Climate Change Vulnerability Assessment for Inland Aquatic Ecosystems in the Great Lakes Basin, Ontario
Climate change will affect all MNRF programs and the natural resources for which it has responsibility. This strategy confirms MNRF’s commitment to the Ontario government’s climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011–2014 period.

**Theme 1: Understand Climate Change**
MNRF will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:
- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

**Theme 2: Mitigate Climate Change**
MNRF will reduce greenhouse gas emissions in support of Ontario’s greenhouse gas emission reduction goals. Strategies:
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario’s resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

**Theme 3: Help Ontarians Adapt**
MNRF will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:
- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.
Climate Change Vulnerability Assessment for Inland Aquatic Ecosystems in the Great Lakes Basin, Ontario

Cindy Chu

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Cover photo: Example of a dried out creek, Cindy Chu.

Cite this report as:
Summary

Climate change is impacting aquatic ecosystems in the Great Lakes Basin (GLB). Surface water temperatures of the Great Lakes, inland lakes and streams are on the rise, water levels are in decline, and the composition of plant and animal communities in wetlands are changing. The objectives of this study were to assess the vulnerability of different indicators; wetland vulnerability to drying, wetland bird species habitat, stream temperatures, stream thermal habitat, inland lake surface temperatures, and walleye biomass, to inform the development of a climate change adaptation strategy for aquatic ecosystems within the GLB of Ontario. Climate models forecast a 4 to 6°C warming of mean annual air temperatures and regional changes in precipitation by the end of the century.

With changing climate conditions, wetlands located in the southern part of the GLB, and much of the eastern region of the Lake Superior basin and southern Ontario may be most vulnerable to drying. This may have significant impacts on the habitat available for wetland-dependent bird species. Maximum weekly average stream temperatures currently range from 13.2°C in the Lake Superior basin to 32.0°C in the Lake Erie basin. Temperatures may warm most in streams of the Upper St. Lawrence basin with average increases of 1.3°C or 2.4°C under the B1 scenario and A2 scenario, respectively. Stream temperatures in Lake Ontario will warm the least, with average increases of 0.9°C to 1.4°C. These changes may decrease coldwater habitat but increase coolwater habitat for fishes in streams throughout the GLB. Currently, maximum surface temperatures of lakes in the GLB range from 18.6°C to 27.4°C. By the 2080s under the A2 scenario, lakes in the southern portion of the basin may warm by 6°C to 14°C whereas lakes in the northern portion of the basin may warm by <9°C. Walleye biomass (kg·ha⁻¹) will not be significantly impacted by projected changes in climate, although some lakes in the Lake Ontario and Upper St. Lawrence basins may see declines of 10–15% by the 2050s and 2080s. Based on these six indicators, the Upper St. Lawrence basin may be the most impacted by climate change, followed by the Lake Erie, Lake Ontario, Lake Superior, and Lake Huron basins. Indicator responses varied among basins, which suggests that planning and management strategies should differ among basins. The results presented in this report do not include the potential impacts of anthropogenic stressors such as water withdrawals, stream regulation, and/or pollution, which may exacerbate the changes in quality and quantity of aquatic habitats. Monitoring and adaptation recommendations are proposed given the anticipated changes in the indicators and the current level of monitoring and research throughout the GLB.

Rèsumé


Compte tenu des changements climatiques, les milieux humides situés dans la partie sud du BGL, ainsi la bonne partie de la région orientale du bassin du lac Supérieur et le Sud de l’Ontario, sont les
plus susceptibles à un dessèchement. Ceci peut avoir une incidence sur l'habitat disponible pour des espèces d’oiseaux de milieux humides. Les températures moyennes hebdomadaires maximales de l'eau varient actuellement entre 13,2°C, dans le bassin du lac Supérieur, et 32,0°C, dans le bassin du lac Érié. Les températures pourraient augmenter le plus dans les cours d’eau du bassin supérieur du fleuve Saint Laurent, avec des hausses moyennes de 1,3°C ou 2,4°C selon le scénario B1 et le scénario A2, respectivement. Les températures de l’eau du lac Ontario augmenteront le moins, avec des hausses moyennes de 0,9°C à 1,4°C. Ces changements pourraient réduire la superficie de l'habitat d'eaux froides, mais augmenter celle de l'habitat d'eaux tempérées pour les poissons des cours d’eau de tout le bassin des Grands Lacs. Actuellement, les températures maximales de surface des lacs du BGL varient entre 18,6°C et 27,4°C. D’ici les années 2080, selon le scénario A2, la température des lacs du sud du bassin pourrait augmenter de 6°C à 14°C, tandis que celle des lacs dans le nord du bassin pourrait augmenter, au plus, de 9°C. La biomasse du doré jaune (kg·ha⁻¹) ne sera pas touchée de manière considérable par les changements climatiques prévus, même si elle devrait connaître une diminution de 10 à 15% dans quelques uns des lacs du bassin du lac Ontario et du bassin supérieur du fleuve Saint Laurent d’ici les années 2050 et 2080. Selon ces six indicateurs, le bassin supérieur du fleuve Saint Laurent pourrait être le plus touché par le changement climatique, suivi des bassins du lac Érié, du lac Ontario, du lac Supérieur et du lac Huron. La réaction aux indicateurs variait d’un bassin à l’autre, ce qui donne à penser que des stratégies de planification et de gestion propres à chaque bassin doivent être élaborées. Les résultats présentés dans ce rapport ne prennent pas en compte les incidences éventuelles des facteurs d’agression d’origine anthropique tels que les prélèvements d’eau, la régulation d’un cours d’eau ou la pollution, ce qui risque d’aggraver les changements au nombre d’habitats aquatiques et à leur qualité. Des recommandations sont également formulées en matière de surveillance et d’adaptation compte tenu des changements prévus aux indicateurs et du niveau actuel de surveillance et de recherche menées dans tout le BGL.

Acknowledgements

This study was made possible by funding from the Ontario Ministry of Natural Resources and Forestry Climate Change Office. The author thanks Nigel Lester who provided the walleye biomass model and input data, and reviewed a draft report, and Lyn Thompson for editorial and communications support. Gary Nielsen and Jenny Gleeson coordinated the Great Lakes Basin Climate Change Vulnerability Assessment.
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Introduction

Climate change is impacting aquatic ecosystems around the world. Permafrost is melting in peatlands, water temperatures in streams (all flowing waters) and lakes are warming, and species ranges are shifting (Parish et al. 2008; Durance and Ormerod 2007; Schneider and Hook 2010; Alofs et al. 2014). In the Great Lakes region, projected declines in water levels are expected to change the water budgets of wetlands, and alter the distribution and abundance of wetland vegetation, birds, and fish communities (Mortsch et al. 2006).

Warmer stream temperatures may provide more suitable habitat for warmwater species during the ice-free season but may limit the distribution of other species that prefer cooler temperatures (Chu et al. 2008). Climate change may also alter the timing of the spring freshet, affect groundwater dynamics, and disrupt annual stream flow patterns (Mohseni et al. 2003). Observed long-term warming has resulted in changes in stream community dynamics and species distributions (Durance and Ormerod 2007).

In inland lakes, higher air temperatures and reduced spring winds could lead to overall reductions in lake volume, warmer surface water temperatures, shallower thermoclines in stratified lakes, longer ice-free periods, increased growing seasons and greater risks of hypoxia (Dove et al. 2011). Between 1968 and 2002, mean annual air temperatures surrounding lakes Huron, Ontario, and Erie warmed an average rate of 0.037° C·y⁻¹, resulting in a cumulative warming of 1.3°C. As a consequence, August surface water temperatures in lakes Huron and Ontario rose 2.9°C and 1.6°C, respectively since 1968 (Dobiesz and Lester 2009). These changes coupled with decreasing lake levels in recent years (IJC 2014) mean significant habitat changes for resident biota.

Given the observed and potential influences of climate change on Great Lakes ecosystems, and the importance of the lakes to the livelihoods of coastal Great Lakes communities, Climate change impacts have been included as an annex of the recently ratified 2012 Great Lakes Water Quality Agreement. While there is widespread agreement of the need to recognize and prepare for climate change, and to develop and integrate risk management strategies into current and new programs, climate-sensitive adaptive processes are only now being designed and tested. These include an assessment of readiness and capacity to respond (e.g., assess organizational readiness and where necessary improve the capacity to respond), followed by vulnerability assessments to identify and prioritize adaptation needs, develop adaptation strategies and monitoring programs, and to measure adaptation success (Gleeson et al. 2011).

One such adaptation program implemented at the federal level by Fisheries and Oceans is the Aquatic Climate Change Adaptation Services Program (2011-2016). This program focuses on adaptation and delivery of Fisheries and Oceans’ mandated areas of responsibility for protecting ecosystem resources, providing emergency response, and maintaining infrastructure and navigable waterways (CSAS 2013). Delivery of this program involves risk assessments for different freshwater and marine ecosystems. In 2012, a risk assessment was conducted for the Freshwater Large Aquatic Basin, which included the Prairies area (Nelson River — Lake Winnipeg Canadian Drainage) and Great Lakes Basin. In this assessment, experts identified six key threats from climate change: altered species distribution and composition; increased habitat and food availability for some species (warm and coolwater fishes); loss of important, essential, and critical habitats; smaller size-at-age for fishes; increased loading of contaminants and nutrients; increased health and safety issues, and increased length of season and demand for services (CSAS 2013). The results suggested that the biological risks as opposed to infrastructure or emergency response risks, posed the greatest risk to Fisheries and Oceans, but further integration with socio-economic and policy assessment were required.
At the provincial level, a Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Great Lakes Basin (GLB) was commissioned as part of the Ministry of Natural Resources and Forestry commitments under the Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health, 2014. It highlights the biological and ecological risks associated with climate change in the GLB. Following the vulnerability and adaptive management process (Gleeson et al. 2011), the main objective of this study was to identify vulnerability indicators for wetland, stream and lake ecosystems to quantify the sensitivity of each system to climate change, and inform an adaptive strategic planning process.

Methods

Study area

The GLB of Ontario spans an area of 230,000 km² and drains into lakes Superior, Huron, Erie, and Ontario (Figure 1). It is part of the Ontario Shield and Mixedwood Plains terrestrial ecozones (Crins et al. 2009). Mean annual air temperature ranges from 9.1°C in the south to 0.5°C in the north. Southern inland lakes and streams flow through urban areas, agricultural lands, and mixed forests underlain by till, glaciolacustrine, and glaciofluvial geology (Crins et al. 2009). Northern streams and inland lakes flow through coniferous forests and are underlain by Precambrian bedrock of the Canadian Shield (Magnuson et al. 1997; Crins et al. 2009). In order to assess regional differences, the indicator results were summarized by each lake basin (Figure 1). These basins range from 22,460 km² to 90,740 km². Climate change models project that air temperatures will increase from 4 to 6°C across the GLB with regional changes in precipitation by the end of the century (McKenney et al. 2010).

Figure 1. Great Lakes Basin of Ontario, subdivided into the major basins; Lake Superior, Lake Huron, Lake Erie, Lake Ontario, and the Upper St. Lawrence River.
Indicators of vulnerability

The potential impacts of climate change on the wetland, stream, and lake ecosystems of the GLB were evaluated using six indicators: wetland vulnerability to drying, wetland-dependent bird habitat, stream temperature, thermal habitat in streams, surface temperatures of inland lakes, and inland lake walleye (Sander vitreus) biomass (Table 1). Existing empirical models were used to relate the ecosystem indicators to climate. Current climate conditions were estimated using the 1971–2000 climate normals (McKenney et al. 2010). Future conditions were projected using ensemble estimates of air temperature and precipitation under the A2 and B1 emissions scenarios for the 2011–2040, 2041–2070, and 2071–2100 time periods hereafter, the 2020s, 2050s, and 2080s, respectively. The ensemble estimates represented air temperature and precipitation changes predicted from the Canadian Coupled Global Climate Model 3 (CGCM-3), U.S. National Center for Atmospheric Research (NRCAR-3) model, Japanese Model for Interdisciplinary Research on Climate (MIROC32) and Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) models, and has been endorsed by the Intergovernmental Panel on Climate Change (IPCC 2007; Lalonde et al. 2012). B1 scenarios represent an environmentally focused future with lower emission levels than the A2 scenarios in which high emission levels are driven by rapid economic development (IPCC 2007). Maximum annual, mean July air temperature, growing season mean, and total precipitation in the growing season were used to project the changes in the indicators (McKenney et al. 2010; Lalonde et al. 2012).

Table 1: Vulnerability indicators used to assess the potential impacts of climate change on the wetlands, streams, and inland lakes of the Great Lakes Basin, Ontario.

<table>
<thead>
<tr>
<th>Aquatic habitat</th>
<th>Vulnerability indicator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetlands</td>
<td>Wetland vulnerability</td>
<td>Vulnerability of wetlands to shrinkage or drying based on groundwater inflows and projected changes in precipitation and air temperature</td>
</tr>
<tr>
<td></td>
<td>Wetland bird habitats. Species: American coot (Fulica americana) and Pied-billed grebe (Podilymbus podiceps)</td>
<td>Hydrological Vulnerability Index (Mortsch et al. 2006) used to identify wetland dependent birds and assess changes in their distributions based on wetland extent indicator</td>
</tr>
<tr>
<td>Streams</td>
<td>Stream temperatures</td>
<td>Maximum weekly average temperature of streams predicted from projected changes in air temperature, groundwater, Shreve value of each stream segment, and watershed slope</td>
</tr>
<tr>
<td></td>
<td>Thermal habitat</td>
<td>Assessed availability and changes in coldwater &lt;19°C, coolwater 19°C–25°C, and warmwater &gt;25°C stream habitats</td>
</tr>
<tr>
<td>Lakes</td>
<td>Inland lake maximum surface temperatures</td>
<td>Maximum surface (0–2 m) temperatures predicted for inland lakes using mean annual air temperature, mean July temperature, longitude of centroid of lake, and day of the year</td>
</tr>
<tr>
<td></td>
<td>Walleye biomass</td>
<td>Published model by Lester et al. (2004) used to estimate changes in walleye biomass (kg x ha⁻¹) in inland lakes throughout the GLB</td>
</tr>
</tbody>
</table>

Wetland vulnerability

Vulnerability to drying and the potential impacts on wetland bird species habitat were the indicators selected for wetland ecosystems. Mapped wetlands were acquired from the Ontario Ministry of Natural Resources and Forestry (OMNR) wetland unit layer within the Land Information Ontario (LIO) database (OMNR 2011). When applicable, evaluated wetlands were included in the analyses because their existence and extents have been verified. Watersheds in the Lake Erie, Lake Ontario, and part of the Upper St. Lawrence basins included evaluated wetlands. Within the LIO database, none of the wetlands
were evaluated for Lake Superior, and only wetlands in the southern region of Lake Huron and the Upper St. Lawrence basins were evaluated therefore, all were included in the analyses. A table of the number of evaluated and unevaluated wetlands in each basin is provided (Table 2). ArcGIS® 9.3 was used for all spatial analyses (Environmental Systems Research Institute Inc., Redlands, California, USA).

Table 2: Number of evaluated and unevaluated wetlands in the Land Information Ontario database (OMNR 2011), and 75th percentiles of the ratios of air temperature and precipitation change used to calculate wetland vulnerability across the Great Lakes Basin, Ontario.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Number of unevaluated wetlands</th>
<th>Evaluated wetlands</th>
<th>Ratio of air temperature to precipitation changes (75th percentile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>47292</td>
<td>47292</td>
<td>11.81</td>
</tr>
<tr>
<td>Lake Huron</td>
<td>98908</td>
<td>11017</td>
<td>12.91</td>
</tr>
<tr>
<td>Lake Erie</td>
<td>23965</td>
<td>17621</td>
<td>15.04</td>
</tr>
<tr>
<td>Lake Ontario</td>
<td>107106</td>
<td>26331</td>
<td>14.28</td>
</tr>
<tr>
<td>Upper St. Lawrence</td>
<td>132135</td>
<td>47969</td>
<td>11.74</td>
</tr>
</tbody>
</table>

Vulnerability of the wetlands to climate change was assessed using projected mean air temperature and total precipitation during the growing season, and groundwater discharge potential. These variables were selected because changes in any one will affect the water budget of these systems. Vulnerability was defined as degraded quality or loss due to drying that may result from increased evapotranspiration at warmer air temperatures, water loss associated with decreased precipitation, and/or low groundwater inflow. Mean (April to September) air temperatures and total precipitation in the growing season from the ensemble projections were spatially joined to the wetland polygons. Base flow index values were also calculated for each wetland polygon. Groundwater discharge potential was based on a base flow index, which relates groundwater potential to underlying surficial geology (Neff et al. 2005). Each wetland polygon was spatially joined to the air temperature, precipitation, and base flow index data layers.

To calculate vulnerability, a rule of thumb of 1:10% was adopted from Trenberth (2011) who found that a ~10% increase in precipitation is needed to offset the increases in evapotranspiration associated with 1°C of warming. Vulnerabilities of the wetlands within each Great Lake watershed were calculated in two stages:

$$Vulnerability = \frac{\text{Change in air temperature}}{\text{Per cent change in precipitation}}$$

(1)

where ratios < 10 = low vulnerability

ratios 10 – 75th percentile = mid vulnerability

ratios > 75th percentile = high vulnerability

The 75th percentile of the air temperature:precipitation data for both scenarios and all time periods were calculated for each lake basin (Table 2). It represented the more extreme increases in air temperature and decreases in precipitation across each basin. Wetlands exposed to ratios of air temperature:precipitation greater than the 75th percentile were interpreted as experiencing harsher conditions than wetlands not exposed to those conditions and were assigned higher vulnerability to climate change.

The air temperature:precipitation vulnerabilities were then compared to the base flow index to incorporate the influence of groundwater influxes into the wetlands. The index has five values, which range
from 0 to 0.821, with 0.821 representing a high potential for groundwater discharge and 0 representing little or no groundwater (Neff et al. 2005). The air temperature and precipitation ratios were combined with the base flow index values to assign vulnerabilities to each wetland. The general premise was that high groundwater potential would buffer against high air temperature-precipitation ratios because influxes of groundwater would reduce the likelihood of drying, that is, decrease vulnerability (Table 3). Base flow index values did not change with climate because estimates of changes in recharge rates and groundwater temperature were not available (Chu et al. 2008).

Table 3: Criteria used to assign the vulnerability of wetlands to groundwater influxes, and changes in air temperature and precipitation associated with climate change. Brackets show ranking scheme representing the wetland vulnerability based on groundwater influxes only (e.g., 0.821 equals high influx therefore, low vulnerability to drying and climate change).

<table>
<thead>
<tr>
<th>Air temperature : precipitation</th>
<th>Base flow index</th>
<th>Wetland vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.821 (low)</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>0.589 (mid)</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>0.321 (mid)</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>0.098 (high)</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>0 (high)</td>
<td>Low</td>
</tr>
<tr>
<td>Mid</td>
<td>0.821 (low)</td>
<td>Low</td>
</tr>
<tr>
<td>Mid</td>
<td>0.589 (mid)</td>
<td>Low</td>
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<td>Mid</td>
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<td>High</td>
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<tr>
<td>High</td>
<td>0.098 (high)</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>0 (high)</td>
<td>High</td>
</tr>
</tbody>
</table>

**Wetland-dependent bird habitats**

Using the Hydrological Vulnerability Index (HVI) developed by Mortsh et al. (2006), two wetland-dependent bird species were identified. The HVI ranks species based on life history characteristics such as marsh dependency, nesting habitat, nest location, and foraging habitat. The two species included in these analyses were American coot (\textit{Fulica americana}) and pied-billed grebe (\textit{Podilymbus podiceps}), which are sensitive to hydrological changes in wetlands. Wetland vulnerabilities were mapped onto the known distributions of the two species to visually assess the overlap between wetland vulnerability and potential species distributions. As outlined above, wetlands with high vulnerability are likely to shrink or dry with climate change therefore, suitable habitats would decline in those areas. American coot and pied-billed grebe data were acquired from the Ontario Breeding Bird Atlas of Bird Studies Canada, in which presence data are represented by \(\sim 10 \text{ km} \times 10 \text{ km}\) grids (BSC 2008).

**Stream temperatures**

Due to the computational requirements of processing all the streams and lakes within the GLB of Ontario, analyses were limited to the main tributaries (longest main channel and connected tributaries) and hydrologically connected lakes within tertiary watersheds. Tertiary watersheds represent the third level of
a standard four-level hierarchy originally developed by the Water Survey of Canada to delineate drainage basins (OMNR 2013). There are 67 tertiary watersheds in the GLB of Ontario, ranging in size from 650 km$^2$ to 25,089 km$^2$ (OMNR 2013). An empirical model of maximum weekly average stream temperature (Melles et al. 2015) was used to predict temperatures in the tributaries. This metric was selected because it has been linked to fish species distributions, and it quantifies the hottest and potentially biologically limiting conditions for biota in streams (Wehrly et al. 2009; Moore et al. 2013). The predictive model is:

$$MWAT = 13.835 + 0.268 \times MAXTA - 4.999 \times GW - 0.0069 \times SLOPE + 2.286 \times \log(SHREVE) \quad (2)$$

where $MWAT$ is the maximum weekly average temperature, $MAXTA$ is the maximum air temperature, $GW$ is base flow index value, $SLOPE$ is the elevation range and $SHREVE$ is the stream order of different segments of the tributaries. Root mean square error for that model (RMSE), which was validated using data from 105 sites across the GLB, was 2.71. This model was used to estimate current and forecast future stream $MWAT$ with climate change. The ensemble climate change model provided the maximum air temperatures used in the analyses. Streams, slopes, and Shreve values of the streams were acquired from the OMNR's Integrated Hydrology (OMNR 2013). Groundwater discharge potential was estimated from the base flow index layer used for the wetlands. The data for these variables were entered into the models to determine the $MWAT$ for streams using the B1 and A2 emissions scenarios and the different time periods.

**Thermal habitat for stream fishes**

The predicted current and projected $MWAT$ in the streams were used to estimate the amount of suitable habitat for coldwater, coolwater, and warmwater fishes inhabiting these systems. Cold, cool, and warm water habitat were defined as streams having $MWAT$’s of $<19°C$, $19 ≤ 25°C$ and $>25°C$, respectively based on a national synthesis of the life history characteristics of Canadian fishes (Coker et al. 2001). Potential changes in habitat availability were assessed spatially and also summarized as total stream area (km$^2$) of suitable habitat for each thermal guild. Maximum weekly average stream temperatures were generated using rasters of the input data. Total suitable stream area was calculated from the $MWAT$ rasters as the count of cells * 900 m (each cell was 30 m × 30 m). In some cases this underestimated stream area of large rivers, but in other cases, this overestimated the area of small headwater streams. Therefore, the stream areas are approximate but comparable among lake basins. More accurate stream areas would require measured widths for every stream in the GLB.

**Lake temperatures**

Maximum surface water temperature and walleye biomass were used to assess the potential impacts of climate change on lake ecosystems in the GLB. Walleye were selected because they are one of the most important fisheries resources in Ontario and changes in their habitat and production may have significant socioeconomic consequences (Minns 2009). Maximum surface (0–2 m) temperatures (MST) in the lakes were predicted using an existing model developed by Sharma et al. (2007) for Canadian lakes. It estimates MST as:

$$MST = - 57.88 + 0.79 \times MJT + 0.26 \times MAT - 0.00151 \times (J)^2 + 0.617 \times J - 0.019 \times longitude + \beta \quad (3)$$

where $MST$ is maximum surface temperature (°C), $MJT$ is mean July temperature (°C), $MAT$ is mean annual air temperature (°C), $J$ is day of the year, longitude is the location of the centroid of each lake (decimal degrees) and $\beta$ is a coefficient describing the interannual variability. For our purposes, $J$ was set to 212 (July 31) and $\beta$ was set to zero. Maximum surface temperature data were not available to estimate RMSE of our predictions, but RMSE reported by Sharma et al. (2007) for 872 validation lakes equalled
2.53. The longitude of each lake as well as the ensemble projections of mean July and mean annual air temperature of each lake were entered into the model to predict MST for the B1 and A2 emissions scenarios for the three time periods.

**Walleye biomass**

A provincial model developed by Lester et al. (2004) was used to estimate the changes in walleye biomass (kg·ha⁻¹) with climate change. This model estimates production from the surface area (ha), maximum and mean depth (m), Secchi depth (m), total dissolved solids (mg·L⁻¹) and total growing degree days (above 5° C) of each lake. These data were compiled from OMNRF’s Broad-scale Monitoring (BsM) database for 134 lakes with walleye in the GLB (Figure 2; unpublished data). Total growing degree days (above 5° C) were estimated from the ensemble model projections of air temperatures under the B1 and A2 emissions scenarios (Table 4).

**Overall vulnerability**

The vulnerabilities of each indicator were ranked as Low, Moderate, or High based on the changes projected for the 2020s, 2050s and 2080s time periods. Regional changes in the indicators were summarized for each lake basin. The overall vulnerability of each basin was calculated as a combined, qualitative score of the vulnerability ranking for each of the six indicators.

![Figure 2](image-url)  
*Figure 2. Location of lakes (n=134) in the Great Lakes Basin, Ontario used to examine the potential impacts of changes in growing degree days (above 5° C) on walleye biomass under an ensemble model of projected changes in air temperature with the B1 and A2 emissions scenarios for the current, 2020s, 2050s, and 2080s time periods. Dark grey lines delineate five major basins of the GLB.*
Table 4. Characteristics used to estimate walleye biomass (kg·ha\(^{-1}\)) in 134 sampled lakes in the Great Lakes Basin.

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**Results**

**Wetlands**

Vulnerability of wetlands to drying due to changes in air temperature and precipitation:

Vulnerability of habitat for wetland-dependent bird species:
Wetland vulnerability was measured as the potential drying or shrinkage of wetlands due to changes in air temperature and precipitation. By the 2020s, most of the wetlands across the GLB may have low vulnerability to climate change under the B1 and A2 emissions scenarios (Figure 3). Wetlands near the north shore of Lake Superior and southern Ontario may be at risk of drying by 2050. By the 2080s, the most vulnerable regions may be in the southern part of the GLB and much of eastern region of the Lake Superior basin with the B1 scenario. Under the A2 scenario, these two regions and the central part of Lake Huron and northwestern part of the Upper St. Lawrence basin may be vulnerable. The eastern portion of the Lake Ontario basin may have low vulnerability but most of the wetlands in the Lake Erie basin were classified as high or mid vulnerability by the 2080s under the A2 scenario (Figure 3).

Figure 3. Vulnerability of wetlands in the Great Lakes Basin (GLB) to groundwater inflows and changes in air temperature and precipitation associated with climate change projected using an ensemble of climate change models and the B1 and A2 emissions scenarios for the present, 2020s (a and b), 2050s (c and e) and 2080s (e and f) time periods. Black lines delineate five major basins of the GLB.
Changes in wetland habitat for American coot and pied-billed grebe varied across the five basins (Figure 4 and 5). Availability of suitable habitat can be inferred from the vulnerabilities of the wetlands to drying (Figure 3). Under the B1 scenario, much of American coot and pied-billed grebe habitat will remain intact by 2020. Under the A2 scenario, habitat in the southern portion of the GLB may be less suitable for both species. In the 2050s, habitat for both species in the southern portion of the GLB may be reduced (Figure 3). By the 2080s, two of the three locations in the Lake Superior basin that American coot inhabit will be highly vulnerable to drying under both the B1 and A2 scenarios (Figure 4). Pied-billed grebe habitat may be reduced in the eastern and most western regions of the study area (Figure 4 and 5). In the Lake Huron basin, ~50% (B1 scenario) or ~70% (A2 scenario) of the wetlands associated with American coot may have a mid to high vulnerability by the 2080s whereas ~40% (B1 scenario) or ~50% (A2 scenario) of the wetlands with pied-billed grebe will be reduced. In the Lake Erie basin, by the 2080s, nearly all of the wetlands with American coot and pied-billed grebe may be mid or high vulnerability with the A2 scenario and ~85% may be mid or high vulnerability under the B1 scenario (Figure 4 and 5). Wetlands with American coot and pied-billed grebe in the western region of the Lake Ontario basin may have mid to high vulnerability by the 2080s under both the B1 and A2 scenarios. American coot and pied-billed grebe habitats in the southern region of the Upper St. Lawrence basin may be greatly reduced by the changes in precipitation and air temperature associated with climate change (Figure 4 and 5).

Streams

Streams with greater warming were interpreted as more vulnerable to climate change because these changes can have chemical and biological consequences:
Figure 4. American coot distribution (purple squares) and vulnerability of wetlands in the Great Lakes Basin (GLB) to groundwater inflows and changes in air temperature and precipitation associated with climate change projected using an ensemble of climate change models and the (a) B1 and (b) A2 emissions scenarios for the 2080s. Black lines delineate five major basins of the GLB.
Figure 5. Pied-billed grebe distribution (blue squares) and vulnerability of wetlands in the Great Lakes Basin (GLB) to groundwater inflows and changes in air temperature and precipitation associated with climate change projected using an ensemble of climate change models and the (a) B1 and (b) A2 emissions scenarios for the 2080s. Black lines delineate five major basins of the GLB.
Maximum weekly average stream temperatures varied regionally (Figure 6). Southern Ontario had the warmest temperatures whereas watersheds along the northeast shore of Lake Superior had the coolest. Maximum weekly average stream temperatures currently range from 13.2°C in the Lake Superior basin to 32.0°C in the Lake Erie basin (Table 5). Streams in the Lake Erie basin had the greatest range of temperatures (~17°C) whereas the basins of Lake Ontario and Lake Superior had the lowest range (~12°C; Table 5). By the 2020s, average stream temperatures across all basins may increase ~1°C under the B1 scenario, and up to ~2°C under the A2 scenario. Average temperatures may warm an additional 1–2°C by the 2050s. Across all basins, the A2 scenario predicted increases in mean MWAT ~0.7°C warmer than the B1 scenario by the 2080s.

Table 5: Range of current and projected maximum weekly average temperature (°C) in streams throughout the main lake basins of the Great Lakes Basin, Ontario. Predicted temperatures were developed using ensemble climate projections of air temperature under the A2 and B1 emissions scenarios for three future time periods. Values in brackets are means.

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Maps of the change in MWAT highlighted areas expected to change the most across the GLB (Figure 6). In the Lake Superior basin, temperatures will increase most for streams draining the eastern shore, but streams draining the northeastern shore may remain the coolest across the basin with some streams experiencing decreases in temperatures. Temperatures in the Lake Huron basin will change the most in streams along the North Channel and north of Lake Simcoe. In Lake Erie, temperatures will increase most in the centre of the basin. Lake Ontario streams in the northeast will increase the most. In the Upper St. Lawrence basin, temperatures will increase most in the northwest and southeast (Figure 6). The greatest average warming may occur in the Upper St. Lawrence basin with an average increase of 1.3°C under the B1 scenario and 2.4°C under the A2 scenario. Stream temperatures in Lake Ontario will warm the least, with average increases of 0.9°C under the B1 scenario and 1.4°C under the A2 scenario (Table 5).

Coldwater (MWAT < 19°C) habitats were the most abundant with 77% of the streams classified as coldwater, 21% and 2% of the streams classified as coolwater (<19 MWAT ≤ 25°C) or warmwater (MWAT > 25°C), respectively (Table 6; Figure 7). By the 2020s, coldwater habitat may decrease by ~8%, coolwater may increase by 7.7%, and warmwater habitat may increase by 0.3%. By the 2050s, coldwater will continue to decrease ~13–15%, with concomitant increases in coolwater and warmwater habitat (Table 6). By the 2080s, 62% (B1 scenario) or 55% (A2 scenario) of the streams will have coldwater habitat (Table 6; Figure 7). Thirty-six (B1 scenario) or 42% (A2 scenario) of the streams will have coolwater habitat. Warmwater habitat will be found in 2–3% of the streams by the 2080s (Table 6; Figure 7). It should be noted that these estimates are based on stream area as opposed to volume. Cold headwater reaches of streams have less water (less volume) than comparatively warmer outlet reaches therefore, the percentages calculated here could be very different if volume as opposed to area is used.
Figure 6. Predicted maximum weekly average temperature (°C) for streams throughout the Great Lakes Basin (GLB), Ontario (a) currently, and under the 2080s air temperature projections of an ensemble of climate change models and the (b) B1 and (c) A2 emissions scenarios. Black lines delineate five major basins of the GLB.
In the Lake Superior basin, by the 2080s, coldwater habitats may decrease by 12–15%, coolwater habitat will increase by 11–13% and warmwater habitat will increase by 1–2%. Coldwater habitat in Lake Huron basin streams will decrease by 20% under the A2 scenario and 12% under the B1 scenario. In the Lake Erie basin, coldwater habitat will decrease by 23% and 33% with the B1 and A2 scenarios, respectively. Coolwater habitat will increase by 22 and 32%, and warmwater habitat will increase by 1%. Fourteen per cent of the streams the Lake Ontario Basin will warm from coldwater to coolwater habitat by the 2080s under the B1 scenario. Under the A2 scenario, 23% of the streams may warm from coldwater to coolwater habitat, but warmwater habitats may increase by less than 1% under both emissions scenarios. Twenty-one and 24% of the streams in the Upper St. Lawrence River will warm from coldwater to coolwater by the 2080s under the B1 and A2 scenarios, respectively. Warmwater habitats will increase by less than 1% (Table 6).

Lakes

Lakes with greater warming in temperature were interpreted as more vulnerable to climate change because these changes can have chemical and biological consequences:
Table 6. Thermal habitat availability for coldwater (<19°C), coolwater (≥19≤25°C) and warmwater (>25°C) stream fishes in the major drainage basins of the Great Lakes, Ontario based on maximum weekly average temperature for streams using current conditions, and under an ensemble model of air temperature changes with the A2 and B1 emissions scenarios for three future time periods.

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Figure 7. Current (a) and future suitability of streams throughout the Great Lakes Basin (GLB), Ontario for coldwater ($< 19\, ^\circ\text{C}$), coolwater ($19 \leq 25\, ^\circ\text{C}$) and warmwater ($> 25\, ^\circ\text{C}$) fishes under the 2080s air temperature projections of an ensemble of climate change models and the (b) B1 and (c) A2 emissions scenarios. Black lines delineate five major basins of the GLB.
Changes in walleye biomass:

Maximum surface temperatures ranged from 18.6° C to 27.4° C across the entire GLB (Figure 8). Maximum surface lake temperatures were warmest in the Lake Erie basin and coolest in the Lake Superior basin (Table 7). Temperatures within each basin ranged ~4° C. By the 2020s, average temperatures in the GLB may be 2–3° C warmer under both scenarios (Table 7). Average temperatures in the GLB may be 3–5° C and 3–6° C warmer by the 2050s and 2080s, respectively (Table 7).

By the 2080s under the A2 scenario, lakes in the southern region of the entire basin may warm by 6–14° C; lakes in the northern region may warm by <9° C (Figure 8). By the 2080s under the B1 scenario, temperatures may warm by 3–9° C across the entire GLB with southern lakes warming more than the northern lakes. Lakes in the western region of the Lake Superior basin may warm more than lakes in the eastern region of the basin (Figure 9). Lakes throughout the western region of the Lake Huron basin may warm more than lakes in the eastern region of the basin. Lake Erie basin has the fewest lakes (n=59) compared to the rest of the GLB (>850 lakes per basin), and all lakes warmed by 6–14° C (Figure 9). Lakes in the southern region of the Lake Ontario and Upper St. Lawrence basins may warm more than lakes in the northern region of both basins.

Walleye biomass (kg·ha⁻¹) currently ranges from 0.59–15.05 kg·ha⁻¹ in the 134 lakes included in the analyses (Figure 2 and 10). Walleye biomass was not significantly different for any of the time periods and emissions scenarios, but did show a declining trend (~10–15%) in the Lake Ontario and Upper St. Lawrence River basins (Figure 10). Under the B1 scenario, by the 2080s average walleye biomass in the GLB will range from 0.42–14.24 kg·ha⁻¹. This may be reduced to 0.29–13.56 kg·ha⁻¹ with the A2 scenario.
Figure 8. Maximum surface (0–2 m) water temperatures (°C) of lakes in the Great Lakes Basin, Ontario under the (a) current, and 2080s air temperature projections of an ensemble of climate change models and the (b) B1 and (c) A2 emissions scenarios.
Table 7. Range of current and predicted maximum surface temperature (°C) in lakes throughout the major lake basins of the Great Lakes Basin, Ontario. Predicted temperatures were developed using ensemble climate projections of air temperature under the A2 and B1 emissions scenarios for three future time periods: 2020s, 2050s and 2080s. Means are included in the brackets.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Number of main stem lakes</th>
<th>Range of lake sizes (km²)</th>
<th>Current</th>
<th>2020s</th>
<th>2050s</th>
<th>2080s</th>
<th>B1 2020s</th>
<th>B1 2050s</th>
<th>B1 2080s</th>
<th>A2 2020s</th>
<th>A2 2050s</th>
<th>A2 2080s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>4783</td>
<td>0.1–4352.7</td>
<td>18.8–22.4 (20.4)</td>
<td>20.1–23.7 (22.5)</td>
<td>21.0–24.7 (23.5)</td>
<td>21.8–25.5 (24.2)</td>
<td>20.4–24.0 (22.8)</td>
<td>22.0–25.7 (24.5)</td>
<td>24.1–27.7 (26.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huron</td>
<td>6120</td>
<td>0.10–727.7</td>
<td>21.1–25.3 (22.5)</td>
<td>23.0–27.5 (24.2)</td>
<td>23.9–28.3 (25.1)</td>
<td>24.7–29.2 (25.9)</td>
<td>23.3–27.8 (24.5)</td>
<td>25.0–29.4 (26.2)</td>
<td>26.9–31.2 (28.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erie</td>
<td>59</td>
<td>0.1–11.4</td>
<td>23.7–27.3 (25.1)</td>
<td>25.3–29.4 (26.9)</td>
<td>26.2–30.2 (27.8)</td>
<td>26.9–31.0 (28.6)</td>
<td>25.7–29.7 (27.1)</td>
<td>27.1–31.4 (28.8)</td>
<td>28.9–33.2 (30.6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ontario</td>
<td>893</td>
<td>0.1–92.0</td>
<td>22.5–25.8 (23.9)</td>
<td>23.6–28.0 (25.2)</td>
<td>24.5–28.9 (26.1)</td>
<td>25.3–29.7 (26.9)</td>
<td>24.0–28.4 (25.6)</td>
<td>25.6–29.9 (27.1)</td>
<td>27.4–31.7 (28.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper St. Lawrence</td>
<td>2585</td>
<td>0.1–206.3</td>
<td>20.8–25.2 (22.8)</td>
<td>22.4–27.5 (24.2)</td>
<td>23.4–28.4 (25.1)</td>
<td>24.2–29.2 (25.9)</td>
<td>22.6–27.9 (24.5)</td>
<td>24.5–29.2 (26.2)</td>
<td>26.5–31.2 (28.1)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Figure 9. Change in maximum surface lake temperatures from current to projected temperatures estimated using an ensemble model of air temperature in the Great Lakes Basin, Ontario under the B1 and A2 emissions scenarios for the 2020s (a and b), 2050s (c and d) and 2080s (e and f) time periods.
Figure 10. Walleye biomass (kg·ha\(^{-1}\)) in 134 lakes in the Great Lakes Basin, Ontario under air temperature projections of an ensemble of climate change models, and the B1 and A2 scenarios for the 2020s, 2050s, and 2080s.
**Overall vulnerability**

Vulnerability results for all of the wetland, stream, and inland lake indicators were summarized into overall vulnerability scores for each basin, which was calculated as the sum of the number of low (value: 0), moderate (+1) or high (+2) rankings for the six indicators. The basins were then ranked in descending order of scores; basins with higher scores had higher vulnerability ranks than basins with lower scores. Based on the six indicators, the Upper St. Lawrence basin may be the most impacted by climate change, followed by Lake Erie, Lake Ontario, Lake Superior, and Lake Huron (Table 8).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Lake Superior</th>
<th>Lake Huron</th>
<th>Lake Erie</th>
<th>Lake Ontario</th>
<th>Upper St. Lawrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vulnerability to drying</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Wetland bird species habitat</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Maximum stream temperature</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Suitable habitat in streams</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Maximum lake surface temperature</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Walleye biomass in lakes</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Overall vulnerability score</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Rank</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
Box A
Case study — Climate change impacts in Peel Region
As an extension of the Great Lakes Basin Vulnerability Assessment, a Peel Region (Mississauga and the western region of Toronto) assessment was conducted to inform planning for the Peel Climate Change Strategy. The wetland vulnerability and stream temperature results are presented here.

Methods:
- Wetland vulnerability — same methods as Great Lakes Basin assessment
- Stream temperatures — An empirical model of maximum weekly average stream temperature was developed from 86 temperature monitoring sites:
  \[
  MWAT = -11.302 + 0.689 \times GW + 1.117 \times MAXT + 1.685 \times \log_{10} SHREVE
  \]
  where MWAT is the maximum weekly average temperature, MAXTA is the maximum air temperature, GW is groundwater discharge, and SHREVE is the stream order of different segments of the streams. Validation with data from 25 sites had root mean square error = 1.98; RMSE values close to 0 indicate good performance of the model.
Box A continued

Results:

- The vulnerability of wetlands to drying will increase from west to the eastern region of the study area under both the B1 and A2 scenarios.
Box A continued

- Maximum weekly average temperatures in streams may warm from 18–24°C to 20–30°C under the 2080s B1 scenario or 24–30°C under the 2080s A2 scenario.
Box B
Case study — Climate change impacts in the Mississippi-Rideau Valley conservation areas

As an extension of the Great Lakes Basin Vulnerability Assessment, a climate change vulnerability assessment was conducted for the Mississippi Valley and Rideau Valley Conservation Authority jurisdictions to inform climate change adaptation planning in that region. The wetland vulnerability, stream temperature, and lake temperature results are presented here.

Methods:

- Wetland vulnerability — same methods as Great Lakes Basin assessment
- Stream temperatures — same methods as Great Lakes Basin assessment
- Lake temperatures — same methods as Great Lakes Basin assessment
Box B continued

Results:

- Most elevated wetlands in Mississippi-Rideau conservation areas will have mid vulnerability to drying associated with air temperature and precipitation changes associated with climate change.
Box B continued

- Maximum weekly average stream temperatures may warm by 4°C with the most pronounced changes in the Rideau Valley watershed.
Lakes in Rideau Valley are warmer than lakes in the Mississippi Valley with ≈2°C change from south to north. Lakes in the south will warm at a faster rate than lakes in the north.
Discussion

Results from the indicators highlight that the impacts of climate change will vary across the GLB and within the different lake basins. Changes in the indicators will have broader implications for different components of the aquatic ecosystems. For example, potential drying and shrinking of the wetlands could lead to reductions in suitable habitat for wetland-dependent species. The regional and temporal differences in the wetland vulnerabilities can be attributed to regional and temporal differences in precipitation. Air temperatures will consistently warm throughout in the study area but precipitation will be more variable throughout the century.

For the wetland extent vulnerability indicator, each wetland was treated as a single homogeneous entity. The low, mid, and high vulnerability rankings were applied uniformly across each of the wetlands. It is possible that the entire wetland patch may not be affected by changes in air temperature and/or precipitation. For example, drying or shrinking of the wetlands may occur around the edges leaving the middle of the wetlands intact. If this is true, wetland vulnerability may be overestimated. Alternatively, if the ground water influxes are less than expected in this study, wetland vulnerability may be underestimated.

Wetland vulnerabilities were calculated by pairwise comparisons between current conditions and each of the scenarios. Future research should examine whether compounding the effects of the air temperature and precipitation changes would produce more accurate pictures of the future. For example, vulnerability criteria could be set to prevent wetlands from getting a low vulnerability (e.g., during the 2050s) after they have been ranked at high or mid vulnerability (e.g., during the 2020s). This would incorporate legacy effects of the previous time period on condition of the wetlands. Studies of the resilience and recovery of wetlands after perturbations would allow one to determine whether legacy effects should be incorporated into the vulnerability criteria.

The wetland-dependent bird species results suggest that their suitable habitat may be significantly impacted by climate change. Both species could see significant reductions in suitable habitat by the 2080s. However, these analyses do not account for adaptation of the birds to new habitat conditions or migration of the birds to other wetlands within or adjacent to the study area. This study also does not consider the fact that other species may come to occupy the wetlands. More detailed estimates of how the wetlands will change (e.g., spatial extent and plant community composition) would provide more realistic estimates of how species distributions may change with climate.

Non-climatic stressors such as agricultural activities and urban development also affect wetland conditions. Run-off from urban and agricultural lands may contain pollutants, nutrients, and sediments that compromise water quality. This may in turn negatively impact plant growth, community composition, and overall availability of wetland habitats (Mortsch et al. 2006).

Changes in stream temperatures may benefit some species more than others. Stream temperature and thermal habitat varied across the GLB with different regions warming at different rates. The overall pattern will remain the same with relatively cold, cool, and warm water areas remaining in the same regions of the GLB. However, the analyses here do not include other factors that affect stream conditions. For example, Casselman et al. (2011) found that in tertiary watersheds throughout the Upper St. Lawrence basin, spring discharge may peak 7 weeks earlier and summer flows may decrease in volume by 44%. These changes compounded with the changes in temperatures could have significant impacts on ecosystem function and biota.

Streams at risk in the short-term (i.e., shifts in thermal habitat from cold to cool or cool to warm) may be given high conservation priority or managed differently than less impacted systems. Alternatively, if we treat
Climate change as an inevitability, streams that are likely to retain some coldwater habitat could be given high conservation priority because they will naturally offer more suitable habitat and thermal refugia for coldwater fishes in the future (Chu et al. 2008). The potential impacts of connectivity changes associated with climate change (e.g., dry stream reaches in the summer) and/or human activities (e.g., improper culvert installations) should also be evaluated in future studies. Connectivity maintains access to critical habitats for different life stages and may provide routes to refugia for species to escape warm temperatures in the summer or ice in the winter.

Increases in lake surface temperatures would open new habitats for warmwater species. Warmer maximum surface water temperatures of the lakes indicate changes in the thermal dynamics of these systems (e.g., shifted thermocline depths, longer periods of stratification, and increased duration of the ice-free season). This will affect the nutrient dynamics, dissolved oxygen concentrations, production, and availability of suitable habitat for warmwater species inhabiting the epilimnion, coolwater species in the metalimnion, and coldwater species in the hypolimnion (Dove et al. 2011). Future studies should assess the metalimnetic and hypolimnetic impacts of habitat change in lakes which stratify.

Changes in walleye biomass were not significant within the basins, but showed a declining trend (~10–15%) in the Lake Ontario and Upper St. Lawrence basins. This may be due to the warming of the lakes and increases in growing degree days above 5°C (GDD5). Walleye are coolwater species preferring temperatures of 22°C (Coker et al. 2001). In some lakes, GDD5 increased by as much as 14°C this warmed the lakes past the thermal preferences of walleye and reduced the availability of suitable thermal-optical habitat (habitat measure in Lester et al. 2004). These changes in production could affect the predator-prey dynamics of these systems, and the socioeconomics of the recreational walleye fishery within the GLB (e.g., Hunt and Kolman 2012). Modelling walleye biomass from climate and lake characteristics is a straightforward approach to estimate possible changes in production. It does not consider other factors that influence walleye biomass such as the presence of competitors, dynamics of prey species, or availability of other habitat requirements (e.g., spawning habitats).

This study provides simple assessments of the impacts of climate change on wetlands, streams and inland lakes in the Great Lakes Basin, Ontario. The individual indicators and overall vulnerability of the lake basins should be incorporated into a cumulative effects approach. This would allow researchers and practitioners to assess the impacts of both climatic and non-climatic stressors such as anthropogenic species introductions (baitfish and vegetation), increasing expansion of urban areas and non-point source pollution on the wetlands, streams, and lakes of the watersheds. Additional indicators of aquatic ecosystem vulnerability should also be explored using complementary methods of statistical and process-based physical modelling approaches to describe other components of and impacts on aquatic ecosystems. This might include:

- Frequency, magnitude, duration, and timing of river and stream flows and the implications for fish spawning and rearing.
- Changes to water balance components of base flow and stream flow and their influence on aquatic habitats.
- Expanding the seasonal temperature-profile for lakes and the associated implications of climate change on the thermal habitat space for fish species.
- Changes to connectivity within and among streams and lakes with changing flow and groundwater conditions.
• Community responses to climate change e.g., changes in species composition, niche partitioning or overlap

• Fish community models of production to predict how total production of the community will change.

**The strengths of the analyses are:**

• Incorporate the dominant physical variables (air temperature, precipitation, and groundwater inflows) that influence wetlands, stream, and lake temperatures.

• Offer easily interpretable guides for setting priority areas for wetland conservation and management.

• Provide a framework for assessing how wetland changes may influence habitat availability and the distribution of wetland-dependent species.

• Provide a framework for species-specific assessments and other community assessments by predicting current and future temperatures along every length of stream e.g., invertebrate distribution patterns.

• Offer easily interpretable guides for prioritizing streams for conservation based on thermal regime shifts.

• Apply established models for temperature, thermal habitat and walleye biomass to estimate changes with climate.

• Offer information that may be used to prioritize management plans within and among the different lake basins.

**The uncertainties are:**

• The pattern of drying in each wetland. In this study, each wetland was treated as a unit and assigned a vulnerability ranking. However, entire wetlands may not be affected uniformly. For example, drying or shrinking may occur around the edges only leaving the middle intact.

• The types of shifts in wetland plant diversity and composition that will affect wetland type (e.g., bog, fen etc.) and other species diversity.

• Specific water budgets of different wetland types is needed as the dominant influxes of waters in the different types vary e.g., marsh are precipitation or surface water driven whereas fens are groundwater driven.

• General rule of thumb of a 10% change in precipitation to offset evapotranspiration associated with a 1°C increase in air temperature needs to be validated for the study area.

• Other factors such as stream regulation and surrounding land use should be incorporated into the stream temperature and habitat analyses because they also influence species distributions in streams.

• Coolwater and coldwater refugia in lakes that stratify should be examined in future studies.

• Changes in thermal habitat are variable among basins and the distributions of species in streams are not uniformly distributed therefore certain watersheds within the basins may require different adaptation strategies than others.

• Other factors that influence walleye biomass such as exploitation, presence of competitors and invasive species should be explored.
Recommendations

Recommendations for data needs and monitoring

**Wetlands**

- Ground-truthing of wetland extents and identification of wetland types (e.g., bogs, fens, marshes etc.) throughout the Great Lakes Basin. These data must be collected and compiled in order to effectively determine the fate of wetlands with climate change.
- Water budget specific to each wetland type would further improve the vulnerability assessments.
- A network of monitoring stations should be established throughout the GLB wetlands to detect any changes in wetland extent and quality.
- Wetland species (e.g., waterfowl and amphibians) should be monitored to determine the effect of changes in wetland extent on their distribution and populations.

**Streams**

- Broad-scale monitoring network for streams throughout GLB, possibly coupled with HYDAT (Water Survey of Canada) stations should be established.
- Water quality monitoring is currently focused in populated areas, need monitoring in more rural/less accessible areas of the GLB.
- Data from hydropower environmental assessment reports should be compiled and could help inform the development of a stream monitoring network throughout GLB.
- Inventory of stream crossings; types and distribution is needed as these can affect the accessibility and connectivity of thermal habitats.
- Local monitoring of streams by municipalities, conservation authorities and other agencies should be continued.
- Empirical model of stream temperatures is needed that accounts for other factors influencing stream temperatures such as impervious cover, stormwater structures.

**Lakes**

- Continued support of the BsM program is necessary to establish the current condition of lakes in the GLB and monitor changes in them over time.
- Predictive models of whole lake fishable biomass would help inform fisheries management planning throughout the GLB.
- Both American and Canadian governments are currently compiling and developing habitat classification tools for the Great Lakes as part of the Great Lakes Aquatic Habitat Framework (University of Michigan) and Great Lakes Nearshore Framework (Environment Canada). These data and classification tools are useful for further climate change studies as such efforts should be made to collaborate with researchers at those agencies.
Recommendations for adaptation

**Wetlands**
- Limit surface and groundwater withdrawals, draining, or infilling of vulnerable wetlands.
- Create suitable habitat for vulnerable wetland-dependent bird species by providing nest boxes or rehabilitating nesting habitats.
- Modify any man-made drainage structures to promote water retention.
- Limit invasive plants species such as common reed (*Phragmites australis*) and water hyacinth (*Eichhornia crassipes*).

**Streams**
- Maintain natural water level and flow regimes in regulated systems.
- Convert top-draw to bottom-draw dams in regulated systems sensitive to climate change.
- Prioritize refugia areas (e.g., coldwater stream areas) for restoration, conservation, and management as many of them will transition to coolwater systems in the next 100 years.
- Groundwater and surface water withdrawals could be limited or regulated to maintain flow and temperatures in the streams.
- Restore or enhance riparian vegetation around streams sensitive to climate change.

**Lakes**
- Maintain natural water level regimes in regulated systems.
- Maintain surface and ground water influxes.
- Limit human activities e.g., shoreline development or watershed run-off that could degrade water quality in lakes but especially those sensitive to warming associated with climate change.
- Fishing regulations such as catch limits, slot size limits, season lengths, and protected areas may be used to manage walleye in lakes where walleye biomass may decline.
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