kudzu (*Pueraria montana*) into the watershed (**Figure 7-18**). This aggressive invader can grow an astonishing 30 cm in a single day, blanketing almost anything in its proximity. As with many invasive species bordering the outer reached of the watershed, kudzu is well positioned to benefit from a longer growing season and an expanding range (Sager and Hicks, 2011).

Figure 7-18 Kudzu is shown blanketing a hillside in Leamington, Ontario. This aggressive invader has become established in southern Ontario and is expected to move north with a warming climate.

Preliminary investigations into already-established invasive species, such as dog-strangling vine and Eurasian watermilfoil, show that these species will likely increase in abundance and distribution across the watershed due to the synergistic effects of habitat degradation and climate change (Sager and Hicks, 2011). Because many invasive species share similar characteristics (Kolar and Lodge, 2001), such as fast growth and high dispersal ability, it is likely that on a regional level, they will show similar responses to climate change. Whether it is through facilitated movement, increased resource availability, range expansion, disturbance, or the degradations of native vegetation, the outcome will be the same: a transformed ecosystem overridden with invasive species and subject to reduced biodiversity. A proactive approach to invasive species management will be critical as the burden of invasive species grows across the Lake Simcoe watershed.

Key Points – Invasive species

- Climate change increases opportunities for non-native species invasions. These species often lack predators and out-compete local and native species.
- There are 32 known terrestrial invasive species in the Lake Simcoe watershed.
- Dog-strangling vine, an invasive species recorded in the Lake Simcoe watershed, has been shown to reduce native plant species richness, pollinator diversity, and nutrient availability.
- High wind gusts, increased air temperature and precipitation associated with climate change are likely to enhance the dispersal of non-native and invasive plan species.
- European common reed, an invasive perennial grass can change its photosynthetic pathway in response to its environment and as a result has rapidly spread through the watershed.
- The range of drought-tolerant invasive species is likely to move northward in response to hotter and dryer conditions associated with climate change.
- Kudzu, a very fast-growing invasive plant recorded in the watershed is likely to benefit from a longer growing season and northward expansion through the watershed.

7.7 Phenology

For many species, seasonal changes in temperature trigger transitions in seasonal life cycle events. Phenology refers to the periodic appearance of these events, and includes aspects such as timing of bloom, bud and leaf emergence, as well as the timing of breeding, migration and stages of development for invertebrates, mammals, amphibians and reptiles (Mortsch et al., 2003). There is now evidence that over the last decades the phenology of many of the Lake Simcoe watershed's species has shifted as a result of climate change.

The seasonal pattern of species' activities is a reflection of the seasonal pattern of suitability of their environment (Visser and Both, 2005). This suitability is often limited to a specific time of the year when conditions are favorable. However, under climate change, the suitability of these habitats inevitably changes. In response, local species may change the timing of their life cycle events (Fitchett et al., 2015). These changes can have catastrophic effects on predator-prey dynamics when the shifts in the timing of events are unequal across trophic levels, causing a mismatch between the phenology of organisms and their food. Alternatively, even species that do not adjust the timing of life cycle events may suffer fitness consequences as these events take place during unfavorable conditions. These changes can have substantial economic and ecological implications as they lead to changes in species abundance and ecosystem composition, which ultimately results in disrupted ecosystem functioning and the subsequent loss of ecosystem services (Heglandet al., 2009; Primack et al., 2009; Visser and Hollerman, 2001).

7.7.1 Plant phenology


Figure 7-19 Earlier flowering can lead to mismatches between flowers and the pollinators, jeopardizing the mutualistic relationship between the two.

Temperature is the main driver of many plant development processes. Higher temperatures are expected to elicit a longer, earlier growing season. More specifically, the growing season may occur up to 45 days earlier by 2080 in the Lake Simcoe region if a high emission scenario (RCP 8.5) is realized. Hence, plant development may commence, as well as progress earlier, leading to the earlier transition to the next ontogenetic stage (Khanduri et al., 2008). These shifts could have negative effects on the reproductive success of the plants and the survival of the species that depend on them (**Figure 7-19**). In addition, human health could be impacted by the shift in the timing of pollen release. In Canada, studies suggest that spring flowering and leafing dates have advanced for both herbaceous and woody plants (Beaubien and Hall-Beyer, 2003; Houle, 2007). Notably, early flowering and leafing onsets tend to be most pronounced in species that develop at the start of spring and for those located in urban areas. While these plants have a head start on the growing season, they may also be more susceptible to frost damage or risk losing synchrony with the spring freshet, which could hinder their growth and reproduction.

Changes in plants' phenology can lead to 'mismatches' between plants and pollinators, with potentially drastic effects on reproduction. These mismatches can considerably decrease the likelihood of pollination and, consequently, the quality and size of seed and fruit yields (Fitchett et al., 2015). Plants pollinated by insects and birds rather than wind are at greater risk of asynchrony due to potential differences in the phenophases of these pollinators (Memmott et al., 2007). For these plants, mismatches could result in insufficient food supply, and the eventual extinction of the pollinator.

7.7.2 Breeding

For many species, breeding is the most demanding period within their life cycle. Synchrony with food abundance is crucial, especially in cases where the main food they rely on to feed their offspring is only available during a relatively short period of time. This poses a clear selection pressure on the timing of reproduction in these species: they have to time their reproduction such that their needs and those of their offspring match the timing of peak abundance of their food source (Visser and Both, 2005). If they breed earlier or later, they may produce fewer offspring with reduced fitness.


Figure 7-20 Red-winged blackbirds have shown earlier occupation of breeding habitat and emergence of hatchlings with increased temperatures.

Although climate change may affect the breeding patterns of many animals, studies have focused primarily on those of avian and amphibian species. For some bird species, increases in winter and spring temperatures have caused earlier occupation of breeding habitat and emergence of hatchlings (McDermid et al., 2015). For example, in North America, the egg-laying date of tree swallows (*Tachycineta bicolor*), red-winged blackbirds (*Agelaius phoeniceus*) (**Figure 7-20**), eastern bluebirds (*Sialis sialis*), and black-throated blue warblers (*Setophaga caerulescens*) has advanced with increasing temperature (Carey, 2009; Dunn and Winkler, 2009; Townsend et al., 2013). However, the magnitude of this shift is not uniform across all species. Furthermore, some species have not altered their breeding pattern at all (Visser et al., 1998). In all cases, there is a risk that the responses of the birds may be different from their main food. Those that are particularly vulnerable are species where the young search for their food themselves, such as plovers and grouse (Visser and Both, 2005). There is evidence that for these two families of birds, the advancements in their hatching dates has distorted the synchrony between the hatchlings and their food source (Baines et al., 1996; Pearce-Higgins, 2005).

Just as with birds, a shifting climate may result in the decline of some amphibian species due to changes in their reproductive behavior and timing. Some temperate frog species have already initiated an earlier breeding season, presumably in response to higher mean daily temperatures and the earlier onset of spring (Klaus and Lougheed, 2013). Based on data obtained from Bird Studies Canada's Marsh Monitoring Program, spring breeding anurans in the Lake Simcoe watershed had advanced their spring calling date between 1994 and 2009 (Walpole and Bowman, 2011a)(**Figure 7-22**). The earliest breeding species in the study were the wood frog (*Lithobates sylvaticus*), spring peeper (*Pseudacris crucifer*) (**Figure 7-21**), and northern leopard frog (*Lithobates pipiens*), whose peak calling date got earlier over time and with increasing spring temperatures. Based on the results, peak calling dates may be advancing more rapidly for these early breeders than for late breeding species.

Figure 7-21 Spring-peepers are among the spring-breeding anurans that have advanced their spring calling date in the Lake Simcoe watershed

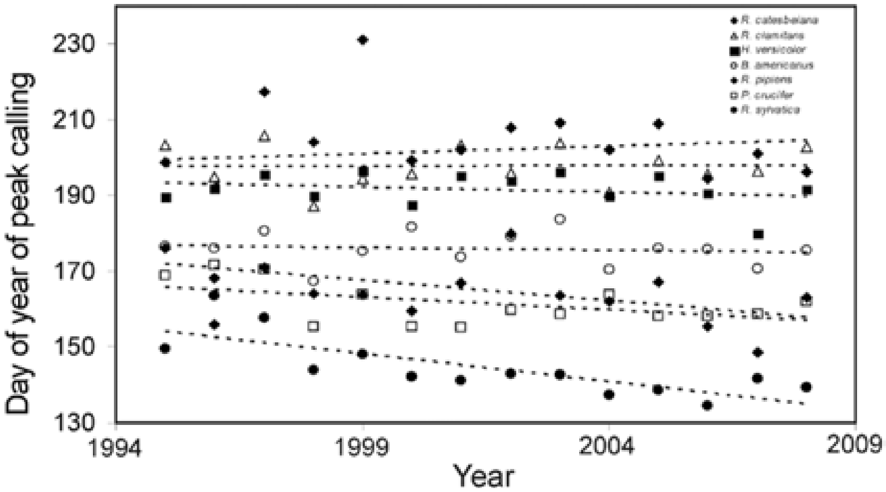


Figure 7-22 Trends in peak calling date for seven anurans detected at survey stations in the Lake Simcoe Watershed between 1995 and 2008. Peak calling date is the average day of year when the highest numbers of frogs per species were calling (Walpole and Bowman, 2011a)

A shift to earlier breeding may leave anurans exposed to fluctuating weather conditions and higher chloride concentrations in ponds and wetlands, leading to increased mortality (Dananay et al., 2015; Olson and Saenz, 2013). Also, survival of annual recruits may be tied to their size at metamorphosis, which may depend on the synchrony between peak food availability and breeding. Furthermore, community asynchronies may render anurans at greater risk of predation. For example, there is evidence that newts (*Triturus* spp.), which prey on anurans, are able to advance their entry in ponds, whereas some late-spring breeding frogs have not substantially altered their reproductive phenology (Visser and Both, 2005). While the newts displaying these trends do not occur in Ontario, this study raises concerns about the potential for similar changes to occur among regional populations. Such changes could have implications for anuran populations as their embryos and larvae face greater levels of newt predation.

For many reptiles, the temperature experienced during incubation can influence whether an egg hatches as a male or female (Janzen, 1994). Therefore, climate change can affect reproduction by acting on the sex ratio of offspring. For example, snapping turtles, which are currently listed as Special Concern under the Ontario Endangered Species Act, 2007 and Special Concern under the federal Species at Risk Act (ECCC, 2016), have a temperature-dependent sex determination; their eggs become female at hot temperatures (approximately 29°C or above) (Rhen and Lang, 1994). As summer temperatures increase, the sex ratio becomes skewed towards females. The feminization of reptile populations can have detrimental effects on population growth and persistence through reduced diversity, which subsequently hinders their ability to reproduce effectively.

7.7.3 Migration

Migration is an adaptive response to geographic and seasonal variation in resources, but climate change may disrupt the relationships between migratory species and their environment. For migrant species, the timing of their arrival and their physical condition at their breeding grounds, wintering grounds, and stopover sites are important determinants of reproductive success and fitness (Both and Visser, 2001; Marra et al., 1998). In order to optimize this success, the timing of the onset of migration and the speed of migration needs to be such that the phenology of food sources is suitable at all stages of their migratory route.

What complicates migration decisions is that not all migrants, or their food sources, use the same cues. Recent analyses of migrant birds demonstrate that temperature is a strong migration cue for short-distance migrants (van Noordwijk, 2003). For many of these species, their departure dates, stop-over or passing dates, and arrival dates have advanced; attributed primarily to an earlier, warmer spring (Visser and Both, 2005). However, long-distance migrants must face added challenges associated with relying on habitats that are thousands of kilometers away. These birds have been found to rely on cues other than temperature to time their migration, such as photoperiod or the North Atlantic Oscillation Index (Hüppop, 2003). Meanwhile, their food source may use temperature as a life cycle cue. A mismatch occurs when migrants cannot shift their behavior enough to coincide with changes in their food source. A study by Butler (2003) illustrated the problems that long-distance migrants face in timing their arrival on the breeding grounds. The analysis focused on the first arrival dates of 103 species on their summering grounds in the northern United Sates, and found that short-distance migrants arrived an average of 13 days earlier than during the interval between 1903 and 1950, while long-distance migrants arrived an average of only 4 days earlier. As climate change progresses and the phenology of different species continues to shift disproportionally, the overlap of the migration routes and food sources will shrink, meaning that by the time migrants arrive at the Lake Simcoe watershed, the food they have traditionally relied on may no longer be available.

Migratory species are already under pressure on many fronts. In the Lake Simcoe watershed, large-scale land-use changes, such as the expansion and intensification of agriculture and urbanization, have caused a loss of forest, shrub, wetland, and grassland habitats. This loss represents the degradation and fragmentation of breeding and feeding grounds used by migratory species. The impacts of climate change on the phenology of migrants and their food source may push their already-declining populations past a tipping point.

Figure 7-23 As long distance migrants, purple martins have not shown significant changes in their migration dates, which could have negative implications for the species if the food they depend on has altered its phenology in response to climate change.

Phenological mismatches among migrating birds are already believed to be occurring for some of the birds that have been spotted in the Lake Simcoe watershed. For example, purple martins (*Progne subis*) have been found to leave their wintering grounds in Brazil at the same time every year despite changes in spring temperatures (Fraser et al., 2013) (**Figure 7-23**). This means the martins likely arrive at their breeding grounds, including those within the Lake Simcoe watershed, after the spring population of the insects they prey upon has peaked and started to decline.

Purple martins are aerial insectivores; meaning they spend much of their lives searching for airborne insects to feed on. An increasing number of the migratory bird species in North America that are considered vulnerable to extinction belong to the aerial insectivores (Nebel et al., 2010). This group, which includes chimney swifts (*Chaetura pelagica*), bank swallows (*Riparia riparia*), and whippoorwills (*Caprimulgus vociferous*), has plunged by 70% in population in Canada (NABCI, 2012). Many birds in this category are now listed as threatened in Canada. Their long migration routes, coupled with their reliance on insects, places them at higher risks of phenological mismatches and hence renders them more vulnerable to the impacts of climate change.

Key Points – Phenology

- The timing of life cycle events (e.g. emergence, growth and reproduction) of many species is triggered by temperature and has shifted in the Lake Simcoe watershed in response to increased air temperature and an earlier and longer growing season.
- Altered phenology can lead to predator-prey mismatch or reduced fitness for individuals when life cycle events are triggered in unfavourable conditions.
- An earlier growing season is likely to trigger earlier plant growth and increase the risk of exposure to lake spring frost.
- Changes to plant phenology can also cause a mismatch between the lifecycles of plant and pollinators. Reduced pollination by insects and birds is likely to cause a reduction in the yield of pollination-dependent crops.
- Asynchrony with food abundance poses a selection pressure on the reproduction on species whose offspring rely on resources that are available for a short period.
- Some bird species (e.g., tree swallows and red-winged blackbirds) occupy their breeding habitat earlier in response to increased air temperature in winter and spring.
- The spring calling data of breeding anurans (e.g., wood frog and spring peeper) in the watershed has advanced between 1994 and 2009 in response to increased air temperature.
- Earlier breeding exposes anurans to elevated chloride concentrations in ponds and wetlands and increases their risk of mortality.
- During incubation, the sex of many reptile species depends on air temperature. Snapping turtle embryos become female when incubated at temperatures above 29°C. Climate change could similarly affect other reptile species with temperature-dependent sex ratios.
- Air temperature is a strong migration cue for short-distance migratory birds. The departure date, stop-over date, and arrival date of many short-distance migratory birds advanced in response to an earlier and warmer spring.
- Long-distance migratory birds often use non-climate cues and a resource mismatch can occur if their food sources peak earlier in response to earlier and warmer spring.
- Fragmentation and habitat degradation are likely to exacerbate climate related migratory impacts.

7.8 Pests and diseases

Figure 7-24 A tree damaged by the emerald ash borer (*Agrilus planipennis*), which has infested much of southern Ontario. The wood-burrowing insect tunnels the tree and cuts off the flow of food and water; eventually leading to tree death.

Insect pests and diseases have been known to have significant impacts on wildlife and human health in the Lake Simcoe watershed, and a changing climate may affect the abundance, as well as the kind of pests and diseases in the area. Native insects and diseases can play a vital role in promoting forest renewal and growth through processes such as pollination, decomposition, and stand thinning. However, when an introduced insect or disease takes hold, a lack of natural enemies or resistance against the invader can allow it to spread rapidly and cause extensive damage (Natural Resources Canada, 2015) (**Figure 7-24).** LSRCA pays close attention to reported and anticipated trends in pests and disease outbreaks in Southern Ontario. This is imperative since the impact of outbreaks on forest succession, structure and composition can extend beyond single stands to potentially include the entire watershed (Winder and Shamoun, 2006). The most devastating pests and diseases have the potential to kill almost all individuals of a given species. While the impacts of pests and diseases on natural heritage systems have largely been addressed from a forestry perspective among the natural resource management agencies, they can also have significant impacts on animal populations, nutrient and water cycling, and overall ecosystem function (Sturrock et al., 2011).

Pests and pathogens are strongly influenced by environmental conditions. As a result of this sensitivity, these organisms will be directly affected by climate change, in addition to being indirectly influenced by climate change impacts on their hosts (Sturrock et al., 2011). Most notably, climate change will influence (Hushaw, 2015):

- The frequency and intensity of outbreaks;
- The spatial patterns, size, and geographical range of outbreaks; and,
- The life cycles of insects and pathogens.

Their sensitivity to temperature, high mobility, short generation times, and high reproductive potential will allow them to respond to and, in some cases, thrive under future climate conditions. The anticipated changes in the distribution, frequency, and severity of pests and disease outbreaks will play a major role in shaping the composition of the Lake Simcoe watershed's habitat and wildlife populations and will need to be considered in LSRCA's natural heritage programs.

7.8.1 Distribution

Most insects and pathogens require certain temperature and humidity ranges for survival and optimal reproduction. In many cases, their range is limited by cold temperatures. Warmer temperatures in the watershed could increase the suitability of climate conditions and increase the length of time vectors are present in the area (Nituch and Bowman, 2013). In addition, parasite and disease ranges could follow expansions or shifts in the ranges of their vectors and hosts. Hence, the Lake Simcoe watershed may be subject to new infestations and increased incidence of pests and diseases. This has been the case for Lyme disease, a bacteria spread by some species of ticks that have become increasingly abundant in Southern Ontario (**Figure 7-25**). It is expected that warming temperatures will not only facilitate a northward expansion of the ticks' range, but also increase their propensity to survive and be propagated (McPherson, 2016). This places residents in the Lake Simcoe watershed at a greater risk for Lyme disease infection.

Figure 7-25 The blacklegged tick (*Ixodes scapularis*), which transmits Lyme disease, is expected to increase in abundance following rising temperatures.

The introduction of pests and diseases into previously inhospitable habitats can also have devastating ecological impacts due to limited resilience among the hosts. These naïve populations may be prone to more severe outbreaks than those who have historically been exposed to the pest or disease; therefore, the introduction of new pests and diseases into the watershed will likely also contribute to increased outbreak severity (Cudmore et al., 2010). Although the possible responses of pests and diseases to climate change are quite variable, it is expected that fast-growing, non-diapausing insect species, or those that do not depend on low temperature to induce diapause will show severe range expansions in response to warming (Bale et al., 2002). New pests and disease vectors with these characteristics are thus more likely to migrate into the watershed and become established at intensities not previously observed in their native range.

7.8.2 Outbreak frequency

The survival, development, and reproductive rate of many pests and pathogens are sensitive to climatic conditions. In the Lake Simcoe watershed and across Canada, warming temperatures will generally accelerate these rates. Many insects and diseases are controlled by winter temperatures, with colder temperatures reducing their populations. As winters get warmer with climate change, the number of pests and diseases that survive the winter may increase, leading to greater outbreaks and infestations (Gleeson et al., 2015). Even within a year or season, some insects may be able to complete more generations under warmer temperatures, a factor that contributes to large-scale outbreaks. The ability to complete more life cycles is especially concerning with regards to herbivorous insects, since multiple generations of these pests can cause significant mortality and damage to long-lived plants and trees (Hushaw, 2015). This is the case for the forest tent caterpillar (*Malacosoma disstria*), which weakens trees through repeated defoliation. Widespread outbreaks typically last 3 years or less at the stand level and up to 6 years at the landscape level (Natural Resources Canada, 2016). As shown in **Figure 7-26,** historically, these outbreaks have occurred in approximately 10 to 12-year cycles, giving the hosts and ecosystem time to recover. However, as climate change shortens these cycles, more frequent forest tent caterpillar outbreaks could impose greater stress on hosts.

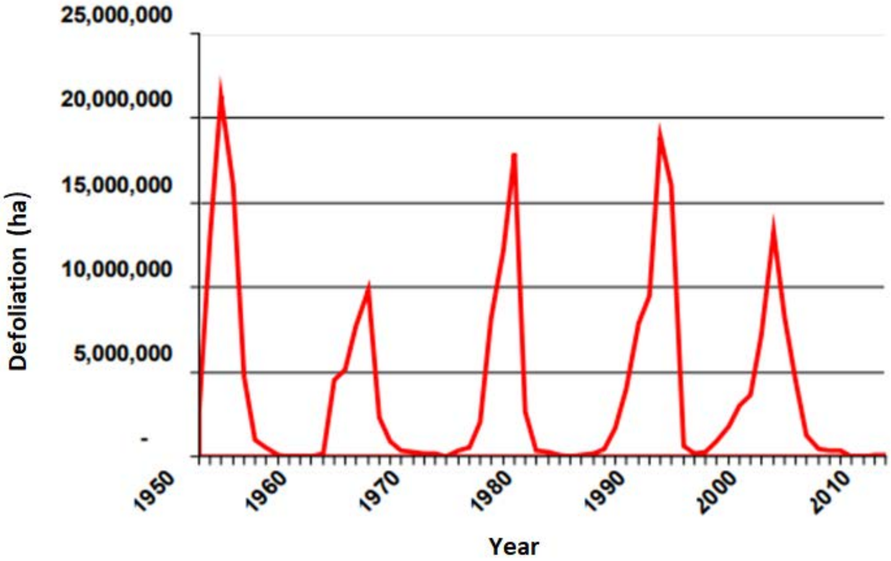


Figure 7-26 Moderate-to-severe forest tent caterpillar defoliation in Ontario, 1950-2011 (MNRF, 2012)

Similarly, high levels of moisture in the form of rain, dew, or high humidity can promote infection by mosquito vectors or fungal plant pathogens, such as those involved in the development of beech bark disease. Generally, high levels of moisture and moderate temperatures accelerate the life cycles of fungi and facilitate spore release and germination (Boland et al., 2004). A trend towards warmer, drier summers in the Lake Simcoe watershed could thus lead to a decrease in the incidence of plant disease caused by fungi, although disease levels may spike when moisture is more abundant, such as during the spring or fall, or following heavy-rain events. On the other hand, some fungal pathogens may thrive in warmer, drier conditions. In either case, climate change may lead to changes in the rates of infection in the watershed, particularly where hosts are under stress.

Generally, variations in climate cycles and extremes will likely benefit pests and pathogens (Hushaw, 2015). Heat, water, or nutritional stress associated with climate change may affect the resilience of host species. If increased temperatures or extreme weather events limit the availability or abundance of food and water, hosts may become more susceptible to heavy parasite loads and to pathogens (Nituch and Bowman, 2013). For example, a study by Harvell et al. (2002) found that amphibians suffering from climate change induced stresses, such as increased ultraviolet radiation, may be more susceptible to pathogens.

For trees, precipitation and temperature extremes may create stress that can increase their susceptibility to attack and reduce their ability to survive and / or recover. An example of a pathogen that may thrive as a result of added stress on their host is Beech Bark Disease, which causes mortality and defects in beech trees (*Fagus*). Trees only succumb to the disease after extensive bark attack by the beech scale insect (*Cryptococcus fagisuga*) which weakens the tree and allows for invasion by two different fungi (*Neonectria faginata* and *Neonectria ditissima*) (Figure 7-27). Climate change may further weaken trees by causing drought periods and flooding to occur more frequently, both of which beech trees are sensitive to (Stephanson and Ribarik Coe, 2017). The synergistic impacts of climate change on Beech Bark Disease were recorded in a study in Northern Maine, which found that a series of mild winters that coincided with severe drought resulted in the resurgence of the disease (Hushaw, 2015).

Figure 7-27 Clusters of the fungus *Neonectria faginata* develop on a beech tree. Climate change will likely weaken trees and render them more vulnerable to infestations by the insects and pathogens that cause beech bark disease.

Considering the abundance of beech trees in the area, a surge in the prevalence of Beech Bark Disease could significantly impact the composition and health of the Lake Simcoe watershed's forests. In terms of the extent of damage, however, not all pests and pathogens pose the same risk. A recent analysis of drought effects on damage by forest insects and pathogens found that insect or fungal species that live in wood caused lower damage than those living on foliage (Jactel et al., 2012). This indicates that the type of feeding plays a role in the level of pest damage, which can help guide management and control efforts when extreme events occur.

7.8.3 Species asynchrony

Climate change will affect the life cycles and developmental stages of pests, pathogens, and their host species, resulting in changes in the phenology of events such as budbreak in tree hosts, spore release by pathogens, and activities of insects that serve as vectors and pests (Sturrock et al., 2011). As a result, the impacts of pest and pathogen could be exacerbated or alleviated, depending on the species involved. For example, natural enemies of defoliator pest species depend on climatic factors to maintain their life processes and synchronicity with their prey. If key predators lose synchronicity with the pests on which they feed, pest populations may thrive and outbreaks may become more severe (Johnston, 2009). On the other hand, life cycle mismatches could reduce pest and pathogen populations. For example, pests that typically feed on young, nutrient rich foliage may be negatively impacted if the growing season begins earlier and causes faster leaf maturation. Pests, pathogens, hosts, and predators all have different sensitivities to climate change, which makes it difficult to predict future changes in synchronicity and subsequent changes in pest / disease prevalence. Investigations into the life cycle, trophic dynamics, and climate sensitivities of pests and diseases found in the Lake Simcoe watershed are needed in order to develop an accurate understanding of how the decoupling of pests, pathogens, and their predators and prey could impact the timing, frequency, and severity of outbreaks.

Key Points – Pests and diseases

- Increased air temperature is likely to expand the range of pests and pathogens currently limited by cooler temperatures and increase the duration that disease vectors can survive in the watershed.
- Increased air temperature and a longer growing season is likely to continue expanding the range of ticks northward, increasing the risk of Lyme disease for watershed residents.
- The introduction of new pests and disease is likely to increase the severity of outbreaks due to limited resilience among native species.
- Many insects and pathogens are limited by cold winter temperatures. Warmer air temperature in winter is likely to enhance their survival, development and reproductive success and result in more frequent and severe outbreaks.
- Increased air temperature can support multiple generations of insects within a single season, resulting in large scale outbreaks of herbivorous insects.
- The forest tent caterpillar weakens trees through repeated defoliation. Climate change causes more frequent outbreak cycles which increases stress on their hosts who have less recovery time between outbreaks.
- High levels of moisture in the form of rain, dew and humidity promotes infection by mosquito vectors of fungal plant pathogens such as those involved in beech bark disease.
- Plants and animals under stress, including climate related stress, are more susceptible to pests, disease and heavy parasite loads.
- Asynchrony between key predators and the pests on which they feed could lead to more frequent and severe outbreaks. Alternately, life cycle mismatching could reduce pest populations.

7.9 Current and future vulnerability assessment

The current and future vulnerability of each watershed indicator of terrestrial natural heritage features (**Table 7-4**) was developed based on the methodologies described in **Chapter 1 – Introduction**. In summary, the current vulnerability score is a combination of an indicator's degree of sensitivity and exposure to climate change in the present. The future vulnerability combines climate model projections and the degree of confidence to an indicator's current vulnerability score to provide the overall vulnerability score for each indicator.

Table 7-4 Current and future vulnerability of terrestrial natural heritage features to climate change in the Lake Simcoe watershed

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
Drying/loss of wetlands	Less summer precipitation	Reduces the amount of water available for pooling	H	H	H	H	H
	Less snow accumulation	Shortens the hydroperiod for wetlands and reduces the amount of water available for pooling	H	H	H	M	M
	Warmer winters	Increases the amount of water that infiltrates into the ground rather than pools at the surface	H	H	H	H	H
Degraded wetland water quality	More extreme rainfall	Sediment, contaminants, and nutrients are washing into wetlands following heavy precipitation events	VH	M	H	VH	VH
	More drought	The concentration of sediment, contaminants, and nutrients increases during low flow periods	VH	M	H	H	H
	More winter rainfall	Higher sediment, contaminants, and nutrient loads in winter and less in spring	M	M	M	M	M
Change in wetland floral and faunal composition	Less summer precipitation (more drought conditions)	Will favour drought-tolerant species	H	H	H	H	H
	Rising temperatures	Shifting climate envelopes will result in new, more climatically suitable species becoming established in wetlands	H	H	H	H	H
	More extreme rainfall	Degraded water quality will favour more robust wetland species as those that are sensitive die out	M	H	M	VH	H
	More drought	Degraded water quality will favour more robust wetland species as those that are sensitive die out	M	H	M	H	M
	More winter rainfall	Degraded water quality will favour more robust wetland species as those that are sensitive die out	M	H	M	M	M
	Rising temperatures	Degraded water quality will favour more robust wetland species as those that are sensitive die out	M	H	M	H	M
Changes in woodland composition	Rising temperatures	As climate envelopes shift, species will move out of the watershed, new species will migrate in, and some species will be extirpated	H	H	H	H	H
Tree mortality following extreme weather events	Ice storms	Ice build-up on tree trunks and branches, causing them to snap	VH	M	H	M	M
	More freeze-thaw cycles	Freeze-thaw cycles cause conifers to dry-out (winter browning)	VH	M	H	H	H
	Drought	Drought conditions impose stress on trees and can cause them to dry out (especially young saplings)	VH	M	H	H	H
More hazards relating to fallen trees	Ice storms	Ice build-up on branches and tree trunks can cause trees to fall or limbs to snap off	VH	M	H	M	M

Watershed indicator	Climate driver(s)	Relationship between indicator and climate driver	Sensitivity	Exposure	Current vulnerability	Confidence	Future vulnerability
Introduction of new species or expansion of existing species ranges following wildlife range shifts	Rising temperatures	As climate envelopes shift, wildlife will migrate to follow shifting habitats/resources	H	VH	VH	H	VH
Loss or decline of vulnerable floral and faunal species following wildlife range shifts	Rising temperatures	Vulnerable species will either be extirpated, or experience population declines if they cannot keep pace with their shifting climate envelopes or compete within their new community assemblages	H	VH	VH	H	VH
The introduction of new invasive species, pests, and diseases	Warmer temperatures	As climate envelopes shift, species will migrate into our watershed from the south	H	VH	VH	H	VH
	More extreme rainfall	Enhanced pathways for species introductions (rain events help with seed dispersal)	L	VH	H	VH	VH
More widespread and aggressive invasive species, pests, and disease outbreaks	More drought	Hotter and dryer conditions may cause drought-tolerant invasive species to thrive in new environments	H	VH	VH	H	VH
	More extreme climate events that disturb the landscape (extreme rainfall, ice storms)	Invasive species can benefit from disturbances and can exploit disturbed sites	M	M	M	M	M
	Warmer temperatures (longer growing season)	Gives fast-growing invasive species more time to grow and out-compete native species. Increases the length of time that pest and disease vectors are present in the area (can complete more generations)	M	VH	H	VH	VH
	Warmer winter temperatures	Greater overwintering survival for pests	M	VH	H	H	H
	More extreme climate events can impose stress on native species (drought, heat wave, ice storms)	Stress will weaken the hosts and render them more susceptible to heavy parasite loads and to pathogens	H	VH	VH	M	H
Earlier breeding and hatching dates	Warmer temperatures	For species that use temperature as a trigger for life cycle events, these events will occur earlier as temperatures rise	H	H	H	H	H
Earlier migration and arrival dates	Warmer temperatures	Migrants (especially short-distance migrants) use temperature as a migration cue. Warmer temperatures cause them to migrate earlier.	M	H	M	H	M

Recommended actions were developed to address these vulnerabilities as the climate changes and they are summarized in **Chapter 8**.

Chapter 8

Recommendations for Action

Goal 1 - Ensure that people, properties and communities remain sufficiently protected as climate conditions change

1. That LSRCA complete a corporate risk assessment to identify LSRCA functional areas, operations and assets that are vulnerable to extreme weather events. The risk scan should then be used to develop and implement adaptation strategies to mitigate any identified risks. Where feasible, LSRCA should assist other municipalities in completing corporate risk assessments.
2. That LSRCA convene a meeting of partners to determine the roles and responsibilities related to the Low Water Response Program and how further collaboration can improve the program in light of climate change.
3. That LSRCA undertake research to understand and map the potential impacts of climate change on groundwater levels and any associated risk to private and communal drinking water wells within the watershed.
4. That LSRCA screen for risks to municipal surface water intakes from contamination as a result of extreme events under climate change conditions. If screening identifies a risk, LSRCA to work with associated municipalities to confirm risk through hydrodynamic modeling and take necessary steps to mitigate the significant threat through the Source Water Protection Program.
5. That LSRCA work with the Province and local municipalities to develop / update intensity-duration-frequency (IDF) curves that consider climate change. Once these IDF curves have been developed / updated, they should be incorporated in LSRCA mapping and other applicable documents, as required.
6. That LSRCA create regulatory floodplain mapping as well as design storm or event-based floodplain mapping which is based on these updated IDF curves that include climate change adaptation factors, once these are available.
7. That LSRCA develop design storm or event-based inundation mapping to consider future climate change impacts from changing intensity, duration and frequency of storms, and share the inundation mapping with emergency response professionals.
8. That LSRCA explore options for increased coordination and collaboration with partners on existing rapid detection and response programs to water quality threats (e.g. harmful algal blooms, *E. coli*) to both drinking water and recreational water use.
9. That LSRCA work with the Province to review water balance policies for developments to ensure that they consider longer-term pre-development and post-development site conditions that incorporate climate impacts.

Goal 2 - Increase watershed resistance and resilience to climate change through conservation, restoration, and improvement of natural ecosystems

10. That LSRCA investigate the need for developing guidelines and standards for natural channel design to consider climate change, in collaboration with other conservation authorities, municipalities and the province.
11. That LSRCA work with partners to increase forest resilience to climate change through the implementation of recommendations from the '*Adapting Forestry Programs to Climate Change'* report, especially the recommendations regarding assisted migration and protecting climate refugia. Any recommendations to promote afforestation success and protect forest functions should continue to be shared with relevant partners.
12. That data be collected on the success of plants established in Low Impact Development or other green infrastructure, as well as trees planted following the recommendations of the '*Adapting Forestry Programs for Climate Change*' report, to ensure that proposed species survive sufficiently to provide climate adaptation benefits. Based on the results of this monitoring, that planting recommendations be modified as necessary.
13. That LSRCA review its Minimum Planting Requirements to ensure that the recommended species lists include species expected to be better adapted to future climates, or which would provide resilience to wildlife communities through a diversity of flowering and leaf-out timing.
14. That LSRCA use models or other tools to identify and prioritize areas where groundwater recharge is necessary and will be most useful (e.g. to support wetlands, coldwater refuges, stream reaches vulnerable to low flows), through the development of a climate significant groundwater recharge area map. Any mapping should be shared with relevant partners, including the Watershed Restoration Services department.
15. That LSRCA work with partners to increase the biodiversity of urban wildlife habitats in order to adapt to shifts in the timing of life cycle events and other climate impacts, through tools such as updated planting lists, education and training, and community plantings.
16. That LSRCA collaborate with partners to develop an Invasive Species Strategy that considers climate change and includes elements such as a species watch list, education and outreach, response protocols, monitoring and citizen science.
17. That LSRCA design restoration projects based on design guidelines, modelling, prioritized opportunities, long-term monitoring and watershed plans which consider the influence of climate change.
18. That the LSRCA give preference to restoration projects that also address climate change impacts.
19. That LSRCA review restoration best management practices to ensure that they are capable of addressing emerging climate impacts.

Goal 3 - Enhance knowledge of the watershed's natural environment and its response to a changing climate through science and monitoring for informed and adaptive decision-making

20. That the Watershed Plans and Strategies department support other LSRCA departments in incorporating anticipated climate impacts into their programs, services, and products by providing regular updates of current climate projections, monitoring data and climate science.
21. That LSRCA model in-stream processes to further understand the vulnerability to erosion, infrastructure damage, and phosphorous transport under future climate conditions. This information should then be used to determine the effectiveness of current BMPs as climate conditions change.
22. That LSRCA use the results of watershed-scale stormwater optimization modeling to assist planning of stormwater infrastructure (grey and green) under climate change conditions. The modeling approach shall be based on that developed for the East Holland River stormwater optimization pilot project and be completed within timeframes that facilitate integration into watershed plan updates and stormwater master plans.
23. That LSRCA investigate whether the 90th percentile storm event will change significantly under climate change, and what impacts this may have on LSRCA programs, services and guidelines.
24. That LSRCA conduct a stream vulnerability assessment to identify thermal refugia, determine their relative potential to withstand climate change impacts, and prioritize reaches for protection and restoration.
25. That climate change adaptation be incorporated into LSRCA's Natural Heritage System Restoration Strategy, through the identification of features which are resilient or vulnerable to a changing climate, and the identification of priority areas for increasing watershed-scale resilience, such as with the establishment of natural heritage corridors.
26. That research be undertaken to further understand the impacts of climate change on aquatic communities. Research topics could include (but are not limited to):
    - Stream overwintering community dynamics and the impacts of changing winter conditions;
    - The effects of changing flow regimes on redds, larvae or juvenile fish and how best to protect them;
    - The impacts of changing lake ice dynamics (e.g. ice cover and thickness) on lake health; and,
    - The impact of climate change on thermal dynamics, dissolved oxygen levels and phosphorous loads on Lake Simcoe.

    Any research conducted should be used to inform climate change and watershed planning and should be shared with partners.
27. That LSRCA review the current monitoring programs to ensure that data collection and analysis of climate, groundwater, and surface water systems are fully integrated, with the goal of effectively tracking climate change and associated adaptation and mitigation measures.
28. That LSRCA develop a robust terrestrial natural heritage monitoring program for the watershed, and that data collected from the program is used to inform other LSRCA programs and plans. The monitoring program should:
    - Identify gaps and opportunities for more robust data collection;

- Integrate ecological and hydrologic systems;
- Monitor to ensure community function;
- Predict and monitor climate impacts (e.g. species range shifts, changes in phenology);
- Utilize available tools and resources, where feasible (e.g. technology, citizen science); and,
- Collaborate with partners to share resources and data.

Goal 4 - Facilitate partnerships and connect people to the watershed in order to build awareness and capacity to adapt to a changing climate in the Lake Simcoe watershed

29. That LSRCA coordinate with MECP to ensure that any updates to the Lake Simcoe Protection Plan and Lake Simcoe Phosphorous Reduction Strategy incorporate climate change.
30. That LSRCA engage citizens, informing them of their role in keeping the Lake Simcoe watershed healthy in the context of a changing climate, by providing regular updates on social media and the website
31. That LSRCA work with municipal partners to undertake climate change risk assessments of urban street trees, and associated risks to public safety or public infrastructure.
32. That LSRCA enhance its erosion and sediment control initiatives to consider climate impacts, including updating resources and training, investigating and promoting improved BMPs and enforcement, and improving access to enhanced weather forecasting and early warning systems.
33. That LSRCA inspire watershed landowners to increase the resilience of coldwater habitats on their properties and support them in creating and restoring aquatic habitats as they may be impacted by climate change (e.g. erosion, changing flow regimes and warming temperatures).
34. That LSRCA engage farmers, farming associations and OMAFRA through knowledge exchange meetings to learn how they are adapting to climate change and how LSRCA can support them in adapting their practices to minimize the impacts of climate change on the environment.
35. That LSRCA engage the Trent-Severn Waterway as they update their watershed plan or rating curve to consider climate change impacts, such as maintaining environmental flows, flood mitigation and reducing the spread of invasive species.
36. That LSRCA work collaboratively with its partners, providing services and resources, education and training as well as facilitating knowledge transfer, in order to maximize efficiencies and ensure a comprehensive watershed scale approach to climate change adaptation.

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Appendices

Appendix 1 – Climate modelling comparison table

	Climate Change Hazards Information Portal	**Climate Atlas of Canada**	**Canadian Centre for Climate Services (ClimateData.ca)**	**Durham Region**	**York Region**
General Circulation Models	An ensemble of 40 (CMIP5)	An ensemble of 24 (CMIP5)	An ensemble of 24 (CMIP5)	HadCM3 and a regional climate model (PRECIS)	?
Downscaling method	Statistical (delta approach)	Bias-Correction/Constructed Analogues with Quantile mapping reordering, Version 2 (BCCAQv2)	Bias-Correction/Constructed Analogues with Quantile mapping reordering, Version 2 (BCCAQv2)	Dynamic downscaling	Statistical and dynamic techniques
Observed data	Shanty Bay climate station 1973-2018	1950-2013 CANGRD interpolated dataset	1950 - 2005 CANGRD interpolated dataset	CANGRD interpolated dataset	4 climate stations in York Region (SENES dataset), CANGRD interpolated dataset
Baseline period	1981-2010	1976-2005	1986-2005	2000-2009	2000-2009 (SENES dataset); (1981-2010 (CANGRD dataset)
Future climate periods	2020s, 2050s, 2080s	2030s (2021-2050), 2070s (2051-2080)	2006-2099	2040-2049	various
Climate Indicator	Projection	Projection	Projection	Projection	Projection
Average air temp	**<u>2080s RCP8.5 mean (change)</u>** **Annual:** 12.3°C (+ 5.5°C) **Spring**: 10.5°C (+ 5°C) **Summer**: 24.5°C (+ 5.5°C) **Autumn**: 14°C (+ 5°C) **Winter**: 0.5°C (+ 6.5°C)	**<u>2070s RCP8. 5 mean (change)</u>** **Annual:** 10.7°C (+ 4.4°C) **Spring**: 9.0°C (+ 3.9°C) **Summer**: 23.1°C (+ 4.4°C) **Autumn**: 12.6°C (+ 4.2°C) **Winter**: - 2.0°C (+ 5.0°C)	**<u>2099 RCP8.5 range</u>** **Annual:** 11.6°C to 15.0°C	**N/A**	**<u>Range of scenario results 2050s change</u>** **Annual:** +2.1°C to +4.3°C **Spring:** + 1.9°C to +4°C **Summer:** +0.3°C to +3.8°C **Autumn:** -0.7°C°C to +3.9°C **Winter:** +1.9°C to +5.7°C

	Climate Change Hazards Information Portal	Climate Atlas of Canada	Canadian Centre for Climate Services (ClimateData.ca)	Durham Region	York Region
Extreme Air temp	**2080s RCP8.5 change** **Number of days >25°C** **Annual:_** +66 days **Number of days >30°C** **Annual:** +51.7 days **Number of days >35°C** **Annual:** +11.3 days	**2070s RCP8.5 mean (change)** **Number of days > 30°C** **Annual:** 49.4 days (+40.9 days)	**2099 RCP8.5 range** **Highest maximum temperature** **Annual**: 37.1°C to 43.4°C **Number of days > 30°C** **Annual**: 70 days to 104 days	**2040s mean annual** **Daily max temp:** 26°C to 29°C **Number of days > 24°C**: 17 to 90 days **Number of days > 30°C:** 6 to 28 days	**Range of scenario results 2050s - mean (change)** **annual days >25°C**: 58 days (+2 to +54 days) **annual days >30°C**: 10 days (+2 to +29 day) **annual days >35°C**: 0.2 days (+0.3 to +14 days)
Growing season	**2080s RCP8.5** **Mean length:** 206.4 days **Days below 0°C:** 76.4 days (- 65.4 days)	**2070s RCP8.5** **Mean length:** 193.3 days (+ 45.2 days) **Frost days (daily minimum <0°C:** 109.4 days (- 48.6 days)	**2099 RCP8.5 range** **Growing degree days (5°C)** **Annual:** 3,320 degree days to 3,967 degree days **Frost days (daily minimum <0°C:** 61 days to 98 days	N/A	**Range of scenario results 2050s -mean** **Length**: +13.3 to +22.3 days **Days below 0°C:** **Annual:** -1.9 to -2.1 days **Spring:** -3.5 to -8.3 days **Summer:** 0 days **Autumn:** -3.3 to +0.6 days **Winter:** +0.5 to -0.9 days
Precipitation	**2080s RCP8.5** **Annual:** 1074.2 mm (+ 10.1%) **Spring**: + 19.9% **Summer**: - 3.6% **Autumn**: + 5.8% **Winter**: + 22.8%	**2070s RCP8.5** **Annual:** 970 mm (+ 10%) **Spring**: 244 mm (+ 17%) **Summer**: 218 mm (- 1%) **Autumn**: 258 (+ 5%) **Winter**: 250 mm (+ 18%)	**2099 RCP8.5 range** **Total precipitation** **Annual:** 766 mm to 1136 mm	**2040s mean annual range** **Total precipitation:** 954 to 1115 mm	**Range of scenario results 2050s** **Total precipitation mean change:** **Annual:** -12.3 to +134.5 mm **Spring:** -24.9 to +4.9 mm **Summer:** -2.5 to +153.6 mm **Autumn:** -9.9 to +7.2 mm **Winter:** -12.3 to +134.5 mm

	Climate Change Hazards Information Portal	Climate Atlas of Canada	Canadian Centre for Climate Services (ClimateData.ca)	Durham Region	York Region
Extreme precipitation	**2080s RCP8.5** **1-day maximum precipitation** **Annual:** 48.42 mm (+ 17.55%) **95th Percentile**: 135.24 mm (+ 94.5%) **99th Percentile**: 336.74 mm (+ 44.6%)	**2070s RCP8.5** **Days >10 mm precipitation** **Annual**: 28.7 days (+ 3.9 days) **Days >20 mm precipitation** **Annual**: 7.6 days (+ 2.1 days)	**2099 RCP8.5 range** **1-day maximum precipitation** **Annual:** 27 mm to 68 mm **Wet Days >10 mm precipitation** **Annual:** 20 days to 34 days **Wet Days >20 mm precipitation** **Annual:** 4 days to 11 days	**2040s mean annual range** **1-day maximum precipitation**: 84 to 122 mm **Number of days > 25 mm**: 9 to 11 days	**Range of scenario results 2050s - change** **1-day maximum precipitation: Annual:** +30.9 to + 45.7 mm **10th Percentile**: -12.1 to +4.4 mm **90th Percentile**: +18.7 to +21.6 mm **Days >20 mm precipitation** **Annual**: +0.1 to +0.2 days **10th Percentile**: +1.7 days **90th Percentile**: +1.9 days

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