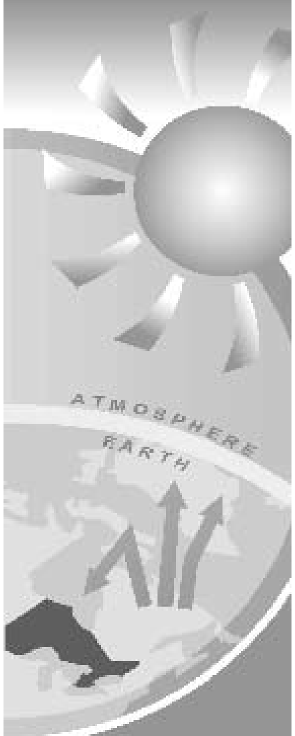
Ministry of Natural Resources

11

CLIMATE CHANGE RESEARCH REPORT

CCRR-11



Responding to Climate Change Through Partnership

A Summary of the Effects of Climate Change on Ontario's Aquatic Ecosystems

Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change
MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change
MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt
MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

A Summary of the Effects of Climate Change on Ontario's Aquatic Ecosystems

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Summary

Climate change will alter Ontario's aquatic ecosystems as a result of increases in air and water temperature, decreases in ice and snow cover, and changes in the timing and amount of precipitation. These changes will affect the hydrological cycle by altering the flow of water and water chemistry. Threats to freshwater fauna include nutrient enrichment, hydrological modifications, habitat degradation and loss, pollution, and the spread of invasive species. A changing climate and increasing levels of ultraviolet light pose additional risks that add to existing threats. The combination of changes in land use, habitat, and climate present a serious challenge to the long-term integrity and health of aquatic ecosystems.

Because fish are cold-blooded, increases in water temperature will affect their distribution, growth, reproduction, and survival. The habitat and productivity for coldwater species, such as lake trout (*Salvelinus namaycush*) and brook trout (*Salvelinus fontinalis*), may decline substantially with increased air and water temperatures. Coolwater fishes likely will respond to climate change in a variety of ways. For example, in the case of walleye (*Sander vitreus*) in central and northern Ontario, warming may increase available habitat. Overall, model projections suggest a northward shift in the location of the walleye fishery. Many warmwater fishes are projected to benefit from warmer water temperatures. For example, smallmouth bass (*Micropterus dolomieui*), which reach the northern extent of their range in Ontario, may expand northward as warmer water temperatures facilitate increased growth and recruitment. A northward expansion of warmwater fish species will disrupt the life history strategies of cool- and coldwater fish species.

Commercial and recreational harvest opportunities for lake trout, brook trout, and perhaps walleye will decline, particularly in southern Ontario. Although these losses may be offset somewhat by increased opportunities to harvest warmwater species, the expected changes in fish communities will bring a variety of social and economic challenges. To meet these challenges, an adaptive approach to fisheries and aquatic ecosystem management in Ontario is needed. Known and potential climate change effects must be incorporated into existing fisheries management plans and strategic plans will need to be revisited to ensure that they reflect anticipated changes.

Given the importance of understanding the range of potential climate change effects on aquatic assets, it is essential that management agencies and organizations identify and apply appropriate effective mitigation and adaptive management strategies. In this report, we review and summarize the known and potential effects of climate change on Ontario's aquatic ecosystems and on the life history of selected coldwater, coolwater, and warmwater fish species.

Résumé

Présentation sommaire des effets du changement climatique sur les écosystèmes aquatiques de l'Ontario

Le changement climatique – hausse de la température de l'air et de l'eau, diminution de la couverture de glace et de neige et changements des périodes et des quantités de précipitations – aura des effets sur les écosystèmes aquatiques de l'Ontario. Ces phénomènes influeront sur le cycle hydrologique, car ils modifieront le débit et la chimie de l'eau. La faune d'eau douce sera confrontée à diverses menaces : enrichissement en matières nutritives, modifications hydrologiques, dégradation et perte d'habitats, pollution, propagation d'espèces envahissantes. Sans compter que la modification du climat et l'accroissement des taux de rayonnement ultraviolet s'ajoutent aux risques existants. L'effet combiné des modifications de l'occupation du territoire, des habitats et du climat font peser un grave danger sur l'intégrité et la santé à long terme des écosystèmes aquatiques.

Les poissons étant des organismes à sang froid, la hausse de la température de l'eau exercera une influence sur leur répartition, leur croissance, leur reproduction et leur survie. L'augmentation de la température de l'air et de l'eau pourrait réduire considérablement l'habitat et la productivité d'espèces d'eau froide, comme le touladi (*Salvelinus namaycush*) et l'omble de fontaine (*Salvelinus fontinalis*). Selon toute probabilité, les poissons d'eau froide réagiront au changement climatique de différentes manières. Par exemple, le réchauffement pourrait

faire augmenter la quantité d'habitat disponible pour le doré jaune (*Sander vitreus*) dans le centre et le nord de l'Ontario. Dans l'ensemble, les projections des modèles indiquent un déplacement vers le nord de la zone de pêche au doré jaune. Selon les projections, bon nombre d'espèces d'eau chaude bénéficieront de la hausse des températures. Ainsi, l'aire de répartition de l'achigan à petite bouche (*Micropterus dolomieui*), qui atteint sa limite nord en Ontario, pourrait s'étendre vers le nord, la hausse de la température de l'eau facilitant la croissance et le recrutement. Or, cette expansion vers le nord de l'aire d'espèces de poissons d'eau chaude perturbera le cycle biologique d'espèces d'eau froide et très froide.

Les possibilités de récolte commerciale et sportive du touladi, de l'omble de fontaine et peut-être du doré jaune diminueront, en particulier dans le sud de la province. Ces pertes pourraient être contrebalancées dans une certaine mesure par l'accroissement des possibilités de pêche aux poissons d'eau chaude, mais les modifications prévues des communautés de poissons créeront différents problèmes sociaux et économiques. Pour contrer ces problèmes, il importe d'adopter une approche adaptative à la gestion des pêcheries et des écosystèmes aquatiques en Ontario. Il faut intégrer les effets connus et appréhendés du changement climatique dans les plans de gestion halieutique en place et revoir les plans stratégiques pour s'assurer qu'ils tiennent compte de ces effets.

Il est important de connaître l'étendue des effets possibles du changement climatique sur le capital aquatique; il est donc essentiel que les entités responsables de sa gestion établissent et mettent en œuvre des stratégies efficaces d'atténuation des effets et de gestion adaptative. Ce rapport passe en revue les effets connus et potentiels du changement climatique sur les écosystèmes aquatiques et sur le cycle biologique des poissons d'eau chaude, d'eau froide et d'eau très froide, et en présente un sommaire.

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1.0 Introduction

Ontario is blessed with substantial freshwater assets found in the Great Lakes, in the thousands of streams/rivers and inland lakes, and in the variety of wetlands found throughout the province. These aquatic assets provide many ecological goods and services such as clean water, biodiversity, and recreational opportunities that contribute to ecosystem composition, structure, and function, as well as human health and well-being.

Since 1900, the Earth's surface has warmed by 0.76±0.19°C, and most of this warming can be traced to human activities since the end of World War II in 1945 (IPCC 2007a). Given that Earth's climate will continue to warm for decades, perhaps centuries (Flannery 2005, IPCC 2007a), the hydrological cycle and biodiversity in every aquatic ecosystem will be affected. For example, climate change will alter water balance through changes to evaporation and precipitation patterns, create increasing numbers of extreme events such as flooding and drought, and physically alter habitat and species relationships throughout the province.

Climate change will affect how agencies such as the Ontario Ministry of Natural Resources (OMNR) care for the province's natural assets. In response, the OMNR is working with clients and partners to understand the ecological and socio-economic effects of climate change, help reduce greenhouse gas emissions, minimize the negative effects of climate change on natural systems where possible, and help Ontarians adapt to any changes that do occur (OMNR 2011).

This report provides information about the known and potential effects of climate change on aquatic ecosystems; selected fish species (lake trout [*Salvelinus namaycush*], brook trout [*Salvelinus fontinalis*], walleye [*Sander vitreus*], and smallmouth bass [*Micropterus dolomieui*]); and outlines research priorities and management strategies available to natural asset managers.

2.0 Organization of this Review

This review is organized by five general themes:

1. **Climate and Change:** An introduction to global warming and climate change.
2. **Climate Models:** Climate models are an important tool to help visualize what our future may look like under a changing climate. This section provides an historical summary of climate change in Ontario and describes some future projections of climate.
3. **Aquatic Ecosystems and Climate Change:** For the purposes of this report, we organize freshwater ecosystems into three categories:
   - Lakes
   - Streams and rivers
   - Wetlands

   This section provides a general description and overview of the known and potential effects of climate change on these aquatic ecosystems.
4. **The Effect of Climate Change on Selected Fish Species:** Many factors affect the distribution and abundance of fishes in Ontario. Climate change may alter the availability of suitable habitat for fishes and will affect the growth, reproduction and recruitment, and distribution of fishes in Ontario (Christie and Regier 1988, Casselman 2002, Chu et al. 2005). Four species (coldwater – lake trout and brook trout, coolwater – walleye, and warmwater – smallmouth bass), were selected to examine the potential effects of climate change on Ontario's fish resources. The different habitat requirements and importance of these species to sport fisheries provide good insight into the challenges facing managers of Ontario's fisheries and aquatic ecosystems.
5. **Adaptation:** An outline of adaptation actions available for use in the development of strategic plans, policies, management, and research projects is provided as a basis for discussion and for setting research priorities.

3.0 Climate and Change

Climate is the “average weather” for a geographic region and is described statistically as the mean and variability of temperature, precipitation, and wind (IPCC 2007a:942). Climate is driven primarily by energy from the Sun in the form of heat and is often the result of complex interactions between the atmosphere, oceans, freshwater, ice, land, and organisms that are influenced by natural events and human activity. For example, solar radiation varies with shifts in the Earth’s orbit and tilt relative to the Sun, both of which change over tens of thousands of years (Ruddiman 2001). The Sun itself releases varying amounts of energy as solar output, which affects global climate in much the same way as heat released from a furnace influences room temperature (Alverson et al. 2001). Natural events such as volcanic eruptions can cool the atmosphere by emitting fine particles, which reflect incoming solar radiation back into space. In extreme cases, volcanic activity can affect the global climate for several years (Robock 2000), such as the 1992 eruption of Mt. Pinatubo that affected Great Lakes water temperatures (King et al. 1997) and fish growth (Casselman 2002).

About 30% of the Sun’s heat (thermal) energy entering Earth’s atmosphere is reflected back into space by clouds, dust particles, snow, and ice. Another 20% is absorbed by clouds, and the remaining 50% is absorbed by rocks, soil, water, plants, and other surfaces. Some of the heat that warms the surface returns to the atmosphere and is absorbed by greenhouse gases. When greenhouse gases absorb this radiation, heat energy is trapped within the atmosphere rather than being radiated back into space. This trapped energy keeps the Earth’s surface temperature warmer than it would otherwise be, and has contributed to the present diversity of life on Earth. Therefore, a consistent concentration of atmospheric greenhouse gas is essential to life on Earth. However, as humans add more greenhouse gas to the atmosphere, more heat energy will be retained and it will become warmer.

Increased heat energy in the lower atmosphere raises air temperatures and changes precipitation patterns, ocean temperatures, freshwater lake and river temperatures, and ice and snow cover (Magnuson et al. 2000, CCME 2003, Trumpickas et al. 2008). The energy reaching Earth from the Sun has remained constant since 1978, so most scientists have concluded that present atmospheric warming is due to greenhouse gas emitted as by-products of human activities (Stott et al. 2000, NAS 2006, IPCC 2007a:10). Although greenhouse gas emissions began increasing with the emergence of agriculture, the industrial revolution that began in Europe around 1750 marked the beginning of the period in which truly significant amounts of carbon dioxide (CO_2) and methane (CH_4) were added to the atmosphere. Since that time, atmospheric CO_2 has increased by about 36% as a result of burning fossil fuels (coal, oil, gas), deforestation in tropical regions, and the draining of wetlands (IPCC 2007a:132). More recently, a variety of artificial compounds such as sulphur hexafluoride (SF_6) and perfluoropentane (C_5F_{12}) have also been emitted into the atmosphere. Although emitted in small quantities, these chemicals are powerful greenhouse gases.

Earth’s oceans absorb about 80% of the heat trapped in the atmosphere (IPCC 2007a:47). As oceans warm, levels rise in response to thermal expansion of the warmer water and the addition of water from melting glaciers and polar ice caps. Melting glaciers and polar ice caps create positive feedback to the ecosystem, which can accelerate warming and climate change. For example, light-coloured surfaces, such as ice and snow reflect more of the Sun’s radiation back into space than dark surfaces such as water, exposed soil, and vegetation. Therefore, the light-coloured surfaces help to keep the Earth’s surface cooler. With the continual loss of snow and ice in northern regions this “albedo effect” will be diminished and more heat will be absorbed by the oceans and terrestrial surfaces.

4.0 Climate Models

Effective planning and management responses to global warming require an understanding of how Ontario's climate may change during the 21st century. Stabilization of greenhouse gas concentrations in the atmosphere is a critical part of any effort to reduce the effects of global warming. If and when stabilization will be achieved remains uncertain. For example, if a country elects to increase reliance on fossil fuels, greenhouse gas emissions will increase faster than if it elects to reduce the use of fossil fuels, introduce more renewable energy, and apply energy conservation measures. Climate models and emission scenarios represent a useful tool to project the Earth's future climate.

Many climate models have been developed to project the potential effects of increased greenhouse gas concentrations on temperature through time. In turn, global warming affects precipitation, wind patterns, and other climatic variables. Each climate model is unique, based on different assumptions, and produces different projections of future climate when fed the same data (Colombo et al. 2007:2). Given the uncertainty about human behaviour and associated greenhouse gas emissions throughout the 21st century, greenhouse gas concentrations are selected and introduced into climate models using one or more of 40 scenarios of human behaviour developed by the Intergovernmental Panel on Climate Change (Figure 1). Each scenario contains a unique set of assumptions about future social and economic conditions (Nakićenović et al. 2000).

Given all of this uncertainty, natural asset managers are urged to use a range or an ensemble of climate models and scenarios to examine known and potential effects of climate change (e.g., Figure 2). In this report, we draw on the mapped projections provided by Colombo et al. (2007) to provide the reader with a sense of the magnitude of change that could result from greenhouse gas emissions generated under the the A2 and B2 scenarios. The A2 scenario

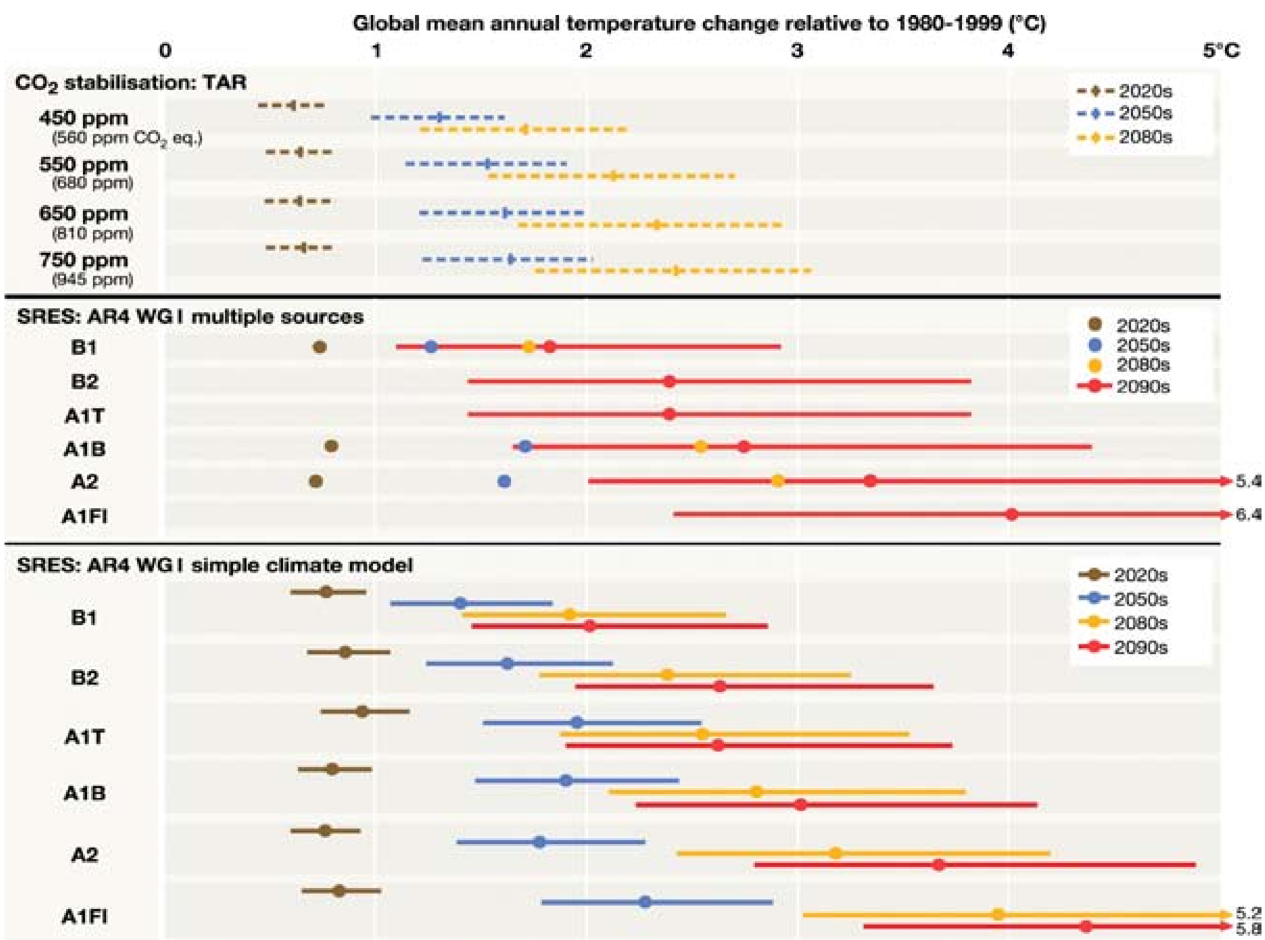

***Figure 1**. Global mean temperature change (°C) projected for various emissions scenarios (Source: IPCC 2007b:66).*

assumes that the human population reaches 15 billion by 2100 and the global economy maintains a high dependence on fossil fuels. By way of contrast, the B2 scenario projects that the human population will reach about 10 billion by 2100, dependency on fossil fuels is reduced, and environmental protection is emphasized.

4.1 Air Temperature

4.1.1 Historical Trends

The average annual global temperature warmed by about 0.76°C over the last century (IPCC 2007a:5), but warming in Canada was double the world average. The average temperature in Canada has increased about 1.2°C in the last 58 years (Environment Canada 2006). That warming was not uniform across the country. For example, average annual temperatures increased about 2°C in northwestern British Columbia and the Kluane region of the Yukon Territory, and by 1.2°C in south-central Canada, but did not change in Atlantic Canada (Environment Canada 2006). During this period, temperatures across Ontario increased 0 to 1.4°C (Chiotti and Lavender 2008).

Temperature increases in Ontario were significant in several locations during the 20th century. For example, the average annual temperature near Belleville in Ontario on the north shore of Lake Ontario has increased by 1.14°C since 1921 (Lemieux et al. 2007). In northwestern Ontario, east of Sioux Lookout, the average annual temperature has increased by 1.19°C since 1930. Significant warming in northeastern Ontario has also occurred. Since 1938, the average annual temperature north of Sudbury has increased by 1.14°C, and along the James Bay coastline, the average annual temperature has increased 1.24°C since 1895 (Lemieux et al. 2007). Warming has been more significant in winter and in spring and is believed to have contributed to changes in evaporation rates, less snowfall, more rainfall, and shorter periods with ice cover (Schindler 1997, Mekis and Hogg 1999, Mortsch et al. 2000, Zhang et al. 2000, Lemieux et al. 2005, Vincent and Mekis 2005).

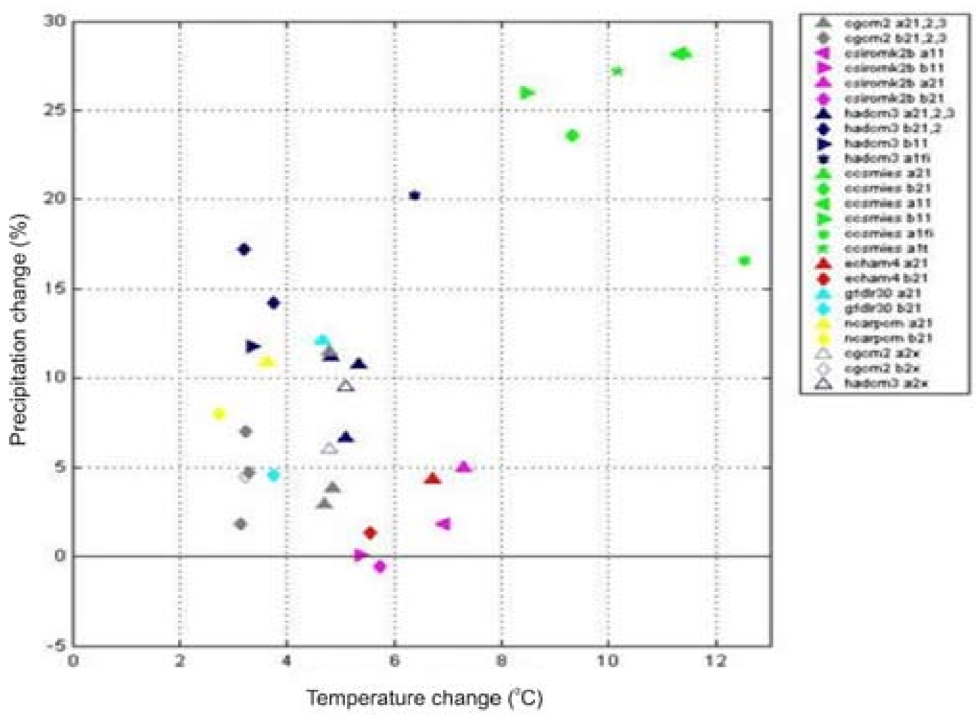

Figure 2. *Average annual changes in temperature (°C) and precipitation (%) at Wabakimi Provincial Park in northwestern Ontario projected for 2100 under various emission scenarios (Source: Lemieux et al. 2007). Each model name is followed by the emission scenario used and represented by a uniquely coloured and shaped plot marker (e.g., cgcm2 a2x means Canadian global climate model, second generation, using the A2 emissions scenario).*

4.1.2 Future Projections

The average annual global temperature is projected to warm 1.1 to 6.4°C during the next century, with land areas warming more than the oceans and higher latitudes warming more than lower latitudes (IPCC 2007a:13). The additional heat in the atmosphere will increase variability in precipitation and wind patterns. For example, as more heat is trapped in the lower atmosphere by additional greenhouse gases, the frequency and size of extreme weather events such as ice storms, heavy rains, droughts, and wind storms are expected to increase (IPCC 2007a:15).

Modelled projections for Ontario suggest that air temperature will increase, but as described above, the size of the projected increase will depend on how much greenhouse gas is released into the atmosphere. For example, projections based on the CGCM2 and A2 scenario indicate that Ontarians will experience significant warming, with maximum increases of average annual temperature of 6 to 7°C near Hudson Bay (Figure 3). The same model projects the average annual temperature of southwestern Ontario, including Toronto and the Niagara Peninsula, to increase by 5 to 6°C. Across the province, warming will be greater in winter than in summer and greater in the north than in the south (Colombo et al. 2007:1) (Tables 1 and 2). Water temperatures will be higher for longer periods of the year as well. For example, Trumpickas et al. (2008) project that under the A2 scenario the number of days during which surface temperatures in Lake Superior are above 4°C will increase by 90 days from the baseline (1971-2000) to the 2071-2100 period (Table 3).

4.2 Precipitation

It is important to note that precipitation scenarios are characterized by much uncertainty. Globally averaged mean water vapour, evaporation, and precipitation are projected to increase (Meehl and Stocker, 2007:750), however, this change will not be consistent everywhere on Earth. For example, precipitation levels are projected to decline in tropical areas and increase at high latitudes (IPCC 2007a:74). In addition, model projections suggest that the frequency of heavy rainfall events will increase in many regions, including some in which the mean rainfall is projected to decrease (IPCC 2007a:74, Meehl and Stocker 2007:750).

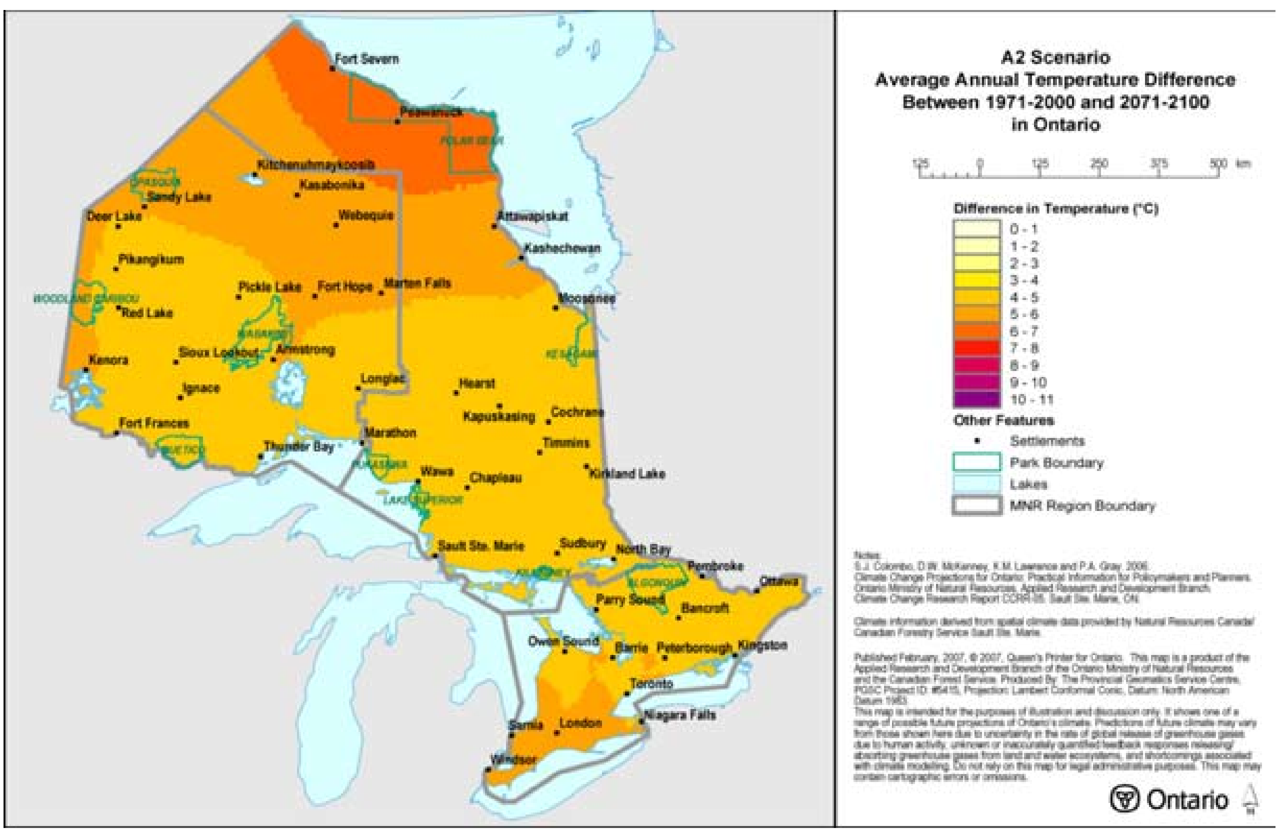

Figure 3. *Projected change in average annual temperature between periods 1971 to 2000 and 2071 to 2100 using the second version of the Canadian Global Climate Model (CGCM2) and the A2 emissions scenario (Source: Colombo et al. 2007:4).*

Table 1. *Projections of average summer (June-August) air temperature increases (°C) for Ontario by MNR Region compared to the 1971 to 2000 reference period (from the CGCM2 model – A2 and B2 scenarios – in Colombo et al. 2007).*

Period	Scenarios	MNR Region		
		Southern	Northeastern	Northwestern
2011-2040	A2	0 to +2	0 to +2	0 to +3
	B2	0 to +2	0 to +3	0 to +2
2041-2070	A2	+1 to +3	+1 to +4	+2 to +4
	B2	+1 to +3	0 to +4	+1 to +4
2071-2100	A2	+3 to +5	+3 to +6	+3 to +6
	B2	+3 to +5	+3 to +5	+3 to +5

Table 2. *Projections of average winter (December to February) air temperature (°C) increases for Ontario by MNR Region compared to the 1971 to 2000 reference period (from CGCM2 model – A2 and B2 scenarios – in Colombo et al. 2007).*

Period	Scenarios	MNR Region		
		Southern	Northeastern	Northwestern
2011-2040	A2	0 to +2	0 to +4	+1 to +3
	B2	0 to +2	0 to +4	0 to +3
2041-2070	A2	+2 to +5	+3 to +7	+2 to +6
	B2	+2 to +4	+2 to +7	+2 to +6
2071-2100	A2	+3 to +6	+4 to +10	+4 to +9
	B2	+3 to +6	+4 to +9	+4 to +8

Table 3. *Projected differences from the 1971 to 2000 base period in the number of days with surface temperatures >4°C for the Great Lakes in Ontario (Source: Trumpickas et al. 2008).*

		Great Lakes			
Period	Scenarios	Lake Superior	Lake Huron	Lake Erie	Lake Ontario
2011-2040	A2	+25	+16	+18	+17
	B2	+30	+19	+19	+19
2041-2070	A2	+52	+37	+36	+44
	B2	+42	+31	+30	+36
2071-2100	A2	+90	+62	+61	+76
	B2	+62	+45	+42	+54

4.2.1 Historical Trends

During the 20th century, total annual precipitation increased 13% in Canada south of 55° latitude (Groisman et al. 2001). During the latter part of the century between 1950 and 1998, total annual precipitation increased by about 5% across Canada (Kharin and Zwiers 2000). This change resulted from an increase in the average number of rainy days (+21.4 between 1950 and 2005), not an increase in the frequency or intensity of extreme precipitation events (Zhang et al. 2001,Vincent and Mekis 2006). The changes in precipitation patterns were not the same across Canada. For example, between 1895 and 1995 in the Great Lakes-St. Lawrence region east of Lake Superior and east of Lake Huron-Georgian Bay, annual precipitation increased by 150 mm (15-20%) (Mekis and Hogg 1999).

4.2.2 Future Projections

Some models and scenarios project that total annual precipitation may increase up to 15% in some areas of the Great Lakes-St. Lawrence Basin (Mortsch et al. 2005). These precipitation changes will vary by season and location. For example, using greenhouse gas concentrations developed for the A2 scenario, the CGCM2 projects decreased precipitation by 2070-2100 in northwestern and southern Ontario, and increased precipitation for northeastern and central Ontario during the warm season (April to September) (Table 4) (Colombo et al. 2007). During the cold season (October to March) areas around Lake Superior, Lake Nipigon, Lake of the Woods, and James Bay are projected to receive more precipitation, while the far north is projected to receive less (Table 5) (Colombo et al. 2007).

4.3 Wind

Although some models suggest that average wind speed will decline during the 21st century, the projections are uncertain (see Breslow and Sailor 2002, Pryor and Barthelmie 2010, Pryor and Ledolter 2010). In addition, wind speed change may be greater in some seasons than others. Continued monitoring and modelling with improved information will help to reduce the uncertainty around forecasts of future wind speeds.

4.4 Extreme Events

Every year extreme weather events (e.g., tornados, intense rainfall, hail, heavy snowfall, drought, and heat waves) alter ecosystems, jeopardize human health and safety, and cost Ontarians millions of dollars (Klaassen et al. 2006, Chiotti and Lavender 2008). While increased atmospheric heat energy and associated moisture enhance the potential for extreme events (Zwiers and Kharin 1998, Kharin and Zwiers 2000, 2005), the types and frequencies of events during the next century are difficult to project. Initial modelling studies suggest that extreme precipitation events will increase 2 to 4 times over the next century (Zwiers and Kharin 1998, Environment Canada 2005, Kharin and Zwiers 2005).

Table 4. *Projected average warm season (April to September) changes in precipitation (% difference) for Ontario by MNR Region compared to the 1971 to 2000 reference period (from the CGCM2 model – A2 and B2 scenarios – in Colombo et al. 2007).*

Period	Scenarios	MNR Region		
		Southern	Northeastern	Northwestern
2011-2040	A2	-10 to +10	-20 to +20	-20 to +20
	B2	-10 to +10	-20 to +20	-20 to +20
2041-2070	A2	-10 to +10	-20 to +20	-10 to +20
	B2	-10 to +20	-20 to +20	-20 to +10
2071-2100	A2	-20 to +10	-20 to +20	-20 to +10
	B2	-10 to +10	-20 to +20	-10 to +10

Table 5. *Projected average cold season (October to March) changes in precipitation (% difference) for Ontario by MNR Region compared to the 1971 to 2000 reference period (from the GCM1 model – A2 and B2 scenarios – in Colombo et al. 2007).*

Period	Scenarios	MNR Region		
		Southern	Northeastern	Northwestern
2011-2040	A2	-30 to 0	-30 to 0	-30 to +40
	B2	-20 to 0	-40 to +20	-40 to +20
2041-2070	A2	-20 to 0	-30 to 0	-30 to +50
	B2	-30 to 0	-40 to +20	-30 to +50
2071-2100	A2	-30 to 0	-30 to +30	-30 to +60
	B2	-30 to 0	-40 to +20	-30 to +50

5.0 The Effects of a Changing Climate on Lake, Stream, River and Wetland Ecosystems in Ontario: A Summary

In Ontario, four major drainage basins determine the amount and direction of flow of surface water (OMNR 1984:14). Within each basin the arrangement of streams, rivers, lakes, wetlands, and ground water determines how surface water is stored and released (OMNR 1984:14). Rivers and lakes in the Hudson Basin drain north into Hudson Bay and James Bay while the rivers and lakes in the Nelson Basin drain west to Manitoba. Water bodies in the Great Lakes Basin (Lake Superior, Lake Huron, Lake Erie, and Lake Ontario) drain into the Great Lakes and rivers and lakes in the Ottawa Basin drain into the Ottawa River en route to the St. Lawrence River (OMNR 1984:31). The drainage basins comprise many secondary and tertiary watersheds (Figure 4).

Figure 4. *The water basin (inset) and secondary watershed classification system used in Ontario.*

5.1 Lake Ecosystems and Climate Change

5.1.1 Introduction

A lake is a standing body of water that occupies a depression in the Earth's surface and is more or less surrounded by land. Lakes gradually fill with sediments that accumulate through run-off and wind erosion, as well as dead organic matter.

Lakes in Ontario, including the Great Lakes, encompass a total surface area of 181,153,000 ha, which is about 17% of the province (OMNR 1984:14). Most of Ontario's lakes are less than 100 ha (OMNR 1984:14). Lakes cover about 8% of the northern Hudson Basin and 18% of the northwestern Nelson Basin. In the Great Lakes/Ottawa River basins, the Great Lakes encompass 24% and other inland lakes encompass 6% of the total drainage area (OMNR 1984:14).

Lakes can be classified according to their vertical temperature profile and the seasonality of that profile (Allan et al. 2005). This classification is helpful when examining the effects of climate change on lake ecosystems. In Ontario, most lakes are classified as dimictic lakes, or lakes that circulate freely twice a year in spring and in fall and are thermally stratified in summer (Wetzel 1975:78).

5.1.2 Hydrological Cycle – Lake Levels

Water balance in a lake is determined by the rate of inflow less the rate of loss, which results from precipitation directly onto the lake surface + inflow from streams and rivers + inflow from run-off + groundwater seepage + groundwater springs – flow through an outlet – seepage into groundwater storage areas – evaporation – transpiration from floating plants (Wetzel 1975:39):

• **Precipitation:** The volume, timing, and intensity of precipitation affect water levels. For example, whether precipitation falls as snow or rain in winter can influence water levels in late summer (Allan et al. 2005, Chiew 2007, Kundzewicz and Mata 2007).

• **Inflow and outflow from streams and rivers:** Climate change will affect the volume and timing of stream and river water that supplies lakes. For example, a reduction in streamflow caused by increased temperatures, decreased precipitation, and increased evaporation will reduce lake water inflows.

• **Inflow from run-off:** A reduction in direct run-off caused by increased temperatures, decreased precipitation, and increased evaporation can reduce water volume in a lake. A change in the timing of run-off (e.g., increased winter rain events) can affect late summer water levels.

• **Groundwater inflow and outflow:** Water seeps into the ground and occupies space in pores and cavities between rocks and in unconsolidated materials such as sand and gravel. This subsurface groundwater is an important source of water for streams, rivers, and lakes in many parts of Ontario. In some areas, natural streamflow is almost entirely sustained by groundwater discharge during periods of low precipitation in summer (OMNR 1984:46). Changes in the timing of snow and rainfall events, increased risk of drought and reduced soil moisture, and higher evaporation rates work to reduce recharge rates and groundwater levels (Mortsch et al. 2003:44). For example, drought conditions in Ontario from 1997 to 2000 increased the vulnerability of southern Ontario rural areas to reduced ground water levels, and in some areas people experienced a complete loss of water supply (Piggott et al. 2001 in Mortsch et al. 2003:45). Extreme rainfall events do not necessarily effectively contribute to aquifer recharge rates because much of the water is lost as overland flow and run-off (SWCS 2003 in Mortsch et al. 2003:45). Therefore, in areas that do experience increased rainfall due to climate change, the form of precipitation (e.g., extreme rainfall events) and the timing (e.g., early snow melts) may in fact reduce groundwater recharge rates.

• **Evaporation:** Unless offset by equal or greater amounts of precipitation, increased evaporation resulting from higher temperatures, a longer growing season, and extended ice-free periods, will reduce the volume of water available for streams, rivers, and lakes (Allan et al. 2005, Kundzewicz and Mata 2007).

• **Transpiration:** The amount of water transpired or emitted by a plant through stomatal openings on its leaves depends on its size, light intensity, temperature, humidity, and wind speed. On a hot, dry day a fully grown tree can lose hundreds of litres of water through its leaves. For example, from 1970 to 1990 annual air temperature in the Experimental Lakes Area of northwestern Ontario increased by 1.6°C, and the resulting evapotranspiration increased by almost 50% (Schindler 1998).

In the Great Lakes, fluctuating water levels are important natural phenomena. Between 1918 and 1998, for example, lake levels fluctuated by 1.19 m in Lake Superior and 2.02 m in Lake Ontario (Moulton and Cuthbert 2000). While these fluctuations will continue as the climate changes, they will occur around lower mean water levels (Taylor et al. 2006). Climate model projections for the Great Lakes suggest that water levels could change between -1.38 and +0.35 m by 2100 (Lofgren et al. 2002). Water levels in other Ontario lakes will also be affected. Lower water levels in Ontario will significantly affect aquatic ecosystems including:

- **Physical and chemical processes**: Changes to the physical and chemical processes such as stratification, nutrient cycling, and oxygen dynamics (Wrona et al. 2006).
- **Levels of contaminants:** Lower water levels could amplify the effects of contamination (Mortsch et al. 2003, Wrona et al. 2006). For example, climate change is projected to increase the intensity of extreme rainfall events (Mortsch et al. 2003:54), which will cause episodic water quality problems because these events will increase run-off of soluble pollutants such as phosphorus, nitrates, and pesticides (Mortsch et al. 2003:54). During warming and drought, stored sulphur in wetlands and the littoral zone of lakes may be exposed to the air and re-oxidized causing the re-acidification of water (Yan et al. 1996, Schindler 1998).
- **Access to aquatic habitats**: In areas where changes in precipitation and evaporation lead to reductions in water levels, fish movement, access to spawning and nursery habitat, and migration may be impaired (Koonce et al. 1996 in Mortsch et al. 2003:94, Wrona et al. 2006). Lake morphology significantly influences the size of littoral zones and the associated availability of fish habitat (Schindler et al. 1996). Lakes with a high proportion of pelagic (open) water (i.e., a low perimeter-to-area ratio) do not provide as much habitat as lakes with a high proportion of littoral habitats (Gasith 1991 in Schindler et al. 1996). In large, deep lakes, the pelagic food webs are probably less affected by littoral zone fluxes than small lakes (Schindler et al. 1996).
- **Streamflow:** Reduced streamflow into lakes will increase lake water renewal time (Schindler et al. 1990, 1996; Schindler 1998; Mortsch et al. 2003:13), which could increase the risk of exposure to anoxic conditions.

5.1.3. Temperature – Lake Water

Lake basin shape, lake size, volume of inflow, depth, exposure to wind, and latitude determine the strength and duration of thermal stratification and the seasonal amount of cold-, cool-, and warmwater habitat available for organisms (Wetzel 1975:16, Allan et al. 2005).

In spring, warming temperatures, rain, and wind break up lake ice. At this time of year, similar temperatures at all depths in combination with wind allow the lake water to circulate freely (Wetzel 1975:69). As spring temperatures increase, the surface waters warm more quickly (and become less dense) than bottom waters, which in turn create a thermal resistance to mixing (Wetzel 1975:69). A difference of a few degrees is enough to stop the mixing action. In Ontario, lakes with sufficient depth thermally stratify into three layers:

- **Epilimnion:** The upper layer comprises warm (in dynamic equilibrium with air temperature), circulating water that is oxygenated and biologically productive (McCombie 1959 in Ryder and Pesendorfer 1988:10, Wetzel 1975:70, Allan et al. 2005). Photosynthesis and other production processes generally occur in the epilimnion (Wetzel 1975:325).
- **Metalimnion:** The middle layer or thermocline contains water with a steep thermal gradient or temperature change. Temperature in the thermocline decreases rapidly at a rate of at least 1°C for each metre of depth (Ryder and Pesendorfer 1988:10).
- **Hypolimnion:** In north-temperate lakes found in Ontario, this is a layer of deep, cold, and relatively undisturbed water underneath the metalimnion in which the temperature decreases more gradually with depth than that in the metalimnion until maximum density is reached at 4°C (Wetzel 1975:70, Ryder and Pesendorfer 1988:10).

With declining air temperatures in late summer and fall, the solar heat entering the lake decreases and is eventually exceeded by heat lost to the atmosphere. As surface waters cool, the denser waters sink, mix, and progressively erode the metalimnion. When the thermocline disappears, mixing of the entire water column resumes. Once the temperature of the water reaches the point of maximum density (4°C) ice begins to form (Wetzel 1975:74).

Where it occurs, groundwater significantly influences the hydrology and thermal regime of streams, rivers, and lakes because it provides baseflow and moderates the effect of seasonal air temperature fluctuations on water in temperate climates (Ward 1985 in Meisner et al. 1988). For example, ground water indirectly contributes more than 50% of the flow in streams that discharge into the Great Lakes (Grannemann et al. 2000 in Mortsch et al. 2003:44). Groundwater temperatures vary little throughout the year and approximate average annual air temperature (see Power et al. 1999).

Accordingly, groundwater is a critical factor in the establishment and maintenance of aquatic habitat (Mortsch et al. 2003:44) because groundwater seeps often provide thermal refuges for fish in summer when water temperatures are high.

Atmospheric warming will influence the quantity and quality of water in streams, lakes, rivers, and wetlands as water temperatures and evaporation rates increase, precipitation patterns change, and as the significance of lake ice dynamics is diminished. For example, Trumpickas et al. (2008) projected that surface water temperatures will increase significantly in all of the Canadian Great Lakes under B2 and A2 climate regimes. The models indicate that the number of days with surface water temperatures greater than 4°C will increase by 90 days in Lake Superior and 61 days in Lake Erie by 2100 (see Table 3). All of these changes potentially will have significant implications to the distribution and abundance of aquatic flora and fauna in Ontario.

In Lake Superior, average annual surface water temperatures could increase by 5°C by 2100 according to the CGCM1 and the HadCM2 scenarios (Lehman 2002 in Mortsch et al. 2003:52). Summer maximum surface water temperatures could be greater than 20°C (Lehman 2002 in Mortsch et al. 2003:52). Trumpickas et al. (2008) estimated a potential increase in maximum temperature of 4.1°C (A2 scenario) and 3.1°C (B2 scenario) in Lake Superior and 4.3°C (A2 scenario) and 2.9°C (B2 scenario) in Lake Ontario by 2100 (Table 6).

In a changing climate, warmer water temperatures will affect several lake ecosystem functions, including, but not limited to:

- **The distribution and abundance of fish**: Thermal stratification in a lake is important because it affects the distribution of temperature-sensitive fishes. Coldwater species are forced down to the deeper hypolimnetic waters during the summer months while cool and warmwater fishes are able to access habitat closer to the surface in the epilimnion. A warmer climate could increase the size of the epilimnion and the biologically active zone (Mortsch et al. 2003:50), which means that the thermocline could be deeper and less coldwater (hypolimnetic habitat) would be available as habitat (Stefan et al. 2001). In addition, the hypolimnion itself could warm (Mortsch et al. 2003:50), which would further reduce availability of coldwater habitat. This effect will likely vary geographically in response to factors such as the physical characteristics of the lake and lower/higher wind speeds in spring (King et al. 1997, Snucins and Gunn 2000). Warmer waters will result in reductions of summer habitats for coldwater species such as lake trout and opossum shrimp (*Mysis relicta*) (Schindler 1998). This may favour warmwater species and lead to changes in the fish communities of many lakes across Ontario. Overall, fish productivity may increase in some lakes due to an increase in growth rates and food supply.
- **Changing contaminant flow:** In a warming climate, the nature and magnitude of contaminant transfer in the food webs will likely change. For example, contaminants in bottom sediments may dissociate from the solid phase with a rise in the rate of organic carbon metabolism and, along with other contaminants originating from low temperature concentration, may reach toxic levels in lake bottom waters (Wrona et al. 2006).
- **Contaminant deposition**: Projected temperature increases and changes in the timing and magnitude of precipitation will affect the deposition of contaminants. This may enhance contaminant influxes into aquatic ecosystems and increase the exposure of aquatic organisms resulting in higher contaminant loads, including biomagnification (Wrona et al. 2006).

Table 6. *Projected increase in maximum temperatures of the Great Lakes in Ontario compared to the 1971 to 2000 average (Source: Trumpickas et al. 2008).*

		Temperature Increase (°C)			
Period	**Scenarios**	**Lake Superior**	**Lake Huron**	**Lake Erie**	**Lake Ontario**
2011-2040	A2	+1.3	+1.4	+1.1	+1.2
	B2	+1.4	+1.3	+0.8	+1.1
2041-2070	A2	+2.6	+2.4	+1.6	+2.2
	B2	+2.1	+2.1	+1.7	+2.0
2071-2100	A2	+4.4	+4.3	+3.7	+4.3
	B2	+3.1	+2.9	+2.5	+2.9

- **Nutrient cycling:** A longer growing season and faster metabolic rates may increase the rate of nutrient cycling (Mortsch et al. 2003:50).
- **An increase in undesirable species**: Warmer water enhances productivity, which could increase the number and growth of undesirable species (e.g., algal blooms) (Mortsch et al. 2003:91). Oxygen levels in the hypolimnion can be reduced by the decomposition of organic matter that drifts down from the surface (Allan et al. 2005). In a warmer climate with more primary productivity, more detritus will drift to the bottom, which in turn will lead to, or increase the risk of, hypolimnetic anoxia.
- **Water quality:** Water quality is likely to be degraded by higher water temperatures (Kundzewicz and Mata 2007). For example, in response to earlier warming in spring Lake Erie algae could increase their nutrient uptake earlier and proliferate longer (Atkinson et al. 1999 in Mortsch et al. 2003:91).

5.1.4 Transparency and Ultraviolet Radiation

Water transparency refers to the ability of water to transmit sunlight (direct solar radiation) and skylight (indirect radiation) (Pinsak 1976:48). Water colour, dissolved solids (e.g., dissolved organic carbon), and suspended particles collectively absorb light and determine the penetration of light at depth (Pinsak 1976:48, Schindler 1998, Dodds 2002:218). Transparency in aquatic ecosystems is important because the amount of available light affects photosynthesis, water chemistry, circulation in lakes, stratification, and the transport of nutrients and other material (Pinsak 1976:49).

The Sun radiates energy in many wavelengths that are necessary for life on Earth. But some high energy wavelengths such as Ultraviolet Radiation-B (UV-B) are detrimental to life because they inhibit survival and growth of organisms (Allen 2001). The ozone layer in the upper atmosphere (stratosphere) absorbs UV radiation and prevents most of it from reaching organisms in aquatic and terrestrial ecosystems. However, decades of emissions of ozone-depleting chemicals such as chlorofluorocarbons destroyed significant amounts of ozone, opened up holes above the Antarctic and to a lesser extent over the Arctic, and increased the amount of harmful UV-B radiation reaching plants and animals on Earth.

In response, countries from around the world agreed to the 1987 Montreal Protocol designed to reduce and eliminate ozone-depleting chemicals from the atmosphere. As a result, the trend of increasing depletion of the global stratospheric ozone observed during the 1980s and 1990s is no longer occurring. However, global stratospheric ozone is still about 4% below pre-1980 values and it is not yet clear whether ozone recovery has begun (IPCC 2007a:28).

While more research is needed, it has been suggested that climate warming and increased acidification will reduce the amount of available dissolved organic matter, which will in turn lead to an increase in UV penetration into aquatic ecosystems (Schindler et al. 1996, Schindler 1998). Potential effects of increased UV radiation on aquatic organisms include but are not limited to:

- Decreased nitrogen uptake rates by plankton
- Reduced populations of consumers that feed on primary producers
- Damage to DNA
- Damage to photosynthetic function
- Effects on the competitive ability of different periphyton species
- Changes in phytoplankton species composition
- Exacerbation of the biotic effects of acid precipitation in lakes
- Immune system suppression in fish (Greifenhagen and Noland 2003)

On the other hand, increased exposure to UV-B may slow infection rates and inhibit the spread of parasites. The influence of these factors on the ability of a pathogen to infect a fish or the ability of a fish to defend itself from the pathogen depends on the host fish species, the type of pathogen, and the presence of other stressors (Snieszko 1974, Schindler 1998, Marcogliese 2001, Dodds 2002:220, Wrona et al. 2006).

5.1.5 Turbidity

High levels of turbidity resulting from earlier spring run-off or extreme rainfall events can limit light penetration, which in turn reduces photosynthesis and the availability of habitat for fish, benthic fauna, and other organisms (Ryder and Pesendorfer 1988:6, Wrona et al. 2006). In a warming climate the frequency and intensity of turbid conditions could change. For example, enhanced permafrost thawing in Ontario's Far North could increase nutrient, sediment, and carbon loadings into aquatic ecosystems, which could have both positive and negative effects on freshwater habitats. As a case in point, increased nutrient and organic carbon loading will enhance productivity in more northerly lakes.

5.1.6 Wind

Wind is an important force in lake ecosystem structure and function because it provides energy for waves, is a principal force for lake currents and shifting ice cover, and influences the thermal regime of lake water (Derecki 1976:76, Ryder and Pesendorfer 1988:5). Although wind patterns will likely change across Ontario in response to a warmer climate with more energy in the atmosphere, it is unclear whether average wind speeds will increase or decrease. Increases in the frequency, duration, and average speed of wind could affect aquatic ecosystems in Ontario by:

- Increasing evaporation rates of lake water
- Increasing speed of ice-out in spring
- Increasing wind erosion and general storm damage along lake coastlines
- Increasing deposition of wind-blown sediment in rivers, lakes, and wetlands
- Deepening thermoclines in lakes

Decreased wind could:

- Decrease the effect of increasing evaporation rates in a warmer climate
- Exert less force on ice movement, particularly during the ice-out period in spring
- Reduce storm damage in coastal areas
- Reduce the effect of airborne sedimentation
- Result in shallower thermoclines in lakes

5.1.7 Ice Dynamics

Ice is a significant force in the structure and function of Ontario's aquatic ecosystems. For example, it reduces evaporation of lake water during winter and protects shorelines from damage caused by extreme winter storms. Warmer temperatures will change the ice regime of water bodies in northern regions, including Ontario (Assel et al. 1995, 2003; Assel and Robertson 1995; Fang and Stefan 1998; Quinn et al. 1999; Magnuson et al. 2000; Lofgren et al. 2002; Kundzewicz and Mata 2007).

In response to warmer temperatures between 1864 and 1995 (an increase in air temperature of 1.2°C over 100 years), ice break-up dates were, on average, 6.5 days earlier and freeze-up dates were 5.8 days later in the Northern Hemisphere (Magnuson et al. 2000). For example, freeze-up dates are 13 days later and break-up dates are 10.6 days earlier on Manitoba's Red River. The duration of ice cover on Lake Superior at Bayfield, Wisconsin decreased between 1857and 2007 at a rate of 3 days per decade, or 45 days over the 150 years (Howk 2009). To the south, freeze-up dates are 37 days later and break-up dates are 7 days earlier in Toronto Harbour (Lofgren et al. 2000).

Lofgren et al. (2002) examined the implications to ice dynamics in Lake Erie and Lake Superior using a 2xCO_2 scenario and the CGCM1 and the HadCM2 climate models. Compared to the 1951 to 1995 period, model results indicate that ice duration (in days) in Lake Superior could decrease by 65 to 74% (CGCM1) or 33 to 40% (HadCM2) by 2100. Similarly, model results project that ice duration on Lake Erie will decrease by 70 to 80% (CGCM1) or 44 to 49% (HadCM2) by 2100 (Lofgren et al. 2002) (Table 7). In addition, the number of ice free days on the Great Lakes will increase significantly (Table 8) (Lofgren et al. 2002). Break-up and freeze-up periods will change for small lakes as well. Stefan and Fang (1997) used the Canadian Climate Centre Global Circulation Model (CCC GCM) and a 2xCO_2 climate change scenario to project that ice-cover will decrease by 45 to 60 days by 2090 on small lakes in Minnesota.

Table 7. *Average ice duration for selected areas in Lake Superior and Lake Erie – historical averages and future projections based on two climate change models (Source: Lofgren et al. 2002).*

Location	Base ice duration (days; 1951-1995 average)	Projected ice duration (days)					
		CGCM1 at $2xCO_2$			HadCM2 at $2xCO_2$		
		2030	2050	2090	2030	2050	2090
Lake Superior Basins							
West Basin	111	83	69	32	97	91	66
East Basin	108	80	65	28	95	90	68
Whitefish Bay	115	91	77	40	103	99	77
Lake Erie Basins							
West Basin	91	44	40	27	76	71	51
Center Basin	77	41	35	11	57	52	39
East Basin	92	51	39	11	69	63	50

Table 8. *Percent of ice-free winters for selected areas in Lake Superior and Lake Erie – historical averages and future projections based on two models (Source: Lofgren et al. 2002).*

Location	Base ice free winters (%; 1951-1995)	Projected ice free winters (%)					
		CGCM1 at $2xCO_2$			HadCM2 at $2xCO_2$		
		2030	2050	2090	2030	2050	2090
Lake Superior Basins							
West Basin	0	2	7	43	0	0	7
East Basin	0	4	9	45	0	0	4
Whitefish Bay	0	0	4	36	0	0	4
Lake Erie Basins							
West Basin	2	33	52	74	6	6	17
Center Basin	2	63	78	96	17	22	61
East Basin	2	63	76	96	15	22	61

In a warmer climate, the role of ice will change significantly. Given that ice dynamics can affect many ecosystem features, there will be negative and positive consequences of less ice in Ontario. Negative effects of climate change on ice dynamics in lake ecosystems include, but are not limited to:

- **Increased evaporation rates:** Climate-induced shortening of the ice-in season will affect evaporation rates (Allan et al. 2005). In the Great Lakes, the greatest losses due to evaporation occur in late autumn and winter when cold, dry air passes over the warmer lakes (Mortsch et al. 2003:49).
- **Loss of shoreline protection:** Ice protects the shoreline and prevents erosion during winter storms. Therefore, a reduction in the ice-in periods will render shorelines more susceptible to extreme storm events (Mortsch et al. 2003:49).
- **Increased productivity:** Extension of the ice-free season and increased water temperatures will lengthen the overall period of productivity. This may lead to increased oxygen consumption in the deeper waters as algae decompose, which may limit the amount of oxygen available for species inhabiting deeper waters (Wrona et al. 2006).

Positive effects of a shorter ice-in period include:

- **Increased potential for over-winter survival:** A shorter ice-in season means a reduced risk of low dissolved oxygen conditions, which will increase the chances of over-winter survival of fish eggs (Mortsch et al. 2003:49) and fish, particularly in some of the more shallow mesotrophic and eutrophic lakes (Stefan et al. 2001).
- **Increased fish productivity:** Loss of winter ice cover and associated warming may be beneficial to fish populations where productivity and growth are currently limited by the duration of open water periods (Hostetler and Small 1999 in Mortsch et al. 2003:87, Stefan et al. 2001).
- **Smaller annual contaminant pulse or toxic shock:** A shorter ice-in season means that fewer atmospheric airborne particulates are stored in the snow and ice pack. Accordingly more of the total annual deposition of toxic material is gradually introduced into the system and the size of the spring-time toxic pulse that is flushed into the lake in spring is smaller.

5.1.8 Chemical Characteristics

5.1.8.1 pH

pH is an abbreviation for the 'potential of Hydrogen' and is a measure of acidity or alkalinity. In acidic reactions, hydrogen ion (H+) activity increases from neutrality (pH 7) and in more alkaline reactions H+ ion activity decreases from neutrality (Wetzel 1975:174). The range of pH in natural waters can extend from <2 to 12, and is governed to a large extent by the interaction of H+ ions arising from the breaking apart of H_2CO_3 (carbonic acid) and from OH- (hydroxyl) ions that result from the break up of the bicarbonate molecule (Wetzel 1975:174).

Acid rain resulting from decades of emissions of sulphur and nitrogen oxides into the atmosphere by Canadian and American industry stressed thousands of streams, rivers, lakes, and wetlands in many parts of North America, including Ontario (Minns et al. 1990, Doka et al. 2003). For example, in the 1970s more than 53% of Ontario was subjected to acidic precipitation ranging from a pH of 4.2 to a pH of 5.5 (Rubec 1981:8). And about half of this area in the central part of the province is underlain by the Precambrian Shield made of granitic rocks where the soils have a low capacity to neutralize acids (Environment Canada 1988, Schindler 1998). Acidification had significant effects on biodiversity in and around affected wetlands, rivers, streams, and lakes. In response to a reduction in some emissions, some lakes are recovering, however, many lakes are still acidifying or showing no signs of recovery (Keller 2009).

Climate change will exacerbate the effects of acid deposition in a variety of conditions:

- In a warmer, drier climate, increased exposure of peatlands and wet soils to atmospheric oxygen will cause re-oxidation of sulphur that has been deposited as acid rain and stored in soils and vegetation.
- During periods of high stream flow, flooding, or extreme precipitation events, pulses of sulphuric acid will be released into streams and rivers following periods of drought (Schindler 1998). Pulses will be more acidic in eastern Ontario because of high sulphate deposition and less acidic in northwestern Ontario where deposition has been lower (Schindler 1998).
- With lower water levels, sulphur rendered inactive and stored in the upper areas of the littoral zone of lakes will be re-oxidized causing lakes to re-acidify (Yan et al. 1996, Magnuson et al. 1997 in Schindler 1998). This will delay recovery of many lakes (Schindler 1998).

Acidification also exacerbates the effects of climatic warming because dissolved organic carbon (DOC) is greatly reduced in acidic lakes below pH 5 due to photolytic bleaching and mineralization (transformation of organic matter into mineral) (Schindler 1998). Reduction of DOC concentrations of 90 to 95% have been documented for acidified lakes in Ontario, which greatly increases the penetration of solar energy and thereby deepens the thermocline (Dillon et al. 1984 in Schindler 1998) and permits increased penetration of harmful UV radiation (Schindler 1998).

5.1.8.2 Oxygen

The distribution and abundance of dissolved oxygen in lake water significantly affects the distribution, growth, and abundance of organisms (Wetzel 1975:123, Upchurch 1976:170). Oxygen levels in water depend on a constant exchange with the atmosphere and photosynthetic activity (Wetzel 1975:123, Upchurch 1976:170, Smith 1980:37). In a warmer climate, oxygen availability is reduced because the amount that can be dissolved in water is lower and because the metabolic rates of organisms are higher (Lehman 2002 in Mortsch et al. 2003:52).

In stratified lakes in summer, dissolved oxygen levels in the epilimnion are constantly being renewed through exposure to the atmosphere. The hypolimnion, on the other hand, deoxygenates in response to bacterial action that uses oxygen to break down detritus (Upchurch 1976:170). In fact, oxygen consumption is very significant at the sediment-water interface, where accumulating organic matter and bacterial metabolism is most intense (Wetzel 1975:127).

As air temperatures cool in the late summer and fall, stratification dissipates, the waters circulate freely and oxygen is absorbed until ice formation when the exchange of oxygen with the atmosphere stops. Oxygen depletion in some Ontario lakes may be severe under ice and may kill fish in winter (Ryder and Pesendorfer 1988:13).

The effects of climate change on dissolved oxygen levels include:

- Warmer water temperatures may reduce the length of the ice season and therefore reduce the risk of winterkill caused by oxygen depletion.
- A warmer climate could extend the period of thermal stratification, which prevents re-oxygenation of the deeper, hypolimnetic waters below the thermocline. Therefore, warmer lake temperatures could lead to anoxia by increasing the metabolic rate of sediment bacteria as well as biological productivity and respiration in the water column, and by decreasing dissolved oxygen saturation values (Blumberg and DiToro 1990 in Mortsch et al. 2003:91). Less dissolved oxygen below the thermocline of the lakes would degrade habitat in stratified lakes for coldwater fish such as lake trout during summer (Crowder et al. 1996, Magnuson 1998 in Mortsch et al. 2003:95).

5.1.8.3 Carbon

Carbon is critical to life because it provides the fundamental building block for organic compounds and photosynthesis. Organic carbon is created from the decomposition of plants and animals. For example, in soils and sediments, organic carbon ranges from freshly deposited litter (e.g., leaves, twigs, and branches) to highly decomposed humus. Carbon is found in different sizes, configurations, and amounts in aquatic ecosystems, such as larger sized particulate organic carbon and smaller sized dissolved organic carbon (DOC). DOC is important because it is:

- A source of energy (e.g., a food source for micro-organisms) in aquatic ecosystems.
- Part of the acid-base chemistry of many low-alkalinity, weakly buffered, freshwater systems.
- Capable of forming water-soluble complexes with trace metals that can be transported and taken up or consumed by organisms. Metals form strong complexes with dissolved organic carbon, which enhances metal solubility while reducing metal bioavailability.
- In conjunction with other dissolved and particulate matter, organic carbon affects light penetration in aquatic ecosystems. High organic carbon loads can significantly impede phototrophic activity. On the other hand, DOC can reduce the effects of UV-B radiation.

Carbon is available from allochthonous and autochthonous sources. Allochthonous carbon comes from soils and vegetation in the surrounding area and in reaction with water can form any number of aqueous compounds (e.g., carbonic acid, bicarbonate, minerals) that affect bio-geo-chemical cycling. Autochthonous carbon is derived in the lake from respiration by organisms such as algae and macrophytes, and through oxidation of organic matter (e.g., detritus) on the bottom of lakes once these organisms die (Wetzel 1975:166, Upchurch 1976:167).

A warmer climate could affect the aquatic ecosystem carbon cycle in many ways, including:

- **Microbial decomposition:** Microbial decomposition rates are likely to increase in response to increasing temperatures (Wrona et al. 2006).
- **Decomposition of organic materials:** Enhanced decomposition of organic materials will increase the availability of dissolved organic carbon balance in northern lakes (Wrona et al. 2006). On the other hand, a longer growing season and faster metabolic rates will result in more demand for carbon potentially decreasing the amount of bio-available carbon in the ecosystem (Mortsch et al. 2003:50).
- **Thermokarsting:** Thawing permafrost and warming of frozen soils will result in the release of organic matter and nutrients (Wrona et al. 2006).
- **The flow of dissolved organic carbon:** In northern Ontario, increased dissolved organic carbon caused by thawing permafrost and increased vegetation productivity may reduce penetration of damaging UV radiation, decrease photochemical processing of organic matter, and decrease primary productivity due to lower light availability (quantity and quality) (Wrona et al. 2006).
- **The flow of dissolved organic carbon:** Warmer temperatures and drier hydrological conditions have been shown to reduce the dissolved organic carbon concentration in lakes, exposing biota to increased UV-B radiation (Schindler et al. 1996).

5.1.8.4 Phosphorus

Biological metabolism and associated productivity is governed to a large extent by the rate of phosphorus cycling in relation to the introduction of natural and human-caused phosphorus to freshwater ecosystems (Schindler 1977 in Steinman and Mulholland 1996, Schindler et al. 1996, Wetzel 1975:215). For example, phosphorus is often the controlling nutrient in the production of phytoplankton (Upchurch 1976:179). The only natural source of phosphorus is limited to the weathering of phosphatic minerals, and in many ecosystems growth of plants and animals is limited by phosphorus availability (Upchurch 1976:179). Once phosphorus is in the food chain, a portion of it is conserved and recycled from producer to consumer to decomposer to producer (Upchurch 1976:179).

During the 20th century, the accelerated use and inefficient recovery of phosphorus in agricultural, domestic, and industrial products led to an increase of phosphorus in aquatic ecosystems (Wetzel 1975:215). Phosphorus functions as a pollutant when it is artificially introduced into aquatic ecosystems, because excessive amounts promote the growth of photosynthetic organisms such as algae to such densities that their biological function degrades, alters, or forms part of a process of degradation of water quality (Environment Canada 2001).

In many systems, such as Lake Ontario, significant progress has been made to reduce the introduction of phosphorus into ecosystems, and as such the productivity of lakes affected by increased introductions of phosphorus has declined (Chu et al. 2004). Even so, phosphorus continues to leach into aquatic ecosystems from surrounding watersheds, particularly from wastewater effluents (Medeiros and Molot 2006).

Generally, a warmer climate will affect the phosphorus cycle in a number of ways, including:

- **The timing of primary productivity:** Mixing depth affects primary productivity. Most algal biomass is produced in a primary bloom in spring and a secondary bloom in autumn in response to thermal mixing and nutrient availability. With a longer more stable thermocline in a warmer climate, the spring algal bloom in some parts of the lake is projected to diminish because the earlier stratification will cap or cut-off nutrient supply (Brooks and Zastrow 2003 in Mortsch et al. 2003:53). Fall production could also decrease due to an extension of the stratified period.
- **An increase in primary productivity in nearshore areas:** Nearshore areas may not be as nutrient limited because they receive nutrients from catchment run-off and are exposed to wave and wind mixing (Bootsma 2001 in Mortsch et al. 2003:53).

5.1.8.5 Nitrogen

Nitrogen is an element that circulates through air, water, soil, plants, and animals as part of the nitrogen cycle, and is an important nutrient for survival, growth, and development. For example, atmospheric nitrogen is converted or fixed by bacteria inhabiting plants into substances such as ammonia that green plants can absorb and use to make proteins that are in turn eaten by animals. In excess quantities and with no other nutrient limitation, nitrogen stimulates growth of aquatic plants and accelerates eutrophication (Upchurch 1976:186). The use of nitrogen compounds (i.e., NO_3^{-1}, NO_2^{-1}, and NH_4^{+1}) in agriculture and domestic activity has increased the influx of nitrogen into Great Lakes (Upchurch 1976:186) and other aquatic ecosystems in Ontario.

In a warmer climate, increased water temperatures will combine with nitrogen to:

- **Increase primary productivity**: In combination with phosphorus and other nutrients, increased nitrogen concentrations will accelerate eutrophication, characterized by abundant plankton and high turbidity (Wetzel 1975:243, Ryder and Pesendorfer 1988:15).

5.1.8.6 Mercury

Mercury is an extremely hazardous material that occurs naturally and is also redistributed into ecosystems through industrial processes. Mercury is found in trace amounts in rocks and soil, and enters terrestrial and aquatic ecosystems as a result of the weathering of rocks and volcanic activity (Goldwater 1971). Historically, artificial sources around the world have included waste from the manufacture of vinyl chloride, the use of mercury compounds on seeds to inhibit fungal growth, as a slimicide in the paper manufacturing industry, and as a by-product of coal combustion to generate electricity (Goldwater 1971, Hodges 1977:423, Sorensen 1991:290).

Plants and animals concentrate or bio-accumulate mercury. In the aquatic food chain, for example, less mercury is excreted than ingested by organisms at each level in the chain. Therefore, algae ingest and accumulate more mercury than exists in the water and fish that feed on the algae bio-accumulate more mercury than is in algae (Goldwater 1971). Mercury accumulation can affect many biological functions. In humans, for example, the consumption of mercury-contaminated fish from the Pacific Ocean near Minimata, Japan resulted in 50 deaths and 200 cases of illness characterized by nervous system failure, vision loss, and brain damage (Hodges 1977:423, Sorensen 1991:286). In fish, mercury toxicity can damage or impair many biological functions including, but not limited to, embryonic development, physiological function (i.e., cause muscle spasms), and tissue viability (e.g., the destruction of gill epithelial membranes) (Sorensen 1991:311).

Mercury is contained in a number of compounds, some of which are more dangerous than others. Organic forms like methyl mercury, rather than inorganic mercurials, are some of the most dangerous, particularly to fish and other wild life (Sorensen 1991:287). For example, seeds treated with methyl mercury (CH_3Hg^+) to act as a fungicide also poisoned birds and other wild life in Sweden in the 1960s (Goldwater 1971). Various forms of mercury discharged into the water can be converted by bacteria living in detritus and in sediments into methyl and dimethyl mercury ($(CH_3)_2Hg$) (Goldwater 1971).

In a warmer climate:

- **Mercury release and uptake will increase:** Mercury release and uptake by biota will likely increase in anoxic conditions because heavy metals such as mercury become more soluble in the absence of oxygen. Oxygen binds with these elements to form insoluble compounds that sink to the bottom and remain trapped in the sediments. As more detritus is added to bottom layers, which in turn requires more oxygen, mercury and other metals are released back into the water for uptake by aquatic organisms (Yediler and Jacobs 1995 in Kling et al. 2003).
- **Mercury toxicity will increase:** Mercury-induced toxicity is a function of species body size, the chemical form of the mercury, and other factors, such as water temperature (Rodgers and Beamish 1981 in Sorensen 1991:295). Metabolism increases at higher temperatures, which increase both the level of mercury accumulation and the susceptibility of fish to it (Macleod and Pessah 1973).

5.1.9 Biological Diversity

Biological diversity refers to the variety of life (as expressed through genes, species, and ecosystems) that is shaped by ecological and evolutionary processes (OMNR 2005:1). Climate change will affect biodiversity of freshwater ecosystems throughout Ontario. The magnitude and extent of the effects and responses of lake ecosystems to a warmer climate will vary from lake to lake. Examples of responses include:

A. Habitat Change – Shifts in Thermal Habitat:

- In many climate warming scenarios, habitat for warm-, cool-, coldwater fish increases in some of the deep stratified lakes if dissolved oxygen concentrations do not become limiting (Mortsch et al. 2003:64). For example, in large deep lakes such as Lake Huron, Lake Superior, and Lake Michigan a warming of 3.5°C is expected to increase available thermal habitat for warmwater fishes that occupy the epilimnion during summer (Allan et al. 2005). Cold- and coolwater fishes are also expected to benefit because this level of warming will not exceed thermal tolerance and will promote metabolic activity (Magnuson et al. 1997).
- In contrast, smaller and shallower lakes may experience a significant loss of cold hypolimnetic volume and consequently coldwater fish may lose habitat (Allan et al. 2005, Magnuson et al. 1997). Lake trout will likely disappear from a number of the shallower lakes in Ontario as temperatures rise. For example, Jackson (2007) found that end-of-summer thermoclines typically reach 15 m in the Atikokan area of northwestern Ontario. Therefore, lakes with maximum depths of less than 20 m were assessed as having high risk of losing lake trout populations due to hypolimnetic habitat loss associated with a warming climate. Lakes with maximum depths of less than 25 m were considered at moderate risk of losing lake trout populations (Jackson 2007).

B. Asynchrony: Decoupling of Ecological Cues:

- Decoupling of ecological cues used by plants likely will occur, but the extent and significance is not well understood (Wrona et al. 2006). Earlier warming of spring temperatures and later cooling in autumn contribute to an earlier start for plant growth and a longer growing season (Mortsch et al. 2003:62). If other factors such as nutrients, water availability, and sunlight are not limited, plant productivity is expected to increase (Mortsch et al. 2003:63).
- Although photoperiod, a biological cue, will not change, water temperature, which influences the timing of spawning events and the growth and survival of biota, will change with climate (Wrona et al. 2006). For some species, such as lake trout, decoupling of ecological cues will significantly affect life-cycle processes.

C. Asynchrony: Decoupling of Species Relationships:

- Predator-prey and parasite-host interactions may be disrupted or decoupled, and important species may disappear from local habitats (National Assessment Synthesis Team 2000).

D. Invasive Species: A Shift in Distribution and Abundance:

- As lake and river waters warm, the distribution of cool- and coldwater fish species will be reduced. In some rivers and lakes a significant increase will occur in the distribution and abundance of warmwater species (Casselman 2002, Casselman et al. 2002, Kling et al. 2003, Shuter and Lester 2004, Chu et al. 2005). In fact, it has been suggested (Magnuson et al. 1997) that warming associated with a doubling of atmospheric CO_2 could result in a 500 to 600 km northward shift in the zoogeographical boundary of some freshwater fish species. For example, it is estimated that a 4°C warming results in a 640 km northward latitudinal shift in thermal regimes for macroinvertebrates (Sweeney et al. 1992 in Allan et al. 2005) and a 500 km northward shift for smallmouth bass and yellow perch (*Perca flavescens*) (Allan et al. 2005). While many aquatic insects have aerial dispersal, fish and other more sedentary organisms do not and may not be able to migrate due to the isolated nature of some lakes and the presence of dams on some waterways (Allan et al. 2005).
- Warmer water temperatures may result in suboptimal thermal regimes that are stressful for fish and render their immune systems more vulnerable to parasites and diseases (Barton and Iwama 1991). This will result in increased incidence of mortality and decreased growth and productivity from disease and/or parasites (Wrona et al. 2006). For example, as southern species migrate northward, they could carry with them diseases not currently found in northern latitudes (Wrona et al. 2006). Climate change may also promote the establishment of new parasites through the accidental or intentional introduction of exotic invasive species and/or through the survival of indigenous fish species that expand their range in response to an increased availability of climate-modified habitat. Opportunities for parasitic infection can result from a change in habitat (e.g., higher temperatures and shorter cold periods can accelerate parasite development) or through the host fish (e.g., shifts in fish feeding affecting parasite development) (Greifenhagen and Noland 2003: 117-118). Higher parasite development rates may increase burdens on fish hosts, which are likely to result in poorer health and decreased productivity of the population (Marcogliese 2001).
- Shifts in thermal regimes that result in increased local densities of hosts, especially intermediate hosts such as planktonic or benthic invertebrates, are also likely to increase parasite species diversity (Marcogliese 2001).

E. Invasive Species: Exotics

- An invasive species has traditionally been defined as a species that is beyond its natural range or natural zone of potential dispersion (Mortsch et al. 2003:63). Many species have invaded Ontario's lakes in the last 200 years. For example, invasive species have entered the Great Lakes through bilge water discharge by ocean-going vessels on the St. Lawrence Seaway and by accidental and deliberate releases of baitfish and other species (Taylor et al. 2006). Warmer waters may improve the chances that invasive species will establish in the Great Lakes and inland waters of Ontario. Species currently limited to more southerly aquatic ecosystems in the United States may be able to extend their range northward in warming waters through intentional (e.g., disposal of bait fish) or accidental releases (e.g., in the bilge water of ships). For example, most Ponto-Caspian invasive species originate in warmer waters, which provide them a competitive advantage over cool and coldwater species inhabiting the Great Lakes (Schindler 2001). Asian carp species are currently thriving in the Mississippi River system and have reached waters as far north as the Chicago Sanitary and Ship Canal. Although an electric barrier currently prevents carp from entering Lake Michigan, the potential for invasion remains. In addition, attempts to transport live carp into Canada have occurred in the past and potentially will occur in the future.

F. Changes in Community Composition:

- Casselman (2002) used representative species from the cold-, cool-, and warmwater thermal guilds to illustrate fish community changes. Beginning with a community in which the three thermal guilds were assumed to be equally represented, a 1°C temperature increase was predicted to change the community structure to 69% warmwater fish, 12% coolwater fish, and 19% coldwater fish. With a 2ºC change, the community would consist of 93% warmwater fish, 1% coolwater fish, and 6% coldwater fish. These predictions did not include other factors that influence fish recruitment and reproduction such as changes in growth, productivity, prey availability, and competition (Casselman 2002). Given the forecasted temperature changes of between 1.1 and 6.4°C by 2100 (IPCC 2007a:13), many of Ontario's aquatic communities will likely be dominated by warmwater fishes.

- The number of species using habitats bounded by a tertiary watershed is strongly correlated with mean annual air temperature (Minns and Moore 1995). Based on this correlation, Minns and Moore (1995) determined that a temperature increase of 4.5 to 5°C could increase species richness in 137 watersheds throughout Ontario from 12 to 60 species. An increase of 10 species within the tertiary watersheds corresponds to approximately one new species per lake (Minns 1989).

5.1.1.0 Non-climate Drivers

Over the last 50 years, non-climatic drivers have significantly affected freshwater ecosystems in North America, including water pollution, dams, wetland drainage, reduction in stream flow, and lowering of the groundwater table (Kundzewicz and Mata 2007). In comparison, climate-related changes have been small; however, this likely will change in the future as the rate and volume of greenhouse gas emissions increase. For the lakes and rivers or wetlands that have been reduced in size as a result of human modification, use, or drainage, climate change likely will exacerbate the situation if it results in reduced net water availability (i.e., precipitation – evaporation) (Kundzewicz and Mata 2007).

5.2 Stream/River Ecosystems and Climate Change

5.2.1 Introduction

A stream is a flowing body of water that moves within a defined channel to progressively lower elevations in response to gravity. Streams usually feed water into a river, pond, wetland, or lake. A stream ecosystem can flow seasonally or year round and often comprises pools and riffles connected by flowing water courses that are defined by morphology (shape), flow velocity, depth, substratum, and temperature conditions (Frissell and Lonzarich 1996). Deep and shallow areas are usually represented as alternating pools and riffles (Hynes 1970:15). A river is larger than a stream and tends to have permanent flow that feeds water into another river, a lake, or a sea.

Streams and rivers are important because they provide primary and secondary habitat for many organisms, transport water to and through terrestrial ecosystems, and provide water, nutrients, and other compounds necessary for life in lake ecosystems (Allan et al. 2005).

5.2.2 Hydrological Cycle – Stream/River Water Levels

A drainage network is a geo-hydraulic continuum where stream and river corridors have surface and groundwater components that are hydrologically and ecologically interconnected (Stanford 1996). Rivers integrate erosional and depositional habitats, where erosion typically occurs in sections with rapid flow (often in narrow upper reaches) while deposition of silt and detritus occurs in regions of slow current (Statzner and Higler 1985 in Ryder and Pesendorfer 1988:5).

Streams and rivers are lotic ecosystems where water moves rapidly through the system, and water balance is determined by the rate of inflow less the rate of loss, which results from precipitation directly onto the river surface + inflow from other streams and rivers + inflow from run-off + groundwater seepage + groundwater springs – flow through an outlet – seepage into groundwater storage areas – evaporation – transpiration from floating plants:

- **Precipitation:** As is the case with lakes, the volume, timing, and intensity of precipitation affect water levels in streams and rivers. For example, whether precipitation falls as snow or rain in winter can influence water levels in late summer (Allan et al. 2005, Chiew 2007, Kundzewicz and Mata 2007).
- **Inflow and outflow from other streams and rivers:** Climate change will affect the volume and timing of stream and river water flow. Therefore, a reduction in stream flow caused by increased temperatures, decreased precipitation, and increased evaporation will reduce overall availability of water to the stream or river.
- **Inflow from run-off:** A reduction in direct run-off caused by increased temperatures, decreased precipitation, and increased evaporation can reduce the volume of water available to a stream or river.
- **Groundwater inflow and outflow:** Like lakes, groundwater is an important source of water for streams and rivers in many parts of Ontario. In some areas, natural stream flow is almost entirely sustained by groundwater discharge during periods of low precipitation during the summer months (OMNR 1984:46). Changes in the timing of snow and rainfall events, increased risk of drought and reduced soil moisture, and higher evaporation rates work to reduce recharge rates and groundwater levels (Mortsch et al. 2003:44). Extreme rainfall events do not necessarily effectively contribute to aquifer recharge rates because much of the water is lost as overland flow and run-off (SWCS 2003 in Mortsch et al. 2003:45). Therefore even if some streams and rivers experience increased rainfall due to climate change, the characteristics (e.g., extreme rainfall events) and the timing (e.g., early snow melts) of precipitation may in fact reduce groundwater recharge rates.

- **Evaporation:** Unless offset by equal or greater amounts of precipitation, increased evaporation resulting from higher temperatures, a longer growing season, and extended ice-free periods, will reduce the volume of water available for streams and rivers (Allan et al. 2005, Kundzewicz and Mata 2007). Changes in temperature, incoming solar radiation, humidity, and wind speed will also affect evaporation (Kundzewicz and Mata 2007).

Potential effects of a warmer climate on stream/river water levels include:

- **Increased effects of flooding:** Flooding can scour aquatic vegetation from the stream bed and increase the volumes of silt and organic debris deposited downstream, which can destroy eggs, displace young of the year fishes, and suppress benthic production. This may affect fish production through changes in food web dynamics (Ryck 1975 in Ryder and Pesendorfer 1988:9). The vulnerability of a particular fish species to flooding increases if the spawning season coincides with periodic floods (Moyle and Vondracek 1985 in Ryder and Pesendorfer 1988:9).
- **Changes to the freshet:** Historically, significant volumes of water have been stored over winter in the snow pack and released in spring. An earlier (and possibly reduced) freshet may occur in response to warming. This may affect the seasonality of river flows in areas where much winter precipitation currently falls as snow (Westmacott and Burn 1997, Whitfield and Canon 2000 in Mortsch et al. 2003:13, Barnett et al. 2005 in Kundzewicz and Mata 2007). For example, in response to warmer winter temperatures and increased winter precipitation in the Great Lakes region for the periods 1976 to 1985 and 1985 to 1995, hydrologic pattern changes included higher winter flows, changes in spring peak, and lower summer flows (Whitfield and Cannon 2000 in Mortsch et al. 2003:14).
- **Run-off patterns:** The timing and magnitude of run-off is a critical factor influencing biota and ecosystem processes (Poff et al. 1997 in Allan et al. 2005). The effect of the various climate change scenarios is based on complex interactions between water gains through precipitation and losses through evaporation and transpiration (Mortsch et al. 2003:41). And, as noted above, timing of these events is important to ecosystem composition, structure, and function. Most climate change projections suggest that for areas with less water in the system, run-off will decline; more run-off will occur in winter and less run-off in summer (Croley 1990, Lofgren et al. 2002 in Mortsch et al. 2003:41, Nohara et al. 2007 in Kundzewicz and Mata 2007). Historically, winter run-off in the Great Lakes region has been limited by prevailing frozen conditions, where most precipitation fell as snow and was stored in the snow pack until spring (Mortsch et al. 2003:42). Warmer winter temperatures may increase the number of winter rainfall events and volume of run-off water. But given that water infiltration into soils is limited by frozen ground conditions, the amount of water traditionally stored in the soil and slowly released will be reduced. Therefore, an increase in winter rainfall will also increase winter run-off into streams and rivers. In addition, the increased winter precipitation could melt some of the snow pack, increasing stream and river flow even more (Mortsch et al. 2003:42).

5.2.3 Temperature – Stream/River

Stream temperatures are spatially heterogeneous, with temperatures in the summer generally following a gradient of cooler waters upstream and warmer waters downstream (Poole and Berman 2001). Channel morphometry, influxes of groundwater, inflows from tributaries, and surface runoff in areas affected by different land use practices increases the thermal heterogeneity in streams (Poole and Berman 2001, Webb et al. 2008).

Streams and rivers respond rapidly to changes in air temperature because they are relatively shallow, with flowing, mixing water (Allan et al. 2005). Water temperature can change at a rate as high as 3°C per hour (Brown 1969 in Ryder and Pesendorfer 1988:9) while diurnal temperature variations up to 6°C can occur in response to the absorption of solar radiation or the release of heat from the water to the atmosphere (Hynes 1970:29).

Small streams have large thermal fluxes while larger rivers have greater thermal stability (Ryder and Pesendorfer, 1988:11). Streams and rivers do not normally thermally stratify because the current is usually strong enough to keep the shallow waters mixed (Hynes 1970:30, Welcomme 1979:43). There are exceptions, particularly in cases where the main river channel exceeds 15 m in depth (Hynes 1970:30).

Water temperature affects the composition of stream and river biological communities (Ryder and Pesendorfer 1988:9). Annual fluctuation in stream temperature is very important to stream organisms because critical life history variables (e.g., reproduction and growth) of lotic plants and animals (from diatoms and aquatic insects to fish and other poikilothermic vertebrates) are regulated by temperature (Hauer and Hill 1996). For example, many organisms use temperature or temperature change as a cue for emergence (aquatic insects) or spawning (fish) (Hauer and Hill 1996).

Global warming is expected to increase water temperatures of most running water ecosystems (Allan et al. 2005). However, the response of stream temperature to climate change is complex and dependent on topography and geography of the drainage basin in which it is located (Meisner et al. 1988) and surrounding vegetation (Hauer and Hill 1996). Typically, the greatest source of heat in freshwater is solar radiation, which is particularly true for rivers or streams that are exposed to direct sunlight over most of their surface (Hauer and Hill 1996). Many small streams, however, are located under tree canopy cover that shades the water from direct sunlight. In such cases, transfer of heat from the air and flows from groundwater are more important than direct solar radiation in governing stream temperatures (Hauer and Hill 1996). Groundwater discharge is important for maintaining cooler temperatures in streams and provides coldwater refugia during summer (Kaya et al. 1977 in Meisner et al. 1988, Bilby 1984, Mortsch et al. 2003:52) and warmwater refugia in winter (Cunjak and Power 1987 in Meisner et al. 1988). This cooling influence could be reduced as groundwater temperatures increase in response to increases in air temperature (Meisner et al. 1988). Chu et al. (2008) found that streams in southern Ontario with high groundwater discharge may naturally offer more suitable habitat and thermal refugia for coldwater fishes as the climate changes.

5.2.4 Turbidity

Turbidity is likely to be more critical in streams and rivers than in lakes because water levels can change rapidly in streams and rivers. In a warmer climate, streams and rivers may be subjected to:

- **Increased erosion:** Increased erosion from increased flow associated with extreme weather events. Flooding results in large inputs of fine particulate organic matter and dissolved organic matter when water enters the stream (Hynes 1975).
- **Enhanced permafrost thawing**: This thawing may increase sediment and organic matter loads in Far North streams and rivers, which may reduce light penetration and productivity (Wrona et al. 2006).

5.2.5 Ice Dynamics

River beds are susceptible to ice scouring (Ryder and Pesendorfer 1988:6). A warmer climate may increase the size of winter habitat through:

- **Increased flow:** An increase in winter flows and reduced ice cover will potentially increase the availability of under-ice habitat. Streams and rivers that traditionally freeze to the bottom during winter will experience increased flow in response to increasing precipitation and higher winter temperatures. Reduced ice thickness in some areas may provide year-round flowing water, which will increase habitat availability and improve survival of species traditionally susceptible to winter kill (Wrona et al. 2006).
- **Increased oxygen:** A climate-induced decrease in the duration of the river-ice season, or an increase in the size and frequency of open water sections where re-aeration can occur, may decrease the potential risk of oxygen depletion (Prowse and Beltaos 2002).

5.2.6 Chemical Characteristics

Overall, the concentrations and types of chemicals in streams and rivers vary greatly according to location, climate, physiography, geology, surrounding land use patterns, and biota (Hynes 1970:36). For example, terrestrial vegetation can store various mineral elements and influence the rate at which various ions such as calcium, magnesium, potassium, and nitrogen are delivered to the stream (Cummins et al. 1984 in Ryder and Pesendorfer 1988:15).

5.2.6.1 Oxygen

Dissolved oxygen concentrations are not uniform within streams and rivers, and are a function of water temperature, groundwater flow, and stream flow (Hauer and Hill 1996). Seasonal variation in dissolved oxygen content of rivers can result from:

- Leaf inputs in the autumn, which increases oxygen demand and reduces oxygen levels
- Seasonal photosynthesis peaks and declines
- Winter ice cover on rivers, which serves to decrease oxygen levels
- High discharge situations, which tend to reduce oxygen content (Hynes 1970:40)

A warmer climate will:

- **Change oxygen levels:** As stream and groundwater temperatures increase, the oxygen saturation potential of the water will decrease and the rates of decomposition and respiration will increase (Kling et al. 2003:26).
- **Increase the significance of cumulative effects:** Some types of land use change will exacerbate the effects of climate change, including the expansion of urban and industrial areas and agricultural practices. For example, a water quality

sensitivity analysis for the Grand River in southwestern Ontario showed that, in conjunction with nutrient loading, the dissolved oxygen levels were more sensitive to changes in water temperature, particularly overnight water temperature, than to changes in flow (Minshall 2000 in Mortsch et al. 2003:52).

5.2.6.2 Carbon

Allochthonous detrital inputs are primary energy sources in streams and rivers. Coarse particulate organic matter (>1 mm diameter), fine particulate organic matter (0.5 µm to 1 mm), and dissolved organic matter (<0.5 µm) are major energy resources for stream ecosystems because they provide a large proportion of the carbon that is used by stream biota (Cummins 1974, Cummins et al. 1983 in Lamberti and Gregory 1996). In a changing climate terrestrial vegetation will change, and any shifts in surrounding vegetation and leaf chemistry may influence carbon availability and the distribution and abundance of stream biota (Allan et al. 2005).

5.2.6.3 Phosphorus

The major sources of phosphorus in both streams and lakes are rainfall and terrestrial run-off (Hynes 1970:47). Phosphorus concentrations in rivers vary spatially from headwaters to the outlet. In a warmer climate, lower stream flow and high non-point source run-off could increase phosphorus levels (Mortsch et al. 2003:55) and result in an associated change in the productivity of aquatic organisms.

5.2.7 Biological Diversity

The variety of species living in a stream or river can vary from the headwaters to the outlet, and can be influenced by the flow, temperature, substrate, and nutrients available along the stream continuum (Vannote et al. 1980).

A warmer climate will:

- **Reduce available habitat:** The coldwater stream habitat for some fish species decreases with warmer air temperatures and warming of surface waters and ground water inputs (Mortsch et al. 2003:64). Meisner (1990a) projected a significant decline in summer brook trout habitat and increased fragmentation of that habitat in two southern Ontario streams in response to a climate change scenario that projected a 4.1°C increase in water temperature.
- **Increase stress on biota:** Warming could increase thermal stress on stream and river biota. Rivers with low oxygen at low flows will severely limit biota survival and activity (Reiger et al. 1996).
- **Increase productivity:** Primary and secondary productivity will increase when nutrients such as phosphorus and nitrogen are not limiting (Kling et al. 2003:26). But productivity could decline in drought conditions if stream and river habitat shrinks (Kling et al. 2003:26).

5.2.8 Non-climate Drivers

In a natural state, stream and river networks are connected systems in which organisms can move and migrate during periods of change (Allan et al. 2005). For example, during previous periods of climatic change, access to new habitats was critical to the survival of fishes (e.g., Briggs 1986 in Allan et al. 2005) and aquatic invertebrates such as stoneflies (Zwick 1981 in Allan et al. 2005). In the contemporary landscape, rivers have been fragmented by a variety of human activities and therefore species and populations are less able to move to new suitable habitats (Allan et al. 2005). Habitat fragmentation poses one of the most significant threats to aquatic biodiversity during rapid climate change (Poff et al. 2001, 2002 in Allan et al. 2005).

Many human activities disturb and uncouple important ecological processes, and these activities will act synergistically with climate change to alter ecosystem composition, structure, and function, including:

- Stream regulation by dams, diversions, and revetments
- Lotic reaches replaced by reservoirs, which results in the loss of up-downstream continuity and creates migration barriers and nutrient sinks
- Channel reconfiguration and simplification with a loss of woody debris and isolation of riparian and hyporheic components
- Dewatering of channels
- Pollution
- Introduction of exotic species
- Water pollution causing toxicity, eutrophication, and acidification
- Accelerated erosion resulting from roads and deforestation
- Over-harvest of species (Stanford 1996)

5.3 Wetlands and Climate Change

5.3.1 Introduction

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. The five major types of wetlands are:

- **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.
- **Marshes:** 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.
- **Shallow open water:** These wetlands, commonly referred to as sloughs or ponds, are small bodies of standing water that represent a transition from lakes to marshes.
- **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 (Zoltai 1988, NAWCC 1993).

Ontario's wetlands comprise 25 to 33% of Canada's wetlands and 6% of the world's wetlands. Currently, Ontario has about 24 to 31 million ha of wetlands, encompassing 22 to 29% of the province's area. Most of these wetlands are located in northern Ontario. The Great Lakes are a globally significant ecosystem that supports many coastal wetlands, some with globally rare flora and fauna (OMNR 2009). About 80% of the wetlands in southern Ontario have been eliminated or significantly modified.

Wetlands are important because they provide a variety of ecological and socio-economic benefits, including, but not limited to:

- Erosion reduction
- Decreased flood damage
- High quality water
- Habitat for flora and fauna
- A stable, long-term supply of groundwater
- Recreation and tourism opportunities
- Carbon sinks
- A source of valuable products such as timber, baitfish, wild rice, and natural medicines (OMNR 2009)

5.3.2 Hydrological Cycle

Water balance in a wetland is determined by the rate of inflow less the rate of loss, which results from precipitation directly onto the wetland surface + inflow from streams, rivers, and lakes + inflow from run-off + groundwater seepage (only in some wetlands) + groundwater springs (only in some wetlands) – flow through an outlet – seepage into groundwater storage areas (only in some wetlands) – evaporation – transpiration from floating plants.

Climate change will affect the water level in wetlands in many ways including the:

- **Elimination of wetlands:** Reduced water levels associated with increased air temperatures, and changes in precipitation and evaporation rates will modify or eliminate wetlands that function to maintain shoreline integrity, reduce erosion, filter contaminants, absorb excess storm water, and provide fish and wildlife habitat (Whillans 1990, Edsall and Charlton 1997 in Mortsch et al. 2003:85, Mortsch 1998, Branfireum et al. 1999, Devito et al. 1999, Lemmen and Warren 2004).
- **Alteration of wetlands:** Fluctuating water levels will influence the distribution and abundance of coastal wetlands. For example, in the event of a 1 m drop in water levels, the in-shore side of the marsh in Presqu'ile Provincial Park on the north shore of Lake Ontario will dry out and the out-shore side of the marsh likely will extend further out into Presqu'ile Bay (Taylor et al. 2006).
- **Drying of wetlands:** Wetlands, such as bogs, that depend on precipitation and surface runoff rather than groundwater are especially sensitive to drying (Koshida and Avis 1998, Mortsch et al. 2003:65, Allan et al. 2005).

- **Changes to habitat:** Changes in timing, duration, height/elevation of annual and seasonal water levels can:
  - Alter natural succession of wetland plants (Bedford 1992 in Mortsch et al. 2003:87, Wilcox and Meeker 1995, Mortsch 1998)
  - Cause shorelines to recede (Gabriel and Kreutzwiser 1993:124, Koonce et al. 1996) and wetlands to shrink (Atkinson et al. 1999)
  - Decrease nursery and spawning areas (Mortsch et al. 2003:87)

Given their reliance on precipitation, bogs are particularly vulnerable to climate change. Precipitation is the main source of water for bogs, since they are isolated from the local groundwater regime by peat accumulation. A decline in precipitation (and resultant drawdown in water level) will alter the distribution and abundance of vegetation.

5.3.3 Temperature – Wetland

Temperature is a key determinant in the distribution, productivity, and functioning of wetland ecosystems. Warmer air temperatures will:

- **Affect the growing season:** Extend the growing season, alter the timing and effect of seasonal events, and increase evaporation and transpiration rates (Mortsch et al. 2006).
- **Dry out some wetlands:** Peatlands are likely to dry due to increased evapotranspiration. The drying will promote establishment of woody species and increase the rate of peat decomposition and carbon loss (Wrona et al. 2006).

5.3.4 Ice Dynamics

In Ontario's 'Far North', a warmer climate will change soil ice conditions and dramatically alter ecosystem composition, structure, and function. In some locations, thermokarsting may lead to ecosystem flips whereby existing terrestrial ecosystems (e.g., forest) are replaced by aquatic ecosystems such as ponds and lakes (Beaulieu and Allard 2003, Wrona et al. 2006). As permafrost soils in shallow open waters warm, nutrient and carbon loading to these freshwater ecosystems will rise. This will enhance nutrient cycling and productivity and alter the generation and consumption of carbon-based trace gases (Wrona et al. 2006).

5.3.5 Chemical Characteristics

5.3.5.1 Oxygen

Wetlands are often anaerobic (without oxygen) which greatly reduces the rate of decomposition relative to aerobic systems. Accordingly, biomass production usually exceeds decomposition and results in the net accumulation of wetland organic matter and carbon. Climate change may further increase productivity in wetlands by extending the growing season in regions where water quantity and quality are not compromised.

5.3.5.2 Carbon

Wetlands are an important source of dissolved organic carbon (DOC) for ponds, lakes, and streams. The outflow of DOC is related to total annual precipitation and basin topography and will be affected by changes in temperature and precipitation. Some climate change scenarios suggest a decrease in wetland discharge and DOC outflow (Clair et al. 1998).

Carbon sequestration is an important part of a wetland's life cycle. The condition of wetlands (e.g., peatlands) as carbon sinks or sources will likely change (Wrona et al. 2006). High latitude aquatic ecosystems function as sinks or sources of carbon, depending on temperature, nutrient status, and moisture levels. Initially peatlands will become sources of carbon as permafrost thaws, soils warm, and accumulated organic matter decomposes (Wrona et al. 2006).

5.3.6 Biological Diversity

One of the most significant effects of climate change on wetland ecosystems will be changes in the distribution and abundance of vegetation. For example, in locations where water levels decline or are inconsistent, wetland vegetation communities requiring less water such as sedges, grasses, wet meadows, and trees will replace emergents and submergents (Mortsch et al. 2003:65).

Effects on faunal diversity will be significant as well. For example, Doka et al. (2006) assessed the vulnerability of 99 fish species inhabiting coastal wetlands in the lower Great Lakes to climate change and reported that vulnerable species included coolwater and warmwater spring spawning species that use shallow, vegetated water. Less vulnerable species included coldwater fall-spawners (such as lake trout) that use deeper, more open-water habitats to spawn. Avifauna will be affected as well. For example, water conditions in May are critical for waterfowl breeding success and the number of spring-time wetlands correlates with annual waterfowl production and breeding pair density. The quality of breeding habitat depends on the type, quality, and permanence of wetland complexes because the persistence of wetlands through the waterfowl breeding season is important for brood survival (Clair et al. 1998).

5.3.7 Non-climate Drivers

About 80% of the wetlands in southern Ontario have been eliminated and as Ontario's population continues to grow, pressure will increase to use remaining areas covered with wetlands for some other purpose. As a result:

- Wetlands have been destroyed or degraded by filling and drainage for land development, and by dredging for commercial and recreational water traffic. The removal of tree cover and shoreline vegetation is a major threat to wetland integrity.
- Wetlands have been polluted by industrial and commercial operations, agricultural run-off, stormwater, and other sources. Pollutants can include sediment, excess nutrients, trace metals, organic pollutants, grease and oil, and salt from roads.
- Wetlands on the Great Lakes are also susceptible to invasion by exotic species such as the zebra mussel (*Dreissena polymorpha*), purple loosestrife (*Lythrum salicaria*), common reed (*Phragmites australis*), and common carp (*Cyprinus carpio*).

6.0 The Effects of Climate Change on Selected Fish Species

Ontario has over 227,000 lakes and thousands of kilometres of rivers and streams (hereafter, "streams" refers to all flowing waters). Included in these waters are 20% of the world's lake trout lakes and more than 3,500 walleye lakes. In addition to climate change, threats to Ontario's fish communities include habitat degradation, over-fishing, and pollution. Therefore assessing the effects of climate change on fisheries is challenging because they will often act indirectly through changes in fish habitat or food supply in lakes, streams, and/or wetlands and exacerbate the negative effects of other threats.

A primary concern for fisheries managers is how climate change will affect aquatic habitats. Potential stresses on fish habitat include declining water quality resulting from increased water temperatures, changes in stratification depth and timing of stratification in lakes, and lower dissolved oxygen levels. The primary water quantity issue includes altered overall water availability due to changes in precipitation patterns and higher evaporation rates.

Fish species are adapted to specific ecological conditions that optimize their growth and survival. Changes in these conditions have negative consequences on fish health, reproduction, recruitment, and survival. Consequently, the most visible effects of climate change on aquatic ecosystems are likely to be changes in fish growth and development, reproduction and recruitment, and distribution (Brandt et al. 2002, Casselman 2002, Jackson and Mandrak 2002, Rahel 2002, Chu et al. 2005).

Projecting how fish communities will be affected by climate change requires an understanding of expected habitat changes and how fish will respond to them (Shuter and Meisner 1992). For example, potential changes in fish habitat depend on the physical characteristics of the system, which climate variables are included in the analyses (e.g., precipitation, water level, evaporation rates), and the climate change model used. Each species' response to climate change will depend on the magnitude and rate of change, and the species' thermal tolerance, habitat requirements, migration potential, and ability to cope with changes in the distribution of prey and predators (Ficke et al. 2005). Therefore, models that use multiple variables to assess the potential impacts of climate change on a species will be more robust than single variable models (Jones et al. 2006).

Although climate change has a variety of potential effects on Ontario's water resources, increased water temperatures and changes in water availability are expected to have the greatest effect on fish habitat. Temperature changes affect fish distributions (Shuter and Post 1990, Jackson and Mandrak 2002, Chu et al. 2005), reproduction and recruitment (Casselman 2002, Casselman et al. 2002), and food habits and growth (Brandt et al. 2002, Vander Zanden et al. 2004a).

Increases in average water temperatures, for example, favour a shift in the community structure from fishes adapted to coldwater to those better suited to warmer waters (Mandrak 1989, Magnuson et al. 1990, 1997, Shuter and Post 1990, Stefan et al. 2001, Casselman and Scott 2002, Chu et al. 2005).

Freshwater fish are cold-blooded: their body temperatures closely match those of the waters they inhabit. Because physiological processes such as growth and development, reproduction, and recruitment are optimized at certain temperatures, changes in water temperatures can have immediate effects on fish populations.

A thermal guild approach, which groups fish species by their temperature preferences, is often used to assess the habitat requirements for many fish species at the same time (Christie and Regier 1988, Casselman 2002, Figure 5). Here we explore some of the known and potential effects of climate change on representative species from three thermal guilds. The coldwater guild (species that prefer temperatures of 10 to 18°C) is represented by lake trout to examine the effects of climate change on lake-dwelling coldwater species and brook trout to explore the effects of climate change on stream-dwelling coldwater fishes. Coolwater species (species that prefer temperatures of 18 to 25°C) are represented by walleye and warmwater species (species that prefer temperatures greater than 25°C) are represented by smallmouth bass. All four species support important recreational fisheries in Ontario.

6.1 Climate Change and Coldwater Lake Fish: Lake Trout

6.1.1 Background

Lake trout occupy freshwater habitats across North America between 43°N to 73°N latitude (Lee et al. 1980, Schindler and Gunn 2004). Only about 1% of Ontario's lakes contain lake trout but this represents 20 to 25% of all lake trout lakes in the world (OMNR 2007). In Ontario, lake trout are found in Lake Ontario, Lake Huron, and Lake Superior, and in deep cold lakes of the Canadian Shield (OMNR 2006a). The lake trout is a long-lived, slow-growing, and late-maturing fish, typical of cold oligotrophic (low-nutrient) waters. Lake trout prefer temperatures around 11.8°C, spawn at around 10°C, and are usually found in the lower layers of cool well-oxygenated lakes deeper than 15 m (OMNR 2006a, Hasnain et al. 2010:31).

Lake trout populations support both winter and summer recreational fisheries. Due to their slow rate of growth and maturation, populations are extremely susceptible to overexploitation. While excessive exploitation has played a role in the decline of lake trout (Olver et al. 1991), many other stressors have had detrimental effects as well. Lake trout and lake trout lakes are particularly vulnerable to the effects

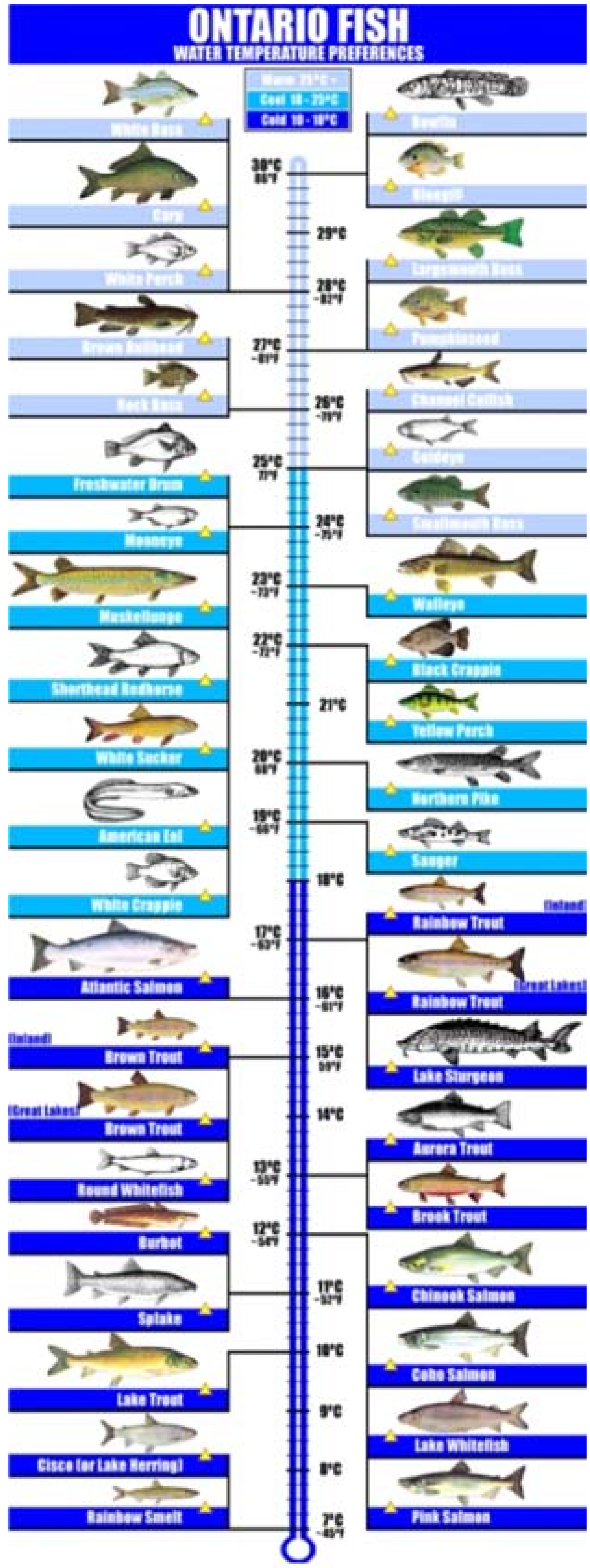

__Figure 5__. Water temperature preferences of Ontario fishes (OMNR 2004).

of acidification, invasive species that have been intentionally or unintentionally introduced, habitat destruction, and increased nutrient loading (Wilton 1985, Evans et al. 1996, Dillon et al. 2004, Steedman et al. 2004, Vander Zanden et al. 2004a,b).

6.1.2 Climate Change and Lake Trout Habitat

Climate change could drastically alter habitat for lake trout by changing the timing and magnitude of thermal stratification in lakes and lowering mean water levels. These changes will affect dissolved oxygen availability, nutrient cycling, and the distribution of prey (Brandt et al. 2002). Lower mean water levels and earlier spring warming may alter the amount of suitable habitat by changing the thermocline depth (the depth where the warm upper layer and cold lower layer meet) and hence the relative volumes of each lake's warm and cold layers. This effect will vary depending on the physical characteristics of each lake (Schindler et al. 1996a, King et al. 1997, Snucins and Gunn 2000, Valeo et al. 2003, Jansen and Hesslein 2004, Jackson 2007). An overview of some of the possible effects of climate change on lake trout populations and habitat have been described by Shuter et al. (1998) and Shuter and Lester (2004) and are summarized in Table 9.

6.1.3 Growth

Lake trout are carnivorous, feeding primarily on small crustaceans (e.g., crayfish), insects, and other fish. Young lake trout feed on zooplankton, insects, freshwater "shrimp," and small aquatic invertebrates (Scott and Crossman 1973, Marcus et al. 1984). In summer, high water temperatures restrict lake trout to deep waters where growth is slow (Burns 1971, Brett 1979). In winter, lake trout continue to feed but growth is minimal (Cunjak and Power 1987). However, for short periods during the spring and fall, surface water temperatures match their thermal preferences (Hawkes 1975; Meisner 1990a,b) and higher growth rates are achieved. This provides young that hatch in the spring with immediate access to food during the growing season. Climate warming will lengthen the summer period, which is less favourable for lake trout growth (Hill and Magnuson 1990, Casselman et al. 2002). And if prey consumption cannot increase with climate warming, annual growth will decline because the fish cannot compensate for the increased metabolic costs of operating at higher temperatures (Hill and Magnuson 1990). These effects on growth may be offset somewhat by shorter, warmer winters, allowing for small increases in winter growth (Shuter and Meisner 1992).

Table 9. *Potential effects of a drier, warmer climate on lake ecosystems and probable consequences for lake trout populations (Source: Shuter and Lester 2004, updated).*

<table>
<tr><th>Physical/chemical change in lake system</th><th>Effect on prey available to young lake trout</th><th>Effect on diversity of prey available to adult lake trout</th><th>Effect on lake trout habitat</th></tr>
<tr><td colspan="4">Drier conditions lead to:</td></tr>
<tr><td>Overall reductions in lake volume</td><td>Uncertain</td><td>Species richness decreases with lake size and volume</td><td>Habitat declines with overall lake volume decline</td></tr>
<tr><td>Reductions in phosphorus inputs</td><td>Productivity declines leading to reduced prey</td><td colspan="2">Uncertain</td></tr>
<tr><td>Reductions in dissolved organic carbon and increased water transparency results in deeper thermoclines or no stratification</td><td colspan="2">Changes in prey types and abundance</td><td>Decrease in thermally suitable habitat</td></tr>
<tr><td colspan="4">Higher air temperatures and lower spring winds lead to:</td></tr>
<tr><td>Shallower thermoclines in stratified lakes</td><td colspan="2">Uncertain</td><td>Increase in thermally suitable habitat</td></tr>
<tr><td>Longer ice-free period and longer stratification period</td><td colspan="2">Increased productivity and longer growing season</td><td rowspan="2">Greater risk of hypoxia</td></tr>
<tr><td>Warmer surface water temperatures</td><td colspan="2">Increased productivity and increased prey abundance</td></tr>
</table>

Climate change may also affect the availability of prey for adult lake trout by changing the spatial distribution of planktivorous fishes, food web interactions with their predators, and consequently, the growth potential of prey. Brandt et al. (2002) used projected changes in surface water temperature to evaluate growth rate potentials of lake trout, Chinook salmon (*Oncorhynchus tshawytscha*), and striped bass (*Morone saxatilis*) in Lake Michigan. Overall, the growth potential of all species increased with climate warming as long as prey availability matched the increased demands of the predators (Brandt et al. 2002). Climate change may also change the production of bottom-dwelling invertebrates that young lake trout feed on, particularly species such as *Mysis* and *Diporeia*. For example, significant changes in coldwater fish populations occurred in the Great Lakes following a dramatic decline in the bottom-dwelling aquatic macroinvertebrate, *Diporeia*, a major food source (Mills et al. 2003).

6.1.4 Reproduction and Recruitment

Lake trout spawn in the fall at temperatures of approximately 10°C. Egg and fry survival and growth are dependent on the availability of coldwater. In eastern Lake Ontario, eggs deposited at a mean spawning temperature of 11.5°C had 10% survival at spring emergence, while 19% of eggs deposited at 9.5°C survived (Casselman 1995). Casselman (2002) combined historical temperature data at spawning with models to simulate changes in lake trout fry survival and found that survival decreased from approximately 25% to 15% over the mid-1960s and from 15% to 10% during the mid-1990s. These data were used to determine that an increase in water temperature of 1°C decreases survival at hatch by 1.5 times, an increase of 2°C decreases survival 2.4 times, and an increase of 3°C decreases survival 20.1 times (Casselman 2002).

6.1.5 Distribution

Distributions of coldwater fishes, such as lake trout, are restricted by warm summer temperatures (Rahel 2002). Climate change is expected to produce northward shifts in fish distributions corresponding to changes in the availability of suitable thermal habitat (Stefan et al. 2001). With business-as-usual climate change conditions (which means a doubling of atmospheric CO_2 by 2050), Chu et al. (2005) projected that coldwater species in Ontario may be extirpated throughout much of their present range. However, some isolated populations of coldwater fishes may remain in deep stratified lakes within their original range (Stefan et al. 1995). The projected disappearance of coldwater species, particularly lake trout, would be most pronounced in lakes Ontario and Erie (Casselman 2002, 2005; Casselman and Scott 2002; Shuter and Lester 2004).

Using a simple method for integrating knowledge of physical limnology, lake geography, and thermal specialization of fish, Minns et al. (2009) generated spatially-based projections of the effects of climate change on lake trout habitat. Minns et al. (2009) project that by 2100 lake trout habitat will be reduced by about 30%, with significant declines (up to 60%) in some southern watersheds in southern and eastern Ontario only partly offset by increases in some watersheds in northwestern Ontario (Figure 6).

6.1.6 Competition and Predation

Competition between members of different species (interspecific competition) or members of the same species (intraspecific competition) can affect growth, recruitment, and mortality. Interspecific competition has already been observed in lakes in south-central Ontario where smallmouth bass introductions have altered lake trout growth and recruitment. Lake trout obtain about 60% of their energy from minnows in lakes where bass and pelagic forage fish are absent. However, this is reduced to about 20% when smallmouth bass or rock bass are present, which consume minnows as well (Vander Zanden et al. 1999). The resulting requirement for a diet shift could cause up to a 90% loss in lake trout reproduction (Vander Zanden et al. 1999, 2004a,b).

Climate change may also lead to increased predation within and among species. For example, warming and possible deepening of lake thermoclines may force adult and juvenile lake trout closer together in the water column, increasing the likelihood that adults will prey on juveniles. Similarly, because rock bass are known predators of larval lake trout, greater overlap between rock bass and lake trout populations could lead to increased loss of trout (Casselman 2005).

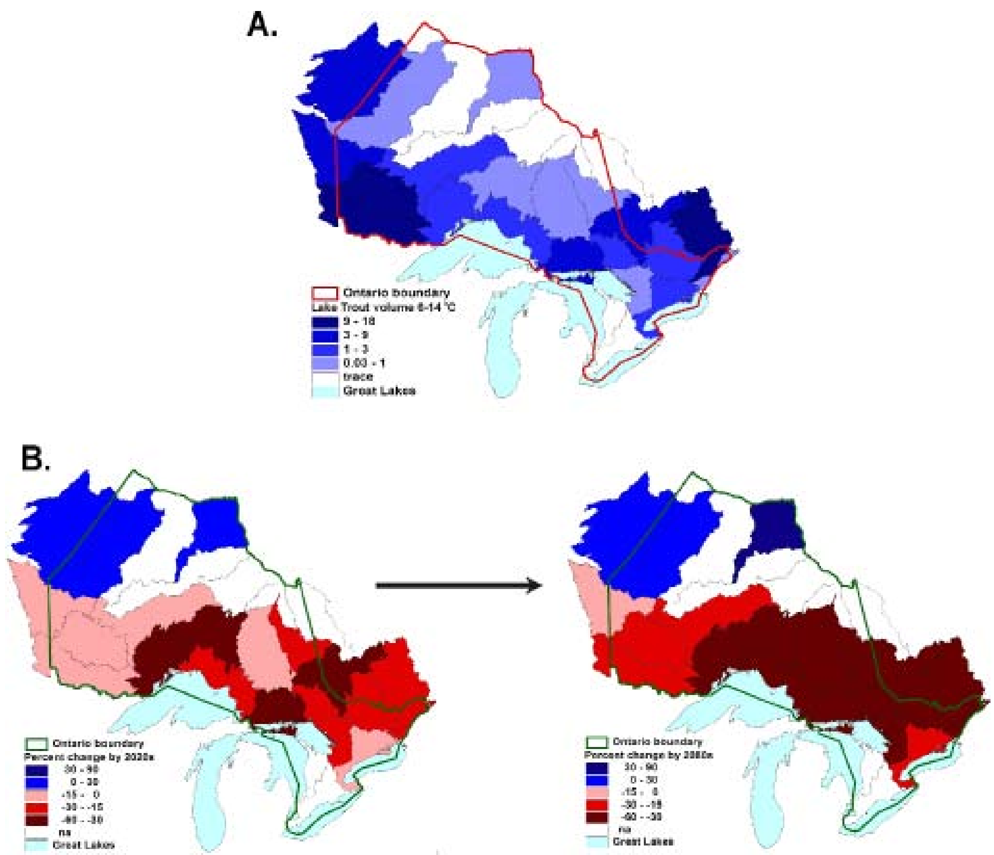

Figure 6. *Regional differences in current and future amounts of lake trout habitat among Ontario secondary watersheds. (A) Total volume (km³) of preferred lake trout habitat by secondary watershed under recent (1975) climatic conditions. Values were obtained by summing across all four thermal classes. (B) Percentage changes in preferred habitat volume from 1975 levels under the climatic conditions forecast for 2025 and 2085, respectively. Climate forecasts are based on the IPCC A2 scenario using the CGCM2. Ontario secondary watersheds are marked by thin solid lines and the Ontario political boundary is marked by the solid red or green lines (Source: Minns et al. 2009:8).*

6.2 Climate Change and Coldwater Stream Fish: Brook Trout

6.2.1 Background

Brook trout, often called speckled trout, are native to eastern North America (Scott and Crossman 1973, Lee et al. 1980) and have been introduced widely throughout montane areas of the west (MacCrimmon and Campbell 1969). There are 4,326 known brook trout waters in Ontario. Approximately one-third of these waters contain populations of hatchery-reared fish to support recreational fishing (OMNR 2006b). Some brook trout spend most of their lives in lakes, while others are entirely stream-dwellers. They generally inhabit clear, cool, well-oxygenated, and shaded streams with temperatures less than 20°C, dissolved oxygen concentrations greater than 5.0 mg/L, and pH levels greater than 6.0 (Scott and Crossman 1973).

6.2.2 Climate Change and Brook Trout Habitat

Brook trout prefer temperatures of 14 to 17°C but can tolerate temperatures ranging from 5 to 20°C (Power 1980). Meisner et al. (1988) suggest that increases in water temperatures of 4 to 5°C in streams at low elevations and latitudes may result in a retraction of suitable coldwater habitat to headwater reaches and groundwater seepage sites. In high elevation streams where brook trout are restricted by low water temperatures all year, warmer waters may increase the amount of suitable habitat. At high latitudes, permafrost may decrease in some areas and produce year-round groundwater flow, providing more stream habitat for brook trout (Meisner et al. 1988).

The timing and volume of stream flows may be altered with climate change (Bruce et al. 2000, Mortsch et al. 2000, 2005). With projected increases in stream flow variability, flows in some brook trout streams in southern Ontario may become more intermittent (Meisner 1990b). This may result in patches of adequate stream habitat interspersed with sub-optimal or overheated areas with little or no flow between them. Using a projected temperature increase of 4.8°C (July and August) in the Humber and Rouge rivers (in southern Ontario), Meisner (1990a) estimated that elevated air and groundwater temperatures reduced summer thermal habitat for brook trout by 42% and 30%, respectively. Projected increases in the variability of winter stream flow due to more rain events and reduced ice cover could adversely affect young brook trout not yet capable of surviving in the faster moving water (Bruce et al. 2000, Mortsch et al. 2000, 2005).

6.2.3 Growth

Brook trout feed on a variety of organisms, including worms, leeches, aquatic and terrestrial insects, spiders, molluscs, crustaceans, salamanders, frogs, rodents, and fish (Scott and Crossman 1973, Raleigh 1982). Higher temperatures increase metabolic rate and can increase growth. But growth rates are highly dependent on both the extent of temperature increases and the availability of prey. If temperatures exceed the optimum range, and/or prey populations are reduced, brook trout growth will decrease and long-term population sustainability will be negatively affected.

6.2.4 Reproduction and Recruitment

Temperature and precipitation appear to be the ecological cues for brook trout spawning activity (Blanchfield and Ridgway 1996). Two key characteristics for successful brook trout spawning are gravel substrate (Young et al. 1989) and groundwater seepage to maintain constant temperature around incubating eggs (Witzel and MacCrimmon 1983, Curry and Noakes 1995, Blanchfield and Ridgway 1996). Groundwater discharges provide thermal refuges and promote adequate growth of young brook trout to ensure over-winter survival (Meisner et al. 1988). Hence, changes in groundwater availability may result in higher rates of mortality and reduced recruitment.

Altered flow regimes in streams may influence growth and recruitment by flushing young brook trout out of optimal habitat during high stream flow periods (Nehring and Anderson 1993, Nuhfer et al. 1994). High flows may carry young brook trout downstream into warmer waters and prevent their migration back into preferred headwater areas (C. Wilson, OMNR, pers. comm., 2010). This may reduce growth rates and increase winter mortality.

Changes in water chemistry may also affect brook trout egg survival. Salmonid eggs and larvae require dissolved oxygen levels of about 9.7 to 9.8 mg/L (Davis 1975). Lower dissolved oxygen content that may be associated with warmer temperatures could impair growth and negatively affect hatching success (Doudoroff and Shumway 1970). Studies also show that brook trout egg survival is low in acidic (low pH) conditions (Ingersoll et al. 1990, Lachance et al. 2000). With potential increases in the frequency of drought (Mortsch et al. 2000, 2005, 2006), stream acidification may become more widespread leading to reduced brook trout egg survival, alevin emergence, and recruitment.

6.2.5 Distribution

As with lake trout, climate change is projected to greatly reduce the distribution of many brook trout populations throughout Ontario. Meisner (1990a) concluded that climate change would reduce brook trout habitat enough to affect

Table 10. *Projected changes in fish species distribution as a result of changing climate. The current distribution indicates the number of watersheds that now contain the species; present indicates the number of watersheds in which the species is expected to occur, and high and low represent the number of watersheds having high and low probabilities, respectively, of the species expanding into them (Source: Chu et al. 2005).*

Species	Tertiary Watersheds								
		Potential distribution in 2020				Potential distribution in 2050			
	Currently inhabited	Present	High	Low	Loss	Present	High	Low	Loss
Brook trout	465	222	16	21	206	208	7	22	228
Walleye	299	305	7	100	--	305	17	138	--
Smallmouth bass	135	135	26	71	--	135	33	74	--

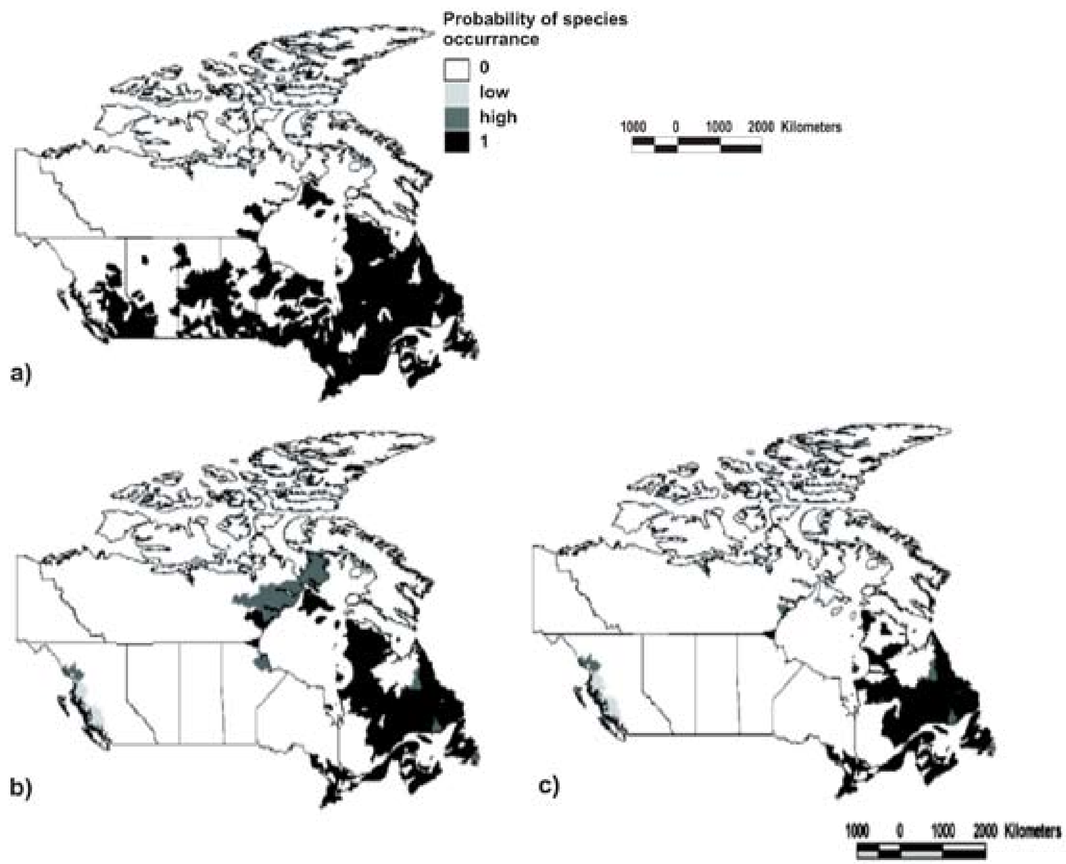

Figure 7. *Projected distributions of brook trout in Canada under the CGCM2/IS92a climate scenario: (a) current, (b) in 2020, and (c) in 2050 (Source: Chu et al. 2005).*

the size and continuity of populations in two southern Ontario streams. At the national scale, Chu et al. (2005) projected a 49% decrease in brook trout distribution in Canada by the year 2050 (Table 10), with ranges shifting northeast towards Québec–Labrador and west towards British Columbia (Figure 7).

6.2.6 Competition and Predation

Brook trout stocking initiatives have shown that the density of brook trout within a lake or stream greatly affects recruitment and growth of young fish (Kerr 2000). Streams with lower brook trout density show faster growth rates and higher recruitment over those streams with higher densities. Increasing temperatures can be expected to decrease thermal habitat, crowding brook trout and increasing both predation and intraspecific competition. The movement of warmwater and invasive fishes into brook trout habitat may also increase interspecies competition and predation. The result will likely be decreased rates of growth and survival.

6.3 Climate Change and Coolwater Fish: Walleye

6.3.1 Background

Walleye are native throughout Canada and the north-central United States (Scott and Crossman 1973, Lee et al. 1980). Walleye tolerate a range of ecological conditions and reach high abundance in large, shallow, turbid lakes, although they also inhabit large streams. The eyes of walleye have a specialized reflective layer that allows them to see well in low light and turbid waters. Walleye generally prefer water temperatures around 20 to 23°C (Christie and Regier 1988, Casselman 2002, Hasnain et al. 2010:28), but spawn in water temperatures of 6 to 12°C (Hasnain et al. 2010:36). In the spring, walleye make spawning migrations to shallow shoals, inshore areas, or tributary streams. They also move daily or seasonally in response to temperature or food availability.

Over 3,500 lakes contain walleye in Ontario and anglers regard this species as a preferred sport fish. In accessible areas, these lakes are fished by anglers during the summer, fall, and winter months. Individually, the economic value of the fishery on each lake is small, but collectively these fisheries comprise a valuable resource (Lester et al. 2000).

6.3.2 Climate Change and Walleye Habitat

The changes in walleye habitat associated with climate change depend on the characteristics of the lake and stream. For example, Jones et al. (2006) found that in Lake Erie, reduced stream flows, warmer stream temperatures, and earlier warming in the spring improved walleye habitat and recruitment by producing better conditions for egg deposition, hatch, and the movement of larvae to nursery grounds. However, reduced lake levels and warmer temperatures in the summer and fall offset these increases and led to net declines in habitat area and volume (Jones et al. 2006). This example illustrates the complexity of predicting climate change effects on coolwater species and their habitats.

6.3.3 Growth

As they grow, the diet of walleye shifts from invertebrates to fish. During the first six weeks of life, they feed on copepod zooplankton, crustaceans, and small fish. Walleye are opportunists and the types and numbers of fish they eat are determined by prey availability. Yellow perch and minnow species are particularly favoured. Other food, such as crayfish, snails, and frogs, are also consumed, but usually only when forage fish and insects are scarce.

Warmer summer temperatures are associated with more rapid growth and earlier maturity of walleye (Shuter and Meisner 1992, Shuter et al. 2002). An earlier spring and later fall associated with warmer temperatures would lengthen the growing season in central and northern Ontario but temperature increases may exceed the optimum for walleye and thus decrease their growth in southern Ontario (Magnuson et al. 1990, Shuter et al. 2002). The extent of this effect, however, will be limited by prey availability and the range of temperature increases experienced.

6.3.4 Reproduction and Recruitment

Walleye spawning typically occurs at temperatures of 7 to 9°C, but can occur between 6 and 12°C (Hasnain et al. 2010:36). Eggs hatch in 12 to 18 days, and the larvae disperse into surface waters. Both stream and lake larval walleye must be transported passively to zooplankton-rich nursery areas to feed. Transport is usually via river flows or lake surface currents.

Walleye recruitment success is closely tied to water temperature. Higher spring warming rates have been positively related to walleye recruitment in Lake Erie (Shuter et al. 2002, Jones et al. 2006, Figure 8). Using historical records,

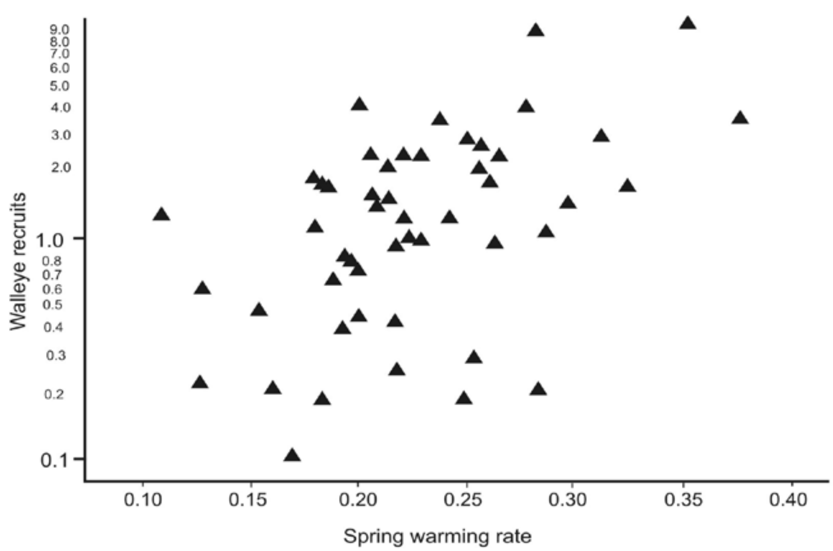

Figure 8: *Annual recruitment of the Lake Erie walleye population (relative units on a logarithmic scale) plotted against the rate of spring warming. Spring warming was estimated for early April to mid-May as the average warming rate (°C/day) for Lake Erie surface water temperatures using surface water temperatures recorded at sites in the western basin of Lake Erie (Source: Shuter et al. 2002; reprinted with permission of the American Fisheries Society).*

Casselman and Scott (2002) examined the relationships between recruitment success and temperatures for three thermal guilds in the Bay of Quinte, Lake Ontario. They estimated that an increase of 1°C in average annual air temperature decreased recruitment of coolwater fish by 2.4 times, while an increase of 2°C reduced recruitment by 17.9 times.

Walleye recruitment can also be influenced by prey abundance, competition, predator–prey interactions, and several other factors. Mortsch and Quinn (1996) used a computer model to compare the effects of increased temperatures, stream flow reductions, and earlier spring seasons on river walleye recruitment. Their results showed all three variables affected walleye recruitment differently. Changes in temperatures, lake levels, and the frequency, magnitude, and average direction of wind events were predicted to negatively affect spawning and recruitment of lake-spawning walleye (Mortsch and Quinn 1996). A simulated 2°C warmer lake temperature increased recruitment, but this effect was completely eliminated by declines in lake level. Recruitment to the nursery grounds was reduced by up to 56% with a 2 m drop in lake level. Thus, if lake levels are reduced by up to 1.8 m, as projected by some models for the Great Lakes region, decreased walleye recruitment may result.

6.3.5 Distribution

Suitable thermal habitat for walleye may shift from southern to central and northern Ontario as the climate warms (Shuter et al. 2002). Under a 'business-as-usual' climate change scenario, Chu et al. (2005) predicted that by 2050 walleye may increase their range by 54% and expand into most of Alberta, Saskatchewan, New Brunswick, and Nova Scotia (Figure 9). Improved habitats for growth and shorter winters would reduce the incidence of winter starvation, thus allowing coolwater and warmwater species to become established in more northerly habitats (Shuter and Post 1990).

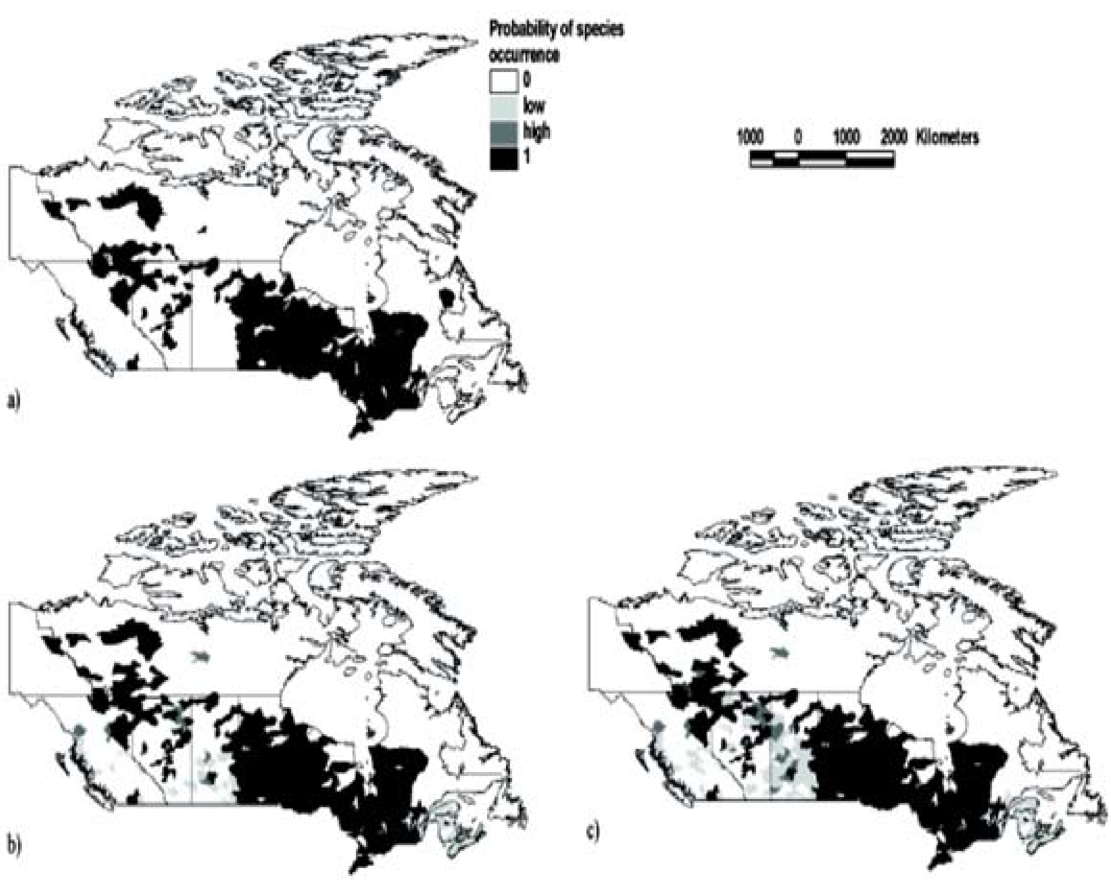

***Figure 9**. Projected distributions of walleye in Canada under the CGCM2 (IS92a) climate scenario: (a) current, (b) in 2020, and (c) in 2050 (Source: Chu et al. 2005).*

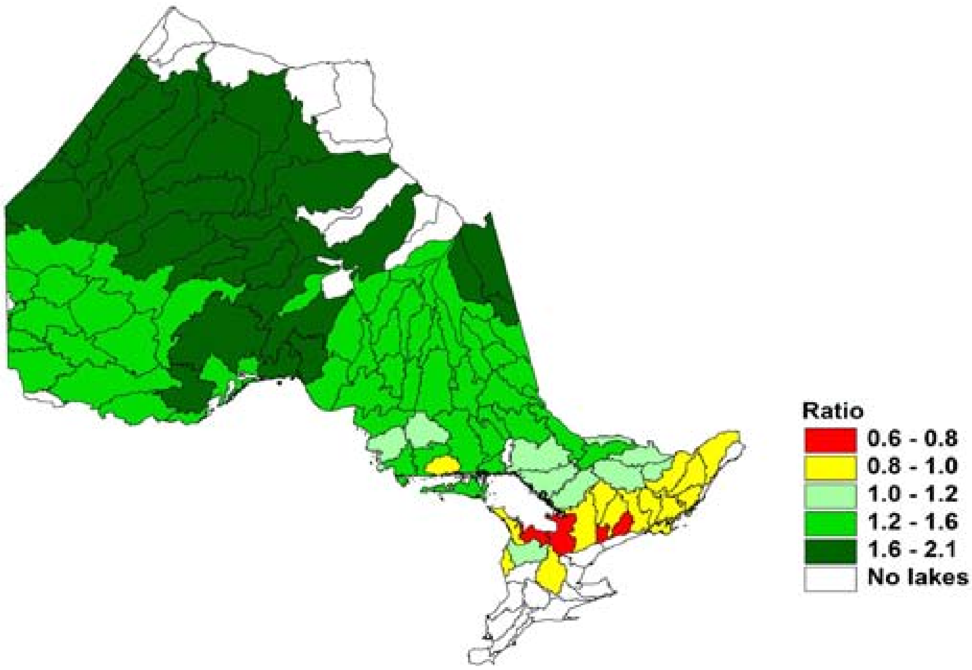

Figure 10. *Relative changes in maximum sustained yield of walleye in Ontario under a 2xCO$_2$ climate change scenario. The ratio is based on the predicted equilibrium maximum sustainable yield (msy) divided by current msy to give a measure of relative change. Maximum sustained yield decreases in the southern part of the province but increases in the central and northern parts (from Shuter et al. 2002).*

As a result of warming, the sustainable walleye fishery may shift northward. Shuter et al. (2002) used information on walleye populations in Ontario and climate change forecasts to determine regional effects on harvest and angling (Figure 10). With increased temperatures, sustainable yield (catch) declined in the south and increased throughout the central and northern parts of the province. Increased temperatures in southern areas were predicted to exceed the optimum temperatures for walleye, reducing their abundance and associated sustainable yields. Other changes, such as reduced water quality or productivity, could also influence the outcome of these forecasts (Shuter et al. 2002).

6.3.6 Competition and Predation

Northern pike (*Esox lucius*), yellow perch, sauger (*Sander canadensis*), and smallmouth bass are the walleye's principal competitors for food (Cohen et al. 1993). Walleye predators include smallmouth bass (Zimmerman 1999), muskellunge (*Esox masquinongy*), and largemouth bass (*Micropterus salmoides*) (Santucci and Wahl 1993, Bozek et al. 1999). In addition, large walleye can be cannibalistic and prey on small walleye in food-limited environments.

During the 1970s, significant shifts in the abundance of alewife (*Alosa pseudoharengus*), white perch (*Morone americana*), and walleye were related to climatic changes and predator–prey interactions (Hurley 1986). Exceptionally cold winter conditions from 1976 through 1978 resulted in catastrophic winterkills of white perch and alewife. This reduced white perch and alewife predation on walleye eggs and fry, and improved walleye recruitment (Casselman et al. 1996, 2002). In a warmer climate, the significance of alewife and white perch predation could increase and limit the distribution and abundance of walleye populations.

6.4 Climate Change and Warmwater Fish: Smallmouth Bass

6.4.1 Background

Smallmouth bass are native to the lakes and streams of the Great Lakes–St. Lawrence and upper Mississippi River drainages of eastern and central North America (Lee et al. 1980). In Canada, smallmouth bass were originally found only in the Great Lakes–St. Lawrence watershed, mainly throughout southern Ontario, selected locations around the north shore of Lake Superior, and in southwestern Québec (Scott and Crossman 1973). They are now found as far north as Timmins in Ontario, west into Manitoba and British Columbia, and east into Nova Scotia (Scott and Crossman 1973). There are 2,421 Ontario lakes and numerous streams known to contain smallmouth bass (OMNR 1987).

In summer, smallmouth bass are typically found in waters with temperatures of 19 to 22°C, although they can tolerate temperatures up to 26 to 27°C (Scott and Crossman 1973, Coble 1975). Smallmouth bass can live as long as 15 years and grow to weights over 4 kg. The smallmouth bass is one of the most popular recreational fish species in Ontario (OMNR 2003).

6.4.2 Climate Change and Smallmouth Bass Habitat

The northern limits of warmwater species are often determined by cold summer temperatures that limit growth (Shuter and Post 1990, Rahel 2002). Waters with temperatures over 27°C and/or below 15°C are poorly suited for smallmouth bass. Only southern regions of Ontario (about one-third of the province) currently have water temperatures within this range. However, climate projections suggest that two-thirds of Ontario will provide optimal water temperatures for smallmouth bass by 2050. Magnuson et al. (1997) predicted that all but the most extreme northern parts of the province may become suitable for smallmouth bass by the end of this century.

6.4.3 Growth

After hatching, smallmouth bass feed on zooplankton (Robbins and MacCrimmon 1974) until they are large enough to eat aquatic insects, large crustaceans, and the fry of other fish. Crayfish are a preferred food of older smallmouth bass and can constitute about two-thirds of the diet, but minnows, yellow perch, darters, sculpins, suckers, sunfishes, and rock bass (*Ambloplites rupestris*) are also important prey (Scott and Crossman 1973, Coble 1975).

Growth rates in smallmouth bass populations are positively related to water temperature (Coble 1967, McCauley and Kilgour 1990). However, because this species does not actively feed during the winter, juvenile fish must reach a threshold size by fall to survive the winter. Warmer temperatures mean a higher rate of growth, which could increase survival and recruitment in northern locations (Shuter and Post 1990).

6.4.4 Reproduction and Recruitment

Smallmouth bass spawn over sandy, gravel, or rocky bottoms of lakes and rivers. Like other members of the bass family, smallmouth bass are nest builders with the males acting as guards over eggs and fry. Once water temperature is sustained at approximately 15°C, the male bass prepares a nest into which females deposit their eggs. The female then leaves the male to guard the eggs and newly hatched fry. Depending on water temperature, the eggs hatch in 2 to 12 days.

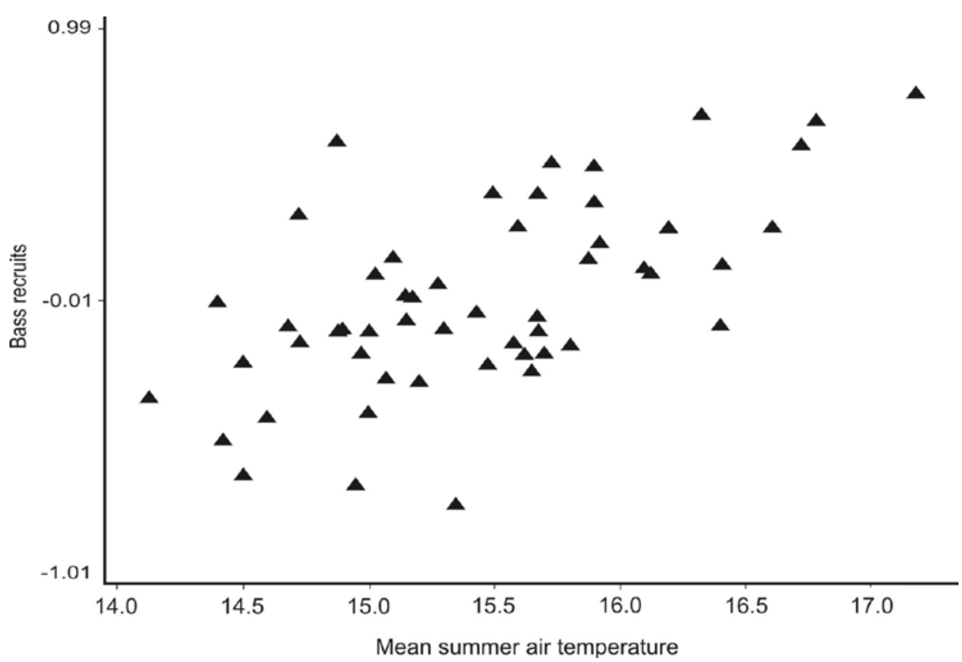

Figure 11. *Annual recruitment to the Lake Opeongo smallmouth bass population (relative units on a logarithmic scale) plotted against mean summer air temperature recorded between 1 June and 30 September at Madawaska, Ontario (Source: Shuter et al. 2002; reprinted with permission of the American Fisheries Society).*

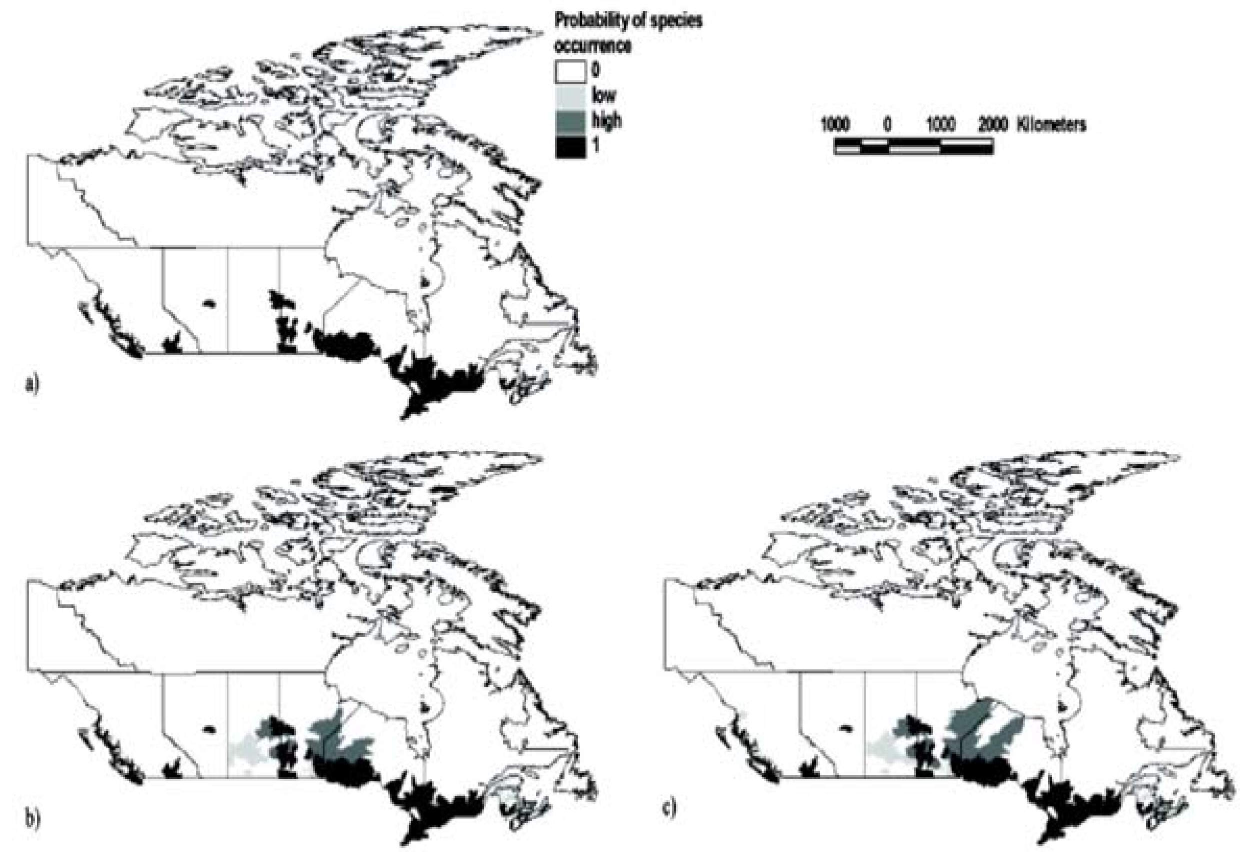

Figure 12. *Projected distribution of the smallmouth bass in Canada under the CGCM2 (IS92a) climate scenario: (a) current, (b) in 2020, and (c) in 2050 (Source: Chu et al. 2005).*

Smallmouth bass recruitment is positively related to temperature (Shuter et al. 1980). In Lake Opeongo, for example, there is a strong correlation between warm summer temperatures, increased growth, and subsequent increases in recruitment (King et al. 1999, Shuter et al. 2002, Figure 11). Recruitment in smallmouth bass populations can be influenced by other factors as well. For example, variations in the timing of ice-out can affect the timing and availability of prey resources such as zooplankton. Earlier ice-outs can increase prey availability and extend the growing season. This may improve winter survival (Casselman et al. 2002). Greater variability in stream flows and extreme precipitation events associated with climate change may negatively affect smallmouth bass recruitment. High spring flows may increase fry and egg displacement downstream and increase mortality of young bass (Lorantas and Kristine 2004).

6.4.5 Distribution

The northern limit of various fish species is projected to advance approximately 120 km for each degree Celsius of warming (Magnuson et al. 1997). Shuter et al. (2002) calculated the northward shift of smallmouth bass using incremental temperature increases and suggested that the rate may be even greater for this species. Under ‘business-as-usual’ climate change scenarios, Chu et al. (2005) projected the northern range of smallmouth bass may expand into northwestern Ontario, northeastern Manitoba, and southcentral Saskatchewan by 2050 (Figure 12).

6.4.6 Competition and Predation

Bass and other warmwater fish introductions cause food web disruptions. The presence of littoral predators, such as smallmouth bass and largemouth bass, has been strongly associated with the absence of minnow (cyprinid) species (Tonn and Magnuson 1982, Jackson and Harvey 1989, Robinson and Tonn 1989, Jackson et al. 1992, Findlay et al. 2000). Consequently, the expansion of smallmouth bass into northern Ontario could lead to the localized extinction of more than 25,000 populations of northern redbelly dace (*Phoxinus eos*), finescale dace (*Phoxinus neogaeus*), fathead minnow (*Pimephales promelas*), and pearl dace (*Margariscus margarita*) (Jackson and Mandrak 2002). This level of extirpation could negatively affect other predatory fish such as lake trout (Vander Zanden et al. 1999).

7.0 Climate Change and Fish Communities

Casselman (2002) used representative species from all three thermal guilds to illustrate potential fish community changes. Beginning with a community in which the three thermal guilds were assumed to be equally represented, a 1ºC temperature increase was predicted to change the community structure to 69% warmwater fish, 12% coolwater fish, and 19% coldwater fish. With a 2ºC change, the community would consist of 93% warmwater fish, 1% coolwater fish, and 6% coldwater fish. These predictions did not include other factors that influence fish recruitment and reproduction such as changes in growth, productivity, prey availability, and competition (Casselman 2002). Given the forecasted temperature changes of between 1.1 and 6.4°C by 2100 (IPCC 2007a:13), many of Ontario's aquatic communities likely will become dominated by warmwater fishes.

Stream fish communities may change significantly with climate change as well. In an assessment of stream fish communities in southern Ontario, Chu et al. (2008) found that the distribution of coldwater stream fishes may be reduced 60 to 100% by 2055. Warmwater species distributions may increase in streams and throughout southern Ontario by at least 60% by 2055.

Climate change may also promote the expansion into Canadian waters of southern fish species currently inhabiting ecosystems in the United States including Asian carp species and other exotics. Mandrak (1989) identified 27 species that may invade the Great Lakes as waters warm (Table 11). The 27 potential invaders are primarily from the minnow, sunfish, sucker, and topminnow families. In a warmer climate the invasion rate of warmwater species could be rapid and could significantly affect commercial and recreational fishing.

Table 11. *Fish species that may invade the lower and upper Great Lakes as a result of changing climate (adapted from Mandrak 1989).*

From Mississippi and Atlantic Coast Basins to lower Great Lakes		**From lower Great Lakes to upper Great Lakes**	
Common name	**Scientific name**	**Common name**	**Scientific name**
Shovelnose sturgeon	*Scaphirhynchus platorynchus*	Grass pickerel	*Esox americanus vermiculatus*
Shortnose gar	*Lepisosteus platostomus*	Chain pickerel	*Esox niger*
Goldeye	*Hiodon alosoides*	Spotted gar	*Lepisosteus oculatus*
Plains minnow	*Hybognathus placitus*	River redhorse	*Moxostoma carinatum*
Ironcolor shiner	*Notropis chalybaeus*	Tonguetied minnow	*Exoglossum laurae*
Ozark minnow	*Notropis nubilis*	Bigmouth shiner	*Notropis dorsalis*
Blacktail shiner	*Cyprinella venusta*	River shiner	*Notropis blennius*
Steelcolor shiner	*Cyprinella whipplei*	Bluespotted sunfish	*Enneacanthus gloriosus*
River carpsucker	*Carpoides carpio*		
Blue sucker	*Cycleptus elongatus*		
Golden topminnow	*Fundulus chrysotus*		
Blackspotted topminnow	*Fundulus olivaceus*		
Plains topminnow	Funduus sciadicus		
Mud sunfish	*Acantharchus pomotis*		
Flier	*Centrarchus macropterus*		
Banded pygmy sunfish	*Elassoma zonatum*		
Blackbanded sunfish	*Enneacanthus chaetodon*		
Banded sunfish	*Enneacanthus obesus*		
Bantam sunfish	*Lepomis symmetricus*		

8.0 Responding to Climate Change

Managing climate-driven changes to Ontario's ecosystems will be a challenge for provincial agencies. Biodiversity will change in response to the combined influence of climate change, human activity, the movement of indigenous and invasive species, and natural disturbances such as flooding, drought, and fire. Some species will adapt to these changing conditions, but others will not. Species with high reproductive rates that can migrate long distances, rapidly colonize new habitats, tolerate human activity, and survive within a broad range of biophysical conditions are likely to be most successful (Gray 2005). In some ecosystems, novel species assemblages will emerge.

Climate change will affect many socio-economic values that are important to Ontarians as well. For example, shorter winters and reduced lake ice cover will affect recreational activities such as ice fishing that depend on snow and ice, but may extend opportunities to pursue other outdoor activities such as camping, canoeing, and open water fishing (Lemieux et al. 2007). Accordingly, knowing when to act and what actions to take depend on understanding the effects of climate change on Ontario's infrastructure, human activities, and ecosystems.

Uncertainty about future greenhouse gas emissions and the spatial distribution of climate change effects require that we use a dynamic adaptive approach to management organized and established according to a number of objectives, including commitments to:

- Understand the effects of climate change through research, inventory, monitoring, and assessment of Ontario's aquatic ecosystems
- Reduce greenhouse gas emissions and increase biological and geological sequestration of carbon
- Reduce the negative effects of climate change using strategic planning, adaptive management, and site-specific management tools and techniques (e.g., wetland protection or remediation)
- Provide education opportunities for all Ontarians
- Help the public adapt to anticipated changes through maintenance of healthy ecosystems, economic diversification, education, and training

8.1 Role of the Ontario Ministry of Natural Resources

Streams, rivers, lakes, and wetlands are critical to the ecological and economic health of Ontario. For example, these ecosystems support large sport and commercial fisheries, and tourist industries. About 1.4 million anglers fish in Ontario each year and spend more than $2.3 billon annually on fisheries-related expenditures. The commercial fishery is one of the largest freshwater fisheries in the world, with a processed value of over $200 million per year, and the baitfish industry is the largest of its kind in Canada.

The Ministry of Natural Resources (MNR) is responsible for the protection and management of Ontario's natural resources. MNR's Biodiversity Branch plays a key role in implementing MNR's strategic directions, which include a commitment to conserving biodiversity and using natural assets in a sustainable manner. The mandate for fisheries management is prescribed by both provincial (e.g., *Fish and Wildlife Conservation Act, 1997* and the *Endangered Species Act, 2007*) and federal legislation (e.g., *Fisheries Act, 1985* and the *Species at Risk Act, 2002*) and through national and international agreements (e.g., Great Lakes Fisheries Convention and the National Species at Risk Accord).

Given the known and potential effects of climate change on Ontario's aquatic ecosystems, management activities will need to adapt to changes in ecosystem composition, structure, and function and their sustainable use. To support adaptive strategies in these key areas, adjustments will be needed to planning and objective setting, assessment, monitoring, and information management activities. This may require re-evaluation of current strategic frameworks such as the *Strategic Plan for Ontario Fisheries* (Second Edition) and other policy guidelines to ensure they address concerns associated with climate change. Fisheries, habitat, and biodiversity conservation plans, inland Fisheries Management Zone plans, and Great Lakes management plans will also need to consider climate change.

8.2 Management Strategies and Science Needs for Future Consideration

Adaptation strategies focus on ways to manage – or live with – expected climate change impacts. Effective adaptation approaches will vary regionally depending on the extent and rate of change in aquatic ecosystems. Given that all ecosystems are unique, regional management strategies should address:

- The distribution of water body types (e.g., the Great Lakes dominate southern Ontario, rivers and streams characterize much of the far north, and small lakes are common throughout the rest of the province)

- The physical relief around river and stream habitats (e.g., areas of high relief may contain refuges that can buffer coldwater fish from warmer temperatures while areas of low relief may not)
- The demand for access to freshwater assets, which varies with population density and the types of human activity
- The direction and extent of climate change

While the effects of climate change on aquatic ecosystems such as water resources and fish species may not be completely understood, 'no regrets' management actions are now available to improve our chances of maintaining healthy aquatic ecosystems and a sustainable fishery in the future. As a first step, MNR should ensure that strategic plans such as *Ontario's Biodiversity Strategy* and the *Strategic Plan for Ontario Fisheries* are updated to reflect climate change effects and responsive strategic management approaches. Management plans, including fisheries and habitat management and biodiversity conservation plans, Great Lakes management plans, and inland Fisheries Management Zone plans could be written to account for climate change and its projected effects. In addition, raising awareness of climate change and its possible effects on aquatic ecosystems and their constituent biodiversity could be incorporated into educational outreach activities to better inform the public and management partners of anticipated changes. Long-term monitoring and scientific research will assist natural asset managers in decision making. These general actions should be followed by more specific, program-targeted discussions on implementing strategies for various management areas. A variety of optional adaptation strategies are described (Table 12) and are available for use in support of evolving policy and program development in a rapidly changing climate.

Table 12. *Fisheries management options for addressing the effects of climate change in Ontario.*

Climate change effect(s)	Policy and program development	Population management	Habitat management	Biodiversity	Monitoring	Science needs
SUSTAINABLE USE OF EXPLOITED SPECIES						
More variable productivity, recruitment, and abundance, changes in life history parameters, and changing community composition resulting in: • More variable yields • Reduced yields of coldwater species; increased yields of warmwater species	1. Re-evaluate allocation and harvest management policies and processes to incorporate climate change. 2. Develop guidelines to reduce non-climatic stresses on fish populations (e.g., habitat degradation, fishing pressure, effect of small dams on thermal conditions in streams). 3. Explicitly incorporate effects of climate change into fisheries management planning. 4. Explicitly incorporate effects of climate change into other planning initiatives (e.g., municipal, land use, lake-wide management plans, water power, and forest management). 5. Increase public and stakeholder awareness of the effects of climate change on fish production and yields. 6. Use a risk management approach to set priorities for adaptive planning. 7. Develop guidelines for an ecosystem approach to fisheries management. 8. Develop guidelines for managing fisheries using a precautionary approach. 9. Develop guidelines to adaptively manage fisheries and aquatic resources in a changing climate.	1. Implement precautionary approach to fisheries management that incorporates climate change scenarios. 2. Implement new or adjust existing regulations to reflect a precautionary approach that accounts for climate change. 3. Examine the effects of fishing practices (e.g., post-release mortality) and work with the industry to mitigate effects. 4. Actively promote the use of under-utilized species (e.g., warmwater species). 5. Develop strategic stocking plans to reduce angling pressure on vulnerable coldwater fish communities. 6. Ensure that annual compliance operating plans incorporate greater emphasis on species under stress from climate change effects. 7. Develop a more flexible regulatory framework to quickly respond to unpredictable events that will affect stock status (e.g., adjust regulations to suit recruitment rates on an annual or biannual basis, or adjust to protect critical growth periods).	1. Protect and rehabilitate critical habitats for exploited species vulnerable to climate change.	1. Review and modify the Natural Heritage Information Centre list of monitored species and adjust harvest regulations. 2. Focus prevention and control methods and rapid response protocols in areas at high risk from invasive species (e.g., restrict or ban the use of live bait). 3. Develop public education materials to reduce the impacts of invasive species.	1. Implement a provincial long-term monitoring program to measure species abundance and life history characteristics of fish populations, exploitation levels, and water quality. 2. Work with First Nations to integrate traditional ecological knowledge of fish populations and fisheries into monitoring programs. 3. Work with First Nations and tourist operators to monitor harvesting activities to examine the effects of climate change on Aboriginal and tourism fisheries. 4. Implement a program to monitor angler expectations for fishing opportunities and acceptance of management actions.	1. Develop risk-based sustainable harvest models and management tools that incorporate climate change scenarios. 2. Conduct research on climate influences on productivity of lakes and fish community dynamics. 3. Develop vulnerability matrices for exploited species. 4. Develop benchmarks and indicators for assessing the status of fish populations due to climate change. 5. Develop methods to quantify effects of invasive species on fish species and habitat under varying climate scenarios. 6. Determine link between environmental data and recruitment success in targeted species. 7. Understand and monitor range expansion of invasive species and their food web effects. 8. Develop tools to assess effectiveness of fish population monitoring. 9. Develop cumulative effect assessments to understand impacts of climate and other stressors on exploited fish species. 10. Develop harvest predictors that include short- and long-term shifts in productive capacity of fish stocks. 11. Generate species-specific understanding of temperature effects on fish physiology and behaviour. 12. Develop case studies over the latitudinal range of a species. Focus on documenting near-extinction events and causes of interannual variation in growth and abundance. 13. Complete studies on how climate change influences productivity in lakes and rivers and how these affect target fish species. 14. Develop measurable ecosystem health criteria and indicators. 15. Complete more studies on the influence of water quality and quantity on recruitment of key species, and use models to project the effects of climate change on these species. 16. Conduct research on the relationships between stream and river morphology, temperature, hydrology, hydraulics and hydrogeology, and fish community dynamics and sustainability, especially for key species.

Climate change effect(s)	Policy and program development	Population management	Habitat management	Biodiversity	Monitoring	Science needs
FISH POPULATION RECOVERY AND REHABILITATION EFFORTS						
Results of changes will be that: • Rehabilitation of coldwater species may take greater effort over longer time frames with less success • Warmwater species may be more readily rehabilitated • Current hatchery or wild strains may not be suitable for rehabilitation in a changing climate	1. Re-evaluate provincial aquaculture policies and strategy to incorporate climate change effects. 2. Re-evaluate fish culture business plan to incorporate climate change effects (e.g., match species to environmental changes and public needs). 3. Re-evaluate provincial fish stocking guidelines to incorporate climate change effects. 4. Set provincial priorities for fish population recovery and rehabilitation by incorporating anticipated effects of climate change.	1. Adapt fish culture facilities and operations to changes in water supply, presence of diseases, and invasive species. 2. Review hatchery brood stocks and production targets to match end-user needs and changing environmental conditions (e.g., genetic strains capable of handling temperature stress and drought). 3. Evaluate stocking success and adjust stocking locations, species, strains, and stocking rates. 4. Implement stringent measures to reduce non-climatic stresses on fish populations.	1. Use climate models to focus habitat rehabilitation efforts where they will be required to complement population recovery. 2. Recognize changing habitat limitations due to climate change in species recovery plans or any management actions aimed at changing fish community structure. 3. Use landscape models to prioritize restoration efforts for key species (e.g., conservation blueprint). 4. Protect, rehabilitate, and enhance streams and lakes and their shorelines and corridors to ensure they are as healthy as possible from a biophysical perspective. 5. Identify major locations of thermal pollution and fish movement in targeted coldwater systems, and use strategies such as small dam modification, removal, or decommissioning to mitigate these problems.	1. Evaluate feasibility of stocking species at risk and the need to develop hatchery brood stock. 2. Consider using restored rivers and streams to help restore species at risk and increase their resilience to variability.	1. Monitor effectiveness of population restoration with changing climate.	1. Develop a vulnerability matrix for stocked species (and strains for stocking). 2. Develop a program for monitoring the effectiveness of stocking activities. 3. Research ways of dealing with water quantity and quality issues in an aquaculture setting. 4. Undertake research into species' suitability for stocking under various climate change scenarios. 5. Research temperature tolerances and culture techniques of species to ensure stocking success given anticipated climate change. 6. Research culture techniques for alternate species (e.g., warmwater species and species at risk). 7. Research relationship between key life cycle requirements and stream conditions and dynamics to improve restoration efforts. 8. Develop models that link changes in habitat suitability to species composition and abundance. 9. Evaluate research and development needs with respect to culture techniques for alternate species. 10. Experiment with different strains, temperature tolerances, and culture techniques.

Climate change effect(s)	Policy and program development	Population management	Habitat management	Biodiversity	Monitoring	Science needs
FISHING EFFORT						
Changes to participation rates. Changes to the seasonal distribution of angling effort. Changes in spatial distribution of angling effort as fish communities change. Changes to species preferred by anglers as fish communities change. Changes to the effectiveness of fishing techniques (e.g., gear, bait, locations, assessment methods).	1. Develop a fisheries management response strategy to address anticipated changes to resource use patterns. 2. Develop a public education strategy to increase public and stakeholder awareness of the effects of climate change on fish communities and angling opportunities.	1. Anticipate and make necessary adjustments to timing and length of fishing seasons, sanctuaries, etc. 2. Anticipate changes in fishing activities and adjust compliance operating plans. 3. Promote use of less popular species (e.g., warmwater species). 4. Review stocking initiatives to incorporate changes in angling activity.			1. Implement a provincial long-term monitoring program to measure changes in the intensity and distribution of fishing effort.	1. Complete studies using climate models to understand potential changes to the winter season and its effects on fish communities. 2. Complete a cost–benefit analysis of the effect of changing seasonal patterns in fishing. 3. Investigate the acceptability of various fishing effort control options. 4. Cost–benefit analyses of increased winter fishing by commercial fishing industry.

Climate change effect(s)	Policy and program development	Population management	Habitat management	Biodiversity	Monitoring	Science needs
FISH HEALTH						
May increase likelihood of successful introduction of new fishborne diseases. Changes to diversity of fish parasites. May increase prevalence, infection rate, and rate of spread of parasites and fishborne diseases. Changes to contaminant levels in fish. Changes to habitat conditions that increase the prevalence of fish kills.	1. Develop adaptive policies and programs and inter-agency agreements for fast response to fish disease. 2. Continue to assist in the development of standard fish consumption guidelines and publication of consumption advisories. 3. Develop a public education strategy and communications plan to increase awareness of the effects of climate change on fish kills, contaminants, fishborne pathogens and parasites, and pathways of transmission and spread of these disease agents.				1. Increase monitoring efforts for contaminants in exploited species. 2. Monitor prevalence and distribution of fish disease across Ontario. 3. Include environmental data monitoring in standard assessment protocols.	1. Develop models for the effects of water temperature and chemistry changes on fish disease vectors and parasite life cycles. 2. Develop risk matrices for fish diseases and parasites in conjunction with projections of climate change. 3. Investigate role of invasive species in the propagation of fish diseases and the concentration of contaminants in food webs. 4. Develop a risk assessment for introductions of fish diseases and parasites in response to climate change.

Climate change effect(s)	Policy and program development	Population management	Habitat management	Monitoring	Science needs
AQUATIC HABITAT					
Change in availability and distribution of habitat types: • Reduced coldwater habitat • Increased warmwater habitat • Decreased base flows and groundwater inputs • Blocked migration routes • Increased or decreased wetland areas affecting fish production Reduced quality of habitat: • Increased shoreline erosion and runoff resulting in loss of spawning habitat • Warmer water and lower dissolved oxygen resulting in increased algal and bacterial growth and fish kills Increased variability of habitat quantity and quality: • More variable lake levels and stream flows • Acidification due to droughts and subsequent runoff	1. Promote integrated watershed planning as way to better manage watersheds and aquatic resources. 2. Focus aquatic management for rivers on maintaining healthy and diverse stream channels and stable, healthy riparian areas and stream corridors. 3. Work with appropriate agencies (e.g., DFO, MOE) to review policies and guidelines for fish habitat protection and enhancement. 4. Develop policy to promote functional characteristics of stream corridors as a way to provide greater resiliency to changing flow, temperature, and habitat conditions. 5. Revise Forest and Water Management Planning Guidelines to incorporate anticipated changes in aquatic habitat. 6. Adjust MNR and DFO compliance protocols to reflect changes to fish habitat protection and enhancement due to climate change. 7. Revise best management practices for other sectors (e.g., agriculture and urbanization) to incorporate anticipated habitat changes. 8. Anticipate need for improved access to lakes and rivers due to low water levels and evaluate legislation and guidelines. 9. Establish regional priorities for protection and rehabilitation of fish habitat by incorporating anticipated effects of climate change. 10. Revise provincial guidelines for removal or decommissioning of small dams to improve thermal condition and fish access. 11. Develop guidelines for establishing enhanced riparian zones that take into account climate change projections. 12. Review and adjust Planning Act, 1990 hazard lands policies and growth–settlement policies around nearshore areas to account for increased variability in water levels, erosion control, and contaminated sediments. 13. Develop an education and awareness program to demonstrate that healthy streams and corridors provide a buffer and adaptation to changing conditions. 14. Develop more conservation programs aimed at protecting fish habitat (e.g., small dam removal, conservation land tax).	1. Review and adjust timing windows for work in aquatic environments based on anticipated changes in climate.	1. Increase buffer zones around riparian areas to account for more variability in water depth and flow. 2. Rebuild or re-establish wider riparian zones and buffers along rivers and streams to handle greater flow variability (e.g., increase bank storage and riparian relief in high flows, increase baseflow conditions, re-adjust baseflow cross-section in low flows). 3. Consider and incorporate anticipated changes to aquatic habitat into the review cycle of water and forest management plans and annual work schedules. 4. Adjust management of water-control structures, levels, and flows to preserve wetland areas and moderate extreme low flows in streams (i.e., hold more water on the landscape for release as needed). 5. Encourage stewardship groups and the public to protect and rehabilitate aquatic habitat, riparian zones, and wetlands areas with emphasis on coldwater systems. 6. Work with other government agencies to identify those habitats exposing fish to higher risk of diseases and contamination to prioritize rehabilitation. 7. Reduce habitat fragmentation by protecting, enhancing, and rehabilitating migration routes to ensure access to critical habitats (e.g., access to coldwater refuges, spawning, and nursery areas). 8. Re-establish healthy stream corridors by encouraging private sector, municipalities, and other agencies to apply stream corridor management guidelines and approach (e.g., natural channel system).	1. Increase provincial monitoring and assessment of aquatic habitats and water quality and quantity parameters. 2. Increase monitoring and mapping of erosion-prone areas for hazard detection. 3. Increase effectiveness monitoring of mitigation measures for water-control structures. 4. Monitor implementation of watershed-based plans and assess their effectiveness.	1. Develop a classification system based on vulnerability indices for lakes, streams, and wetland areas. 2. Develop better modelling tools that can illustrate the resulting distribution of aquatic ecosystems in response to climate projections. 3. Use modelling to project effects on specific watersheds to better guide development in riparian and buffer zones and floodplains. 4. Compile more studies on technologies used to prevent effects on fish of water control structures and relate these to species present in regional watersheds as to their effectiveness (e.g., salmon fish ladder is used by 75% of migratory fish, but only 56% make it through). 5. Explore emerging technologies to reduce effects of water-control structures on fish. 6. Investigate the relationship between flow control release times and methodologies compared with critical periods in target fish species' life cycles to assess effects, and use model projections to determine how current regimes may change. 7. Develop a classification system based on vulnerability indices for lakes, streams, and wetland areas. 8. Develop better modelling tools that can illustrate the resulting distribution of aquatic ecosystems in response to climate projections. 9. Use modelling to predict effects on specific watersheds to better guide development on stream corridors and buffer zones. 10. Develop a standard suite of indicators to monitor status and trends of fisheries and aquatic habitat related to climate change effects.

Climate change effect(s)	Policy and program development	Population management	Habitat management	Monitoring	Science needs
BIODIVERSITY					
Changes to fish species distributions and range: • Expansion of range of warmwater species • Reduced numbers of populations of coldwater species Changes to the number, types, distribution, and range of invasive species: • More invasive species migrating to and surviving in Ontario waters • Increased effects on species at risk and other native species from invasive species Species at Risk: • Changes to status of species currently listed at risk. • Changes to the distribution and range of species at risk Fish community structure and function: • Changes to species dominance, trophic interactions, and competition for habitat	1. Develop legislation and stronger policies to prevent the anticipated increase in introductions and spread of invasive species. 2. Identify areas of aquatic ecosystem representation within the Parks and Protected Areas system that anticipate the effects of climate change. 3. Incorporate information on the effects of climate change into the existing invasive species awareness program. 4. Work with U.S. and Canadian federal agencies to develop and adopt a plan to prevent invasive species from entering the Great Lakes. 5. Develop rapid-response protocols for invasive species. 6. Incorporate effects of climate change into species at risk regulation and policy development. 7. Re-evaluate priorities for species at risk recovery planning in a changing climate. 8. Increase public and stakeholder awareness of the effects of climate change on species at risk. 9. Revise allocation and harvest management policies to address anticipated changes in fish communities resulting from climate change.	1. Develop fish community rather than species-specific management strategies. 2. Implement new regulations or adjust existing regulations to respond to changes to distributions and ranges of fish species. 3. Review and adjust fishing regulations using a precautionary approach to prevent the anticipated increase in introductions and spread of invasive species in Fisheries Management Zones. 4. Develop brood stocks of species at risk (e.g., Atlantic salmon, native unionid clams). 5. Manage fish populations to maintain genetic diversity in order to adapt to climate change.	1. Protect habitat for species at risk, particularly areas containing the species most vulnerable to climate change. 2. Increase the resistance and resilience of species at risk through habitat protection, rehabilitation and relocation, provision of migratory corridors, reduction of non-climatic stressors, and emphasis on management and control of invasive species.	1. Incorporate species at risk, invasive species and biodiversity monitoring into a provincial aquatics monitoring program. 2. Monitor trends in spatial distribution of fish species as part of routine monitoring. 3. Monitor trends in stream morphology, temperature, and habitat conditions as part of routine monitoring. 4. Increase monitoring for invasive species in areas of high risk and in northern fringe areas of their range. 5. Engage the public in monitoring and reporting by promoting public invasive species identification and distribution mapping.	1. Study trophic changes in lakes and rivers and the effects of these changes on key species. 2. Document changes to native habitat caused by invasive species 3. Research habitat requirements of species at risk to assess future effects of climate change versus other anthropogenic influences. 4. Determine effects of changing primary productivity on species at risk. 5. Develop models to project the effects of water temperature and chemistry changes on fish prey. 6. Develop methods to monitor the prey and plankton base within a lake or river ecosystem. 7. Study changes in habitat condition, stream flow, and groundwater discharges and their effect on fish species. 8. Conduct research on critical prey species used by target species. 9. Determine the effects of invasive species on energy flow through food webs. 15. Investigate role of invasive species in structuring fish communities. 16. Conduct research to identify optimal habitat for target species and use models to project changes in habitat distribution. 17. Apply knowledge of invasion pathways to help design monitoring programs. 18. Understand effects of invasive species on fish communities (e.g., the influence of bass on lake trout) and how they will change in response to climate. 19. Develop a better understanding of the habitat requirements for species at risk.

Climate change effect(s)	Policy and program development	Population management	Habitat management	Monitoring	Science needs
SOCIOECONOMIC VALUES AND DEMANDS					
Increased competition between ecological and societal uses of water (e.g., greater need for more water-control structures for hydropower generation). Greater public demand for more active management strategies (e.g., to preserve habitats and stocks). Greater public demand for more involvement in fisheries management decisions. Change to socioeconomic value: • Shifting economic value of different resources (e.g., warmwater fishery versus coldwater fishery) • Change in distribution of benefits among sectors (e.g., tourism versus commercial) • Regional shifts in socioeconomic benefits derived from fisheries resources • Changes to cultural use of fisheries resources	1. Review water uses (e.g., hydro power, water withdrawal) and develop allocation guidelines that ensure protection of aquatic biota and habitat given climate change. 2. Understand environmental goods and services provided by healthy aquatic systems and ensure an appropriate balance between uses. 3. Develop adaptation plans coordinated across levels of government involving industry, community leaders, and stakeholders. 4. Implement a process for co-management of fisheries. 5. Increase partnerships, collaborations, and public activities to establish common goals, prioritize actions, and mitigate or adapt to climate change. 6. Develop a strategy to enhance public knowledge of the biological and socioeconomic effects of climate change. 7. Develop a strategy to resolve aquatic resource–use conflicts among stakeholders (e.g., expand Great Lakes Fishery Commission sessions for stakeholders). 8. Evaluate the vulnerability of fisheries sectors (e.g., tourism, commercial, aboriginal) to climate change. Develop a strategy to increase resilience and reduce potential losses.	1. Develop more programs to enhance public knowledge of biological and socioeconomic effects of climate change.	1. Apply ecological flow guidelines to protect aquatic habitat and biota from increased water demands.	1. Incorporate socioeconomic parameters into provincial fisheries monitoring programs. 2. Work with DFO to incorporate additional socioeconomic data and analysis in the federal Recreational Fishing Survey. 3. Integrate socioeconomic monitoring for fisheries with other corporate initiatives.	1. Develop ecological flow levels for protecting habitats in a rapidly changing climate.

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