Impacts of climate change on fish species and aquatic ecosystems in the Great Lakes and Prairie regions of Canada: a compilation of reports

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ABSTRACT

This compilation report aims to provide a summary of available information on climate change effects on aquatic life in the Freshwater basins of Canada. An important outcome of this review is a summary of gaps of knowledge. The first chapter is a review of predicted climate induced changes on freshwater fish communities and food webs and details the effects of changes in biotic and abiotic processes on freshwater fish communities and food webs. The second chapter describes the impact that changes in climate are expected to have both directly and indirectly on a variety of fish species and their habitats. The third Chapter describes suitable thermal habitat for stream biota based on different climate variables to assess the potential impacts of climate change on the distribution of coldwater stream fish species in the Great Lakes Basin. The last chapter provides an overview of climate change impacts on water temperature, water chemistry, ice cover, water levels, and productivity. This report provides significant evidence that under a changing climate we can expect significant changes in the spatial extent and duration of preferred thermal habitat for ecologically and economically important fish across the Freshwater region. Warming temperatures expected with climate change will cause areas to approach water temperatures that are no longer thermally optimum for fish species. Species will need to migrate to find suitable habitats and productivity and survival success may decline for some species. Greater habitat overlap may intensify interguild competition and food web interactions. These changes in thermal habitat may intensify top down food web effects.

RÉSUMÉ

Le présent rapport de compilation vise à fournir un résumé des renseignements disponibles sur les répercussions des changements climatiques sur la vie aquatique dans les bassins d'eau douce du Canada. L'un des résultats importants de cet examen est un résumé des lacunes en matière de connaissances. Le premier chapitre est un examen des répercussions des changements climatiques prévues sur les communautés de poissons d'eau douce et les réseaux trophiques et on y expose en détail les répercussions des changements dans les processus biotiques et abiotiques sur les communautés de poissons d'eau douce et les réseaux trophiques. Le deuxième chapitre décrit les répercussions que les changements climatiques devraient avoir à la fois directement et indirectement sur diverses espèces de poissons et leurs habitats. Le troisième chapitre décrit l'habitat thermique propice au biote des cours d'eau selon différentes variables climatiques pour évaluer les répercussions que pourrait avoir le changements climatiques sur la répartition des espèces de poissons des cours d'eau froide dans le bassin des Grands Lacs. Le dernier chapitre donne un aperçu des répercussions des changements climatiques sur la température de l'eau, la chimie de l'eau, la couverture de glace, les niveaux d'eau et la productivité. Le présent rapport fournit des preuves significatives que dans le contexte des changements climatiques nous pouvons nous attendre à des changements importants dans l'étendue spatiale et la durée de l'habitat thermique préféré des poissons importants sur les plans économique et écologique dans la Région du bassin d'eau douce. Le réchauffement climatique prévu en raison des changements climatiques entraînera une augmentation de la température de l'eau dans certaines zones à des niveaux qui ne sont plus optimaux pour certaines espèces de poissons. Ces espèces devront migrer afin de trouver des habitats propices; la productivité et le succès de la reproduction pourraient connaître un déclin chez certaines espèces. Le chevauchement accru des habitats pourrait augmenter la compétition entre les espèces et les interactions dans le réseau trophique. Ces changements dans l'habitat thermique pourraient aussi accroître les effets descendants sur le réseau trophique.

PREFACE

Fisheries and Oceans Canada (DFO) received funding for the Aquatic Climate Change Adaptation Services Program (ACCASP; 2011-2016) in order to implement a science-based climate change program focused on adaptation and delivery of Fisheries and Oceans' mandated areas of responsibility. The Program will undertake risk assessments, foster the development of applied science-based tools and research projects in order to gain a better understanding of the impacts of climate change and enable adaptation.
To tackle the primary objective of the Program, an assessment of the risks that climate change poses to the delivery of DFO's mandate across the diverse aquatic ecosystems of Canada were performed. Fisheries and Oceans Canada has various responsibilities within this area. DFO is responsible for management of all fisheries in Canada, but in most freshwaters these responsibilities are delegated to the provinces. Fisheries management includes programs to conserve and manage fishery resources for sustainable use. Legislative responsibilities and policies are also administered by Fisheries and Oceans Canada for the purpose of conserving, restoring and developing fisheries resources.

The first step of this assessment was to focus efforts on extracting all known information based on the available literature. This Compilation Report thus aims to achieve part of this goal through examining the impacts of climate change on fish species and aquatic ecosystems in the Great Lakes and Prairie Freshwater regions. The results will help DFO decision-makers adapt decisions to reflect climate change considerations in informing priorities for fish and aquatic life. This report is organized into 4 main chapters to achieve this goal. Each Chapter is designed to read independently but all inform the same goal.

The first chapter "Impacts of climate change on fish communities and foodwebs of Great Lakes, St. Lawrence River and the Saskachewan-Nelson River watersheds" by S. Hasnain is a review of predicted climate induced changes on freshwater fish communities and food webs in three major watersheds of Canada: the Laurentian Great Lakes, St. Lawrence River and Saskatchewan-Nelson River Basin. In the first section, a brief overview of the climate change models and scenarios used within the literature is provided. Projected trends in hydrology expected for these regions as a result of climate change were described. The second section details the effects of changes in biotic and abiotic processes on freshwater fish communities and food webs in these regions as a result of climate change. The review concluded by identifying current gaps in knowledge within the literature and making recommendations for future research.

The second chapter "The effects of climate change on fish species of the Great Lakes and Prairie Regions of Canada" Guzzo and Chapelsky describes the impact that changes in climate are expected to have both directly (e.g. through temperature effects on consumption/ metabolism) and indirectly (e.g. through trophic dynamics, habitat changes) on a variety of fish species and their habitats. Both of these systems are predicted to undergo changes resulting from climate change, however, biotic and abiotic changes that can affect fish communities will vary among systems (Magnuson et al. 1997; Gunn et al. 2004). The thermal regimes of lakes respond to climate change because they are controlled by solar radiation, wind, air temperature and humidity as well as other factors. These variables impact the thermal habitat, survival rates, and winter survival for warm-, cool- and cold-water fish species.

The third Chapter "Climate Change Risk Assessment: Streams in the Great Lakes Basin" by Chu and Fischer describes suitable thermal habitat for stream biota. Available habitat is influenced by air temperature, water temperature, precipitation, flow, land use, channel and

floodplain morphology and riparian vegetation. Thus, air temperature is to be used as a suitable predictor of stream temperatures. Stream temperatures follow the seasonal pattern of warming and cooling. Ground water discharge into streams is crucial to thermal habitats as it provides a constant flux that approximate mean annual air temperature. Consequently ground water discharge allows for a thermal condition for species that prefer cooler temperatures in the summer and warmer temperatures in the winter. This allows for a thermally diverse habitat and distribution of species. Chu and Fischer use this information to:

- Assess the potential impacts of climate change on the distribution of coldwater stream fish species in the Great Lakes Basin (532 watersheds)
- Likelihood index developed by Chu et al., 2008
- Develop adaptation options for those impacts

The results show a decrease in watersheds ability to support coldwater fish. Presently 420 watersheds have high likelihood of supporting coldwater fish, by 2100 this diminished to 96. Watersheds with higher ground water inflows and lower increases in air temperature have the highest potential for retaining cold water species.

The last review chapter "Potential effects of climate change on Fish Habitat, primary production, secondary productivity and connectivity in Freshwater ecosystems by Vianna provides an overview of climate change impacts around the world as well as a detailed description of the characteristics of the Great Lakes, and Saskatchewan-Nelson River watersheds. It goes into detail about the effects on lakes, rivers, and wetlands for each of the following: water temperature, water chemistry, ice cover, water levels, and productivity. The research also identifies gaps in knowledge.

Managing climate-driven changes in the Freshwater region will be a challenge for provincial and federal agencies. Biodiversity will change in response to the combined influence of climate change, human activity, movement of species including aquatic invasive species, changes in predator-prey relationship and ultimate impact on available habitat suitability. Some species will adapt to these changing conditions while others will not. Species with high reproductive rates and with the ability to migrade long distance, rapidly colonize and have higher thermal tolerances will be the most successful (Gray, 2005).

More research is needed to understand how the dynamics of the climate and ecosystem will function under changing conditions. It is necessary to build an understanding of the effects of climate through reseach, monitoring and assessments of the aquatic environment. Monitoring should strive to evaluate fish populations in regions of rapid change.

While the effects of climate change on aquatic ecosystems such as habitat availability and the species specific impacts are not completely understood, "no regrets" management actions are required to improve our changes of maintaining a healthly aquatic ecosystem and a sustainable fishery in the future.

EXECUTIVE SUMMARY

Climate change is expected to have an immense impact on freshwater fish communities and food webs in the Laurentian Great Lakes, St. Lawrence River and Saskatchewan-Nelson River Basin watersheds. Rising mean annual air temperatures are expected to affect abiotic processes governing these ecosystems resulting in changes in water temperatures, precipitation and flow regimes, dissolved oxygen and ice cover which will directly impact fish biodiversity in the regions. These abiotic changes, in turn, cause changes in biological interactions between species, especially the dynamics of ecological invasions and disease which will further impact fish communities and food webs in these regions.

Climate change is expected to modify patterns of precipitation, runoff and evaporation at a global scale. These changes may lead to a shift in peak stream flows from spring to late winter in snowmelt regions, affecting reproductive cycles of riverine fishes (Rahel and Olden 2008). Inter and intra-annual flow variation can affect the connectivity of intermittent streams, influencing dispersal, reproduction and population characteristics of fish species (Brooks 2009). As future thermal environments will likely exist within the optimum range of temperatures for these species, warm water fishes are predicted to experience an increase in thermal habitat as a result of rising temperatures (Schindler 2001; Daufresne and Boet 2007; Lyons et al. 2010).

Declining lake levels can negatively impact biodiversity, as shorelines provide important nursery habitat for many fish species. Increasing water temperatures are expected to greatly influence the composition of freshwater fish communities. Considering that the majority of these species occur in Northern latitudes, which are expected to undergo the greatest increase in mean annual air temperatures globally, coldwater fish species are predicted to experience local extinctions and extirpations at a large scale. This is especially true for species at the southern boundary range where these species are maintained within a few degrees of their thermal limits (Schindler 2001; Heino et al. 2009).

The consequences of changes in water temperature over the freshwater lakes (and its organisms) will be mediated by alterations in thermal stratification. The warming of non-stratified lakes would will move the distribution boundary of many warm and cool water species northward, at the same time excluding them from small lakes with now deeper thermoclines and hypoxic hypolimnion (Schindler *et al*. 1990). In stratified lakes, the declining oxygen level below the thermocline will degrade the habitat for cold water fishes and organisms (Magnuson *et al*. 1997).

Besides obvious reductions in water availability, other indirect effects may complicate the predictions about responses of productivity to climate change, including: (i) increasing eutrophication and thermal stratification can exacerbate hypoxia for many organisms; (ii) a shift in phytoplankton composition towards toxic algae (cyanobacteria) can compromise production at higher trophic levels; (iii) changes in ice cover may decrease or increase productivity, depending on ice characteristics; (iv) increasing input of nutrients may be accompanied by increasing pollutant concentrations and water turbidity, compromising light penetration and photosynthesis; (v) although photosynthesis is benefited by increasing light penetration, it may be accompanied by increasing UV penetration, which can damage organisms and compromise production.

CHAPTER 1: IMPACTS OF CLIMATE CHANGE ON FISH COMMUNITIES AND FOOD WEBS OF GREAT LAKES, ST. LAWRENCE RIVER AND SASKATCHEWAN-NELSON RIVER WATERSHEDS BY S.S. HASNAIN

OVERVIEW

A rise in CO_2 emissions over the past half century has resulted in an increase of 0.6ºC in average global temperatures (Crowley 2000). Global climate models (GCMs) predict this trend will continue through this century with increases of 1-5°C in average air temperature (Winder and Schindler 2004; Bryant 2009). Regional variation in rising temperatures is expected to impact organisms, communities and ecosystems in a spatially heterogeneous manner (Walther *et al*. 2002). In mid to high latitudes the freeze-free periods have lengthened, with a 10% decrease in snow cover and ice extent since the 1960s (Walther *et al*. 2002). Rising temperatures have also resulted in increased variation in global precipitation regimes. In the Northern Hemisphere, a decadal increase in precipitation of 0.5±1% has been noted during autumn and winter while in the sub-tropics precipitation has been decreasing by 0.3% per decade (Walther *et al*. 2002).

Climate induced changes to global hydrological cycles are predicted to adversely impact freshwater ecosystems (Magnuson *et al*. 1997; Schindler 1997; Sala *et al*. 2000; Schindler 2001). Freshwater ecosystems are considered the most vulnerable to anthropogenic stressors including climate change (Sala *et al*. 2000; Heino *et al*. 2009). A global analysis of biodiversity changes across 10 terrestrial and aquatic biomes suggested that global fresh-water biodiversity is declining at far greater rates than the most affected terrestrial ecosystems (Sala *et al*. 2000).

Climate change impacts on freshwater ecosystems are dependent on a variety of physical and biological factors such as ecosystem type, complexity, resilience, and taxonomic biodiversity. Small transient streams, for example will be more vulnerable to low flows and floods anticipated by changes in precipitation regimes, while small, shallow ponds would be more susceptible to thermal stress as compared to large lakes (Heino *et al*. 2009). The impact of climate change on freshwater biodiversity has been shown to vary depending on taxa. For example, thermal habitat for coldwater species will decrease with increasing water temperatures, resulting in range contractions at southern limits for many taxa, while warmwater species experience expansions at their northern range limits (Magnuson *et al*. 1990; Magnuson *et al*. 1997; Schindler 1997; Schindler 2001; Willis and Magnuson 2006; Sharma *et al*. 2011). To understand, predict and assess the impacts of global climate change on freshwater biodiversity, different, often-disparate, responses across all taxa and ecosystem types must be considered from a community or ecosystem perspective.

The purpose of this review is to summarize climate induced changes on freshwater fish communities and food webs in three major watersheds of Canada: the Laurentian Great Lakes, St. Lawrence River and Saskatchewan-Nelson River Basin. In the first section, a brief overview of the climate change models and scenarios used within the literature will be provided. Projected trends in hydrology expected for these regions as a result of climate change will be described. The second section will detail the effects of changes in biotic and abiotic processes on freshwater fish communities and food webs in these regions as a result of climate change. The review will conclude by identifying current gaps in knowledge within the literature and making recommendations for future research.

CLIMATE CHANGE MODELS

Climate change models are the most important tool used to predict and assess the impacts of climate change on the physical and biological processes governing aquatic ecosystems. Generally, climate change models are a mathematical representation of the atmospheric, ocean, terrestrial and cyrospheric (ice and snow) processes that govern the global climate system. These models utilize historic climate data and patterns to project future climate under different CO_2 emission scenarios. There are a number of models utilized to assess climate change impacts within the literature. The following models were most commonly utilized to assess the impacts of climate change on freshwater fish communities and food webs and will be briefly discussed below: CGCM1-3, CSIRO-MK30, ECHAM3-5, GFDL CM2.0-2.1, HADCM2-3, and PCM.

CGCM1-3

This model was developed by the Canadian Centre for Climate Modelling and Analysis in 2000, with subsequent iterations in 2001 (CGCM2) and 2005 (CGCM3) (Flato *et al*. 2000, Flato and Boer 2001).It is composed of an atmospheric portion, which models change in atmosphere and sea-ice, and an oceanic component that, when coupled together, allow for integration of all processes during climate simulations. This modelling framework specifically includes in-land seas as a separate landscape feature (Randal *et al* 2007).

CSIRO-MK30

This model was developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in 2002 (Gordon *et al*. 2002; Randal *et al*. 2007). It consists of two major components: AGCM (the Atmospheric General Circulation Model) containing the atmospheric, land surface, and sea-ice models, and the OGCM (the Ocean General Circulation Model), which are coupled together during climate simulations (Gordon *et al*. 2002; Randal *et al*. 2007).

ECHAM3-5

Developed by the Max Planck Institut für Meterologie, this model, ECHAM3 (1992) and subsequent iterations, ECHAM4 (1996) and ECHAM5 (2003), are based on global forecast models created by the European Centre for Medium Range Weather Forecasts. Consisting of an atmospheric general circulation model ECHAM5 and the atmosphere ocean model ECHAM5/MPI-OM, these components are also coupled within this modelling framework. A special feature of this model is the inclusion of variations in the orbital mechanisms that can potentially cause global climate change, based on their influence on major climate events in the past (e.g. Pleistocene ice age; Milankovitch 1941; Roeckner *et al*. 2003; Randal *et al* 2007).

GFDL CM2.0-2.1

This model was developed by the Geophysical Fluid Dynamics Laboratory in 2005 and consists of four separate components: atmosphere, land, sea ice, and ocean, which are coupled together during climate simulations (Delworth *et al*. 2006). There are two versions of this coupled model, CM2.0 and CM2.1 with minor differences in the atmospheric component. In CM2.1, network surface radiation is increased to deal with the cold bias in the earlier version of the model, and the Caspian Sea is included as distinct land surface type and specifications for greenhouse gas emissions. Also, tropospheric and stratospheric ozone and the three-dimensional distribution of natural and anthropogenic aerosols are updated (Delworth *et al*. 2006)

HadCM2-3

This model was developed by the Hadley Centre for Climate Change Research and Prediction in 1995 (HadCM2), and expanded in 1999 (HadCM3). It was the first climate model configuration to couple atmospheric and oceanic processes, thereby removing the need for flux adjustments to prevent models from drifting into unrealistic climate states (Pope *et al*. 2000; Randall *et al*. 2007). This model also has the capability to capture the time-dependent fingerprint of historical climate change using scenarios with natural and human-induced changes, making it a useful tool for detecting climate changes in the past (Pope *et al*. 2000; Stott *et al*. 2000).

PCM

The Parallel Climate Model (PCM) was developed by the National Centre for Atmospheric Research in 1998 (Randall *et al*. 2007). It consists of three components: atmosphere, ocean and sea-ice, which are also coupled together during climate simulations (Washington *et al*. 2000).

CLIMATE CHANGE SCENARIOS

Climate change models are parameterized by a variety of climate change scenarios in order to project future impacts of climate change. These scenarios provide a range of possible trends in future CO_2 output over a 100 year period, based on predictions about future trends in economic development, population growth, energy use, and land-use change (Nakicenovic *et al*. 2000). Currently, standardized CO_2 scenarios have been developed and applied in climate change models by the Intergovernmental Panel on Climate Change (IPCC) and within the literature. These scenarios fall within four scenario families: A1, A2, B1 and B2. A brief description of each family is provided below:

A1

In the A1 scenario family, the future is described as one of rapid economic and population growth, peaking in the mid-century and declining afterwards and included the introduction of new technologies in energy consumption ranging from carbon intensive to decarbonisation (Nakicenovic *et al*. 2000). Final energy intensities (energy use per unit GDP) decline at 1.3% per year.

A2

This scenario family represents a more heterogeneous world, characterized by a slow but continuous increase of global population and regionalized patterns in economic growth and technological innovation with a 0.5-0.7% per annum decline is predicted for final energy intensities (Nakicenovic *et al*. 2000).

B1

The B1 scenario envisions a future with highly developed social and environmental consciousness and sustainable development, with a smooth transition from conventional oil and gas resources to alternative energy systems leading to low greenhouse gas emissions (Nakicenovic *et al*. 2000).

B2

The B2 scenarios are similar in to B1, but assume heterogeneous global development (Nakicenovic *et al*. 2000). Sustainability and alternate energy development are regionally distributed and uneven (Nakicenovic *et al*. 2000). Final energy intensities are predicted to decline by 1% per annum.

AREAS OF INTEREST

This literature review focuses on describing the impacts of climate change on freshwater fish communities and food webs within three regions in Canada. However, very few studies within the literature have examined possible climate change impacts or provided future climate projections for these regions.

Laurentian Great Lakes

For the Laurentian Great Lakes, general circulation models have predicted that a doubling of CO_2 will result in an overall decline in water levels and outflows across the region. The greatest declines are predicted for lakes Michigan and Huron, with a 0.99m-2.48m drop in lake levels among different scenarios (Magnuson *et al*. 1997). The smallest decline is predicted for Lake Superior (-0.23 to -0.47 m) (Magnuson *et al*. 1997). Mean annual outflows are expected to experience an average decrease of 30% across all lakes, with the greatest decline predicted for Lake Erie Basin and the least for Lake Superior (Magnuson *et al*. 1997). For the 121 regional watersheds draining into the Great Lakes region, moisture storage is predicted to decline substantially despite an increase in precipitation in northern sub-basins, as a result of increased evapotranspiration due to rising mean annual air temperatures (Magnuson *et al*. 1997). Duration of ice cover throughout the regions is expected to reduce from 13-16 weeks to 5-13 weeks, with mid lake areas ice free for most winters (Magnuson *et al*. 1997).

St. Lawrence River

For the St. Lawrence river region, climate models under two scenarios (A2 and B2) have projected an increase in winter and decrease in spring discharge as a result of increasing mean temperatures and decreasing snow/precipitation ratio during the winter and spring periods (Boyer *et al*. 2010). Changes in seasonal discharge are expected to result in changes in sediment transport, with increased sediment transport for winter and decreased sediment transport for spring and causing irrevocable changes in river morphology (Boyer *et al*. 2010).

Saskatchewan-Nelson River Basin

There is very little information available within the literature for climate change impacts for the Saskatchewan-Nelson River Basin. Generally, it is expected that increasing temperatures will have the greatest impacts on hydrology among all other environmental variables (Westmacott and Burn 1997). Increased evaporation and decreased net precipitation are expected to result in reduced runoff, groundwater flow and hydrological inputs, causing reduced flow rates for streams and rivers (Westmacott and Burn 1997). Snowmelt is also expected to occur earlier, resulting in increased discharge and flow in spring (Westmacott and Burn 1997).

IMPACTS OF CLIMATE CHANGE ON FRESHWATER FISH COMMUNITIES AND FOOD WEBS

Within the literature, gaps in the information exists with regards to specific climate change impacts for the Laurentian Great Lakes, St. Lawrence River and Saskatchewan-Nelson River Basin watersheds. Therefore, literature detailing climate change impacts on freshwater fish communities and food webs across all regions was included in this review. Considering the similarities in hydrology, morphology and biodiversity across global aquatic ecosystems, it is reasonable to use data from relevant literature for other regions to determine climate impacts for these regions.

Climate change can impact freshwater fish communities and food webs either directly, through climate-induced changes in abiotic processes governing these systems, or indirectly, through biotic processes influenced by abiotic changes in the environment. These impacts are detailed in subsequent sections.

Abiotic Processes

As indicated previously, climate change will have numerous impacts on abiotic processes governing freshwater ecosystems, including but not limited to water temperature, flow rates, flooding, onset and duration of ice cover, sediment transport and disturbance frequency and magnitude (Magnuson *et al*. 1997; Ficke *et al*. 2007; Buisson *et al*. 2008; Prowse *et al*. 2009; Morrongiello *et al*. 2011). For freshwater fish, these processes are important determinants of growth, survival, and reproductive successes, thereby influencing the biodiversity present within local assemblages and community composition. As obligate poikiloectotherms, fish are dependent on environmental temperature to regulate important physiological process such as metabolic rate and protein synthesis (McCarthy and Houlihan 1997; McCarthy *et al*. 1999; Beitinger *et al*. 2000). Additionally, perturbations in temperature have been shown to adversely impact egg development in fish by arresting the development of previtellogenic and mature oocytes leading to decreased hatching success (Van der Kraak and Pankhurst 1997). Young of the year (YOY) fish density is positively related to high flows in the short-term during spawning and variability in flow during egg and larval development (Craven *et al*. 2010). This section will outline changes expected in freshwater fish communities and food webs as a result of changes in water temperature, flow, dissolved O_2 and ice cover.

WATER TEMPERATURE

Coldwater Fish

Increasing water temperatures are expected to greatly influence the composition of freshwater fish communities. Coldwater species (optimal temperatures <19°C), such as Arctic Charr, are predicted to experience a short-term increase in growth followed by loss of thermal habitat in the long term due to limited thermal tolerance (Coker *et al*. 2001; Graham and Harrod 2009; Prowse *et al*. 2009). Considering that the majority of these species occur in Northern latitudes, which are expected to undergo the greatest increase in mean annual air temperatures globally, coldwater fish species are predicted to experience local extinctions and extirpations at a large scale. This is especially true for species at the southern boundary range where these species are maintained within a few degrees of their thermal limits (Schindler 2001; Heino *et al*. 2009). An analysis of climate change impacts on 132 freshwater fish species in forty-three watersheds of Southern Ontario predicted a 67% reduction in coldwater fish habitat by 2025, with coldwater fish species present in 0-37% of watersheds by 2055 (Chu *et al*. 2008). A 50%

reduction in thermal habitat is predicted for cold and coolwater fish (optimal temperatures between 19°C and 25°C) in the Continental United States, with least impacts expected at higher latitudes (Eaton and Scheller 1996; Coker *et al*. 2001). For Wisconsin, thermal habitat for coldwater fish is predicted to decrease under double CO_2 emission simulations (DeStasio *et al*. 1996).

Salmonids as a group are especially vulnerable (Woodward *et al* 2010). For Cisco, local extirpations are linked with mean annual air temperatures, and are expected to increase as temperatures rise in the next century (Sharma *et al*. 2011). By the year 2050, climate models predict a 49% decrease in range size for Brook Trout and a 75% decrease for Arctic Charr (Chu *et al*. 2005). Brown and Rainbow Trout are also predicted to experience large reductions in range size (Preston 2006; Jeppesen *et al*. 2010). In general, a northward moving extirpation of Salmonids is expected with rising temperatures (Jonsson and Jonsson 2009).

Warm and Coolwater Fish
As future thermal environments will likely exist within the optimum range of temperatures (>25°C) for these species, warm fishes are predicted to experience an increase in thermal habitat as a result of rising temperatures (Schindler 2001; Daufresne and Boet 2007; Lyons *et al*. 2010). In large bodies of water that experience thermal stratification, the size of the epilimnion, the top most layer of warm water, is expected to increase in size as warming continues, thus increasing the size of available habitat for warm and coolwater species (Fang and Stefan 1999; Ficke *et al*. 2007; Chu *et al*. 2008). However, rising temperatures at the southern distribution for many species may approach lethal temperatures, resulting in possible reductions in size of favourable habitat. A 14.2% decrease in warmwater fish habitat is predicted in southern United States as a result of climate warming (Eaton and Scheller 1996).

Rising temperatures are likely to favour fish species whose current distribution and reproductive success is constrained by colder temperatures, discounting other limiting factors such as competition, predation and disease (Graham and Harrod 2009).   It is predicted that streams with suitable thermal habitat for warmwater fish will increase by 31% across the continental United States (Rahel and Olden 2008; Lyons *et al*. 2010). Twenty three species in Wisconsin are expected to increase their range, due to increased availability of suitable stream habitat (Lyons *et al*. 2010). Specifically, Centrarchids and Perchids, such as Green Sunfish, Bluegill and Largemouth Bass, are predicted to experience range expansions, with a 950% increase in habitat for Largemouth Bass (DeStasio *et al*. 1996; Eaton and Scheller 1996; Dukes and Mooney 1999). It should be noted that the magnitude of range expansion for warmwater fish is species specific and dependant on an assortment of factors such as dispersal capability, geographic barriers, and prey availability (DeStasio *et al*. 1996).

Spawning and Reproduction
Temperature is also a critical factor in the reproduction of many freshwater fish species. Changes in thermal regimes may lead to a decoupling of the thermal and hydrological conditions essential for reproductive success, altering spawning times and duration of the incubation period (Jones *et al*. 2006; Morrongiello *et al*. 2011). It is predicted that rising temperatures will lead to earlier spawning times and increased duration of the growing season for spring spawning species while fall spawners will experience delayed time of spawning in the autumn or early winter and advanced time of egg hatching and alevin emergence in spring (Jonsson and Jonsson 2009). Hatching times may advance by minutes to hours for smaller eggs, and from hours to days for large egg, especially for coldwater species with long incubation

periods (Pankhurst and Munday 2011). Whether shorter incubation periods affect individual fitness depends on the potential for mismatch between the timing of hatching and favourable conditions for larval survival (Pankhurst and Munday 2011).

At the larval stage, development rates increase with warmer temperatures resulting in shorter durations at each developmental stage. Time until yolk absorption, metamorphosis and pelagic larval duration (PLD), are all negatively correlated with temperature (Pankhurst and Munday 2011). For many species, high levels of mortality are associated with the larval stage. Faster growth and reduced PLD at higher temperatures might increase larval survivorship by reducing the amount of time spent at this stage (Pankhurst and Munday 2011).

Small increases in temperature may favour recruitment in some species, especially at higher latitudes (Jonsson and Jonsson 2009; Pankhurst and Munday 2011). However, large temperature increases could lead to recruitment failures, especially at low latitudes, where temperatures may supersede the optimal requirement for egg and larval development (Jonsson and Jonsson 2009; Pankhurst and Munday 2011). For Brown Trout, increasing stream temperatures in the winter and spring have been shown to result in an increase in the mean mass of pre-smolts, with small increases (<2-5°C) in winter and spring beneficial for growth resulting in greater survival of year old smolts (Elliott and Elliott 2010). In contrast, a 4°C increase in winter/spring, and 3°C increase in summer/ autumn resulted in a negative effect on trout growth (Elliott and Elliott 2010). Rising temperatures also impact over-wintering success in juvenile Roach (Brodersen *et al*. 2011). A few degree increases in winter temperatures above 0°C has been shown to result in increased survival, although winter temperatures greater than 2°C are detrimental to juvenile growth and survival (Brodersen *et al*. 2011).

For new world Shiners (Family: Atherinopsidae), which exhibit temperature-dependent sex determination (TSD) where the phenotypic sex of an individual is determined partly or wholly by the temperature experienced during gonadal sex differentiation, increasing temperatures have been shown to induce germ cell degeneration and decreased fertility (Strussmann *et al*. 2010). In the short term, shiners are expected to experience shortening or overall disruption of spawning activity. Over the long term, more subtle dysfunctions may occur at the population level such as highly skewed sex ratios and partial or total loss of fertility (Strussmann *et al*. 2010). This phenomenon has been documented in natural populations that are confined to landlocked, inland water habitats (Strussmann *et al*. 2010). The severity and recurrence of these dysfunctions are dependent on the magnitude, speed and pattern of thermal change and the rate at which physiological and behavioural traits can evolve to match the new conditions imposed by the changing climate (Strussmann *et al*. 2010).

FLOW AND HYDROLOGY

Stream and Rivers

Climate change is expected to modify patterns of precipitation, runoff and evaporation at a global scale. These changes may lead to a shift in peak stream flows from spring to late winter in snowmelt regions, affecting reproductive cycles of riverine fishes (Rahel and Olden 2008). Increasing variations in flow, such intense flash floods, as a consequence of these changes, may also contribute to changes in biodiversity (Heino *et al*. 2009). A global assessment of 133 river basins under A2 and B2 climate change scenarios predict an 80% reduction in stream discharge (Xenopoulos *et al*. 2005). For a quarter of all river basins outlined in this assessment,

reduction in stream discharge was responsible for the loss of more than 22% of fish biodiversity (Xenopoulos *et al*. 2005).

For low order and intermittent streams, flow regimes are important factors affecting stream ecology (Brooks 2009). Inter and intra-annual flow variation can affect the connectivity of intermittent streams, influencing dispersal, reproduction and population characteristics of fish species (Brooks 2009). Intermittent streams in the forests of North-Eastern US have been shown to be important habitat for Coho Salmon and the loss of these streams due to changes in precipitation and lower stream levels can negatively impact these populations (Brooks 2009). Substantial reductions in groundwater levels may result in the loss of tributaries as freshwater refugia during base flow periods, resulting in the loss of critical seasonal habitat for many species (Morrongiello *et al*. 2011).

Changes in stream and river discharge can negatively influence recruitment success of riverine fish populations directly through discharge induced mortality or indirectly through discharge-associated increases in energy expenditure or reduced prey availability, especially in poorly structured or degraded habitat (Nunn *et al*. 2007). In the Great Lakes region, Walleye recruitment is negatively correlated with discharge (Jones *et al*. 2006). Recruitment of larval Walleye has been shown to improve by 90% with a 4°C increase in water temperatures and a 40% reduction in amount of discharge (Jones *et al*. 2006). Poor recruitment for Pike and Yellow Perch has been linked with low discharge in the St. Lawrence River (Hudon *et al*. 2010). For Salmonids, the influence of changes in flow regimes on recruitment is dependent on spawning season. High frequency flows in winter negatively impact fall spawning species such a Brook Trout and Brown Trout (Wenger *et al*. 2011). Spring spawning species varied in their response with Cutthroat Trout and Rainbow Trout exhibiting modest negative response and strong positive response, respectively, to winter high flows (Wenger *et al*. 2011).

Lakes
Warming temperatures are expected to result in declining lake levels, through increased evapotranspiration, decreased precipitation and an overall reduction in discharge from surrounding watersheds. Declining lake levels can negatively impact biodiversity, as shorelines provide important nursery habitat for many fish species. For Walleye, reduced lake levels as a result of climate change consistently result in reduced fish recruitment, with a two-metre drop in lake levels leading to 56% decline in recruitment (Jones *et al*. 2006). Changes in water levels can profoundly impact trophic dynamics. For Poyang Lake in South China, more diverse basal food sources were associated with higher water levels in the wet season resulting in omnivory, whereas in the dry season low water levels limited prey diversity and availability for freshwater fish (Wang *et al*. 2011).

Wetlands
For the Great Lakes region, wetlands are expected to experience large seasonal changes in water levels, especially in winter and spring (Mortsch 1998). Due to warmer temperatures, winter precipitation is predicted to take the form of rain, resulting in higher water levels (Mortsch 1998). Lack of snowmelt and runoff during spring months will result in lower lake levels, allowing for marshes to dominate other wetland types, such as swamps which are less resilient due to vegetative characteristics such as trees that require long term climate stability and cannot regenerate over short time scales (Mortsch 1998). However, the impacts of these changes on fish communities and food webs have not been summarised within the literature.

Dissolved Oxygen

Increasing water temperatures can greatly impact dissolved oxygen levels in freshwater systems. Oxygen solubility in water has an inverse relationship with water temperature (Ficke *et al*. 2007). Under higher temperature regimes, the aerobic metabolic rates of fishes increase, but dissolved oxygen levels decrease leading to an increased demand for biological oxygen (Ficke *et al*. 2007). This results in "oxygen squeeze" where oxygen supply cannot meet demand (Ficke *et al*. 2007). Low levels of dissolved oxygen create an inhospitable environment for large fish, which require greater oxygen intake to meet metabolic demands (Willis and Magnuson 2006). For five lakes in Wisconsin, large bodied fish, such as Cisco and Lake Whitefish, were shown to be abundant when dissolved oxygen levels were high, whereas small bodied species, such as Mimic Shiner and Bluntnose Minnow, dominated when oxygen levels fell below 4mg/L (Willis and Magnuson 2006). In shallow, weakly stratified lakes, coldwater fish are expected to experience a decrease in available habitat due to low dissolved oxygen levels in the hypolimnion as a result of higher water temperatures (Fang *et al*. 1999).

Ice Cover

Rising temperatures are expected to delay the onset and reduce the duration of ice cover in northern freshwater systems (Heino *et al*. 2009). Reduction in the extent and duration of ice cover is expected to have profound impacts on freshwater organisms (Heino *et al*. 2009). For Lakes in Wisconsin, the abundance of Smallmouth Bass, Pumpkinseed, and Yellow Perch has been shown to increase in years, with a longer ice-free season and high nitrogen summer (Willis and Magnuson 2006). Longer ice-free seasons are likely to favour warmwater fish species by extending boundaries of thermal habitat conditions (Keller 2007).

Ice cover is as an important regulator of metabolic processes for many fish species. Research from Atlantic Salmon populations in Norway shows that northern populations experiencing extensive ice cover, experience higher levels of energy loss during ice free periods as compared to southern populations and thus are expected to be negatively impacted by changes in ice cover as a result of global warming temperatures (Finstad and Forseth 2006). Additionally, juveniles in ice free conditions have been shown to lose greater amounts of energy, as a result of increased consumption, as compared to juveniles reared under extensive ice cover (Finstad *et al*. 2004).

Changes in ice cover are also expected to impact competitive interactions in northern ecosystems that historically experience extensive ice cover during the winter months. A 25-year time series from a Norwegian lake with both Brown Trout and Arctic Charr populations has demonstrated that the abundance of these species is dependent on the ice break-up date (Helland *et al*. 2011). Arctic Charr abundance increases in cold dark environments, typified by ice-covered lakes (Helland *et al*. 2011). However, as ice cover disappears with warmer winters, Brown Trout is expected to experience higher population growth rates due to favourable conditions for reproduction and larval recruitment in ice-free lakes (Helland *et al*. 2011). For the Great Lakes region, ice cover provides favourable habitat for zooplankton and other microorganisms during the winter (Assel 1991). Reduction in the extent of ice over is expected to result in a reduction in the abundance of these taxa, negatively impacting fish species that rely on them as a primary food source (Assel 1991).

Reduced ice cover is also expected to influence winter fish mortality as a result of low dissolved oxygen levels, a phenomenon described within the literature as winter kill. Winter kill occurs in the northern regions of North America, in mostly shallow oligotrophic and mesotrophic lakes which experience extensive ice cover throughout winter (Fang and Stefan 2000).

Hundreds of lakes in northern United States are artificially aerated during the winter to decrease mortality associated with winter kill (Fang and Stefan 2000). Under double CO_2 emission scenarios, winterkill is expected to disappear entirely throughout northern US due to substantial reductions in extent and duration of ice cover (Fang and Stefan 2000).

BIOTIC PROCESSES

Climate change may also indirectly impact freshwater fish communities through changes in biological processes as a result of changes in the abiotic environment. Biotic interactions such as competition, predation and disease are important in maintaining fish communities and food webs. For example, elevated turbidity and low levels of dissolved oxygen have been shown to negatively impact prey detection rates, resulting in decreased predation of invertebrate larvae by cyprinid species, such as Golden Orfe (Liljendahl-Nurminen *et al*. 2008). Changes in ice cover have been shown to influence competition between species for similar resources and seasonal changes in lake levels have been associated with changes in diet preference for many fish species (Helland *et al*. 2011; Wang *et al*. 2011). This section will summarise literature concerning the impacts of biotic processes, specifically invasive species and disease on freshwater fish communities and food webs.

Invasive species

As mentioned in previous sections, increasing temperatures are predicted to result in an increase in habitat for warm and coolwater fish, especially species that are constrained in their northern range limits by low water temperatures (Schindler 1997; Schindler 2001). Overall, the distributions of warm-water fish species are predicted to shift 500 km northwards with a doubling of CO_2 in the atmosphere (Eaton and Scheller 1996; Heino *et al*. 2009). With climate warming, 19 warmwater fish species from the Mississippi or Atlantic Coastal basins are predicted to invade lower Great Lakes (Ontario, Erie, and Michigan) and 8 potential warmwater fish species in the lower Great Lakes could invade upper Great Lakes (Huron and Superior) (Mandrak 1989; Rahel and Olden 2008). These potential invaders are primarily minnows, sunfishes, suckers, and topminnows (Mandrak 1989).

Smallmouth Bass may become a pervasive invasive species, as the majority of aquatic systems in Canada and continental US are predicted to be suitable habitat for smallmouth bass by 2100 (Sharma and Jackson 2008). Climate models predict that 20% of all lakes within Canada with Lake Trout populations will be vulnerable to Smallmouth Bass invasions by the year 2050 (Sharma *et al*. 2009). By 2100, 9700 lakes would be vulnerable to potential Smallmouth Bass invasion (Sharma *et al*. 2009). Northern expansion of Smallmouth Bass range in Canada may result in decreases in cyprinid ranges with a 7.48% reduction for Northern Redbelly Dace, 8.78% reduction for Finescale Dace, 9.35% reduction for Fathead Dace and 7.61% reduction for Pearl Minnow (Jackson and Mandrak 2002). Similar trends are expected for the Common Carp, another potential invader in North American watersheds (Rahel and Olden 2008; Britton *et al*. 2010).

The movement of littoral predators northwards into newly available habitat can have many consequences for aquatic food webs (Keller 2007). Invasions by littoral predators such as Smallmouth Bass can out-compete keystone species such as Lake Trout and Arctic Charr, for existing food resources (Keller 2007; Heino *et al*. 2009; Sharma *et al*. 2009). In lakes containing Smallmouth Bass populations, Lake Trout are forced to forage on zooplankton species, as their preferred littoral fish prey are consumed by Smallmouth Bass (Sharma and Jackson 2008).

Disease

Changes in water temperatures are expected to influence disease dynamics and host susceptibility in aquatic ecosystems by affecting the prevalence of exiting pathogens and introducing novel hosts and pathogens (Marcogliese 2001; Rahel *et al*. 2008; Jonsson and Jonsson 2009). Warming temperatures will likely favour either hosts or pathogens, changing the prevalence and distribution of disease. Stress induced by changes in important biotic and abiotic processes may also result in immunosuppression resulting in increased susceptibility to pathogens (Marcogliese 2001). However, there are no general patterns within the literature with regards to climate change impacts on diseases as contradictory responses are observed across different host-pathogen complexes. For example, a number of endemic diseases affecting Salmonids, such as enteric red mouth, furunculosis, proliferative kidney disease and white spot are predicted to become more prevalent and difficult to control as water temperatures increase (Marcos-López *et al*. 2010; Tam *et al*. 2011). However, other pathogens such as viral hemorrhagic septicemia (VHSV), infectious hematopoietic necrosis virus (IHNV) and spring viraemia of carp virus (SCVC) are predicted to decline, as infection generally establishes when water temperatures fall below 14°C VHSV and IHNV and 17°C for SCVC (Marcos-López *et al*. 2010). Similarly, for Ichthyophthirius multifiliis and Flavobacterium columnare, prevalence of infection has been shown to increase with temperature, whereas the infection rate of other pathogens declines substantially (Karvonen *et al*. 2010).

Climate change also alters the threat level associated with exotic pathogens (Jeppesen *et al*. 2010; Marcos-López *et al*. 2010; Tam *et al*. 2011). As species expand into newly available habitat, they not only provide novel hosts for existing pathogens but also introduce exotic pathogens into ecosystems (Marcogliese 2001; Heino *et al*. 2009; Marcos-López *et al*. 2010). In the case of the United Kingdom, warming temperatures have been associated with the introduction of epizootic hematopoietic necrosis and epizootic ulcerative syndrome (Marcos-López *et al*. 2010).

GAPS IN KNOWLEDGE

From this review it is clear that there exists a lack of region specific climate forecasting for freshwater ecosystems within the literature, especially for the St. Lawrence River and Saskatchewan-Nelson River watersheds. While climate projections from other regions are useful in providing generalized expectations for abiotic and biotic impacts of warming temperatures, regional differences in precipitation regimes, geo-morphology, water chemistry and biological diversity can influence the extent and magnitude of these impacts. Therefore, region specific parameters should be applied in future climate projections when determining impacts on regional ecosystems. It should be noted that for the Laurentian Great Lakes and surrounding watersheds, this approach has been successfully applied and has provided important insights on climate change impacts on freshwater ecosystems for this region (Mandrak 1989; Magnuson *et al*. 1990; Assel 1991; Mortsch 1998; Casselman 2002; Jones *et al*. 2006; Chu *et al*. 2008).

Research on climate impacts on freshwater ecosystems is also limited to species-specific studies, especially economically important groups such as Salmonids. While this research is beneficial in demonstrating the economic impacts of global climate change and informing relevant policy, it disregards the importance of community and food web level interactions in determining the survival and persistence of these species in the future. The impacts of climate change on freshwater ecosystems must be considered at the community and

food web level perspective in order to understand the extent and magnitude of these impacts on biological diversity in these systems.

CONCLUSIONS

Climate change is expected to have an immense impact on freshwater fish communities and food webs in the Laurentian Great Lakes, St. Lawrence River and Saskatchewan-Nelson River Basin watersheds. Rising mean annual air temperatures are expected to affect abiotic processes governing these ecosystems resulting in changes in water temperatures, precipitation and flow regimes, dissolved oxygen and ice cover which will directly impact fish biodiversity in the regions. These abiotic changes, in turn, cause changes in biological interactions between species, especially the dynamics of ecological invasions and disease which will further impact fish communities and food webs in these regions.

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CHAPTER 2: THE EFFECTS OF CLIMATE CHANGE ON FISH SPECIES OF THE GREAT LAKES AND PRAIRIE REGIONS OF CANADA BY M. GUZZO AND A. CHAPELSKY

INTRODUCTION

The Earth's climate has warmed by ~0.74°C over the last ~100 years, with two main periods of warming, between 1910 – 1945 and 1976 onwards. Global air temperatures have risen by 0.13°C decade $^{-1}$ over the last 50 years (1956 – 2005); nearly double that of the 50 years previous, and 8 of the warmest years on record (since 1880) have occurred since 2002 (Hansen *et al.* 2006; IPCC 2007). Under current greenhouse gas emissions policies, mean global air temperatures are predicted to rise by 0.2°C decade $^{-1}$ over the next 100 years (IPCC 2007). While, these global changes may seem minor, regional changes, which are much more spatially heterogeneous, may be more extreme. Regional projections for North America indicate increases in mean annual air temperature by 3 – 5.5°C by the end of the 21st century (IPCC 2007). These regional changes are ecologically relevant, as organisms, populations and communities do not respond to global approximated averages (Walther *et al.* 2002).

Ample evidence now exists on the effects of recent climate change on a broad range of organisms from diverse geographical distributions and environments (Parmesan 2006). Of these systems, freshwater lakes and streams are expected to be particularly sensitive to climate change, as they integrate the effects of climate change on terrestrial and atmospheric processes through the transport of water, nutrients and energy (Williamson *et al.* 2008). Canada contains a vast portion of the world's freshwater reserves. In addition to being used as a source of drinking water and recreation, many of these systems support ecologically, commercially and culturally valuable fish species. The most recent regional (CRCM 4.2) climate projection models developed by the Canadian Center for Climate Modelling and Analysis, predict changes in climate to continue. Even if levels of greenhouse gas emissions were to become stable, regions of Canada such as the Great Lakes and Prairies are expected to increase in temperature and by the year 2100 (IPCC 2007). These changes in climate are expected to have both direct (e.g. through temperature effects on consumption/metabolism; i.e., McDonald *et al.* 1996) and indirect effects (e.g. through trophic dynamics, habitat changes; i.e., VanderZanden *et al.* 1999; Schinder *et al.* 1996a) on a variety of fish species.

Fish are ectothermic heterotherms whose body temperatures follow that of the habitat in which they reside. Fish occupy temperatures available to them in order to optimize metabolic processes. These "optimal" temperature ranges can vary with age, size, condition, past thermal adaptations and most notably, species (Crawshaw and O'Connor 1996). There exist three thermal guilds: warm-water eurotherms (~28°C, e.g. centrachids); cool-water mesotherms (~24°C e.g. percids); and cold-water stenotherms (~15°C, e.g. salmonids) (Magnuson et al. 1979, Magnuson and DeStasio 1996). As a result, fish of differing thermal guilds will differ in their within-lake and geographical distributional responses to climate change.

To date, most broad-scale analyses of climatic effects on fish have focused on temperature changes, with the exclusion of many other climate driven variables (Wenger *et al.* 2011). This report seeks to summarize key direct and indirect effects of recent climate change on fish species occupying inland lakes and streams of the Great Lakes and Prairie regions of Canada.

INLAND LAKES

boreal sheild lakes

The temperate nature of the Great Lakes region makes it home to a variety of lakes ranging in size, classification (eutrophic to oligotrophic) and mixing regimes (isothermal to dimictic; Magnuson *et al.* 1997). Inland lakes within the Great Lakes region are home to fish species from a variety of thermal guilds ranging from warm- to cold-water fish species (Scott and Crossman 1973). The most common type of lake in this region is deep, clear Boreal Shield Lakes carved of Precambrian bedrock (Gunn *et al.* 2004). Boreal Shield lakes are predicted to undergo several changes resulting from climate change; however, much uncertainty exists as to how these biotic and abiotic changes will affect fish communities (Magnuson *et al.* 1997; Gunn *et al.* 2004).

The thermal regimes of lakes respond to climate change because they are controlled by solar radiation, wind, air temperature and humidity (Magnuson *et al.* 1997). In large, deep lakes of mid- to high- latitude that stratify, higher air temperatures will increase the temperature of epilimnetic waters and could lead to a larger thermal gradients and shallower thermoclines (McCormick 1990; King *et al.* 1997; King *et al.* 1999; Snucins and Gunn 2000; Sharma *et al.* 2011). This could increase the thermal habitat, survival rates, and winter survival for warm-, cool- and cold-water fish species in many large (> 500 ha) boreal shield lakes. In small, stratified lakes (< 500 ha), increased air temperatures will also lead to drier conditions and increased evaporation from lakes. Schindler (1998) and Schindler *et al.* (1996) proposed that in addition to warming, increased water clarity resulting from decreased Dissolved Organic Carbon (DOC) inputs could shrink hypolimnetic, summer refuge habitat (through thermocline deepening) for Lake Trout and other cold-water fish species in small boreal shield lakes, thus decreasing population sustainability. This work also suggested that increased wind, due to a recent forest fire, was key in aiding with vertical deepening of the thermocline layer. In similar boreal shield lakes, Plumb and Blanchfield (2009) found that optimal habitat for Lake Trout (*Salvelinus namaycush*) was decreased in a warmer drier summer and that optimal habitat had almost disappeared by the end of summer. This increased exposure to suboptimal temperatures as summer progresses could reduce growth particularly if resources are limited and being partitioned among competitor species (cool- and warm- water species). Jansen and Hesslein (2004) determined that increases in air temperature by 2, 4, 9°C resulted in mixed layer water temperature increases in a small boreal shield lake. Duration of classic lake trout habitat (5-15°C) in spring decreased and was pushed later into fall. Overall these changes shortened the window for littoral feeding by Lake Trout by up to 24 days. Jansen and Hesslein further concluded that a 4°C increase in air temperature resulted in increased of vertical and temporal habitat, while a 9°C increase in air temperature resulted in loss of littoral habitat for cool-water fish species such as Yellow Perch. However, young of year Yellow Perch, which have higher thermal range than adults could benefit if nutrients increase with climate change, potentially increasing recruitment.

Longer ice-free seasons will result in longer periods of thermal stratification in lakes, increasing the potential for late season anoxia in the hypolimnion of deep boreal lakes (De Stasio *et al.* 1996) and the loss of some suitable habitat for cold-water stenotherms (Keller 2007). At the same time, shorter winters could reduce the possibility of winter kills in shallow lakes, where anoxic conditions develop under the ice during prolonged periods of ice-cover (Fang and Stefan 1998).

Jackson (2007) determined the risk of Lake Trout populations in the Atikokan area of NW Ontario. In this region, 99 lakes have Lake Trout and are greater than 25 ha in size. Of

these, fourteen lakes have a maximum depth of less than 20 m, and of these, 4 have maximum depths less than 15 m. Thermocline depths in Atikokan Area lakes typically reach the 15 m range by the end of summer suggesting that Lake Trout in these lakes already face a lack of summer habitat. With further warmer, dryer conditions, under limnological changes suggested by Schindler *et al.* (1996) and Stefan *et al.* (1998), where thermoclines deepen and anoxic zones increase, these lakes would be highly to moderately vulnerable to loss of suitable Lake Trout habitat. Most Lake Trout lakes (69%) in the Atikokan Area are inhabited by deep-water prey species such as Lake Whitefish (*Corigonus lavaretus*), Cisco (*Coregonus artedii*), or Rainbow Smelt (*Osmerus mordax*). Assuming these species are the primary forage species for Lake Trout when present, these lakes should be at lower risk of loss of access to littoral zone prey species when epilimnetic temperatures exceed thermal preferences.

Warming temperatures can also affect the geographical distribution of fish species, where reductions in suitable habitat for cold-water species and expansion of habitat for warm- and cool- water fish species could result in increased competitive interactions and changes in food web dynamics. Invasions of cool- and warm-water fish into new habitats promoted by increased mixed-layer temperatures could have negative effects on native fish species (Shuter and Post 1990). A modeling exercise by Sharma *et al.* (2011) found that 25-70% of Cisco populations in Wisconsin lakes would be extirpated by 2100, mainly as a result of increasing temperatures and changing mixing regimes. These extirpations of Cisco however, were enhanced by invasion of Rainbow Smelt, which prey on young Cisco. Vander Zanden *et al.* (1999) found that invasion of Smallmouth Bass (*Micropterus dolomieu*) led to a decrease in littoral prey fish abundance, decreased trophic positions and increased reliance on zooplankton by Lake Trout. Further, Sharma *et al.* (2009) determined that the number of Ontario lakes with vulnerable Lake Trout populations could increase from 118 (1%) to 1612 (20%) following projected climate warming, provided that Smallmouth Bass are able to disperse northwards under climate change. In Jackson's (2007) study of Lake Trout in the Atikokan area, he concluded that of the 30 lakes that do not have deep water prey species, 2 are inhabited by smallmouth bass and are considered at highest risk for changes in fish community to occur. The remaining 28 lakes without smallmouth bass are considered at moderately high risk; however, future introductions of Smallmouth Bass to these lakes could be problematic. Furthermore, a study by Wall and Blanchfield (2011) found that the distribution of Lake Trout in a small boreal lake was altered as a result of invasion by Yellow Perch into the lake. Cyprinid biomass declined following the invasion and Lake Trout distributions became more pelagic as they presumably began to feed on Yellow Perch.

Temperature is a physical regulatory factor in fish and is expressed in the control of reproductive processes from gamete development, maturation, ovulation, spermiation, spawning, embryogenesis, and hatching, to larval and juvenile survival (Pankhurst and Munday 2011). Increased temperature can affect fish reproduction, for example, Lake Whitefish will have delayed ovulation and spawning (Wahl and Loffler 2009) and Rainbow Trout (*Oncorhynchus mykiss*) will undergo reduced fertility and survival (Pankhurst *et al.* 1996; Pankhurst and Thomas 1998). Water temperature effects on the timing of spawning can vary depending on the when in the annual cycle spawning occurs. Elevated spring water temperatures will truncate spring spawning while longer summers will delay autumn spawning (Pankhurst and Munday 2011). This could affect recruitment. A study by Warren *et al.* (2012) found that increased temperatures led to a reduction of redd (nest) construction and delayed spawning by fall spawning Brook Trout (*Salvelinus fontinalis*). This delayed spawning would in turn influence emergence synchrony with prey items. These deviations can alter timed emergence with times of elevated prey availability and thus impact juvenile Brook Trout success. Additional studies found that warmer springs would result in earlier phytoplankton blooms and associated

zooplankton dynamics (Sommer *et al.* 2007; Berger *et al.* 2010; Shimoda *et al.* 2011). This could again result in an asynchrony among hatching fry and prey availability, potentially impacting juvenile success of spring spawning fish species such as Yellow Perch (*Perca flavescens*) and Walleye (*Stizostedion vitreum*). A study by Shuter *et al.* (1980) on Lake Huron and Lake Opeongo found that the recruitment of Smallmouth Bass, a warm-water, spring spawner, is related to temperature regimes experienced during the first year of life. Increased temperatures after spawning could result in males which guard nests to abandon them, resulting in increased mortality among fry.

Drier watersheds resulting from increased evaporation due to warming could also lead to decreased DOC and phosphorous inputs into lakes (Schindler 1998). This decreased nutrient input from watersheds could lead to lake productivity decline and in turn may lower food availability to fish. Resulting decreases in lake volume could have effects on prey availability, as species richness has been shown to decrease with lake volume (Mandrak 1995). Additionally, decreased volume and increased water retention times of lakes could lead to increased concentrations of pollutants in the system, which can then biomagnify in predatory fish species (Magnuson *et al.* 1997).

Exponential increases in metabolic costs occur with even small increases in temperature. This cost will continue to increase until inhibiting temperatures are reached and fish can no longer continue to exist in a particular environment (Williamson *et al.* 2008). Increased metabolism due to warming can also affect recruitment of fish. Young of the year fish often have no energy reserves, so food and resources they accumulate over their first summer must sustain them through winter (McDonald *et al.* 1996). Simulations of bioenergetics of young of the year Lake Trout in arctic lakes found that a 3 °C increase in July temperature would require young Lake Trout to increase consumption by 8.7 fold to maintain body weight. And even under the most benign climate change scenarios and when food availability is doubled, the average young Lake Trout would still starve to death before the end of its first year of life (McDonald *et al.* 1996). While this study took place in arctic regions, similar increases in temperature expected at more southern latitudes (IPCC 2007) may have similar effects on Lake Trout and other cold-water fish species.

Direct damage of increasing water temperatures could also be problematic as air temperatures continue to rise. For example, in the warm years following an El Nino event, exposure to bottom temperatures of ~20 °C led to the loss of stocked juvenile Lake Trout in Gullrock Lake, located in Northern Ontario (Gunn 2002).

Small prairie lakes

The Prairie region of Canada is home to a diversity of water bodies, including large eutrophic lakes, pothole and oxbow lakes, vernal ponds, and playas. Like the Great Lakes region, the Prairies are predicted to increase in both surface temperatures and precipitation in the coming years (IPCC 2007). However, there are some notable differences in how these systems and the fish that inhabit them will be affected by climate change. Increased evaporation is expected to decrease water levels and the extent of open water, under double CO_2 climate change projections. This warming of surface waters could lead to increased salinity and extirpation of endemic fish species already close to their thermal and saline limits (Covich *et al.* 1997). This was also reported by Cooper and Wissel (2012), who stated that mesosaline lakes are highly sensitive to changes in salinity and thus vulnerable to climate change. Decreased water levels in lakes will lower volume and in turn could affect species diversity (Mandrak 1995). Serada *et al.* (2011) reports that during 1938 through 2004, in west-central Saskatchewan, mean annual temperatures have increased by 0.71 °C, with increases in water salinity also observed. These changes were linked to a 30% loss in diversity of macro invertebrates and

decreases in algal primary production. These reductions in production and losses of invertebrate taxa due to could reduce food sources for fish, and was also suggested by Benoy *et al.* (2007). Increased air temperatures in winter for prairies (5 – 8 °C) would shorten duration of winter in shallow prairie lakes and decrease proportion of lakes that go anoxic and would allow for fishless lakes to begin supporting fish. Further, lakes containing only stickleback could develop more diverse fish communities. However, increased algal production due to warmer air temperatures could increase oxygen demand, potentially negating changes from shorter ice cover (Jackson *et al.* 2007).

A study by Tetrault *et al.* 2012 suggested that increases in human populations and climate change could challenge the ability of effluent dominated streams to assimilate nutrients and contaminants. This could potentially reduce performance of fish occupying these streams through decreases in recruitment and histopathological effects on cyprinid species.

LAKE WINNIPEG
Lake Winnipeg is a large shallow, inland lake located in the province of Manitoba. It is Canada's 6th largest freshwater lake. The lake is composed of a deep north basin and a relatively shallow south basin. Lake Winnipeg supports a substantial recreation and commercial fishery, where Walleye represent the greatest harvest biomass (Franzin *et al.* 2005; ECMW 2011).

Based on thermal preferences of various fish species and under the assumption that Lake Winnipeg is mostly isothermal (there are some exceptions), a 2°C increase in mid-summer monthly water temperature by middle of 21st century could limit success of up to 12 species in Lake Winnipeg and a further 2 °C increase would affect another 15 species by the end of the century. Prominent species included are Lake Sturgeon, Lake Trout and Burbot, which would be limited by 2050 and Lake Cisco and Lake Whitefish, which would be limited by the end of century (Franzin *et al.* 2005; McCollough *et al.* 2005). Although the direct effects of temperature may exceed thermal maxima and adaptation capabilities, some thermal refugia may continue to exist (i.e. areas with stratification). Annual or intermitted temperature stress would first be reflected by increased prominence of disease in fish, decreased condition and reduced size-age-age. The appendix of Franzin *et al.* (2005) specifies all species tolerances and which will be exceeded by the climate projections of McCullough (2005).

The northern limits of percid and centracids have been related to survival of young of year through their first winter (Shuter and Post 1980). Climate warming could improve this aspect for populations of fish living near their northern limits in Lake Winnipeg, such as walleye. Most species in Lake Winnipeg are near their northern range, so fish composition may not change much on a whole-lake scale. However it may change basin-specific composition, with in general, decreases in cold water species in the southern basin.

Based on predictions of McCullough (2005), by the year 2045 winter ice break up in the will occur a week earlier in the south basin and a week and half earlier in the north basin. By 2085 south basin ice off would be 1.5-2 weeks earlier and in north basin 2-3 weeks earlier. This shortening of the ice covered season and increased length of the growing season (days with >10 °C temperature) would allow warm- and cool-water species, like walleye, yellow perch, white bass to produce larger young of year, resulting in increased over winter survival (Franzin et al. 2005). The effects of a warmer summer and shorter winter on cold-water species like Lake Whitefish and Lake Trout that spawn in fall, or Burbot that spawn during winter is not clear. The eggs of fall spawners usually hatch in synchrony with zooplankton blooms and changes to this synchrony could potentially have an effect on recruitment, however this needs to be investigated.

Total productivity in the lake would likely increase with response to increased temperatures and growing season. Loss of Cisco and Lake Whitefish probably will shunt zooplankton production into smaller-sized zooplanktivorous fishes favoured by Walleye and Sauger over larger-sized prey. The net effect of environmental and fish community change expected under a climate warming scenario may well be more and larger Walleye and Sauger with higher yields of these two high value species to commercial fisheries (Franzin *et al.* 2005).

With increased evaporation due to rising temperatures, water supply to Lake Winnipeg may not be sufficient to maintain both important spawning streams and suitable water quality conditions in the lake for Walleye and Sauger and other cold-water species (Franzin *et al.* 2005)

STREAMS

GREAT LAKES REGION

The Great Lakes Region of Ontario contains streams that vary greatly in their surrounding climate and landscapes. Streams in the North flow through the Canadian Shield bedrock are relatively cooler and more connected than those in the South. Northern streams are surrounded by boreal forest, including tree species such as black spruce and jackpine. Southern streams typically flow through mixed-forest and agriculture and are under laid by thick soils (Chu and Jones 2011). Chu *et al.* (2008) assessed the thermal diversity of stream fish in Ontario and determined how air temperature and groundwater affect this diversity. The author then went on to use the CGCM2 and HadCM3 with emissions A2 and B2 to predict effects of climate change on thermal diversity of fish. In all scenarios, there were reductions in the proportion of sites with cold-water fish species, and increases in the proportion of sites with warm-water fish species. In all models, cold-water fish distributions were shown to be reduced up to 67%. Under the most moderate scenario (CGCM2 B2), cold-water fish would exist in 16 of 43 watersheds tested by 2055, most of which were located in eastern Ontario. Using the HadCM3 (A2) scenario, all cold-water species would be lost by 2055 (Chu *et al.* 2008). Warm-water fish distributions were shown to increase with climate change, with HadCM3 (A2) scenario showing greatest increases, where warm-water species predicted to exist in all 43 sites by 2055. CGCM2 B2 predicted that warm-water species would be the dominant guild in >66% of sites in southern Ontario by 2055.

GENERAL STREAM LITERATURE

This review has found very few papers that specifically study the effects of climate change on streams of the Great Lakes and Prairie regions of Canada. Much of the literature on stream fish relating to climate change originates in Europe or the northern United States and is focused on temperature and flow volumes as primary drivers of climate change. As a result, this section will discuss the potential effects of climate on stream fish in these two regions by relating the forecasted changes in temperature, precipitation and evaporation to published literature.

Lotic systems represent highly heterogeneous environments with habitats shaped by area, depth, flow, and substrate composition (Allan 1995; Ostrand and Wilde 2004). Flows vary naturally between rivers, streams, and watersheds due to seasonal and inter annual climatic differences, as well as topography and latitude (Meyer *et al.* 1999). These naturally occurring variations in disturbance adapts streams to varying conditions of drought, which are predicted to increase in frequency as a result of climate change in prairie regions (IPCC 2007). Systems with repeated drying periods are expected to succeed better under drought conditions than flood adapted systems, and the opposite to be true under increased precipitation conditions (Meyer *et al.* 1999). This might suggest that fish inhabiting lower areas of streams (typically warm and cool

water fish) where flow may be more frequently interrupted, might be better adapted for climate change than those which inhabit headwater areas (typically cold water fish; Ostrand and Wilde 2004; Wenger *et al.* 2011)

The thermal range of fish species strongly influences their geographical distribution in lotic systems and therefore, will determine the ability of these species to adapt to climate change (Buisson *et al.* 2008; Buisson and Grenouillet 2009; Logez *et al.* 2012). The expansion of habitat by warm- and cool- water fish species and the reduction of habitat for cold-water fish species are largely dependent on the magnitude of climate change. Like shallow lakes, suitable thermal habitat for all thermal guilds of fish is expected to decrease under warming conditions. If changes in thermal habitat are highly heterogeneous, the vagility of individual fish species and their ability to disperse to find suitable habitats, could allow for success under climate change (Reynolds *et al.* 2005; Griffiths 2006; Van Damme *et al.* 2007; Tudorache *et al.* 2008).

Increased temperatures are also expected to decrease stream flow through increases in evaporation. Tisseuil *et al.* (2012) found that by 2100, stream flow would decrease by 15% with temperature increases of 1.2 °C. These declining river flows can affect freshwater biodiversity, both at the species level, through reduced breeding success and post-spawning recruitment, and at the community level, through modified biotic interactions (Jackson 1989; Walsh and Kilsby 2007). Decreased flow can directly limit hydrological connectivity and increase fragmentation of populations. It can reduce recruitment through poor breeding conditions and reduce larval survival through increased metabolic costs, reduced habitat, and food and degraded water quality. Decreased flow can lead to indirect effects such as competition from reduced food availability and invasive predation and competition (Lake 2003; Morrongiello *et al.* 2011). Extended droughts could also result in the acidification of streams due to oxidation of organic sulphur (Schindler *et al.* 1997). This, in turn, could potentially affect lower food web species such as Benthos and Cyprinids, which serve as prey for larger predatory fish. A study of prairie streams in Northern Texas found the presence and abundance of Cyprinids to decrease when stream pools became smaller and more saline (Ostrand and Wild 2004).

Warming temperatures are also expected to increase the frequency of winter and summer floods through increased melt events and precipitation. This could have effects on recruitment for river spawning fish, since such flows can scour eggs from gravel nests or wash away newly emerged fry. Thus, fall-spawning Trout are sensitive to winter floods and spring-spawning Trout are sensitive to summer floods (Wenger *et al.* 2011). Additionally, increased metabolic costs, similar to in lakes, may affect the survival and increase metabolic costs for young fish species.

GAPS IN INFORMATION

Boreal Shield Lakes
Boreal Shield Lakes seem to have the best information available on the effects of climate change on fish. Despite this, many questions still remain to be answered: Will cold-water fish habitat increase or decrease? How will a longer ice-free season affect fish and their food webs? We recommend that future studies take advantage of long-term monitoring datasets (i.e. The Experimental Lakes Area and Harkness Laboratory of Fisheries Research) to better quantify and model effects of climate change to boreal shield fish and their ecosystems.

Streams of the Great Lakes Basin

We have found few studies that directly speak to the effects of climate change on stream fish of the Great Lakes Basin. Generally, warm-water species will expand their range northward becoming more abundant in the region, while cold-water fish species will become less abundant as thermal regimes surpass preferred temperatures. Work by Chu and co-authors (2008, 2010, and 2011) provide a foundation for future studies and monitoring programs that can be initiated to further our understanding of climate effects of stream fish in this region.

Lake Winnipeg

Despite, supporting one of Canada's largest freshwater fisheries little is known about the lake and the potential effects of climate change on the Lake Winnipeg fishery. Very few published literature exists describing the interactions of fish in this system and the food web. Lake Winnipeg is predicted to also undergo eutrophication with climate change, creating an urgent need for research to gain detailed baseline knowledge of the current ecological state of the fish community. The existing commercial fisheries dataset can serve as a starting point and direct priorities for future research on this system.

Small Prairie Lakes and Streams

There exists a lack of information specific to climate effects on Prairie lakes and streams in Canada. Because Canadian Prairie regions are forecasted to have warmer, drier conditions, it we used studies in prairie regions of USA and Europe with similar climate expectations to discuss potential effects to Canadian prairie fish. The warming climate in this region and increasing demand for water from both agriculture and a growing human population demand the need for research and monitoring to expand in this region.

CONCLUSION

Overall, our understanding of the effects of climate change on inland lakes and streams of the Great Lakes and Prairie regions is limited. This poor understanding is likely driven by uncertainty of the actual direct effects of climate on aquatic systems and of the interactions of climate-driven effects on watersheds, aquatic habitats and biota. Our poor understanding is further exacerbated by uncertainties in regional climate change models for climate variables such as wind and precipitation, both of which play key roles in the structuring of thermal habitat and in the transport of nutrients to food webs. As climate change research moves forward, there is a need to not only understand changes to fish communities, but how these changes are elicited through changes in limnology. Holistic models incorporating climate drivers, abiotic and biotic factors represent the most promising avenue to better manage our Canadian fisheries in the future.

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CHAPTER 3: CLIMATE CHANGE RISK ASSESSMENT: STREAMS IN THE GREAT LAKES BASIN, ONTARIO BY C. CHU AND F. FISCHER

INTRODUCTION

Climate change is affecting aquatic ecosystems around the world. Changes in air temperatures, precipitation patterns and extreme weather events associated with a changing climate have and will continue to affect water quality and quantity (Durance and Ormerod 2007). Human activities such as non-native species introductions, river regulation, groundwater withdrawal, shoreline development, and point and non-point source pollution further stress these ecosystems.

In streams and rivers (hereafter all flowing waters are called streams); climate change may alter the timing of the spring freshet and disrupt annual stream flow patterns (Mohseni *et al*. 2003). These effects may lead to a reduction in fish species richness and suitable fish habitat (Meisner 1990; Xenopoulos *et al*. 2005; Dove *et al*. 2011). Already, long-term increases in water temperatures and associated changes in stream biota have been detected (Durance and Ormerod 2007). Increasing demands for fresh water and freshwater resources will strain the quantity and quality of water flowing through streams (Schindler 2001).

Water temperature, and consequently, suitable thermal habitat for stream biota, are influenced by several factors including air temperature, precipitation, flow, land use, channel and floodplain morphology, and riparian vegetation (Poole and Berman 2001). However, air temperature has been identified as a main predictor of stream temperatures, and groundwater discharges into streams have been identified as crucial components of suitable thermal habitat for fishes (Power *et al*. 1999; Poole and Berman 2001). Stream temperatures follow the seasonal pattern of warming and cooling of air temperatures, and groundwater discharge to a stream provides a constant influx of water at a temperature that approximates the surrounding mean annual air temperature (Power *et al*. 1999). Consequently, groundwater discharge provides thermal refugia for species that prefer cooler temperatures in the summer while providing habitat free of ice for all species in the winter. The interaction between air and groundwater temperatures provides thermally diverse habitats in streams that influence the distribution of species within a watershed (Chu *et al*. 2008).

Warmer in-stream temperatures associated with climate change may provide suitable habitat for warmwater species throughout the ice-free season but may limit the distribution of other species that prefer cooler temperatures (Chu *et al*. 2008). Chu *et al*. (2008) developed an index of the likelihood that streams within quaternary watersheds in southern Ontario will retain coldwater fish species (e.g., Brook Trout, *Salvelinus fontinalis,* and Mottled Sculpin, *Cottus bairdii*) based on maximum air temperature and groundwater discharge potential. Those results indicated that watersheds with high groundwater discharge potential could provide thermal refugia for coldwater species during a period of rapid climate change.

In response to the impacts of climate change on Canada's aquatic ecosystems, Fisheries and Oceans Canada initiated the Aquatic Climate Change Adaptation Services Program. This initiative focuses on understanding climate trends, improving projections, and assessing the impacts, risks and vulnerabilities for freshwater and marine sub-regions of Canada. The objective of this study was to assess the potential impacts of climate change on streams within the quaternary watersheds of the Great Lakes Basin, Ontario using the likelihood

index developed by Chu *et al*. (2008). These results were used to develop adaptation options for streams in the Great Lakes Basin.

STUDY AREA: GREAT LAKES BASIN, ONTARIO

The Great Lakes Basin (GLB) of Ontario spans an area of approximately 230,000 km^2 with streams that flow through a range of landscapes and climates (Figure 1). Northern streams drain the bedrock of the Canadian Shield and are exposed to mean annual air temperatures near 2°C. They flow through coniferous forests of black spruce, balsam fir, jack pine and tamarack and are hydrologically connected to more lakes than their southern counterparts. Streams in the southern region of the GLB are exposed to mean annual air temperatures near 9.1°C, and flow through urban areas, agricultural lands and mixed forests of pine, maple and beech that have an underlying mix of till, glaciolacustrine and glaciofluvial geology (Magnuson *et al.* 1997; OMNR 2007).

Figure 1: The Great Lakes Basin, Ontario (shaded in grey).

METHODS

Quaternary watershed boundaries, climate and groundwater data layers were needed to meet the objectives of this study. The quaternary watershed boundaries are part of a standard hierarchy of primary through quaternary watershed units established by the Water Survey of Canada to delineate streams and their surrounding watersheds (OMNR 2002). There are 532 quaternary watersheds in the GLB of Ontario.

Present climatic conditions were estimated using the 1971-2000 Canadian Climate Normals data. Future climatic conditions were estimated using the Canadian Global Climate

Model 3 (CGCM3) with the B1 and A2 emissions scenarios for the 2011-2040, 2041-2070 and 2071-2100 time periods. The B1 scenario represents a world that is environmentally focused with lower emission levels than the A2 scenario. The A2 scenario represents a world where high emission levels are driven by rapid economic development (IPCC 2007). The current and future climatic conditions were provided by Natural Resources Canada and Ontario Ministry of Natural Resources, Northeast Region, following the methodology outlined in McKenney *et al.* (2010).

A base flow index developed by Neff *et al.* (2005) was used to represent groundwater discharge potential throughout the watersheds. This index represents the long-term average rate of base flow relative to the long-term average rate of total stream flow in five classifications of Quaternary geology: coarse and fine textured sediments, till, shallow bedrock and organic deposits (Neff *et al.* 2005). The index ranges from 0–0.821, with higher values indicating greater base flow (Table 1). The base flow index was not altered for the future projections because it is primarily a function of geology and the changes in groundwater temperatures may take decades or centuries to be realized (Chu *et al.* 2008).

An index developed by Chu *et al.* (2008; Table 2) was used to assess the climate change risk for coldwater stream fishes (e.g., Brook Trout, *Salvelinus fontinalis,* and Mottled Sculpin, *Cottus bairdii*) in the GLB. This index is based on maximum air temperature and groundwater discharge potential and indicates that watersheds with high groundwater discharge potential may provide thermal refugia for coldwater species during a period of rapid climatic change. Chu *et al.* (2008) also indicated that coldwater stream fishes were not found in six quaternary watersheds in southern Ontario that have been extensively sampled (i.e., where the complete fish community is known). It was assumed that coldwater stream fish species are present in all of the remaining 526 quaternary watersheds and those watersheds were included in the analyses.

Using ArcGIS® 9.0 (Environmental Systems Research Institute Inc., Redlands, California, USA), area-weighted maximum air temperature and groundwater discharge potential for the 1971-2000 Climate Normals and the CGCM3 B1 and A2 scenarios for 2011-2040, 2041-2070, and 2071-2100 time periods were calculated for the 526 quaternary watersheds within the GLB. These values were compared to the likelihood index (Table 2) to rank the watersheds by their potential (high, mid or low) to retain coldwater stream fish species as climate changes.

Table 1: Base flow index developed by Neff et al. (2005) used to represent groundwater discharge potential of different quaternary geology types. Higher values indicate greater base flow and likely greater groundwater discharge.

Quaternary geology type	Example of geological material	Base flow index value
Organic	peat, muck and marl	0
Fine	silt and clay, minor sand, basin and quiet water deposits	0.098
Till	silty clay to clay matrix, moderate to high matrix carbonate content, clast poor	0.329
Bedrock	undifferentiated carbonate and clastic sedimentary rock, exposed at surface or covered by a discontinuous, thin layer of drift	0.586
Coarse	gravel, sand, silt and clay, deposited on modern flood plains	0.821

Table 2: Likelihood that watersheds will retain coldwater species in 2055 based on maximum air temperature projections from the Canadian Global Climate Model 2 A2 scenario and groundwater discharge potential (Chu et al. 2008).

Attribute	Likelihood of retaining cold-water species		
	Low	**Mid**	**High**
Maximum air temperature (°C)	>29.34	29.34-28.49	<28.49
Base flow index value	<0.36	0.36-0.54	>0.54

RESULTS

Currently, groundwater discharge potential of the GLB quaternary watersheds ranges from 0.111 to 0.821, where values approaching 1 indicate high groundwater inflows (Table 3). Maximum air temperature across the watersheds is currently 28.40ºC. Under the CGCM3 B1 and A2 scenarios respectively, maximum air temperature may increase to 31.06ºC and 32.96ºC by 2100 (Table 3).

Coldwater fish species are not currently found in six of the 532 quaternary watersheds of the GLB (Figure 2). The results for the remaining 526 watersheds show a decrease from 420 watersheds that currently have a high likelihood of supporting coldwater fish species to 96 and 29 watersheds by 2100 under the CGCM3 B1 and A2 scenarios, respectively (Figure 2; Table 4). The number of watersheds with a mid-likelihood of retaining coldwater species may increase from 67 currently to 367 under the CGCM3 B1 scenario and 434 under the CGCM3 A2 scenario by 2100 (Figure 2; Table 4). Under both the CGCM3 B1 and A2 scenarios, 63 of the 526 quaternary watersheds (as opposed to the current 39) may have a low likelihood of retaining coldwater fish species by 2100 (Figure 2; Table 4).

Watersheds with higher groundwater inflows and comparatively lower increases in air temperatures have the highest potential for retaining coldwater species. These include the watersheds draining the north shore of Lake Superior and in particular, the watersheds draining the Pukaskwa National Park area and watersheds near the Steel River (Figure 2). Watersheds in southern Ontario may have a low likelihood of retaining coldwater stream fish species by 2100 (Figure 2). Most of the watersheds in the central and the most northwestern regions of the GLB may have a mid-likelihood of retaining coldwater stream fish species (Figure 2).

Table 3: Maximum air temperature and Base Flow Index (BFI) characteristics of the 526 quaternary watersheds in the Great Lakes Basin, Ontario under the Canadian Global Climate Model 3 (CGCM3) B1 and A2 scenarios for the 2011-2040, 2041-2070 and 2071-2100 time periods. Base flow index values are measures of groundwater discharge potential; values close to 1 indicate high groundwater inflows.

| | | | **Maximum air temperature** | | | | | |
| | | | **CGCM3 B1** | | | **CGCM3 A2** | | |
	BFI	**Present**	**2011-2040**	**2041-2070**	**2071-2100**	**2011-2040**	**2041-2070**	**2071-2100**
Minimum	0.111	19.42	21.72	22.74	22.83	21.89	23.01	24.93
Mean	0.515	24.80	26.57	27.67	27.96	27.09	28.18	29.92
Maximum	0.821	28.40	29.93	30.75	31.06	30.65	31.60	32.96
Standard deviation	0.121	1.50	1.44	1.46	1.55	1.59	1.60	1.47

Table 4: Likelihood rankings of the quaternary watersheds in the Great Lakes Basin, Ontario to retain coldwater stream fish species under present air temperature and groundwater conditions, and under the 2011-2040, 2041-2070 and 2071-2100 air temperature projections of the Canadian Global Climate Model 3 (CGCM3) with the B1 and A2 scenarios.

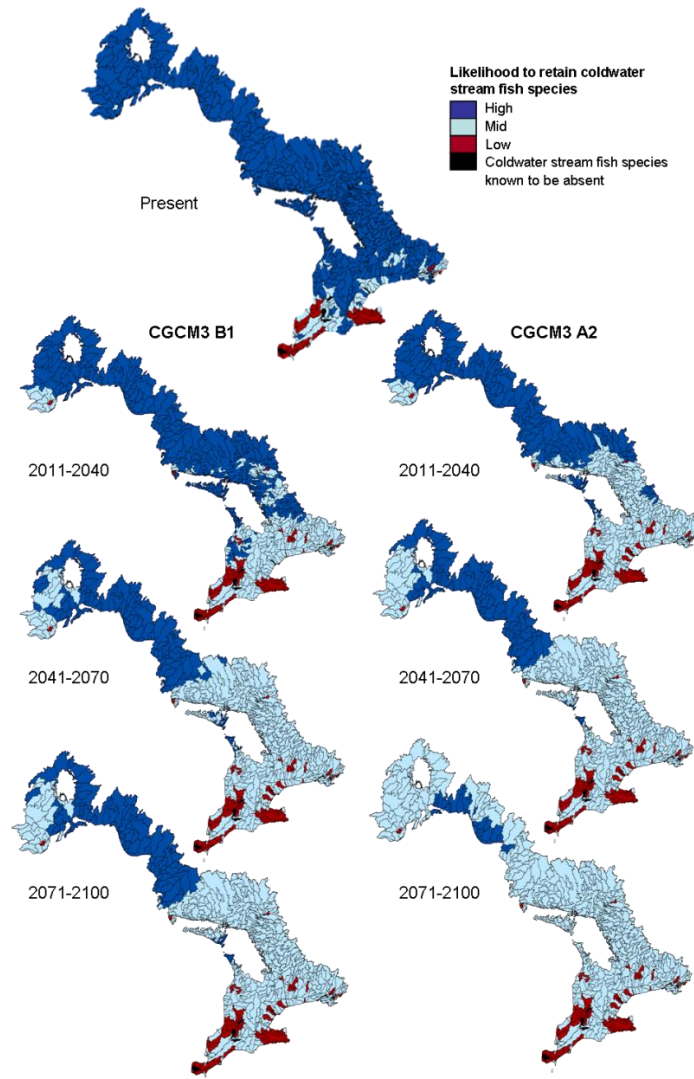| Likelihood to retain coldwater fish species	Present	CGCM3 B1			CGCM3 A2		
		2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100
High	420	259	108	96	174	92	29
Mid	67	205	355	367	289	371	434
Low	39	62	63	63	63	63	63

Figure 2: Likelihood that quaternary watersheds may retain coldwater stream fish species given groundwater conditions and the 2011-2040, 2041-2070, and 2071-2100 air temperature projections of the Canadian Global Climate Model 3 (CGCM3) B1 and A2 scenarios.

DISCUSSION

This study used air temperature and groundwater discharge as surrogates for in-stream temperatures and subsequently, suitable thermal habitat for coldwater fish species in streams throughout the GLB. The resulting patterns reflect regional changes in maximum air temperatures and differences in underlying geology. They also suggest that suitable thermal habitat for coldwater species may be reduced within many of the watersheds by 2100 although the magnitude of change differs for each climate scenario.

The likelihood rankings for the watersheds of high, mid or low have different implications for the likely changes in thermal habitat and species distributions within the streams. 'High' suggests that the thermal regimes in those systems likely will be maintained and coldwater fishes may maintain their current level of occupancy. The 'mid' ranking indicates that there may be some habitat fragmentation associated with increasing air and subsequently, in-stream temperatures, which may cause some retraction of coldwater species' ranges. The 'low' ranking suggests that there may be severe degradation of suitable thermal habitat resulting in coldwater species persisting in a few refugia (such as headwater reaches with groundwater seeps) or in the worst case, those species being extirpated from the watersheds.

The results of this study serve as a guide for prioritizing watersheds in the GLB for conservation. Two approaches may be taken: watersheds at risk in the short-term (i.e., have a low likelihood to retain coldwater fish species) may be given high conservation priority or alternatively, watersheds that are likely to retain coldwater species may be given high conservation priority because they will naturally offer thermal refugia in the future (Chu *et al*. 2008). This suggests that either watersheds in southern Ontario or watersheds along the north shore of Lake Superior may be given conservation priority.

Although air temperature and groundwater inflows are major drivers of in-stream water temperatures, temperatures in the GLB are also influenced by other factors (Poole and Berman 2001; Chu *et al*. 2010). Changes in rain patterns, groundwater seeps and recharge rates, snow accumulation, and melt patterns could also disrupt water quality and the fluvial and thermal regimes in the streams (Ducharne 2008). Human activities such as stream regulation, riparian deforestation, and groundwater and surface water withdrawals will also affect in-stream conditions (Poole and Berman 2001; Chu *et al*. 2010). In addition to temperature, the distributions of coldwater species within the watersheds are affected by species-specific habitat preferences for different substrates, vegetation, and flow regimes. Changes in these variables also could affect the distributions of coldwater species within the watersheds.

As temperatures warm, coldwater species may seek refuge in the comparatively cooler headwaters of the streams (Meisner 1990; Power *et al*. 1999). This suggests that, in a changing climate, the headwater regions of the watersheds could be given higher conservation priority than the lower reaches. The effects of changes in different climate variables, human activities and the habitat preferences of different species should be incorporated into future studies to explore the cumulative effects of climate change on stream ecosystems in the GLB.

ADAPTATION OPTIONS

Several actions can assist efforts to maintain the thermal regimes of streams as the climate warms and as population stressors such as water use, urban development, and point and non-point source pollution likely increase (Dove *et al*. 2011; Chu 2012):

- Introduce or extend riparian buffers adjacent to streams to provide shading that reduces stream temperatures and buffers the streams against deleterious runoff
- In regulated streams, consider converting top-draw dams and storm water ponds to bottom-draw systems so cooler waters drain into downstream reaches
- Limit and regulate land-use (particularly activities that increase impervious surface cover) in the surrounding watersheds
- Limit or regulate ground water and surface water withdrawals to maintain flow and temperatures in the streams
- Limit the use of tile drainage in watersheds with agricultural lands to promote groundwater recharge
- Increase connectivity by removing dams where possible, installing fish ladders and other techniques to restore and maintain connectivity in streams
- In forested areas, promote conifer species to maintain cooler stream temperatures and increase stream shading
- Modify road construction and stream crossing standards to maintain fluvial regimes
- Protect and rehabilitate critical habitats for highly vulnerable fish species (e.g. coldwater species)
- With existing legislation and policies such as the Fisheries Act, protect and rehabilitate habitats for coldwater species

CONCLUSION

Changes in air temperatures, precipitation patterns and extreme weather events associated with climate change have and will continue to influence stream ecosystems. This study indicated that there will be a reduction in the number of watersheds in the GLB that have a high likelihood of retaining coldwater fish species as the climate changes. Watersheds draining the north shore of Lake Superior and in particular, the watersheds draining the Pukaskwa National Park area and watersheds near the Steel River will likely retain coldwater stream fish species while watersheds in southern Ontario have a low likelihood of retaining coldwater species by 2100. Several adaptation options, which include riparian reforestation, bottom-draw dam operations and land use changes would minimize the potential impacts of climate change on stream fishes. The results presented in this report do not include the anthropogenic stressors such as groundwater withdrawals, stream regulation or pollution that may exacerbate the changes in the availability of suitable habitat in the streams.

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CHAPTER 4: POTENTIAL EFFECTS OF CLIMATE CHANGE ON FISH HABITAT, PRIMARY AND SECONDARY PRODUCTIVITY, AND CONNECTIVITY IN FRESHWATER ECOSYSTEMS BY D. MOIANA VIANNA

INTRODUCTION

Climate Changes in the world

The mean global temperature is expected to increase between 1 to 7°C over the next 100 years (IPCC 2001), leading to changes in precipitation patterns and intensity, and sudden irreversible changes. Some of the expected general effects of climate changes over freshwater ecosystems are increased water temperature, reduced levels of dissolved oxygen, increased toxicity of pollutants, changes in dissolved organic carbon levels, alterations in stream flow regimes, reduction in ice cover, alterations in primary and secondary productivity, changes in the connectivity between water bodies, altered hydrological regimes, deterioration of thermal conditions for fishes, increased stratification, alterations in the food web, and changes in habitat suitability for different organisms (Schindler 1997; Kling *et al*. 2003; Ficke *et al*. 2007; IPCC 2007). Higher latitudes are likely to experience more dramatic changes in temperature than the tropics or subtropics (Hassol 2004). The Intergovernmental Panel on Climate Change (IPCC; 2007) projected the annual runoff in high latitude regions to increase by 10-40% by midcentury, due to global warming. Precipitation is expected to increase globally, even though there is a high inter decadal variability (positive trend from 1901 to 2005, negative trend for 1951 and 2005) and a dependency on the region from which the data was sourced (Reichwaldt and Ghadouani 2012). This increase could occur with an accompanying higher number of "extreme" events (Folland *et al*. 2001; Palmer and Räisänen 2002; Meehl *et al*. 2007). Winter rainfall is likely to increase at mid and high latitudes of the Northern Hemisphere, but it will occur as intense events with longer dry periods between them. Therefore, it is expected that dry areas will become even drier (due to increased evaporation and transpiration, and possible decreases in runoff; Palmer and Räisänen 2002). This is already happening and is predicted to continue (Meehl *et al*. 2007; Sillmann and Roeckner 2008).

Since 1900, the world mean air temperature has risen 0.6°C; night temperatures have increased more than day temperatures, while spring and winter have demonstrated more warming than other seasons (Karl *et al*. 1996; Browne and Hunt 2007; IPCC 2007; Füssel 2009; Pederson *et al*. 2010). Over the last 30 years, the intensity and frequency of extreme events (e.g. droughts, floods and storms) have been increasing nearly all over the world, and that is thought to be a consequence of climate warming (Meehl *et al*. 2007; Emanuel *et al*. 2008). Milly *et al*. (2002) found that great floods have become significantly more frequent in the 20th century, which is consistent with results from their climate model. The same model predicts that the trend will continue. Since 1950, extremely cold and extremely warm temperatures (>98.5 or <1.5 percentile) in most land regions have increased much faster than changes in mean air temperature, with the largest positive trends in Canada and Eurasia, where daily maximum temperatures increased by 1 to 3°C during this period. The positive trend covers an area significantly greater than what could be explained by natural variability. In most cases, positive trends are stronger and cover a larger area for daily minimum temperatures than for maximum temperatures. The areas of cooling are smaller and can be responding to unforced natural variability (Brown *et al*. 2008). The North Atlantic Oscillation (NAO) influences extreme daily temperatures in many regions, with expected extreme winter daily temperatures reduced by 2°C over Eurasia but increasing temperatures over northeastern North America (Brown *et al*. 2008).

Climate projections for the 21st century show an increase in all temperature-based indices (Sillmann and Roeckner 2008). Recent studies predict significant increases in incidence of extreme precipitation (maximum 5-day precipitation and the 95th percentile of precipitation) in most regions, especially in those that are already wet. Wuebbles and Hayhoe (2004), using projections for high-, mid- and low-range emission scenarios, estimated that 24h and 7-day heavy rainfall events will double in the Midwest US by the end of the century. They predict also that regional winter temperatures will rise by 1 to 7°C, and summer temperatures will rise between 3 and 11°C (ranges over both models used and all scenarios), while Christensen *et al*. (2007) used 21 models and found that northern Canada and Alaska can warm up to 10°C in the winter, and most of the continent could warm up by 3– 5°C during summer. Most models show an increase in winter precipitation of about 15% in the north of the continent, and a decrease of about 20% in the south during summer (Christensen *et al*. 2007). It is expected that the precipitation distribution will change, becoming more concentrated on winter and less frequent in the summer (Wuebbles and Hayhoe 2004). The more frequent intense precipitation will lead to a higher runoff, increasing the risk of floods. At the same time, the warmer temperatures could increase evaporation and transpiration, lowering soil moisture levels during the summer, which in turn influences the runoff generation through the year.

The consequences of climate changes are extent and dramatic. According to Füssel (2009), "*a global warming of 1–2.5°C and 1.5–2.5°C above preindustrial levels would trigger total loss of Arctic summer ice and radical shrinking or complete melting of the Greenland ice sheet, respectively*". The average snow cover and mountain glaciers have already decreased in both hemispheres (IPCC 2007). Nevertheless, the effects of global warming are expected to be stronger in the Northern Hemisphere, and many trends have been intensifying on the last decades. Northern snowpack has been already reduced by 10% since the 1960's, and ice cover on lakes and rivers in this region has been 2 weeks shorter (IPCC 2007). Maximum areal extent of frozen ground was reduced in nearly 7% since 1900, with decreases in spring reaching 15% (IPCC 2007), and from 1972 to 2003 the annual snow cover decreased about 10% (Prowse *et al*. 2009a). Due to a higher warming during these seasons, spring and summer suffered the larger decreases (Christensen *et al*. 2007). The warming also caused a decrease in water from snow in the mountains of North America, ranging from 15% to 30% since the 1960's (Mote *et al*. 2005; Lemke *et al*. 2007). While global mean temperature rose 0.6°C on the last century, the increase in mid and high latitudes in Northern regions was between 2%-4% (IPCC 2007). The most significant warming occurred in Alaska and northwestern Canada, followed by the continental interior, the southeastern US, and eastern Canada (Christensen *et al*. 2007). North America has already suffered a decrease in mean snow cover area, and spring snowmelt is coming earlier (Lemke *et al*. 2007). On this continent, winter and spring has been warming over the last 50 years, and spring warming has extended the growing season an average of 2 days per decade (Bonsal and Prowse 2003; Feng and Hu 2004).

Climate Changes in Canada and the Laurentian Great Lakes region

In North America, the regions most affected by warming would be high latitudes in the winter, and the southwestern US in the summer. The annual mean precipitation might increase by 20-30% in Canada during the winter (Meehl *et al*. 2007; Füssel 2009).

In models of Northern Canada, although there is variability between projections, all results (from seven Atmosphere-Ocean General Circulation Models, AOGCMs, recommended by IPCC) forecasted higher temperatures, and most of them predicted increasing precipitation over the entire region. Over the last 50-60 years, the western Artic warmed by 1.5-2.0°C, while the extreme northeast Artic cooled 1-1.5°C. Between 1948 and 2005, all regions had an increase in temperature, specially the Yukon (2.2°C) and Mackenzie (2.0°C). Major changes

occurred during winter and spring. Winter in the Yukon became 4.5°C warmer, in Mackenzie about 4.3°C, and in the Arctic tundra region about 1.7°C (Prowse *et al.* 2009*b*). Since 1950, the whole country warmed by 1.2°C (Prowse *et al.* 2009*b*).

The Canadian west and the Prairies have been suffering decreases in snowfall and precipitation (Vincent and Mekis 2006). Although there is considerable temporal and regional variability, total annual stream flows have declined in Canada during the 20th century (Gan 2000; Déry and Wood 2005; Rood *et al.* 2005). The total annual snowfall decreased in the south and increased in the north and north-east during the last 60 years. There was an increase from 1900 until 1970, and then a decrease until the 1980s, corresponding to a reduction in the frequency of frost days (Vincent and Mekis 2006).

Great Lakes

About 20,000 years ago, as Earth's climate warmed, the glacial continental ice sheet retreated. That caused the glacier (up to 3,2km thick) to create the Great Lakes basin. As the glacier melted, the water filled the basins, and between 3,500- 4,000 years ago, the water reached their modern levels, and the lakes covered the actual area. They cover, in total, more than 243.400 km^2. Today the Great Lakes contain about 18% of the world's total surface freshwater, and provide drinking water for over 40 million American and Canadian citizens (NOAA 2012). Besides the five great lakes, the region holds hundreds of thousands of smaller lakes, streams and wetlands, forming the greatest concentration of small water bodies in the world in an area of this size (Kling *et al.* 2003). The northern upland region, on the Canadian Shield, has relatively poor, thin coarse-textured soils covered by extensive spruce and fir forests. This, together with the colder climate, discouraged the creation of larger population centers. In the lowland areas on south and east the soils are fertile and deep. This, along with the warmer climate, encouraged a large proportion of the agricultural production for EUA and Canada. Oak and hickory forests, and prairies are the most common natural habitats on that area (Kling *et al.* 2003).

The five great lakes are as follows:

Lake Superior has the greatest mean depth and largest heat storage capacity. It is located farther north and west then the other lakes (centered approximately 47.5◦ N, 88◦W), and has the lowest air temperatures. During most winters, the air is cold enough to provide an extensive ice cover. It forms first at shallow and protected areas (like the Whitefish Basin; mean depth 41m), then a large mid-lake ice cover develops on West basin (mean depth 135 m), and at last the mid-lake ice forms on East Basin (Assel *et al.* 2003).

Lake Michigan is the second largest Great Lake by volume, and is the only Great Lake located entirely within the United States. It is directly connected to Lake Huron by the Straits of Mackinac. The lake's northern end is colder and the southern basin is more temperate (Fuller *et al.*1995; http://www.great-lakes.net/lakes). The precipitation range is between 700 mm in the northwest to 1200 mm in the southeast. Annual mean air temperature range is from 4°C in the north to 15°C in the south. Here the soil frost and snow cover play important roles in water and energy cycles. Snow accumulations are greatest in the north and on the downwind (southeastern) shores of the Great Lakes, specifically the Upper Peninsula of Michigan State and along the Indiana and Michigan coastline of Lake Michigan (Cherkauer and Sinha 2010).

Lake Huron is the third largest in volume, and the mean water depth is the second lowest. It is hydrologically inseparable from Lake Michigan. The Huron lakeshore extends 3,827 miles, and is characterized by shallow, sandy beaches and the rocky shores of Georgian Bay. Lake Huron's drainage area covers parts of Michigan and Ontario. The largest part of this lake is at a

similar latitude band to that of the north half of Lake Michigan (44°N to 46°N), and normally, winter air temperatures are lower than those at southern Lake Michigan (Fuller *et al.*1995, Cherkauer and Sinha 2010; http://www.great-lakes.net/lakes/huron.html).

The Lake Michigan-Huron system has had its water level permanently reduced by 0.27m since 1900 due to artificial channel changes in the St Clair River (Derecki 1985). However, among the great lakes, it is still the one less affected by engineering modifications that alter water-level, including inflows from upstream lakes and outflows to downstream lakes (Changnon 1987). For this reason, the Lake Michigan-Huron system is considered a sensitive proxy for understanding the relation between climate and water level fluctuations in the region (Argyilian and Forman 2003).

Lake Erie is the shallowest of the Great Lakes. Having the smallest heat storage, it is the most vulnerable to climate changes. It also presents the highest winter-average perimeter air temperature amongst the Great Lakes. First the ice cover on mid-lake areas forms on the shallow West Basin (mean depth 9m), followed by Central Basin (mean depth 19m, and at last on East Basin (mean depth 27m) (Assel *et al.* 2003).

Lake Ontario is located farthest east, and the second farthest south (between 43°N to 44°N). Cold air currents coming from the northwest and west are moderated by the presence of Lake Superior, Michigan and Huron. Because of its mean depth (86m), and mild winter temperatures, Lake Ontario has a small potential for ice formation (Assel *et al.* 2003).

The main features affecting ice cover are summarized on the Table1.1.

Table 1.1. Great Lakes features affecting ice cover. (Assel et al. 2003).

	Superior	Michigan	Huron	Erie	Ontario
Mean depth(m)*	148	85	59	19	86
Volume (km^3)	12100	4920	3540	484	1640

*Mean depth is lake volume divided by the surface area

The St. Lawrence River drains the Great Lakes area towards the Atlantic Ocean. The whole hydrographic region (including the Great Lakes) has a surface area of 1.6 million km^2, the third largest in North America (State of the St. Lawrence Monitoring Committee 2008). Along its main channel, the St. Lawrence River has a great variety of environments, defined in part by a gradient of water salinity, from freshwater in its headwaters in Lake Ontario, passing through a long stretch of estuary, including the fluvial and upper estuary sections, and finally reaching the saline Gulf of St. Lawrence. Wetlands are mostly concentrated in the freshwater section. The St. Lawrence River ecosystems have been suffering many of the common modern impacts on rivers, such as flow regulation, pollution, riverbank denaturalization, erosion, and impoverishment of biological diversity (State of the St. Lawrence Monitoring Committee 2008). Water levels have changed in the last century, mostly due to a regulation plan started in 1964 (Boyer *et al.* 2010*a*). The mean water level in spring is 0.4 m lower than before 1964, and spring water level peak has been reduced by more than 0.6 m and is now occurring 15 days later (Boyer *et al.* 2010*a*). Wetlands have been especially vulnerable to these changes, presenting a shift in vegetation from low to high marsh, which has been magnified by invasive plant species (State of the St. Lawrence Monitoring Committee 2008). Projected changes in temperature increase and alteration in precipitation regimes include further decrease in water level and discharges by the end of this century and increasing sediment accumulation, with important

implications for tributary rivers and associated wetlands (Croley 2003; Boyer *et al*. 2010*a*, 2010*b*).

Due to the highly variable climate of the Great Lakes region, when considering a range of several years, it is difficult to detect long-term trends (Kling *et al*. 2003). Nevertheless, long term analyses have shown significant changes in precipitation, temperature, and extreme events over the last decades (Kunkel 2003). It is now well accepted that in the Great Lakes region, winter is getting shorter, annual mean temperatures are rising, and the frequency of extreme events (heat, precipitation, storms) is increasing since 1948 (Kunkel *et al*. 1999).

The annual mean temperatures in southern Canada increased between 0.5-1.5°C since 1911; about 0.11°C per decade in spring and 0.6°C in winter. Most of this warming is associated with an increase in night temperatures, and not daytime temperatures, therefore diminishing the diurnal temperature range (Zhang *et al*. 2000). During the last 25 years, the largest rates were registered in the Mackenzie Basin with annual temperatures increasing by 1.5 to 2°C, and the greatest warming occurred during winter and spring (~+3°C; Bonsal and Kochtubajda 2009). Over the last 20 years, active layer and permafrost thermal monitoring activities detected a recent warming of the permafrost in many regions of the Canadian permafrost zone (Smith *et al*. 2005).

The annual precipitation in the Great Lakes region increased about 2% during the last century (Magnuson *et al*. 1997; Stone *et al*. 2000; IPCC 2001). Zhang *et al*. (2000) found an increase between 5-53% in annual precipitation over most of the country, with the greatest values North of 60°N, and also some negative trends in eastern Canada, especially during spring (Vincent and Mekis 2006). Vincent and Mekis (2006) found that Canadian indices for 1950-2003 present more days with precipitation reduced daily intensity and a decrease in the number of consecutive dry days. Although southern Canada has been becoming warmer and wetter throughout the century, the west and the Prairies have experienced a decrease in both precipitation and snowfall (Vincent and Mekis 2006).

Vincent and Mekis (2006) did not find significant trends in indices of extreme precipitation. However, the Great Lakes region has shown an increase in the frequency of heavy summer rainstorms, which could be leading to increased runoff and floods (Kunkel *et al*. 1999). Kunkel (2003) attests that "*there has been no discernible trend in the frequency of the most extreme events in Canada, but the frequency of less extreme events has increased in some parts of Canada, notably in the Arctic*". Even though extreme precipitation events increased significantly in the US between 1920 and 1930, the frequencies in the end of 1800s and beginning of 1900s were similar to those between the 1980s and the 1990s, indicating that this variability could be natural, even though anthropic impacts should be taken into account (Kunkel 2003).

In the Great Lakes region, freeze up on inland lakes and on the bays of the Great Lakes has been occurring later in fall (1.5 days per decade), and the spring break up is happening earlier (about 2 days per decade); the trend is consistent over the last century, but has increased after the 1980's. Michigan, Minnesota and Wisconsin had the greatest changes in ice cover on inland lakes (Kling *et al*. 2003). The Great Lakes themselves had an extremely variable ice cover extension since 1963 (without long term trends), however, the last decade showed an ice cover decline (Kling *et al*. 2003). As an example, in 2001−2002 many inland New York lakes with a history of ice cover did not freeze. Annual variations in ice cover are also influenced by large-scale climate drivers such as El Niño, the North Atlantic Oscillation (NOA), and the strength of the Aleutian low. These drivers can in turn be influenced by the buildup of heat-trapping (Kling *et al*. 2003).

A warming of 3-11°C has been predicted for the Great Lakes region (Kling *et al*. 2003). Given that during the last 20,000 years a change of 5-6°C caused the region to go through a dramatic alteration in the distributions of forests, prairies and other vegetation, this projected future increase in temperature is a matter of great concern (Kling *et al*. 2003). It is a consensus between the models that the Great Lakes region is expected to become warmer and most likely drier. Most of them predict increases between 3-7°C in mean annual temperatures until the end of the 21st century, and 3-11°C during the summer (Kling *et al*. 2003) – summer and winter would be the most affected (Magnuson *et al*. 1997). Just like what has been happening throughout the world (Karl *et al*. 1996; Browne and Hunt 2007; Füssel, 2009; Pederson *et al*. 2010), temperatures at night are likely to increase more than during day time, and extreme heat (>32°C) can become more common (Kling *et al*. 2003). Since 1950, 24 hours and week-long strong rainfalls have become more frequent, leading to more frequent floods in streams and rivers (Kling et. al 2003). The changes should be less severe in the center of the Great Lakes region (Jones *et al*. 2006).

Annual mean precipitation could increase by 10-20% until the end of the century. The precipitation might decrease in summer and increase during the winter and spring, especially in western Ontario, northern Minnesota, Wisconsin and Michigan, therefore affecting the freshwater systems in the region (Magnuson *et al*. 1997; Kling *et al*. 2003). That could leave the total amount balanced, if not for the higher transpiration and evaporation that can take place, drying the area. This would lower surface and ground water levels (stream flows and water levels could lower by 0.2-2.5m), and would make soils up to 30% drier in the summer in the Great Lakes region (Magnuson *et al*. 1997; Kling *et al*. 2003). Runoff is predicted to decrease during the summer, and increase modestly during spring and fall (Kling *et al*. 2003). It is also possible that the actual increasing trend in 24hour rains and consecutive rainy days will proceed (Kling *et al*. 2003). The ice cover on the Great Lakes is predicted to be reduced in extension and duration, and smaller lakes might even no longer freeze on warmer years, especially in the south (Magnuson *et al*. 1997). Temperature simulations show that stratified lakes will be 1-7°C warmer for surface waters, and 6°C cooler to 8°C warmer for deep waters (Magnuson *et al*. 1997).

Predictions vary amongst models, and so far there is no universally accepted methodology to compare the reliability of the results from distinct General Circulation Models (GCMs). Therefore they must be regarded as all equally probable alternative futures, instead of accurate forecasts.

Saskatchewan-Nelson River watershed and the Prairies Provinces
The Saskatchewan-Nelson River watershed covers the provinces of Manitoba, Saskatchewan and Alberta; all part of the western Prairies Provinces. The province of Saskatchewan is a dryland, with hot and short summers, and long cold winters. The precipitation is low and the evaporation is high. Saskatchewan and Manitoba are dominated by the Saskatchewan–Nelson River Basin, which consists of the Saskatchewan River system (336,700 km^2), the Red and Assiniboine rivers system (290,808 km^2), and the Winnipeg River (139,565 km^2). Within Alberta, the Prairie is dominated by the Athabasca (155,000 km^2) and Peace River (293,000 km^2) systems (Gan 2000). Most of the Saskatchewan River basin, as well as all of the major rivers crossing the western Prairie Provinces originate by snowmelt from the Rocky Mountains (Cohen 1991; Schindler and Donahue 2006). The current reduction in snow packs and mountain glaciers is already affecting rivers, streams and groundwater resources in the region. The largest glaciers in the head of Saskatchewan, Athabasca and Bow rivers, have already decreased by 25% in the last century, and the shrinking rates have accelerated in the

last 60 years (Demuth and Pietroniro 2002; Watson and Luckman 2004). Further snow melting will significantly affect the whole hydrology in this basin (Schindler and Donahue 2006).

Despite the fact that Canada has a great amount of freshwater, it is not well distributed around the country. The Western Prairie Provinces, an area of nearly 2 million km^2, lie in the rain shadow of the Rocky Mountains, therefore being the driest large area in southern Canada (less than 500 mm/year of precipitation; Schindler and Donahue 2006). Precipitation is usually at its maximum in late spring or in the summer when a thermal low is often present over the warm, sunny Prairies, and when there could be up to 30 days of thunderstorms per year. The annual streamflow presents highly temporal and spatial variability, and the western Prairie Provinces were identified by the Millennium Ecosystem Assessment as a future "hotspot" for ecological degradation due to a combination of human impacts and climate changes. Past trends and future projections for the prairies are summarized in Table 1.2.

The temperatures in many regions of the western Prairie Provinces have already increased 1-4°C since 1925, with the largest increases happening after 1970 (Schindler and Donahue 2006). The region is expected to warm up even more by 2050. General Circulation Models (GCM) such as GISS (Goddard Institute for Space Studies), GFDL (Geophysical Fluid Dynamics Laboratory), OSU (Oregon State University), and CCC (Canadian Climate Center) all show similar results, with the greatest warming in the winter (up to 8°C; Gan 2000). The warming trend means that, even without any decrease in precipitation, the Canadian Rocky snowline will climb higher, and the snowfall/rainfall ratio will lower, possibly leading to stronger floods in the winter and lower streamflow in spring and summer, making the region even drier (Gan 2000).

The Canadian plains are in serious risk of potential drought (Schindler and Donahue 2006). Modeling suggests a decrease in summer streamflow and lake levels, retreating glaciers, drier soils, surface water deficits; which are all connected to higher temperatures and increased evapotranspiration. As the snow and ice accumulation decreases, summer and spring runoff loses its most reliable source of water (Sauchyn *et al.* 2006). The impacts from declining water levels would be both environmental (such as loss of wetlands, changes in shorelines, etc.) and socioeconomic (e.g. reduced hydropower, reduced marina access and shipping) (Hartman 1990).

Predicting the future net water basin supply can be very challenging. Cohen (1991) studied it at the Saskatchewan River basin using five GCMs (GISS84, GISS87, GFDL80, GFDL87, and OSU) and although most of them presented a positive change, no consensus was found in the results. They suggested a reduction in soil moisture, but other specialists believe that GCMs tend to over-estimate potential evapotranspiration at the expense of soil moisture (Gan 2000). Cohen's results for runoff were contradictory: GISS simulated an increase in runoff in the Rockies, and GFDL produced a decrease in runoff.

Table 1.2. Summary of past trend analysis on historical data, hypothesis of researchers, and GCMs' projections under $2xCO_2$ scenarios in the Prairies: (Gan 2000)

Climatic Variable	Analysis from Historical Data GCMs' projections under 2XCO2 Variable and/or Hypothesis of Researchers	GCMs' projections under 2xCO2 climate scenario
Temperature	Positive trends in January, March, April and June (Gan 1998); Positive annual Winter warming could reach 8°C trends (Gullet and Skinner 1992 apud Gan 2000)	Unanimous warming projections by GISS, GFDL, OSU, and CCC; Winter warming could reach 8°C (Cohen 1991)
Precipitation	Scattered negative trends in the Prairies (Gan 1998; Schindler and Donahue 2006)	Conflicting projections between GISS, GFDL, OSU and CCC; Precipitation may increase in the eastern Prairies but decrease in the West (Brklacich et al. 1994)
Streamflow	Scattered negative trends in May and June (Gan 1998). Long-term decrease in glaciers in eastern Rocky Mountains will reduce streamflow (Poitras et al. 2011).	More positive than negative change in the annual runoff of Saskatchewan River Basin based on climate projected by GISS, GFDL and USU (Cohen 1991).
Snow Cover and Snowmelt	Earlier onset and decreasing trend volume on spring snowmelt runoff (Burn 2008) and positive streamflow trends in March. Decrease in winter and spring snow cover (Brown and Goodison 1996).	GCMs project a decrease in snowpack and an earlier snowmelt (Thomas 1990; Kling et al. 2003). GISS, GFDL and OSU projected increase in snowmelt in central Saskatchewan, but mostly the reverse in southern Saskatchewan (Cohen 1991).
Soil moisture	Decrease in summer soil moisture in Saskatchewan (Wheaton *et al.* 1992 apud Gan 2000).	GFDL, UKMO and OSU projected a decrease in July soil moisture (Kellogg and Zhao 1988). GISS, GFDL87 and OSU projected a decrease in summer soil moisture (Cohen 1991).
Evapotranspiration (ET)	Positive trends in potential ET especially in March to June, but negative trends in actual ET from April to October (Gan 1998). Actual ET will increase (Williams *et al.* 1988 apud Gan 2000). Actual ET in Eastern Prairies will decrease (Raddatz and Shaykewich 1997).	Greenhouse induced climate change and CO2-induced changes in plant growth and stomata response tend to have opposite effect on ET. So ET projections depend on the GCMs and parameters used (Rosenberg *et al.* 1990 apud Gan 2000).

There is still a lot to be learned about precipitation trends in Canadian Prairies. Gan (1998) found scattered negative trends across the region, and also some declining streamflow trends, but on a whole, they were not statistically significant. There was a reduction in summer precipitation on three sites in Saskatchewan between 1910 and 1970, but it could not be concluded that it was a response to global warming (Ripley 1986). More recent studies have found steady decreases for some regions. Schindler and Donahue (2006) studied 10 sites in the western prairies, and nearly half of them had 14-24% less total annual precipitation in the last decade then they had in the beginning of the record period (1909-2003). Gan (2000) already called attention to the fact that although some droughts are part of the natural occurrences in this area, they could become more severe or frequent in the future as a consequence of climate changes. The drought in 1999-2005 was the worst over the instrumental record (Hanesiak *et al*. 2011).

The summer streamflow in the western Prairie Provinces is 20-84% lower today than in the beginning of the 20th century (Schindler and Donahue 2006). Lower stream flows may be caused in part by a reduction in the eastern Rocky Mountains glacier, which could be an effect of global warming (Kling *et al*. 2003). However, damming, human water withdrawals, and increased evaporation and evapotranspiration can also have influenced the flow declines (Schindler and Donahue 2006).

The effects of climate change on Evapotranspiration (ET) will depend on a number of factors. Although higher temperatures lead to higher potential ET, the ET itself depends on the available soil moisture and the counter effect that CO_2 will produce in plant growth and stomata responses (Gan 2000). In the prairies of Alberta, the potential ET increased, but the actual ET decreased (Gan 1998). This could be explained as a result of drier conditions, so that there was not enough moisture for ET to happen. Alberta presents an annual areal ET of about 350mm, and annual precipitation of nearly 450mm, so it is clear that ET is an important regulatory mechanism in the water budgets of the region (Gan 2000).

WATER TEMPERATURE

Temperature plays a decisive role in freshwater ecosystems, influencing the quality and quantity of water (Dove-Thompson *et al*. 2011). Although each system will respond in a different manner, some aspects are common to all of them. A warming in the water will affect dissolved oxygen (DO) concentration, dissolved organic carbon (DOC), contaminant flow and deposition, production, distribution and abundance of fish, earlier emergence of insects, nutrient cycling, decomposition, and many other ecological and chemical processes (Shuter *et al*. 1980; Shuter and Post 1990; Shuter *et al*. 2002; Kling *et al*. 2003; Mortsch *et al*. 2003; Wrona *et al*. 2006; Ormerod 2009). Also, because most freshwater organisms are ectothermic, warming in the water can affect the metabolism and development of much of the fauna (Shuter *et al*. 1980; Durance and Ormerod 2007). The warmer temperatures will probably displace some species (that were in their optimal thermal conditions, and suddenly found themselves in waters that became too warm) and facilitate the invasion by alien ones (those who were previously excluded from the habitat because it presented temperatures below their optimum). This could generally move the distribution of many organisms to the North (Shuter and Post 1990; Schindler 2001). But to complicate things even further, these changes interact with other anthropic alterations such as eutrophication, sediment release, acidification, impoundment, urbanization, hydropower development, flood-risk management and exotic species invasion (Shuter and Post 1990; Evans *et al*. 2006; Durance and Ormerod 2007; Durance and Ormerod 2009). Some factors can buffer stream temperatures, like the presence of woody riparian vegetation, porous soils, and active groundwater connections (Kling *et al*. 2003).

LAKES

Global mean air temperature directly influences water temperatures, so that temperature trends in the Great Lakes might track global climate changes (King *et al.* 1999; Shuter *et al.* 2002). There is evidence that summer surface water temperatures in Lakes Superior and Michigan-Huron increased faster than regional air temperatures. This is probably due to a diminished ice cover, leading to earlier stratification, resulting in longer surface water temperature warming period (Austin and Colman 2007).

Since 1918 water temperatures have been increasing in the Great Lakes region (Shuter *et al.* 2002; Jones *et al.* 2006), with higher rates during winter, and to a lesser extent in summer (McCormick and Fahnenstiel 1999; Shuter *et al.* 2002). McCormick and Fahnenstiel (1999) worked with long term data (25-87 years) and found evidence of warming in 4 of the 7 analyzed locations at the Great Lakes, two of them significant (Sault Saint Marie and Put-in-Bay), and two of them had weak trends (Bay City and St. Joseph). The water temperature in the Great Lakes is expected to rise by 3-8°C during winter and 3-9°C in summer by the end of 21st century (Jones *et al.* 2006). Summer surface water temperatures in inland lakes could increase by 1-7 °C and deep water could experience a change from +8°C to -6°C. The cooling can happen when the air warming leads small, deep lakes into earlier stratification during the spring, when the deep temperatures are lower (Kling *et al.* 2003). Mortsch and Quinn (1996) used four GCMs to analyze the trends in Great Lakes and suggested that the higher rates of temperature increase and precipitation decline will occur in the southwestern part of the basin (Indiana, Ohio). Areas in the north will have lighter impacts. There will also be a decline in annual runoff, with higher winter flow, lower summer flow, and earlier spring peak runoff events (Mortsch and Quinn 1996). It is expected that by 2070, the Great Lakes climate will have fully surpassed all historical ranges, and therefore the predictions for the end of the century must be regarded as speculative (Trumpickas *et al.* 2009).

Lake Erie is the most vulnerable of the Great Lakes regarding warming temperatures, mostly because it is much smaller in volume, having a much lower heat storage capacity (Jones *et al.* 2006). However, Trumpickas *et al.* (2009) predicted that between 2070-2100 the Lake Superior temperature cycles will have changed the most, and Lake Erie's will have changed the least. Lake Erie water presented an increasing temperature trend between 1965 and 2000, with the highest values during summer and winter (Jones *et al.* 2006). The annual runoff, ice cover, and water levels are predicted to lower in the future (Jones *et al.* 2006). If those trends continue, in the next 100 years the mean water temperature might rise from 24.8°C to 26.7°C, and a western basin will become virtually ice-free during the winter (Jones *et al.* 2006). This could affect the water quality (e.g., an earlier spring warming could increase nutrient intake by algae, allowing them to proliferate longer; Mortsch *et al.* 2003).

The water temperature in the Bay of Quinte, in Lake Ontario has been increasing since 1950 (+1.1°C), with winter water temperatures increasing since the 1970s (Minns *et al.* 2011; Casselman 2002). That trend could continue, as summer air temperatures are expected to rise 2-3°C between 2041-2070, and 5-4°C between 2071-2100, while precipitations are expected to decline by 0-10% (Colombo *et al.* 2007). For 2xCO_2 scenarios, mean water temperatures in the Great Lakes region could increase 1-7°C (De Stasio 1996). From 1972 until 2008, the warming of surface waters increased the maximum Schmidt's stability values at the deeper sites but there was no change in the thermocline depth or bottom temperatures. There was no temporal change in hypolimnetic warming, but it was inversely correlated with mean summer flow from the main river draining into the Bay (Minns *et al.* 2011).

Lake Superior potential increase in maximum temperature is estimated as 4.1°C (Trumpickas *et al.* 2008). Other studies show that Lake Superior might increase mean annual surface water temperatures by 5°C by the year 2100 (Lehman 2002), and the summer maximum surface water temperature could surpass 20°C (Lehman 2002).

The consequences of changes in water temperature over the freshwater lakes (and its organisms) will probably be mediated by alterations in thermal stratification. An analysis of 25 years data showed a consistent trend towards earlier summer stratification in Lakes Superior and Michigan-Huron (Austin and Colman 2007).

STRATIFICATION

In lentic water bodies, warmer air temperatures can warm the upper layers of water, making them less dense than the colder water from the bottom. Density differences contribute to the development of chemical differences in water layers of different depths. Putting it very simply, stratification occurs when a layer of warmer, fresher, less dense, oxygen rich and usually nutrient poor water overlay colder, denser, oxygen poor and usually nutrient rich water, preventing the mixing of the two layers, isolating the lower part of the water column, restricting the replenishment of oxygen from the atmosphere. For that to happen, the water body must be sufficiently deep (Boehrer and Schultze 2007). There can be also a decrease in production caused by a decrease in nutrient recharges, since the mixing between the layers is negligible. The most sensitive types of lake for this to impact are deep and oligotrophic, such as Lake Ontario (Kling *et al.* 2003). Shallow water bodies do not stratify, and therefore are less influenced by weather condition from preceding winters (Gerten and Adrian 2002).

Lake Michigan-Huron shows a trend towards earlier summer stratification. Lake Erie stratifies earlier than the other Great Lakes but there is still not enough data to evaluate trends (Austin and Colman 2007). In Lake Superior, the summer water temperature rose nearly 2.5°C from 1979-2006; significantly more than the air temperature did. That can be linked to a decline in winter ice cover, leading to an earlier set of the positively stratified season (almost 12 hours earlier every year). The earlier the stratified season starts, the longer the period over which the lake warms during summer, causing a stronger surface water warming than what would be expected by just an increase in air temperature. This happens because after the surface water reaches 3.9°C, the warming rate is significantly greater than before. So, the earlier the water reaches that temperature, the warmer the lake will be (Austin and Colman 2007). The rates found from 1979-2006 are significantly higher than those found by McCormick and Fahenstiel (1999) using data from 1906 to 1992 (Austin and Colman 2007). McCormick and Fahenstiel (1999) found that five out of seven sites in eastern Great Lakes had extensions in summer stratification for a duration of one to six days per decade. The longer the stratification period, the higher the risk of oxygen depletion, which creates "dead zones" for deep water organisms (Kling et al. 2003; Ficke *et al.* 2007). Higher temperatures increase the metabolism in most organisms, leading to a greater oxygen demand, decreasing even further the already low oxygen supplies in deep water (Ficke *et al.* 2007). The water overturn is the main form of oxygen replenishment. If there is not enough mixing, anoxia or hypoxia can happen, and organisms can become "temperature squeezed between the epilimnion (sometimes too warm for them, and with low amount of nutrients) and the hypoxic hypolimnion (Matthews *et al.* 1985 apud Ficke *et al.* 2007).

The projected increase in temperature driven by a $2xCO_2$ scenario would be enough to make the thermocline change its depth to between 4m shallower and 3.5m deeper than the levels presented in late 1990's, and the longer summer stratification is expected to increase hypolimnetic anoxia in the lower Great Lakes (Magnuson et.al. 1997). Schindler *et al.* (1996a)

suggested that climatic warming caused a small reduction in hypolimnetic oxygen at Experimental Lakes Area (ELA), but the trends were not significant.

The influence of lake size on stratification and optical environments

In the ELA, a warmer climate and changes in precipitation had very different effects over thermoclines in small and large lakes. Schindler *et al*. (1990; 1996*a*; 1996*b*; 1997) suggested that small boreal lakes would develop deeper thermoclines in response to higher air temperatures. In fact, Lake 239, a very small boreal lake (0.5 km^2) in northwestern Ontario, suffered an increase in its summer thermocline depth between the 1970s and the 1990s. The main reason was the decline in dissolved organic carbon (DOC) inputs from terrestrial catchments and upstream, which was a result of a drought (Schindler *et al*. 1990; Schindler *et al*. 1996*b*; Schindler *et al*. 1997). Snucins and Gunn (2000) studied 86 small lakes (<500ha) in Ontario, and found similar results. This is possibly due to warmer air? temperatures, together with lower precipitation, and consequently lower hydrologic inputs, therefore decreasing the amount of DOC in the water. Less DOC makes the water clearer, increasing solar penetration, which coupled with faster winds, deepened the thermocline, and resulted in an increasing transparency trend since the 1970s (Schindler *et al*. 1990; Schindler *et al* 1996*a*; Schindler *et al*. 1996*b*). Reduction in DOC should affect many other chemical processes. For example, Schindler *et al*. (1997) cites flocculation of chemical substances, participation in photochemical reactions, and "fuelling" microbial food chains. Highly reactive and toxic compounds such as peroxides, superoxides and hydroxyl radicals can have their photochemical production increased in clearer water (Cooper *et al*. 1994 apud Schindler *et al*. 1997).

Fee *et al*. (1996) provide more details on the role of lake size in shaping the relations between climate change-induced DOC decrease, water clarity and thermoclines depth. They show that greater transparency will only deepen thermoclines in lakes smaller than about 500ha in area, because in those the thermocline is only a few meters deep.

Larger lakes have more variable responses (Schindler *et al*. 1990; Schindler *et al*. 1996*a*; Schindler *et al*. 1996*b*). South Bay of Lake Huron (73.6km^2) had a shallower midsummer thermocline as response to an increase in temperature (King *et al*. 1997). Other studies reported formation of shallower thermoclines in warmer years, which is probably linked to the fast formation of spring stratification (Snucins and Gunn 2000). Empirical observations suggest that lake size strongly influences thermocline response to changes in temperature (Gorham and Boyce 1989). Larger lakes have thermoclines that are so deep that solar energy cannot penetrate it all even in the most transparent lakes in Ontario, therefore light will have little influence in the thermocline depth (Schindler 2001).

Deeper lakes might present higher increases in integrated temperature than shallow lakes. Empirical evidence includes Lake 239, in the Experimental Lakes Area (ELA), which increased its mean summer water temperature 10% more per degree rise in air temperature than Lake 240, which is shallower. Other ELA lakes show the same pattern (Schindler 2007). Schindler (2007) concludes that although volume-weighted mean seasonal water temperature is higher for shallower lakes, the rate of warming in lakes in the same region is virtually the same.

When a small lake becomes clearer, there are also other consequences. The photosynthetic zone becomes deeper, increasing primary productivity in lakes that were light limited (although it will probably not affect nutrient-limited lakes) (Fee *et al*. 1996). On the other hand, in small lakes with less DOC in the water the UV-B radiation will penetrate more intensely, potentially damaging freshwater biota (Williamson *et al*. 1996; Schindler 1997). At the same time, the depletion of stratospheric ozone is expected to increase UV radiation on the Earth's surface (Schindler 1997). Temperature increases at ELA were correlated with a reduction of

15±25% in DOC (Schindler *et al*. 1996*b*; Schindler *et al*. 1997). UV radiation can penetrate several meters into clear boreal lakes. The relationship between DOC and UV penetration is negatively exponential (Williamson *et al*. 1996), therefore even small decreases in DOC in clear water lakes can lead to a dramatic UV exposure of aquatic organisms, and the same can happen in shallow ponds and streams (Schindler 1997). The stronger effects of UV penetration would be felt by lakes that already have very low DOC concentrations – which is the case for many lakes in arctic and alpine areas (where allochthonous sources of DOC are rare), and for about 20% of the lakes in the boreal areas of Ontario (Neary *et al*. 1990). This can turn the habitat inhospitable for zooplankton in shallow waters (Schindler 1997). In larger lakes, if thermoclines become stronger and shallower as predicted, some organisms will be even more exposed to UV radiation, since they'll be confined to a narrower layer of water near the surface (DeStasio *et al*. 1996; Magnuson *et al*. 1997).

Snucins and Gunn (2000) suggest that small (<500 ha) clear lakes (DOC <2mg L^{-1}) will be more susceptible to warming temperatures then colored lakes (DOC >4mg L^{-1}), because colored lakes have more stable deep water temperatures. Clear lakes also exhibit stronger thermal changes in response to small differences in DOC, so they will likely be more sensitive to changes in DOC balances affected by runoff inputs, climate change or acidification.

Another form by which climate change can affect water transparency (not only in lakes), is the increasing turbidity brought by an early spring runoff or extreme rainfalls, which limits light penetration, reduces photosynthesis and reduces habitat availability for aquatic organisms (Wrona *et al*. 2006).

All the above mentioned changes in temperature, transparency and stratification would affect phytoplankton, zooplankton, benthos and fishes. In cases where there is more available photosynthetic radiation, phytoplankton could increase in productivity, but many unexpected interactions between those factors could occur. The same is valid for zooplankton (Magnuson *et al*. 1997).

The warming of non-stratified lakes would certainly move the distribution boundary of many warm and cool water species northward, at the same time excluding them from small lakes with now deeper thermoclines and hypoxic hypolimnion (Schindler *et al*. 1990). In stratified lakes, the declining oxygen level below the thermocline will degrade the habitat for cold water fishes and organisms (Magnuson *et al*. 1997). A large part of the freshwater biota (including fishes) should grow faster in warmer waters. But that would demand increasing feeding rates, and we are not sure yet if there would be resources enough to allow that (Kling *et al*. 2003).

In the Great Lakes, current hypolimnion is too cold for some warm and cool water species like Yellow Perch *Perca flavescens* and White Bass *Morone chrysops*. A thickening of the warmer epilimnion therefore would benefit them, increasing their thermal niche. Although they are native for the area, an invasion in northern areas could cause competition with the original communities, with unknown outcomes (Kling *et al*. 2003). The potential of invasions caused by changes in thermal conditions in freshwater systems has been largely studied (Meisner *et al*. 1987; Mandrak 1989; Casselman 2002; Kling *et al*. 2003).

RIVERS AND STREAMS

Rivers are extremely responsive systems when it comes to climate changes effects, tracking air temperatures very closely, especially in headwaters (Caissie 2006; Ormerod 2009). That facilitates predictions of changes in organisms with known temperature tolerances (Magnuson *et al*. 1997). Rivers and streams present many of the same impacts as lakes (e.g.

changes in DO, DOC, water chemistry, UV penetration, alterations in primary and secondary productivity), so ecological effects are inevitable as the climate alters water temperature and river flow.

The St. Lawrence River water warmed 1.3°C between 1960 and 2007 (0.27°C per year). Six of the ten warmest years and none of the 10 coldest years were observed after 1981. Those changes increased fish growing season by 5 weeks, with 20% more degree-days in the warmest years (Hudon *et al*. 2010). In the UK, forest and moorland streams at temperate headwaters at Llyn Brianne warmed by 1.4°C and 1.7°C respectively between (1981–2005) (Durance and Ormerod 2007). Other 50 streams in the UK also presented an increase by 2.1– 2.9 °C in winter and 1.1–1.5 °C in summer from 1980 to 2006, with the highest trends in the winter (Ormerod 2009).

Stream temperature was found to increase about 0.9°C for every degree increase in air temperature in the Mississippi river basin in Central US (Stefan and Preud'homme 1993). This does not hold true, however, for streams with groundwater flow. In this case, their temperature follows closely to the annual mean air temperature (Meisner 1990). But decreases in groundwater flow can change this balance, making them more susceptible to air temperature variations. Forest fires (that can become more frequent with decreased air moisture) can also accelerate streams warming, because the shadow of riparian forest is important in preventing direct sunlight from reaching the water (Schindler 1997).

Studies trying to predict possible outcomes for rivers and streams provide a series of complex results. Decreases in stream flow into lakes will delay water renewal, possibly decreasing oxygen levels (Schindler *et al*. 1990; Schindler *et al*. 1996; Mortsch *et al*. 2003). The forecasts depend also on air warming and cooling in each season, and on potential changes in precipitation.

WETLANDS

Freshwater wetlands are usually shallow and present rapid evaporation, which contributes to make them especially sensitive to climate changes (Johnson *et al*. 2005). However, the literature dealing with the possible future of these systems under climate changes is still scarce, and most papers deal with a broad range of issues at once, therefore each subject can receive only a relatively superficial analysis. Over the last 50 years, wetlands have been so affected by non-climate drivers (such as drainage, use, pollution, and invasive species), that in comparison, climate related changes are still not so drastic (Dove-Thompson *et al*. 2011).

Ontario has 25-33% of Canadian wetlands, mostly on its north; nearly 80% of them have already been destroyed or greatly modified (Dove-Thompson *et al*. 2011). However, as climate warms, what is left of those systems can be further compromised, and many of the non-climate drivers can be intensified (e.g. increases in water temperature can intensify concentration of pollutants , or favor invasion by warm water species; Mandrak 1989; Schindler *et al*. 1996*a*; Mandrak and Cudmore 2010). Wetlands that depend mostly on precipitation or runoff rather than underground water, such as bogs and peatlands, are more vulnerable to dry out because of increased evapotranspiration, if precipitation does not compensate for it. The soil drying and aeration, coupled with the increased temperatures, would benefit woody species and microbial peat decomposition, releasing carbon and possibly causing a positive feedback on global warming (Wrona *et al*. 2006).

Wetlands in dry areas, such as the Prairies Potholes Region (PPR), can dry up easily if the temperatures increase without a corresponding increase in precipitation (Johnson *et al*. 2010). Ecological consequences would be disastrous, as the PPR is the most productive habitat

for waterfowl in the world. Between 50-80% of the continent's ducks depend on that region, and their numbers are correlated with the availability of ponds (Johnson *et al.* 2005). The PPR precipitation has a strong east-west gradient, being 3 times drier on the east (300 mm/year to 900 mm/year), as the moisture decreases toward the rain shadow of the Rocky Mountains. The air temperature has a north-south gradient, ranging from mean annual temperature of 1°C to 10°C. The whole region became warmer and wetter over the 20th century, but not uniformly (Millett *et al.* 2009). The diurnal range decreased; minimum daily temperatures warmed by 1°C, while maximum daily temperatures cooled by 0.15°C. Minimum temperatures warmed more in winter than in summer, and maximum temperatures fell in summer and rose in winter. Mean annual precipitation increased by 49mm (9%). The moisture east-west gradient steepened during the 20th century, increasing an average of 9%, with stations in the west (particularly in the western Canadian prairies) becoming drier, and stations in the east were becoming wetter. This trend, if extended, can reduce the productive wetlands area. The warming in the PPR had a level similar to the mean global changes; both are expected to keep warming over the next century (Millett *et al.* 2009). Trends in precipitation are difficult to predict, and for the PPR, forecasts range from no change to an increase of 10% to a decrease of 20%, with reductions in the summer rainfall and increases in frequency of extreme precipitation during spring and fall (Johnson *et al.* 2005).

Johnson *et al.* (2005) modeled three scenarios showing that the PPR is extremely sensitive to changes in air temperature and precipitation patterns. Under an increase of 3°C in annual mean air temperature alone, there was great increase in emergent vegetation, with denser vegetation on the warmer regions. Under a 3°C increase in temperature plus a 20% increase in precipitation, the results were very similar to historic data, showing that in this case, the changes in precipitation and temperature should compensate for each other. Under a 3°C temperature increase and a 20% decrease in precipitation, the changes were dramatic. Five out of six stations became completely dominated by dry marsh conditions, and nearly the entire region failed to produce and maintain open water enough to be classified as hemimarsh. Overall, besides the impacts on all other native organisms, southeastern Saskatchewan would become a more variable and less reliable region for waterfowl production than it was during the last 100 years.

WATER CHEMISTRY
The effects of climate change upon water chemistry are strongly dependent on changes in precipitation and runoff. If precipitation does not offset evaporation, droughts could happen. Beside the other consequences of periodic droughts already discussed, post-drought rains can mobilize sulfates and acidity, delivering strong acid pulses to the watershed, slowing or even impeding recovery of aquatic systems already acid-stressed (Lazerte 1993). Some of the streams most susceptible to acid rain are in Ontario Canadian Shield (DeVito and Hill 1997). The forecasted increase in intensity and frequency of strong precipitation will cause greater runoff of phosphorous (P), nitrates, pesticides and other contaminants (Mortsch *et al.* 2003). Lower water levels can also make soft water lakes more susceptible to acidification because of the lower groundwater inputs that would bring chemicals able to neutralize the acids (Webster *et al.* 1990; Carpenter *et al.* 1992). In western Ontario, between 1969 and 1989, decreases in precipitation combined with increased evaporation lowered the water levels in lakes and streams, leading to higher concentrations of chemicals (Schindler *et al.* 1990).

Lower water levels may also worsen the effects of contamination (Mortsch *et al.* 2003; Wrona *et al.* 2006). Schindler *et al.* (2001) reviewed a range of possible effects of climate

change on water chemistry, including: (i) decreases in volume can make lakes much more saline; (ii) changes in chemical composition can be dramatic, to the point where concentrations increase to exceed the solubility of some salts; (iii) waters dominated by calcium bicarbonate can change to sulfate sodium or other cation-anion combinations; (iv) sodium chloride becomes dominant as other less soluble salts precipitate, therefore excluding the majority of organisms.

LAKES

The relationship between climate alterations and pollutants is complex. Reduced flow will reduce input of pesticides and other pollutants to the water. But it will also increase the water retention in lakes, consequently increasing retention of chemical constituents (Schindler 1997). Schindler (1997) compiled a summary of the effects of climate changes on freshwater systems concerning water renewal times, the main points are: (i) doubling in water renewal time is similar to doubling the loading of conservative chemicals in its effect on concentration at a lentic water body; (ii) longer water renewal times can increase eutrophication; (iii) longer water renewal times can retain more sulfate, nitrate and other conservative compounds; and (iv) it can also reduce lake's capacity to eliminate persistent dissolved substances and pollutants. In ELA lakes, water renewal time increased by about four times due to a small warming and drying (Schindler *et al*. 1996*a*). But in some cases, longer water residence may provide time for biological and chemical removal process to occur, decreasing concentration of chemical components (such as P), dissolved organic carbon (DOC), and silica in lakes and streams in ELA (Schindler *et al*. 1996a). On the other hand, calcium can be released from sediments, therefore increasing its concentration where the water renewal is slow enough. The difference between calcium and sulfate reactivity will cause lakes to become more alkaline with time, while streams will become more acidic. This was observed in eastern Ontario, and there are many reports of lakes more alkaline than their surface inputs (Schiff and Anderson 1986).

Warmer water will increase revolatilization and decomposition of pesticides. The volatized contaminants will be transported to other locations, and probably accumulate in cooler waters (Mackay and Wania 1995). As temperature increases, perennial snow and ice accumulated over long periods can melt, releasing contaminants into freshwater systems, which may be toxic to organisms (Wrona *et al*. 2006). The toxicity of some pollutants can be increased under higher temperatures. For fishes, this is true for most of common pollutants, such as organophosphates and heavy metals (Murty 1986*b* apud Ficke *et al*. 2007). This could happen because of the enhanced production of bioactivated free radicals that are more toxic than the parent compound (Nemcsók *et al*. 1987). If climate change induces lower oxygen concentrations in the water as expected, it can further increase toxicity as heavy metals (including mercury) become more soluble in the absence of oxygen, therefore making them more available for intake by organisms. Oxygen binds with these metals, forming insoluble compounds that will accumulate in the sediments at the bottom of the water body (Kling *et al*. 2003). In addition, as Schindler (1997) summarizes in his review, mercury methylation increases and demethylation decreases with warming waters, enhancing the risk of animal contamination. One complicating factor is that increased light leads to higher losses of methyl mercury to the atmosphere. Another is that, as catchments dry, mercury exports to aquatic systems decrease, because it is complexed with DOC. If DOC declines, methylation is expected to increase. Another potential effect of warming waters is its accelerating the effect on trophic transfers, which will magnify mercury concentrations, especially at high trophic levels (including humans) (Moore *et al*. 1997, Wrona *et al*. 2006). This problem arises from increased metabolism promoted by higher temperatures, leading to higher intake of the toxin (Murty 1986a apud Ficke *et al*. 2007; Schindler 1997). However, higher metabolism could enable organisms to excrete the toxin faster. Of course, this will not happen with toxins for which there are no metabolic pathways to allow excretion.

Because there are so many factors involved, and their interactions defining contaminant concentrations and toxicity are rather complex, the outcomes in different freshwater ecosystems will probably have great variability (Schindler 1997).

Oxygen

Oxygen usually enters the water bodies through photosynthesis or by diffusion from the atmosphere, a process that can be enhanced by mixing and turbulence (e.g. by wind or water flow). The levels of dissolved oxygen (DO) can be reduced due to many reasons, including decomposition of organic matter and respiration (by animals, microbes or plants). This lowers the DO in the water column, especially at night, when it cannot be compensated by photosynthesis.

Oxygen is less soluble in warmer water, and higher temperatures also increase metabolic rates, enhancing respiration and accelerating the oxygen depletion (Minns *et al.* 2011). If no oxygen recharge occurs, DO can drop below 2-3mg/l, a concentration considered hypoxic (Ficke *et al.* 2007). For those reasons, organisms exposed to warmer water can become "oxygen squeezed", because the DO supply cannot reach their needs (Ficke *et al.* 2007). In some cases, however, the increase in water temperatures can also lead to an increase in mixing down of oxygenated surface waters, balancing the enhanced demands, which has been observed for instance in Bay of Quinte (Minns *et al.* 2011).

So far there is no evidence of increasing trends in hypoxia or anoxia in individual systems, but given the information discussed above, warmer temperatures have the potential to provoke a decline in DO levels (Ficke *et al.* 2007).

In lakes, oxygen concentrations can be affected by many factors, such as ice cover, excess of nutrients, or temperature. Reductions in ice cover duration and/or extension can increase the DO levels by exposing more water surface to the atmosphere. However, the biological changes discussed above can also increase oxygen demands. Changes in precipitation, stream flow and lake volume will all affect the DO concentration (Bengtsson *et al.* 2011).

In Lake Erie, the government has been spending billions of dollars trying to reduce the P input into the lake, as P can enhance algal growth which later will be decomposed and consume DO. Hypoxia during the summer is currently a serious problem in Lake Erie, especially at Central Basin, due to the smaller volume of water (Dissolved Oxygen Depletion in Lake Erie Program - http://www.epa.gov/glindicators/water/oxygenb.html). In Bay of Quinte, oxygen has also been found to respond to decreases in P loading. Although DO depletion was variable, it presented a downward trend in response to decreases in P inputs. No relationship was found between increasing surface water temperature (nearly 1°C from 1972 to 2008) and DO concentrations (Minns *et al.* 2011).

RIVERS AND STREAMS

Even clean streams can be affected by low or intermittent flow, which can decrease oxygen levels, decrease DOC input and increase dependence on water from the hyporheic zone. The hyporheic zone is rich in nutrients and poor in oxygen, which can be deleterious to underground biota (Stanley and Valett 1991 apud Carpenter *et al.* 1992; Carpenter *et al.* 1992; Eimers *et al.* 2008).

Generally, increasing temperatures accelerate metabolism, resulting in higher respiration and lowering the respiration/photosynthesis ratio (if there is no other limiting factor). If this occurs in streams, there will be smaller amounts of organic matter to be flushed downstream,

affecting other freshwater systems (Busch and Fisher 1981). Increased soil respiration can reduce the amount of carbon available to be carried by water flow (Meyer and Pulliam 1991 apud Carpenter *et al.* 1992). However, trend results are difficult to extrapolate to different areas because of the many differences not only in the analyzed systems, but also in the methodology used.

Schindler (1997) presents a broad summary of the expected effects of climate changes on streams. Lower stream flow generally leads to lower exports of chemicals from catchments, and prolonged contact with soil increases the concentration of many compounds (Schindler *et al.* 1996a; Webster *et al.* 1996; Hinton *et al.* 1997). In ELA, the DOC in lakes declined due to lower export as temperatures increased (Schindler *et al.* 1997). There is not much available data linking nitrogen availability with climate changes. Silica had lower exports, probably because of reduced weathering, and that could affect diatoms (Kilham *et al.* 1996). In ELA, streams had a greater export of base cations, suffering acidification, particularly during periods of drought. One reason could be the reoxidation of sulfur, which accumulated from the reduction of atmospheric sulfates (Schindler 1996a).

WETLANDS

Much of the DOC in estuaries, lakes, rivers and streams comes from wetlands (Pastor *et al.* 2003). As with other systems, the outflow of DOC in wetlands is connected to precipitation, basin topography, and will be affected by climate change (Clair and Ehrman 1998; Pastor *et al.* 2003). However, there is evidence that discharge from wetlands (especially peatlands) into downstream ecosystems is the most influential of these factors (Pastor *et al.* 2003). It is expected that wetland discharge will be reduced, decreasing DOC outflow (Clair and Ehrman 1998).

Pastor *et al.* (2003) suggest that as climate change reduces discharges, bogs will reduce DOC flows to fens, and fens will deliver less DOC to water bodies downstream. The carbon (C) that is not being flushed out can either accumulate in the peat, or be released to the atmosphere (Pastor *et al.* 2003). Increasing temperatures can accelerate decomposition, making wetlands stop acting as carbon sinks and start acting as sources of carbon to the atmosphere (e.g. decomposing peat releases C; Wrona *et al.* 2006).

ICE COVER

The ice cover duration (number of days between freezing and ice break-up in rivers and lakes) and extension (area of the water surface covered by ice) has been decreasing with variable rates in many freshwater systems, mainly influenced by mean annual air temperatures and water depth (Shuter *et al.* 1983; Anderson *et al.* 1996; Magnuson *et al.* 2000; Lenormand *et al.* 2002; Assel *et al.* 2003; Futter 2003; Jensen *et al.* 2007; Duguay *et al.* 2006; Brown and Duguay 2010; Mishra *et al.* 2011*a,b*; Wang *et al.* 2012). In the last 100 years the temperature in the Northern Hemisphere increased by 1.2°C, the freeze up dates have been happening later (0.58 days per decade), and the break up is happening earlier (0.65 days per decade; Magnuson *et al.* 2000). Ice duration in the Northern Hemisphere has been reduced over the last two centuries ; shortening by 2 weeks during the 20th century (Magnuson *et al.* 2000; IPCC 2001; Assel *et al.* 2003). Snow cover presents a reducing trend since the 16th century, which was also observed at the Great Lakes region (Assel and Robertson 1995). Those changes can have broad ecological consequences.

The ice cover plays a decisive role in freshwater ecosystems. It reduces wind mixing, and protects from wave impacts, heat loss, and absorption of incoming shortwave radiation

(IPCC 2001; Jones *et al.* 2006; Wrona *et al.* 2006). It also changes evaporation patterns, interferes with oxygen diffusion from the atmosphere to the water, and affects shore erosion, transport of sediments, and survival of fish spawn over the winter (Derecki 1976; Shuter and Post 1990; Bolsenga 1992; Assel *et al.* 2003). Other potential impacts of changes in the ice cover regimes are alterations in the fisheries composition, possible increase in phosphorus amount in the water, and alterations in zooplankton activity (Vanderploeg *et al.* 1992; Magnuson *et al.* 1997; Nicholls 1998; Assel *et al.* 2003). A reduced ice-thickness can also increase under-ice habitat availability, winter productivity, and smaller ice cover, which can increase oxygen concentrations because of the greater area of open water exposed to the atmosphere, allowing aeration (Prowse and Beltaos 2002; Wrona *et al.* 2006).

LAKES

Several studies show a trend towards shorter ice duration in Canadian Lakes, especially in the Great Lakes region: Hudson Bay (Gagnon and Gough 2005), Lake Superior (Assel 2003, Howk 2009), Lake Ontario (Futter 2003), Wisconsin Lakes (Anderson *et al.* 1996), Michigan, Minnesota and Wisconsin (Kling *et al.* 2003), Lake Michigan (Assel and Robertson 1995), Experimental Lakes Area (ELA) (Schindler *et al.* 1990), and the Great Lakes (Trumpickas *et al.* 2009, IPCC 2001, Mishra *et al* 2011a,b). Since the 1970s, that holds true for all of the Great Lakes, with Lake Ontario having the strongest trend, and Lakes Erie and St. Clair having the smallest. The total ice cover loss for overall Great Lakes is 71%, with Lake Ontario losing 88%, Lake Michigan 71%, and St. Clair 37% (Wang et.al. 2012). The ice duration in Lake Superior has been decreasing 3 days per decade since 1857 (Howk 2009).

Kling *et al.* (2003) summarized different projections in the Great Lakes Region, including:

(1) Small inland lakes: Reductions in ice cover duration by 45-60 days under a $2XCO_2$ scenario.
(2) Lake Erie: would jump from the current 2% of winters being ice-free to up to 61% of winters becoming ice-free by 2030, and 4-96% of winters becoming ice-free by 2090.
(3) Lake Superior: currently presents ice on every winter, but by 2030 it could become ice free in up to 4% of the winters, and by 2090 it could be ice free in 4-45% of the winters.
(4) Lake Superior and Erie: present ice cover duration of 77-111 days, but it is expected to have a drop of 11-58 days by 2030, and of 33-88 days by 2090.

Declines in ice cover duration, extension, and thickness are already observed over the Great Lakes and are expected to continue (Kling *et al.* 2003; Trumpickas *et al.* 2009, Mishra *et al.* 2011*a*, *b*). The small lakes in the south should be the most affected, perhaps even no longer freezing every year (Magnuson *et al.* 1997). Some of those declines are associated with increases in temperatures in the winter, fall and spring (Assel and Robertson 1995; Anderson *et al.* 1996). Also, lower annual maximum ice concentrations (AMIC) can occur in winters after an intense warm El Niño or be linked to Southern Oscillation patterns (Assel 1998; Wang *et al.* 2012). Considering the period from 1963 to 2001, the time averaged AMIC over the winters 1998–2001 (32%) is the lowest consecutive four-winter average in the Great Lakes (Assel *et al.* 2003).

The relation between ice cover duration and mean annual air temperature is the base model which forecasts that a 4-5°C increase in mean winter temperature (from 1951-1980 indices) would result in maximum ice cover between 0 and 9% for the Great Lakes (Assel *et al.* 1985). Small inland lakes in this region respond to a small increase in air temperature (0.08-0.21°C) with a significant reduction in ice duration of 0.2-2.0 days per decade (Mishra *et al.* 2011a). Assel (1991) calculated that in a $2xCO_2$ scenario (compared to 1980 CO_2 indices), the

Great Lakes would be ice free in some winters. Compared to the period 1951-1980, the mean ice duration would decrease to 5-13 weeks on Lake Superior and to 8-13 weeks on Lake Erie. For Lake Erie, the ice would be mostly concentrated on the west basin, then on the central and the east basin. Wisconsin lakes also would have a reduction in ice duration; the average break up dates would be 0.82 days earlier per year in southern lakes, and 0.45 days earlier per year in northern lakes (Anderson *et al.* 1996). The inter-annual changes were related to the warm phase of El Niño/Southern Oscillation (ENSO; Anderson *et al.* 1996). This is important because El Niño events are becoming stronger, and their influence on earlier ice breakup has increased (IPCC 2001).

According to two global climate models (CGM1 Ensemble Mean and the 'Combined Effects of Projected Greenhouse Gases and Sulphate Aerosol Increases – Canadian Model'), Southern Ontario is one of Canada's areas that will have the smallest changes. Even so, if the Great Lakes are already showing so many effects of climate change, there is reason to be concerned (Futter 2003).

In Northern Lakes, such as Lake Superior, ice coverage has a decisive influence on the start of the next stratification season; therefore it drives important ecological aspects of the system (Austin and Colman 2007). In general, a shorter duration of ice cover can cause earlier temperature stratification, with all the consequences already discussed. It can also increase the UV penetration in the water, damaging organisms (Wrona *et al.* 2006). A longer open water season can enhance heat storage in the lake, diminishing ice thickness during winter, creating a positive feedback, confirming the results of Austin and Colman (2007; Mishra *et al* 2011b).

RIVERS AND STREAMS

Ice breakup dates are also occurring earlier in rivers and streams in the Northern Hemisphere, and the ice duration seems to have been reducing nearly 10 days per century in this region (Magnuson *et al.* 2000; Beltaos and Prowse 2009). Zhang *et al.* (2001) found a reducing ice duration trend in 30% of the analyzed Canadian rivers (most of them in the east) in the past 30-50 years. Hodgkins *et al.* (2005) also found a trend in 12 of 16 analyzed river stations in the US (in nine stations, there was a decrease of 20 days in the ice duration from 1936 to 2000).

The most comprehensive analyses on long term river ice trends come from the Former Soviet Union, such as the work of Borshch *et al.* (2001). This review shows that most rivers in Western Siberia, European Russia, and Danube have been reducing the ice duration by 20 days per century, and this trend is correlated with increases in mean air temperature. No ice trends were found for Eastern Siberia. However, although air temperature is decisive, the identification of ice duration trends depend also on the geographic scale, location of the water body, and the period of time considered in the study (Futter 2003).

Ice cover in lotic systems affects many of the same aspects they do in lakes, but also have a pronounced effect on sediment transport, river morphology and biochemical exchanges (Prowse 2001*a*, 2001*b*). It can also create breakup and freeze up jams, causing floods, with important ecological and socio economic effects. There is evidence that ice jamming severity has been increasing in the Miramichi River, New Brunswick, between 1962-1996, coupled with increases in air temperatures and flow (Beltaos 2004). At the same time, there has been a reduction in frequency of ice-jam floods in Peace River (Alberta), which caused some parts of the Peace-Athabasca Delta to dry up, severely disturbing the local fauna and flora (Beltaos *et al.* 2006). Suggested causes are stream regulation and reduced snow packs in the upper part of the river that usually provides most of the spring flow (Beltaos *et al.* 2006). Projections show that the differential rates of temperature increases across major latitudinal ranges of some large

northern rivers, coupled with decreasing latitudinal spring temperature gradient, might decrease frequency and intensity of dynamic river ice breakups, replacing them with less dramatic thermal events (Wrona *et al.* 2006).

A reduced ice cover may increase the UV penetration in the water, damaging organisms (Wrona *et al.* 2006), but also increase under ice habitat availability. The water flow might also increase a response to not only ice melting but also to increased precipitation (Wrona *et al.* 2006a; Beltaos and Prowse 2009). Some streams that would normally freeze completely during winter may start to flow year-round, possibly reducing winter-kill in some species (Wrona *et al.* 2006b; Beltaos and Prowse 2009). The potential effects of that reduction will not simply make conditions more benign, but instead some negative aspects of the ice regimen might get worse. For example, it has been found that increased incidence of mid-winter break up events (due to higher temperatures) in Canada could enhance the frequency and severity of ice jams(Beltaos and Prowse 2001; Prowse and Beltaos 2002).

Under a warming climate, the permafrost can thaw; increasing sediment and organic matter inputs in rivers and streams in the Far North, increasing turbidity and decreasing photosynthesis rates (Wrona *et al.* 2006).

There is not much information available about ice cover trends on Canadian rivers and streams, but changes in ice dynamics and snowfall will have a direct influence on the runoff of many of these systems.

WETLANDS

Earlier ice breakup will make wet periods in wetlands shorter, especially in ephemeral systems (Kling *et al.* 2003). It would affect timing of stream flows, floods, and the timing of amphibian and insects life cycles (Kling *et al.* 2003).

The warming in Ontario's "Far North" will change soil conditions and severely alter ecosystem composition, function, and structure. In some sites, terrestrial ecosystems will be replaced by aquatic ones, such as ponds and lakes. As permafrost thaws in thermokarst areas, depressions may be formed, creating wetlands and ponds. These new freshwater ecosystems would provide habitat for many aquatic species previously excluded from the area (Wrona *et al.* 2006*b*).

On the other hand, permafrost thaw in ice-rich systems can lead to large lake drainage; increasing groundwater flux can drain other lakes. The thawing of the permafrost will make the freshwater systems more connected to the underground waters, which can lead them to go through a drawdown. Lakes and wetlands in this situation experience great changes in their hydrology and biota, and, in the long term, they can become terrestrial systems (Wrona *et al.* 2006*b*).

Permafrost thawing can also release carbon and nutrients, probably increasing productivity and nutrient cycling, but also releasing carbon back to the atmosphere (Wrona *et al.* 2006*a*).

WATER LEVEL

Most global models predict only modest changes in precipitation over Canada. This can give the idea that they will provoke only modest effects on water budgets. This is misleading, because increasing evaporation can affect water levels substantially. In the Great Lakes

catchment, evapotranspiration is expected to greatly increase (Mortsch and Quinn 1996). In the Experimental Lakes Area (ELA), an increase of 2°C in mean air temperature (from 14° to 16°C) increased evaporation in 30%. That caused permanent first order streams to become ephemeral (Schindler *et al*. 1996a). Greater wind velocity and reduced humidity contribute to enhanced evaporation at an exponential rate. At the ELA, stronger winds have already been recorded (Schindler *et al*. 1990). From 1970 to 1990, there was an increase in mean annual temperatures of 1.6°C at ELA, and a decrease in precipitation of nearly 40%. The 70% reduction in runoff catchments recorded for that period is thought to be a consequence of the decline in precipitation and an increase in evaporation. Some first order streams that would flow permanently in the ice free season in the 1970s became dry for an average of 150 days in late 1980s (Schindler *et al*. 1996a).

The annual average precipitation in Canada is likely to increase overall with increases in winter and decreases in summer, depending on the area (IPCC 2007). But due to increased evaporation, only areas with greatly increased precipitation will be safe from draught (Schindler 2001; IPCC 2007). In western Ontario, under $2xCO_2$ scenarios, air temperature could increase in summer and winter, while precipitation decreases in summer. It is likely to increase during the winter in western Ontario, northern Minnesota, Wisconsin and Michigan (Magnuson *et al*. 1997). Most of the predictions also point to lower levels of water in the Canadian Prairies, caused mainly by the forecasted decreases in precipitation and increases in evaporation. The lower levels would occur during the summer (Schindler and Donahue 2006).

The projected changes in precipitation are likely to severely affect all freshwater systems. Much of the precipitation that used to fall as snow will come as rainfall, changing timing and intensity of water flow (Kling *et al*. 2003). An increase in frequency of heavy rainfall may cause more frequent flooding, especially when coupled with inappropriate land management practices and urbanization. Alterations in flood regimes are likely to increase erosion, bring additional water pollution from pesticides and other contaminants, delay recovery from acid rain, change nutrient recharge in water bodies, and reduce safe breeding sites, affecting amphibians, migratory shorebirds, and waterfowls (Kling *et al*. 2003; Dove-Thompson *et al*. 2011).

The water levels are also affected by El Niño, which in turn affects many other features of water bodies, including flow timing, water mixing, nutrient concentrations, and primary productivity (Anderson *et al*. 1996; Covich *et al*. 1997; Magnuson *et al*. 1997; Melack *et al*. 1997). The mature phase of El Niño, when the Pacific Ocean reaches the highest temperatures, is the one that brings the strongest effects (around March). However, because many human activities modify freshwater systems, it is not always clear how great the effects due only to climate are (Covich *et al*. 1997).

A decrease in summer water levels in water bodies will influence the availability and quality of aquatic habitats. It will change biological processes (such as fish migration and movement pathways), and physical and chemical processes (e.g. stratification, nutrient cycling, dissolved oxygen dynamics; Wrona *et al*. 2006b).

LAKES
The Great Lakes water levels have been highly variable since 1900 (Lofgren *et al*. 2002). So far, there are no clear long term trends. Until the late 1990s, the Great Lakes presented extremely high water levels during three decades (Sousounis and Bisanz 2000). Despite the many uncertainties, the majority of models project declining levels in both the inland lakes and the Great Lakes, due mainly to increased evaporation in excess of precipitation (Cohen 1986; Magnuson *et al*. 1997; Kling *et al*. 2003; Angel and Kunkel 2010). The reduction

in ice cover permits greater evaporation from open water during the winter, also contributing to lower water levels (Kling *et al.* 2003). Croley (1990) worked with a hydrologic model, using results of three GCM simulations, predicting a decrease in net basin supplies of 23-51%. These results were used by Hartmann (1990) to determine water levels, predicting declines between 0.13-2.5m on the Great Lakes.

A summary of the predictions of future water levels from different studies on the Great Lakes region is presented by Kling *et al.* (2003). They include:

(1) Groundwater near Lansing, Michigan: changes from -0.6 to + 0.1m by 2030.
(2) Crystal Lakes, Winscosin: changes of -1.0 to 1.9m under a $2xCO_2$ scenario.
(3) Lake Michigan-Huron: a reduction from 0.99 to 2.48m under a $2XCO_2$ scenario, changes from +0.05 to -0.72m by 2030, and +0.35 to -1.38m by 2090.
(4) Lake Superior: reductions of 0.23 to 0.47m under a $2xCO_2$ scenario, reductions of 0.01 to 0.22 m by 2030, and changes between +0.11 to -0.42m by 2090.
(5) Lake Erie and Michigan-Huron: one GCM predicted a decrease of 1-1.5m by 2090, and the other GCM predicted a small increase (Lofgren *et al.* 2002)

Using an updated GCM produced for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC 2007), Angel and Kunkel (2010) modeled water level changes in the Great Lakes, using high, moderate and low CO_2 emission scenarios. The forecasted annual precipitation varied from -5cm to +20cm by the end of this century. If precipitation remains unaltered and temperature rises, the water levels might decrease. If precipitation increases, it may offset the evaporation, diminishing the decline in water levels, or maybe increasing them slightly. A decrease in precipitation would cause greater reductions in lake levels. They found that, for the high emissions scenario, between 2080 and 2094 the median decline is predicted to be 1.2m in Lake Superior, 0.41m in Lake Michigan-Huron, 0.32m in Lake Erie, and 0.39m in Lake Ontario.

The full range of projections is:

(1) Lake Superior: – 0.58m to +0.35m
(2) Lake Michigan-Huron: -1.77m to +0.89m
(3) Lake Erie: -1.31m to +0.61m
(4) Lake Ontario: – 1.65m to +0.80m

In the ELA region in northwestern Ontario, an increase of 8°C in annual mean temperature would produce an increase of 35mm in average evaporation (or 68mm per degree increase in summer air temperature). The base data is from 1970 to 1990, when the average evaporation and evapotranspiration was 9mm per year. To offset this water loss, the precipitation would have to increase considerably, especially in the summer (Schindler 1997). Increases in evaporation, if not accompanied by a comparable increase in precipitation (or greater stomatal resistance from increasing atmospheric CO_2), will cause a reduction in lake levels, stream flows, water renewal, water levels in wetlands, soil moisture, and groundwater levels (Schindler *et al.* 1997). An empirical relationship estimated by Revelle and Waggoner (1983 apud Udall 2007) for data in western North America reveal that stream flow is much more sensible to changes in temperature than precipitation (i.e. Flow (m^3) = 9274+52(Precipitation in mm) – 2400 (Temperature in Celsius)). For instance, a warming of 2°C in a region with annual precipitation of 500mm or less would reduce stream flow more severely than a decrease of 10% in precipitation. Decreasing precipitation, earlier ice breakup and earlier spring snowmelt seem to reduce spring flows and advance them in time at the ELA and other areas in north east North America (Magnuson *et al.* 1997).

Rivers and streams

Rivers and streams will also be severely affected. If there is enough increase in winter and spring precipitation, it may increase water levels, surface runoff (especially if precipitation occurs over frozen soils), spring floods and groundwater recharges. Nutrient and sediment retention should decrease. In these seasons, hydrologic connectivity in wetlands could increase (Kling *et al.* 2003).

More frequent floods can also increase turbidity, which affects streams and rivers more dramatically than lakes, because of the rapid changes in stream and river water levels. The increased flows can also enhance the inputs of particulate and dissolved organic matter in the streams (Dove-Thompson *et al.* 2011). Floods have great influence in local fisheries success, as they can displace adults and juveniles, and damage eggs and larvae (Welcomme 1979 apud Ficke *et al.* 2007). Long droughts reduce abundance, benefit some species (usually generalists) and can displace others (more specialized) (Poff *et al.* 2001 apud Ficke *et al.* 2007; Matthews and Marsh-Matthews 2003).

Milly (2002) and Manabe (2004) both calculated the future outflow of the St. Lawrence River in quadrupled CO_2 experiments, and found a 20% and 12% increase, respectively, in annual mean simulated outflow. These results suggest an increasing net basin supply, which could increase water levels in the Great Lakes, especially Lake Ontario (Angel and Kunkel 2010). Beltaos (2002) registered dramatic increases in peak winter flows of the Saint John River, NB, produced by increasing incidence of winter days with mean air temperature above 0°C since the 1920s, plus a 1°C increase per century in mean monthly winter temperature.

Projected changes to the 30-yr mean annual stream flows and winter stream flows in 10 basins (Nelson, Churchill, North Saskatchewan, South Saskatchewan, Peace, Athabasca, Mackenzie, Yukon, Fraser, and Columbia) found increases in all regions, except for southern areas of Columbia and some parts of the South Saskatchewan basin (Poitras *et al.* 2011). The changes were connected to increasing air temperatures, increasing precipitation, increases in the frequency of extreme precipitation events, delays in the onset of snow, and early snowmelt. Although higher temperatures could lead to higher evapotranspiration, favouring decreases in runoff generation, this could be offset by more precipitation (Poitras *et al.* 2011). High latitude regions are projected to increase annual runoff by 10%-40% by mid-century under warmer temperatures (IPCC 2007).

However, most studies predict lower annual mean discharges or lower summer water levels, which may dry up headwater streams and make some perennial water bodies become intermittent (Croley 2003; Schindler and Donahue 2006). The St. Lawrence River mean annual water level declined significantly from 1919 to 2007. The discharge levels dropped nearly 3.6cm per year from 1955 to1982, but it is impossible to know how it was connected with climate, because at the same time a major shoreline alteration was made (Hudon *et al.* 2010). A reduction between 4% and 24% in annual mean discharge is expected at the Great Lakes-St. Lawrence watershed until the end of the century, mainly due to increased evaporation (Croley 2003). In some St. Lawrence tributaries, discharge is expected to decrease in spring, but the frequency of high discharges may increase in winter (Boyer *et al.* 2010a). These changes in discharge, in association with lower water level in the main river channel, are predicted to extend the sediment accumulation zones and to modify the deposition patterns in the mouth of tributaries, with possible consequences for wetlands (Boyer *et al.* 2010a). As discussed in previous sections, the lower runoff should decrease organic carbon inputs, allowing for greater UV radiation upon aquatic organisms. Aquatic habitat will decrease in extension, and species with resting life stages or rapid colonizers would be benefited. Also, if the water levels become too low, organisms can experience increasing competition, low oxygen, higher predation rates

and higher risk of disease (Welcome 1979; Ficke *et al*. 2007; Val and Almeida-Val 1995; apud Ficke *et al*. 2007).

In most Canadian rivers outside mountains, the spring snowmelt is the main water source for the maximum flow. In average, 25-50% of the total annual flow occurs during the melting of winter snow packs (Newbury and Gaboury 1993 apud Schindler 2001). Earlier ice-out and snow melt will drive peak flows to occur earlier, and ephemeral streams could dry earlier in the season. The anoxia could occur earlier in backwater pools (Kling *et al*. 2003). In North and South Saskatchewan River basins, the importance of the glacier runoff is greatest at the headwater catchments and has a diminishing influence downstream (Schindler 2001). However, the glacier is being reduced, causing decreasing annual and late summer stream flows, with stronger effects on years with little snowfall. The projected increases in precipitation may compensate, increasing spring snowmelt peak, but there will be no storage of water to maintain the flow as would happen with snowmelt. The mountain headwater basins would suffer more, with the Prairies probably being spared (Sauchyn *et al*. 2006). The IPCC (2001) projected that warmer temperatures would cause an increase in glacier contributions to stream flow in short and medium term, and decrease in the long term. However, historical stream flow and meteorological data indicate that the increased flux period has already happened, and we are currently experiencing the long term trend of declining flows. This will reduce even further the already scarce hydrological resources across a large area in Alberta and Saskatchewan (Demuth and Pietroniro 2002). The glaciers on the eastern slopes of the Rocky Mountains present strong declining trends that were present since the last century, and became stronger after the 1950's (Demuth and Pietroniro 2002; Sauchyn *et al*. 2006).

In the Western Prairie Provinces, the snow packs are no longer accumulating as much as it used to, because part of the snowfall is now coming as rain, and the snow that actually hits the ground is being subjected to periodic melts during winter. The smaller snow packs are not enough to sustain high river flows during May and June, and the earlier melt exacerbates droughts (Schindler and Donahue 2006). Over the 20th century, the declines in annual river flow were moderate, but summer flows suffered a dramatic decline: today they are 20-84% lower than about 100 years ago (Schindler and Donahue 2006). Burn *et al*. (2008) also analyzed stream flow from 1966 to 2005 in the prairies, and found decreasing trends in the snowmelt spring runoff volume and peak flow, earlier occurrence in the spring snowmelt runoff event peak date, and decreasing trends in the seasonal (1 March–31 October) runoff volume.

The causes are not only changes in precipitation, but also increasing evapotranspiration and evaporation driven by warmer temperatures (Burn *et al*. 2008). Though there is evidence that the climatic effects are the main change drivers, direct human impacts such as water withdrawals and damming also play important roles. The most affected was the South Saskatchewan River: the summer flows are now 84% lower than in the beginning of the 20th century (Schindler and Donahue 2006). The Athabasca River, that does not have much direct human interference, also had a decrease in summer flow of 30% since the 1970s, despite the increased flows from glaciers that were melting because of a warming of 2°C in mean annual air temperature in its headwaters (Schindler and Donahue 2006).

Wetlands
Wetlands are extremely sensitive to climate alterations. Warming air temperatures and changes in the frequency/intensity of extreme events can lead to changes in base flows, altered hydrology (depth and hydroperiod), stress over the wildlife, extended range and activity of pests and disease vectors, increased flooding, landslides, soil erosion, increased runoff leading to a decrease in recharge of some floodplain aquifers, decreased quantity and quality of water, and others (Kling *et al* 2003).

Permafrost thawing, changes in precipitation amount and distributions, and increasing evaporation and transpiration are drivers that alter wetland water levels. Most projections show decreases in water availability on the Prairies, which contains a large fraction of Canadian wetlands (Gan 2000; Schindler and Donahue 2006). A decrease in spring flows will lower water levels in important deltaic ecosystems. Prowse *et al*. (1996) predict lower frequency and intensity of spring floods – a process that renews the wetlands.

In places where the water level declines or becomes inconsistent, emergent and submergent plants will be replaced by formations with lower water demands, such as sedges, grasses, wet meadows, and trees (Mortsch *et al*. 2003). Annual and perennial plant species of marsh wetlands might shift their distribution in response to water level declines, but species with slow growth, like trees, may not respond fast enough. If changes are dramatic, the wetland may dry up and cease to exist (Mortsch *et al*. 2003). The in-shore side of the marsh in Presqu'ile Provincial Park (north shore of Lake Ontario) will dry out if water levels drop 1m (Taylor *et al*. 2006).

Drought and lower water levels might increase UV exposure of aquatic organisms, especially in shallow and clear water (Kling *et al*. 2003). The reduced water levels will lower the ground water supply recharge, sometimes up to the point of completely drying up streams and reducing wetland areas, or simply decreasing the water quality, shrinking the available habitat for wildlife (Kling *et al*. 2003). The Great Lakes shoreline fens are especially susceptible because they rely more on regional ground water input than on the water level of the great Lakes (Mortsch *et al*. 2003).

The warmer temperatures will increase decomposition rates, but the fluctuation in water levels coupled with warmer water can reduce the assimilation of nutrients (and human/agricultural wastes; Mastalerz *et al*. 2001; Grigal 2002). This could happen in the peatlands, which occupy 365,157km^2 in Manitoba, Saskatchewan and Alberta, and store 2.1% of global terrestrial carbon (Vitt *et al*. 2000). There is a risk that decomposition rates in that region could increase. At the same time, nutrient and heavy metal release will also be altered: there will be more soil exposed to oxygen, immobilizing mercury (because it binds with oxygen), and the activity of denitrifying bacteria on wetland soil could be reduced. However, if precipitation increases, water levels in wetlands could rise, enhancing anaerobic decay and formation and release of methane (Wrona *et al*. 2006).

Connectivity
Lower summer water levels will reduce hydrological connections and groundwater recharge, possibly causing isolation and fragmentation amongst wetland complexes (Kling *et al*. 2003). Species inhabiting intermittent freshwater systems, such as ponds and temporary wetlands, would be the most affected by a decrease in connectivity (Bouvier *et al*. 2010a). However, the projected increase in precipitation during winter and spring would provoke the opposite effects (Kling *et al*. 2003). In a scenario of increasing frequency of large flood events, as predicted by several climate models, water body connectivity is expected to increase in many systems (Museth *et al*. 2011). The ecological impact is nonetheless dependent on historical and current conditions. In some systems, increasing flood frequency may be beneficial to aquatic communities by reestablishing connectivity where it used to be limited by anthropogenic impacts, while river systems that have a natural history of less intense floods may be severally impacted by a changing climate (Poff 2002). Given the large natural variation in flooding regimes across scales and geographic regions, the ecological consequences of climate affecting connectivity should be highly system specific. Predictions are difficult, given that current climate models are not designed for regional spatial scales (Poff 2002). However, the capacity of the models in dealing with regional scales is increasing (Kienzle *et al*. 2012).

One anthropogenic factor that will probably interact with climate change to affect water level and connectivity is river impoundment. In a global analysis using a range of climate change projections, Palmer *et al.* (2008) conclude that changes in river discharge and connectivity are expected to be much more severe in dam-impacted basins. In regions with projected increase in discharge, floods might be magnified especially in catchment areas above dams, increasing the dispersal of organisms in these restricted areas. Conversely, impounded rivers that are predicted to lose water in future climate scenarios should present greater losses of aquatic habitat and connectivity then those unimpacted by dams. These differences are expected to be intensified due to water consumption in populated areas (Palmer *et al.* 2008). Another complicating factor that must be taken into account is the intensification of human interference to regulate river flows in response to increasing risk of floods. It will probably result in the construction of more dams and levees that could likely reverse the potential for climate induced increases in connectivity (Kostyack *et al.* 2011).

Perhaps more important than the overall connectivity level, is the maintenance of a gradient of connectivity levels, allowing the existence of water bodies with different hydrological regimes, environmental conditions, and successional stages to sustain a variety of species with different niches and life history strategies (Wellborn *et al.* 1996; Mims and Olden 2012). This continuum of habitat connectivity is proposed by Lesack and Marsh (2010) as a key factor for the maintenance of diversity in lake communities of a given hydrographic region. They identify two endpoints in this continuum: (i) relatively isolated lakes with shorter and more variable contact with the river and dependent on the occasional occurrence of high floods; (ii) lakes with long and less variable connection times with multiple river water resets per year. The first group, which they call the "snowflake class endpoint", is generally formed by a large number of generally small lakes with more dissimilar community composition, while the second group, which they call "cookie class endpoint", is formed by less numerous and larger lakes with high community similarity. In their study of the Mackenzie River Delta system, they predict that a future scenario of decreasing annual river peak levels and rising sea level will promote a shift towards the cookie class endpoint, with probably serious consequences for biodiversity in this system.

PRODUCTIVITY

Temperature is an important limiting factor for almost every biological rate. In general, increases in temperature are expected to positively affect primary and secondary productivities due to higher metabolism, faster reproduction, trophic transfers and turnover rates, besides prolonged growing seasons. However, the many indirect effects caused by warming can offset this potential or even lead to decreased productivity. For instance, if aquatic habitat shrinks due to drier conditions, lower or intermittent flow and reductions in water volume can diminish aquatic productivity, especially in small oligotrophic lakes (Kling *et al.* 2003). Besides obvious reductions in water availability, other indirect effects may complicate the predictions about responses of productivity to climate change, including: (i) increasing eutrophication and thermal stratification can exacerbate hypoxia for many organisms; (ii) a shift in phytoplankton composition towards toxic algae (cyanobacteria) can compromise production at higher trophic levels; (iii) changes in ice cover may decrease or increase productivity, depending on ice characteristics; (iv) increasing input of nutrients may be accompanied by increasing pollutant concentrations and water turbidity, compromising light penetration and photosynthesis; (v) although photosynthesis is benefited by increasing light penetration, it may be accompanied by increasing UV penetration, which can damage organisms and compromise production (Schindler *et al.* 1997). These and other factors are discussed below and in the next sections.

The simple input of excess nutrients (e.g. sewage discharges) can increase primary productivity or lead to eutrophication. Climate changes can accelerate both processes, or reduce recovery after eutrophication (Nicholls 1998). Although the relationship between climate change and eutrophication is complex, it is generally accepted that warmer temperatures will lead to higher lake trophic status, possibly increasing hypolimnetic oxygen depletion in productive lakes (Blumberg *et al*. 1990; Allan *et al*. 2005). The fact that oxygen saturation occurs at lower concentrations in warmer waters exacerbates this process (Stefan and Preud'homme 1993).

Schindler *et al*. (1978, Schindler 2001) showed that phytoplankton diversity increases slightly with warmer temperatures, but there were no major changes in dominance. Abundance also increased, but that could be attributed to enhanced nutrient inputs and water clarity. As primary productivity increases (which is predicted by most studies), the abundance of higher trophic levels, including herbivorous cladocerans (e.g. *Daphnia*) should also increase (Sweetman *et al*. 2008). Empirical results show that in 81 European shallow lakes, total phosphorus was the main predictor of zooplankton community structure and biomass, and climate was the second most important factor. However, benthic and plant associated taxa are more strongly related to macrophytes coverage (Gyllström *et al*. 2005)

Climate changes are also expected to alter ranges and composition of invertebrates. Species that are currently limited to southern regions due to temperature limitations are likely to move north, invading arctic freshwater systems (Wrona *et al*. 2006).

As with many other organisms, higher temperatures increase zooplankton metabolism. Warmer climate induces earlier maturation, more frequent broods, and probable greater species richness in zooplankton communities (Orcutt and Porter 1984; Stemberger *et al*. 1996). Schindler (1968) found that zooplankton feeding, assimilation growth and reproduction nearly double for an increase of 10°C in air temperature under experimental conditions. But waters with temperature of 25°C or more can cause changes in community composition, directly and indirectly favoring small body sized over the larger zooplankton species. This shift alters water transparency, nutrient regeneration rates, and probably diminishes secondary production, because smaller females usually have lower reproduction rates, and support lower biomass (Moore and Folt 1993). In turn, zooplanktivory by fishes can increase due to higher recruitment and lower winter mortality rates (Mooij and Van Nes 1998; Nyberg *et al*. 2001; Mooji *et al*. 2007).

Cyanobacteria

Cyanobacterial blooms have important ecological and economic consequences: bluegreen algae are inedible to most zooplankton species that planktivorous fishes feed upon, and some cyanobacteria species produce alkaloids that can intoxicate fishes (and humans who consume them; George *et al*. 1990; Banens and Davis 1998). However, not many studies have directly measured the freshwater cyanobacteria's responses to climate changes, and most of them were conducted on reservoirs (Reichwaldt and Ghadouani 2012). Much of the literature reports significant changes in physicochemical properties of the water system as responses to changes in rainfall, and those affect phytoplankton and zooplankton communities (Codd 2000; Bouvy *et al*. 2003). The main effects observed are: flushing, nutrient input, reduction of conductivity (especially after drought), and water mixing due to strong winds or water inflow (Reichwaldt and Ghadouani 2012). The outcomes will depend on characteristics of the changes (e.g. intensity and frequency of rainfalls), previous conditions of the water body, and land use in the catchment region (Kosten *et al*. 2011; Nõges *et al*. 2011).

Temperature increase, stronger stratification, and longer droughts are likely to lead to a higher frequency of toxic cyanobacterial blooms in the future, as they are favored by a stable and warmer water column (George *et al*. 1990; IPCC 2007*a*; Paerl and Huisman 2008; Reichwaldt and Ghadouani 2012). Evidence suggests that blooms are increasing in frequency and extension (Paerl and Huisman, 2008). There is still little information on how the predicted changes in precipitation will affect them (Reichwaldt and Ghadouani 2012).

Increases in nutrient input can be one of the consequences of higher runoff driven by increased precipitation, either by a larger number of lighter rainfalls or higher frequency of strong rainfalls. Cyanobacteria would benefit because they can adjust their buoyancy and exploit resources (light, nutrients, carbon) more efficiently (George *et al*. 1990; Paerl *et al*. 2011). Laboratory experiments suggest that at higher temperatures (17-24°C), cyanobacteria and chlorophytes should be favored, while at cooler environments (less than 14°C) diatoms should be benefitted in a wider range of nutrient conditions (Tilman *et al*. 1986). Reichwaldt and Ghadouani (2012) present a review on how cyanobacterial blooms could be affected by different scenarios: the potentially longer dry period between the rainfall events might increase stratification, which is also positive for these organisms. However, if strong rainfalls occur, a large part of the algal biomass can be flushed and the bloom may reappear after a few days, or the water layers can get mixed, and the blooms may be disrupted (Jacobsen and Simonsen 1993; Figueredo and Giani 2001; Ahn *et al*. 2002; Bouvy *et al*. 2003; Reichwaldt and Guadhouani 2012). Intense rainfalls can also increase the turbidity of the water due to sediment and dissolved organic carbon (DOC) input (Figueredo and Giani 2001; Ahn *et al*. 2002). Besides this, cyanobacterial toxin concentrations may rise, either because of increased cyanobacterial biomass, or because favorable growth conditions can lead to increased toxin production rates. Once again, the outcomes depend on precipitation patterns; although turbidity generally benefits cyanobacteria, low light penetration after storms can favor non-toxic strains, or even non cyanobacterial species (Bouvy *et al*. 2003; Paerl *et al*. 2011). One of the consequences of very strong rainfalls is the temporarily absence of cyanobacterial dominance, which in the short term can lead to decreased total chlorophyll biomass, with higher diversity (Bouvy *et al*. 1999). Later, the increasing nutrient input due to higher runoff should favor cyanobacteria once more. In their review, Reichwaldt and Ghandouana (2012) present evidence that the input of inorganic nutrients can lead to blooms dominated by toxic strains. The impacts of changes in precipitation patterns on cyanobacteria are very complex, and will be strongly dependent on the species involved and the site characteristics.

Mooji *et al*. (2007) predict that climate warming will lead to lower critical nutrient loadings in lakes, because of an increased phytoplankton growth rate and higher P availability due to higher release and mineralization resulting from higher temperatures. The most benefited would be cyanobacteria, because it responds faster to temperature increases and has high P affinity. The lakes will have an increasing tendency to become turbid, and the water quality will decrease. The poor edibility of cyanobacteria makes this a bad scenario for higher trophic levels (Mooji *et al*. 2007). Shallow lakes should be the most affected by warmer temperatures. Amongst other details, their models assume that winter net precipitation (especially frequency of extreme rainfalls) will increase, bringing higher P contents into lakes, and that internal nutrient loading will increase with temperature. Their results are in accordance with other predictions that the effects of climate change may mimic those of eutrophication (Kilham *et al*. 1996; Porter *et al*.1996; Shimoda *et al*. 2011).

Effects of ice on productivity
Ice cover has mixed effects on plankton. If the ice is covered by snow, which is the case in most of north temperate North America and Europe, the Photosynthetically Active Radiation

(PAR) can be much reduced, inhibiting photosynthesis, and the phytoplankton is then replaced by heterotrophic phlagellates (Rodhe 1955 and Wright 1964 apud Vanderploeg *et al* 1992; Allen 1969; Bolsenga and Vanderploeg 1992). The reduction in photosynthesis combined with respiratory demands from the sediment can lead shallow eutrophic lakes into anoxia, killing fishes (Greenbank 1945).

If the ice is clear, it can encourage spring blooms, because it permits light to penetrate in the water, increasing phytoplankton bloom, while preventing water mixing by wind (which could remove the algae from the photic zone). On its turn, this will encourage a zooplankton bloom. Because many freshwater calanoid copepods are active and reproducing during the winter and spring, the ice cover can increase their success, by facilitating the occurrence of spring blooms (Vanderploeg *et al*. 1992). This can affect directly the survival of larval whitefish, which depend on copepods as their main food source in April and May (Taylor *et al*. 1987). Vanderploeg *et al*. (1992) hypothesize that if ice is clear, than it will benefit larval recruitment, but if ice is white or covered by snow, it will be detrimental since it can reduce the PAR to less than 10% (Bolsenga and Vanderploeg 1992). They suggest that more studies are necessary to understand the role of winter to the annual production cycle.

Vanderploeg *et al*. (1992) studied the Grand Traverse Bay, on Lake Michigan during the winter ice-cover period, and registered a winter-spring phytoplankton bloom in the upper 40m. This led to an increase of 4 to 7-fold in feeding rate of *Diaptomus*, increasing egg production. After the ice melted, high algal concentration and intense zooplankton feeding persisted. The ice on the lake was clear, as may be common in large lakes and bays, due to strong winds blowing the snow off the ice, or in low latitudes, where rain and higher temperatures cause snowmelt. It may be an important process, since winter calanoid copepods use these blooms to enhance their reproductive rates (Vanderploeg *et al*. 1992).

Reductions in the ice cover can lead also to increasing P concentrations and facilitating eutrophication, which has been observed in the Great Lakes (Nicholls 1998). However, less ice means more open water surface, increasing DO concentrations (Prowse and Beltaos 2002; Wrona *et al*. 2006). A longer ice-free period coupled with warmer maximum summer water temperature can also increase algal productivity. The most sensitive ecosystems to this process are lakes moderate in area, depth and nutrient concentration (Kling *et al*. 2003). Changes in the distribution of productivity across the water column may also occur. Records from 50 lakes in the central Canadian Artic treeline region suggest that shorter ice cover duration, coupled with longer growing season and/or thermal stability were responsible for the observed shifts from benthic to planktonic diatom taxa (Ruhland *et al*. 2003; Smol *et al*. 2005; Sweetman *et al*. 2008).

Lakes
Empirical studies suggest that total productivity might increase in lakes due to temperature increases, and DO concentrations may decrease (Blumberg and Di Toro 1990; Regier *et al*. 1990). However, because there is no consensus on the future cloud cover conditions, there is also no certainty in productivity forecasts (Dickinson 1989). Intensification in cloud cover can be fatal for deep water algae in oligo and mesotrophic lakes during summer stratification (Carpenter *et al*. 1992). At this depth, they are provided with enough nutrients, but suffer grazing pressures, low temperatures and low Photosynthetic Available Radiation. The stronger stratification enhances the importance of metalimnion for phytoplankton (Carpenter *et al*. 1992). In this scenario, photosynthesis would be limited to shallow and nutrient poor waters, reducing primary productivity by a factor of 2 or 3 (Carpenter *et al*. 1992). Deep and oligotrophic lakes, (such as Lake Ontario) are the most vulnerable to this kind of impact (Magnuson 2002 apud Ficke *et al*. 2007; Kling *et al*. 2003).

Shimoda *et al.* (2011) made an extensive review of changes in phytoplankton dynamics due to climate changes in north temperate deep lakes. Models and empirical data agree that spring phytoplankton blooms are occurring earlier in response to increasing temperature trends. Spring phytoplankton blooms have advanced between 1-2 weeks, considering a large number of lakes in North America and Europe and a variety of historical records. Their numerical experiments suggest that earlier stratification onset will lead to a mean of 10 days advance in spring phytoplankton bloom in north deep temperate lakes (Shimoda *et al.* 2011). It can cause a mismatch between the timing of the phytoplankton spring peak and the zooplankton spring peak, leading to decreasing grazing pressure over phytoplankton, preventing a great fraction of primary productivity (Winder and Schindler 2004). However, this has just been described in deep lakes, and is related to stratification patterns; therefore, it might not occur in shallow water bodies (Mooji *et al.* 2007).

Twenty years of climatic, ecological and hydrologic data (1970-1990) from the Experimental Lakes Area showed that air and lake temperature increased about 2°C, and was accompanied by deepening in thermoclines. A 3 week reduction in ice cover duration, and lower precipitation leading to lower water renewal rates, caused increased chemical concentrations in lakes and streams, and increased transparency. In Lake 239, the phytoplankton community responded to those changes with an increase in diversity and populations, but there was no clear trend in primary productivity (Schindler *et al.* 1990).

If precipitation rises along with temperature, enough to increase runoff, there will be a greater input of organic matter and nutrients into water bodies. This can be enhanced by the thawing of the permafrost, as discussed before. On the other hand, a very high load of organic matter can create turbidity, especially in lakes and ponds, limiting photosynthesis and diminishing primary productivity (Wrona *et al.* 2006). It can also decrease oxygen levels, compromising secondary productivity, especially fish stocks (George *et al.* 1990; Schindler *et al.* 1990; Carpenter *et al.* 1992; Paerl and Huisman 2008). It must be noted also that increased runoff, instead of simply increasing the input of nutrients, could also increase the flushing of pollutants into the system, or could dilute nutrients and contaminants (Carpenter *et al.* 1992; Magnuson 2002 apud Ficke *et al.* 2007). Mooji *et al.* (2007) notes that high P loading may be diluted by increased precipitation. Higher internal loading might be temporary, and higher cyanobacterial growth can be controlled by wind disturbance and increased cloud cover (Howard and Easthope 2002). If precipitation decreases, declining water flows will simultaneously cause a reduction in nutrient input and an increase in nutrients residence time, counterbalancing each other effects, especially in lakes (Schindler *et al.* 1996a; Bertahas *et al.* 2006).

Responses and effects of aquatic vegetation can also be variable. In some cases, macrophyte response may be explosive: an increase of 2-3°C was found to cause a 300-500% increase in shoot biomass of *Elodea Canadensis* (Kankaala *et al.* 2002). Their presence can contribute to keep lakes clear (Rooney and Kalff 2000; Kankaala *et al.* 2002). However, when this large amount of macrophytes or algae die, bacterial and fungal decomposition will grow and decrease the oxygen levels, which can lead to system hypoxia (Ficke *et al.* 2007). Also, the macrophytes can trap sediment, and prevent nutrient flushing, leading the system to eutrophication. If they are emergent, with large rafts, their presence can also reduce wind mixing, increasing stratification, and reducing oxygen levels in deeper water layers (Welcomme 1979 in Ficke *et al.* 2007). An exaggerated amount of macrophytes can reduce fish habitat (Ficke *et al.* 2007). On the other hand, experiments suggest that a moderate warming can leave macrophytes largely unaffected (McKee *et al.* 2002). Outdoor microcosm studies found only subtle effects of increased temperatures (even combined with increased nutrient inputs) over

clear state macrophyte dominated lakes, although there was some trends in water chemistry that support the idea of a moderate warming causing an increased eutrophication effect (McKee *et al.* 2002). In the long term, this could destabilize macrophytes, leading the clear lake into a turbid state (Mooij *et al.* 2005)

The projected increase in dissolved organic carbon (DOC) will probably enhance primary productivity and carbon fixation, which may reduce CO_2 emissions from lake waters to atmosphere. This effect is not expected from nutrient loading in high latitude rivers due to the rapid renewal rates of those waters (Wrona *et al.* 2006).

Rivers and streams
In some cases, stream productivity is also subjected to flood influence (Carpenter *et al.* 1992). When storms alter the hyporheic volume, the photosynthesis/respiration ratio can increase, turning a system from an organic matter processor into an organic matter exporter (Fisher 1990; Carpenter *et al.* 1992).

In UK streams, for every 1°C increase in temperature, spring macroinvertebrate abundance might suffer a reduction by 21%. If temperature increases by 3°C, many species would be spared, but 4-10 most scarce taxa (performing 5-12% of the species) could disappear locally (Durance and Ormerod 2007). Although acidification has usually stronger impacts on macroinvertebrates, reducing species richness and simplifying communities, climate changes can intensify those effects and delay recovery (Durance and Ormerod 2007).

As it was observed in Mediterranean regions of California, changes in precipitation may also change invertebrates community composition, since species have different tolerances to high and low water flow, (Beche and Resh 2007; Ormerod 2009). Spring invertebrate abundance has been reduced in some European headwaters, and some cold or cool water species were locally lost, in a fashion similar to the one observed in European lakes after temperatures rose (Burgmer *et al.* 2007; Durance and Ormerod 2007)

Another potential source of impacts by climate changes comes from studies that indicate that leaves grown under high concentrations of CO_2 have lower nutritional value (Lindroth *et al.* 2001). Because leaves are a major source of energy and nutrients for many freshwater systems (especially streams), this could cause significant damage to food chains (Kling *et al.* 2003).

Wetlands
Because wetlands are mainly anaerobic, they present much lower rates of decomposition compared to aerobic systems. Since productivity usually surpasses decomposition, organic matter accumulates, and wetlands act as a carbon sink. Longer growing seasons due to warmer temperatures can increase the productivity even more, if the region does not suffer water declines (Kling *et al.* 2003; Wrona *et al.* 2006).

Rapid land use changes, deterioration of riparian vegetation and wetlands, and an increase in discharges of human, animal, and agricultural wastes, will all increase the nutrients in water bodies, especially in the Western Prairie Provinces (Schindler and Donahue 2006). The forecasted decrease in water flow will increase water retention time, increasing the nutrients concentration even more, leading to greater algal blooms (Schinder and Donahue 2006). Warmer waters, with reduced ice cover and less sport fishes will aggravate eutrophication problems and benefit cyanobacteria (Schindler and Donahue 2006).

GAPS IN KNOWLEDGE

AVAILABLE DATA

In order to make good prediction models, it is necessary to have good quality long term historic data. Nevertheless, this data is not available for many regions. One of the main aspects to be considered is stream flow, and there has been a decline in the amount on stream flow data being collected. Mishra and Coulibaly (2010) reported that nearly all Canadian main watersheds present deficient hydrometric networks, and the poorest ones are in Alberta (North Saskatchewan, Oldman, and Red Deer basins), Northern Ontario (Hudson Bay basin), and the Northwest Territories. Insufficient funding, inadequate institutional frameworks, a lack of appreciation of the worth of long term hydrological data are the most common reasons for closure of monitoring stations. The update of those networks could provide important data for management decisions concerning water resources (Mishra and Coulibaly 2010).

A similar situation affects historical data gathering on weather, snowpack, water quality and quantity. Governmental agencies entitled to monitor environmental changes and enforce laws of freshwater protection have been suffering severe funding cuts (Schindler and Donahue 2006). Therefore, in a moment where the impacts are aggravating, our ability to monitor, forecast and manage impacts is being impaired by the incompleteness or inexistence of historic data (Mishra and Coulibaly 2010). Research stations that have provided good quality data for decades are not safe from interruption or even closure. This is the case of the Experimental Lakes Area (ELA), which is planned to be shut down.

Most of the studies over the region of interest are concentrated on the Great Lakes. The Saint Lawrence River is especially deprived of research concerning climate changes, and so are the wetlands in general. Johnson *et al.* (2005) highlight that:

> No geographically extensive analyses of the quantitative relationships between climate and prairie wetland structure and function have been conducted for the Prairie Potholes Region. Most of the research progress in prairie wetland ecology has come from intensively studied but geographically restricted sites. The broader extra site patterns have not been determined.

This lack of knowledge does not reflect the huge importance of wetlands for productivity, diversity maintenance and ecosystem services (Bouvier *et al.* 2009).

Because lakes, rivers, streams, and wetlands respond differently to the same set of conditions, it is necessary to gather more information on those systems that have so far being neglected. Differences in hydrology, land use, and aquatic biota, can all interfere with outcomes of climatic changes. We still do not understand how the climate changes will interact with other anthropic impacts, such as nutrients and toxic inputs, acidification, and biological invasions. Most likely, the consequences will be cumulative or synergistic (Wrona *et al.* 2006). Several other factors, such as Albedo (ice reflectivity), vegetation, oceans, soil, and atmospheric gases, all interact creating positive or negative feedback loops, which impairs even further our abilities to forecast future consequences of climate change (Davies and Simonovic 2005). Despite the huge importance of understanding these feedbacks, quantifying or even identifying them, persists as a great challenge. Therefore, much research is still needed on the long term and simultaneous measurement of these many environmental factors, as well as on theoretical investigations on how these factors are expected to interact. Below are some of them main gaps in knowledge for the areas we are studying.

Connectivity

Connectivity among aquatic systems is another challenging factor. Knowing connectivity is crucial to integrating changes in local ecosystems to larger spatial and temporal scales (e.g. to metacommunities and regional biota). So far, generic inferences about climate change effects on connectivity have been made on the basis of available information on changes in hydrology and water level, but specific predictions about connectivity and dispersal of organisms in known systems are still lacking. This lack of information can be partially explained by methodological difficulties, given that suitable indices of system-wide connectivity have been only recently developed (Cote *et al.* 2009; Fullerton *et al.* 2010; Eros *et al.* 2012).

water temperature

There is little historical data on water temperature for systems other than lakes. For wetlands, there is nearly nothing specifically about water temperature; only general aspects and possible consequences of climate change. No quantitative estimations for water temperature increases were found for the wetlands in the region of interest.

Water Chemistry

Most of the possible changes discussed on the water chemistry session are directly dependent on precipitation regimes. Until now, the predictions about precipitation are far from conclusive, and therefore, we cannot access which of the many possible scenarios best represent the future.

Even if the predictions on precipitation and temperature changes were accurate, we are still not sure about how DOC concentrations will respond to them.

Although there are abundant examples of interactions between temperature, discharge and chemical changes in freshwater systems, they are still poorly quantified (Ormerod 2009).

In lakes, the changes in water chemistry are influenced by many factors such as basin size, morphometry, water regime, extent of wetlands in the basin, and groundwater flows (Schindler 2001). This makes it difficult to extrapolate results from one location to another.

Many of the effects of climate change are counter intuitive, therefore, they can only be accessed through long term observations (e.g. lakes becoming alkaline at the same region where streams were going through acidification, or the many different responses of productivity to temperature and precipitation changes; Schindler 1997). Unfortunately, information about these effects is not always available.

There is very little information about water chemistry of systems other than lakes, especially for the region of interest.

Ice Cover

Ice cover has little predictability due to its high variability. Ice cover standard deviations are larger than the climatological means for each of the Great Lakes (Wang *et al.* 2012). To further complicate the issue, other factors affecting ice formation must be accounted for, like morphological features of the water body, snow cover, wind speed, cloud cover, plus other human impacts such as discharges from power plants.

There is not much available information regarding ice cover for other freshwater systems other than lakes in Canada, and the few that exist are generally focused on the Artic regions. Canadian rivers and streams do not present enough information to permit an overview of current ice trends and future climate change impacts over ice dynamics. The Saint Lawrence River is especially deprived of research concerning climate changes.

Ice break up jams and freeze up jams are a concern. Although there is a clear relation between these occurrences and the climate factors (e.g. abundant rainfall, increasing the runoff, and great amounts of frazil slush via cold weather), it is not yet possible to undoubtedly link these events to climate changes. It will probably be 20 more years before it is possible to reevaluate the question (Beltaos and Prowse 2009).

Water Level

Water levels are difficult to predict for many of the same reasons that complicate other impacts:

(1) Reliable long term datasets are not always available, especially for freshwater systems other than lakes.
(2) Other complicating factors can interfere with the final results, like increasing water demand by human population, industries and agriculture. Changes in water quality and abundance can lead to different allocation of hydrological resources, sometimes resulting in droughts that are not necessarily related to climate changes (Covich *et al*. 1997)
(3) The path of future CO_2 (and other gases) emissions is still unknown
(4) Different GCMs provide variable results, with varying initial conditions, and so far we have no means to access their accuracy when it comes to predicting future trends (Angel and Kunkel 2010).

In order to identify trends, it is necessary to have reliable historic data. With few exceptions, the records of water levels in Canadian Prairie wetlands registered since the 1960s were not referenced to stable benchmarks. This prevents the identification of long term trends in the elevation of the wetland bottom, which can be a problem, since sedimentation can amount to over 10cm in 30-40 years, as is happening to the Canadian Prairies wetlands (Conly *et al*. 2004).

There is nearly no information available on how climate changes will affect the connectivity between freshwater systems in Canada, and even less for the region of interest.

Productivity

The lack of a clear trend in the effects of climate changes over productivity, and the many expected indirect effects previously discussed, show that the relationship between them is complex. There is scarce information specific on climate changes effects on productivity for the area of interest, and most of what is available is focused on lakes.

Most studies on cyanobacterial blooms were conducted in reservoirs (Reichwaldt and Ghadouani 2012). Therefore, there is little information to support predictions on natural systems. It is important to identify spatial dynamics of blooms within a system after precipitation, because it will allow the development of better management plans to prevent blooms (Reichwaldt and Ghadouani 2012). The interactions leading to increasing toxin concentrations in freshwater systems are still not clear; neither are the impacts of precipitation changes over those interactions. Therefore, predictions about changes concerning toxicity are vague (Reichwaldt and Ghadouani 2012).

Although many impacts have been well documented, we still lack quantitative knowledge on how they will interact with each other. As an example, it is well accepted that climate change will lead to increased productivity in many water bodies, but it is unknown how this will interact with enhanced UV penetration, acidification, pollution, and other impacts (Ficke *et al*. 2007; Sweetman *et al*. 2008).

Shifts in diatom communities are relatively well documented, but higher taxa (e.g. cladocerans) did not receive much attention, so their responses to climate change are still reasonably unknown (Sweetman *et al.* 2008).

The effects of changes in precipitation, temperature and ice cover have very mixed effects over phytoplankton and zooplankton, and are highly dependent on a series of variables, such as previous state of the water body, land use, physicochemical characteristics of each ecosystem, and others. Also, the interactions between the various changes (e.g. increased temperature and increased UV penetration in the water) can produce unexpected results, further complicating the forecasts.

Although there is a reasonable agreement that primary productivity will increase with climate changes, responses of higher trophic levels are much more variable, complex and unpredictable than in algal communities (Beisner *et al.* 1997; Rouse *et al.* 1997; Sweetman *et al.* 2008). As pointed out by Sweetman *et al.* (2008), "*understanding the responses of organisms at multiple trophic levels will be essential for a holistic understanding of the impacts of climate warming on freshwater ecosystems*".

General Circulation Models
It is generally assumed that General Circulation Models (GCMs) produce reliable climate representations at global scales, but have limited ability to simulate regional climate, but methods for downscaling are improving (Melak *et al.* 1997; Evans and Schreider 2002; Ficke *et al.* 2007; Kienzle *et al.* 2012). Chen (2011), in concordance with IPCC (2007), advises that the focus of future studies of climate changes, extreme weather, as well as models based on future simulations of global warming, should be regional.

However, some uncertainties about the modeling still remain. Poulin *et al.* (2011) defends that "*the impact of hydrological model structure uncertainty is more significant than the effect of parameter uncertainty, under recent past climate as well as future climate conditions*"; therefore, the use of hydrological models with varying complexity levels should be considered part of the global uncertainty related to hydrological model structure. One additional difficulty on forecasting impacts of climate changes is that, due to regional differences, no uniform ecosystem impacts deriving from trends in warming temperatures and precipitation were found across the whole North America (Millet *et al.* 2009). Also, there is still little agreement on direction and magnitude of historical data of evapotranspiration trends, and even less on predictions (Barnett *et al.* 2005).

Finally, there should be more communication between those who develop the climate change models and those who use it (Clair 1998). Carpenter's (1992) criticism still holds true: "*Aquatic ecologists and climatologists must adjust their research to a common scale. Aquatic ecologists must reinvigorate research at landscape and watershed scales, breaching the walls that divide hydrology, wetland ecology, stream ecology, and limnology. We need mesoscale climate models capable of translating global scenarios to ecosystem scales and accommodating effects of freshwaters on climate. Models that account for effects of precipitation, plant responses to CO$_2$, vegetation change, and soil change on runoff are also needed*". It is followed by Chen (2011), who also argues for a more regional assessment of future climate change and impacts of extreme weather events.

CONCLUSION

There is a large consensus that climate is changing in Canada and in other parts of the world, and that the changes and associated consequences will be likely aggravated in the near future. The predictability of climate change effects on aquatic ecosystems in Canada is highly scale-dependent though. Such dependency is due to three main factors: (i) availability of long-term historic data; (ii) emphasis of climate models on the large (global) scale; (iii) a strengthening at the local scale of interdependencies between the many processes determining ecosystem dynamics and structure. Processes varying at the broad scale, and for which qualitative predictions are the most consistent, include increases in mean air and water surface temperature, increasing evaporation, decreasing snow and ice cover, and changes in the timing of seasonal events such as earlier ice break up, snow melt, and thermal stratification, as well as later freeze up dates. Among broad scale changes in the biotic component, range expansion of warmwater species and range contraction of coldwater species northwards are the most noticeable. Forecasts concerning changes in precipitation are less certain and should vary at a more regional scale. The prairies and wetland ecosystems will be especially sensible and dependent on whether increasing evaporation will be balanced or not by changes in precipitation and/or water discharges. Changes in hydrological regimes, including water level and streamflow, will depend on a number of other factors, such as precipitation itself, evaporation, snowmelt, and how they interact. Associated with variations in soil composition, relieve, land use and other anthropogenic factors, these series of relatively unpredictable changes in hydrology will cascade down to the local scale and determine many important ecosystem features, such as strength and depth of thermal stratification, water transparency, chemistry and contamination, which in turn will determine primary productivity and mediate species interactions within the aquatic environment. Predicting these ecosystem responses, which are important from the management perspective, will require more long-term data monitoring programs and models that emphasize regional and local scale processes, besides a better integration of knowledge between climatologists, hydrologists, and ecologists.

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