STATE OF THE GREAT LAKES 2017

TECHNICAL REPORT

Indicators to assess the status and trends of the Great Lakes ecosystem

Environment and Climate Change Canada
and the
U.S. Environmental Protection Agency

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State of the Great Lakes 2017

By the Governments of Canada and the United States of America

Prepared by Environment and Climate Change Canada

and the

U.S. Environmental Protection Agency

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1. Introduction

The Great Lakes contain one fifth of the world's fresh surface water supply and are one of the most ecologically diverse ecosystems on earth. They provide drinking water to tens of millions of Canadians and Americans and are important to the economies of both Canada and the United States, supporting manufacturing, transportation, farming, tourism, recreation, clean energy production, and other forms of economic growth.

2017 marks the 45th anniversary of the signing of the Great Lakes Water Quality Agreement (GLWQA) by the Governments of Canada and the United States. The Agreement commits both countries to working cooperatively to restore and protect the water quality and aquatic ecosystem health of the Great Lakes. Through the Agreement, the Governments of Canada and the United States engage the provincial and state governments of Ontario, Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin, Tribes, First Nations, Métis, municipal governments, watershed management agencies, other local public agencies, industry and the public in actions to ensure that the Great Lakes remain an important and vibrant natural resource for the benefit and enjoyment of this generation and those to come.

The 2012 GLWQA is organized as a series of Articles and Annexes. The Articles describe the general and specific objectives of the Agreement, define principles and approaches, and lay out the structure and process for its implementation.

Canada and the United States, the Parties to the GLWQA, have committed to work to attain nine general objectives. The Waters of the Great Lakes should:

i. *Be a source of safe, high-quality drinking water*;
ii. *Allow for swimming and other recreational use, unrestricted by environmental quality concerns*;
iii. *Allow for human consumption of fish and wildlife unrestricted by concerns due to harmful pollutants*;
iv. *Be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife or organisms, through direct exposure or indirect exposure through the food chain*;
v. *Support healthy and productive wetlands and other habitats to sustain resilient populations of native species*;
vi. *Be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem*;
vii. *Be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes*;
viii. *Be free from the harmful impacts of contaminated groundwater*; and,
ix. *Be free from other substances, materials or conditions that may negatively impact the chemical, physical or biological integrity of the Waters of the Great Lakes*.

The ten Annexes of the 2012 GLWQA, listed below, describe commitments on specific environmental issues that can affect the quality of the waters of the Great Lakes:

1. Areas of Concern
2. Lakewide Management
3. Chemicals of Mutual Concern
4. Nutrients
5. Discharges from Vessels
6. Aquatic Invasive Species
7. Habitats and Species
8. Groundwater
9. Climate Change Impacts
10. Science

The 2012 GLWQA recognizes that the effective implementation of management decisions, policies and programs must be based on the best available science, research and knowledge. The Science Annex (Annex 10) of the 2012 GLWQA commits the United States and Canada to enhancing the coordination, integration, synthesis, and assessment of science activities across all Annexes of the Agreement. Science provides the foundation for management actions and policy decisions in support of meeting the objectives of the Agreement.

Annex 10 also commits the Parties to establishing science-based ecosystem indicators "to anticipate emerging threats and to measure progress in relation to achievement of the General and Specific Objectives of the [GLWQA]".

The Parties have also committed to issuing every three years a State of the Great Lakes report (SOGL) which describes "basin-wide environmental trends and lake-specific conditions using ecosystem indicators". Most of the indicator work falls to the Ecosystem Indicator and Reporting (EI&R) Task Team under Annex 10.

Environment and Climate Change Canada and United States Environmental Protection Agency have been leading the assessment of the state of the Great Lakes for the Parties since 1994 with the first State of the Great Lakes report released in 1995. In 1998, a suite of indicators was introduced to allow for consistent and comprehensive assessments with repeatability amongst the reporting cycles. Over time the indicator suite has been improved and strengthened. The indicator suite currently includes nine high-level indicators supported by 44 sub-indicators. The nine indicators are used to report on progress towards the General Objectives of the Great Lakes Water Quality Agreement.

No one agency or organization has the jurisdiction or the capacity to monitor, manage, restore and protect an ecosystem as large as the Great Lakes so assessing the environmental conditions of the Great Lakes using ecosystem indicators involves hundreds of people from many agencies and organizations on both sides of the border. The information in this document, ***State of the Great Lakes 2017 Technical Report***, has been assembled with involvement from more than 180 scientists and experts from the Great Lakes community within Canada and the United States. These experts represent over 30 different agencies and organizations.

Assessments of the Great Lakes help governments to identify current, new and emerging challenges to Great Lakes water quality and ecosystem health. Assessments also help governments to evaluate the effectiveness of programs in place to address challenges, and help inform and engage others.

State of the Great Lakes 2017 Technical Report. This technical report contains the full sub-indicator reports as prepared by the primary authors and contributors and the nine high-level indicator assessments. It also contains detailed references to data sources. Sub-indicator reports provide the status and/or trend for the Great Lakes overall and, where possible, on an individual lake basin scale.

State of the Great Lakes 2017 Highlights Report. The Highlights report is a synopsis of the ecosystem indicator assessments prepared for the *State of the Great Lakes 2017 Technical Report*. This report highlights current conditions in the "What are the Great Lakes Indicators Telling Us" section. A summary of the nine high-level indicator assessments is included in the subsequent pages of the report including assessments of Drinking Water, Beaches, Fish Consumption, Toxic Chemicals, Habitat and Species, Nutrients and Algae, Invasive Species, Groundwater Quality and Watershed Impacts and Climate Trends.

2. What Are the Great Lakes Indicators Telling Us?

Can we drink the water?
Yes. The Great Lakes remain a source of high quality drinking water.
Drinking Water Indicator – Status: Good, Trend: Unchanging

Can we swim at the beaches?
Yes. But some beaches are unsafe for swimming some of the time due to bacterial contamination.
Beaches Indicator – Status: Fair to Good; Trend: Unchanging

Can we eat the fish?
Yes. But contaminants in fish require limits to be placed on the amount of fish consumed in order to safe guard human health
Fish Consumption Indicator – Status: Fair; Trend: Unchanging

Are the lakes free from pollutants at levels harmful to human health and the environment?
Generally, yes. But some pollutants in local areas, including in designated Areas of Concern, remain at problem concentrations.
Toxic Chemicals Indicator – Status: Fair; Trend: Unchanging to Improving

Are the lakes supporting healthy wetlands and other habitats for native species?
In some instances, yes, and in others no. Results vary significantly from location to location.
Habitat and Species Indicator – Status: Fair; Trend: Unchanging

Are the lakes free from excess nutrients?
No. Nutrient loadings in Lake Erie and some nearshore areas of Lakes Huron, Michigan and Ontario are causing severe impacts due to the formation of toxic and nuisance algae.
Nutrients and Algae Indicator – Status: Fair; Trend: Unchanging to Deteriorating

Are we winning the battle against aquatic invasive species?
No. While the introduction of new non-native species has declined, the spread and impacts of aquatic invasive species already in the lakes continues.
Invasive Species Indicator – Status: Poor; Trend: Deteriorating

Is groundwater negatively affecting the water quality of the lakes?
Generally, no. But some localized areas of contamination exist.
Groundwater Quality Indicator – Status: Fair; Trend: Undetermined

Are land use changes impacting the lakes?
Yes. Growth, development and land-use activities stress the waters of the Great Lakes.
Watershed Impacts Indicator – Status: Fair; Trend: Unchanging

The overall assessment for ecosystem conditions in the Great Lakes is *Fair* and the trend is *Unchanging* since the last assessment in 2011. While progress to restore the Great Lakes has been made, including the reduction of toxic chemicals, challenges with issues such as invasive species and nutrients still remain. In addition, the ecosystem is large and complex and it can take years to respond to restoration activities and policy changes.

This overall assessment is based on the nine science-based indicators that assess water quality and ecosystem health. The assessment also takes into consideration climate trends. There are 44 sub-indicators that feed into the nine high-level indicators that will be used for state of the Great Lakes reporting and are used to measure progress against the nine General Objectives of the Agreement. Status and Trend definitions can be found in Appendix 2.

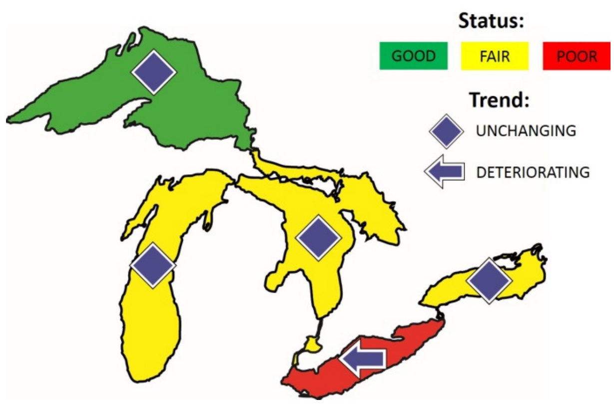
Status:

GOOD FAIR POOR

Excerpt from GLWQA Objective	Great Lakes Indicator	Status and Trend
Be a source of safe drinking water	Drinking Water	*Status:* Good; *Trend*: Unchanging
Allow for swimming and other recreational use	Beaches	*Status:* Fair-Good; *Trend:* Unchanging
Allow for human consumption of fish and wildlife	Fish Consumption	*Status:* Fair; *Trend:* Unchanging
Be free from pollutants	Toxic Chemicals	*Status:* Fair; *Trend:* Unchanging-Improving
Support healthy and productive wetlands and other habitats to support native species	Habitat and Species	*Status:* Fair; *Trend:* Unchanging
Be free from nutrients in amounts that promote growth of algae and cyanobacteria	Nutrients and Algae	*Status:* Fair; *Trend:* Unchanging-Deteriorating
Be free from the introduction and spread of invasive species	Invasive Species	*Status:* Poor; *Trend:* Deteriorating
Be free from contaminated groundwater	Groundwater	*Status*: Fair; *Trend*: Undetermined
Be free from other substances, materials or conditions that negatively impact the waters of the Great Lakes	Watershed Impacts and Climate Trends	Watershed Impacts: *Status:* Fair; *Trend:* Unchanging Climate Trends: No Overall Assessment

Lake Assessments

The indicator and sub-indicator information can also be used to determine an overall assessment for each Great Lake. Lake Superior is assessed as Good and Unchanging, and Lakes Michigan, Huron and Ontario are assessed as Fair and Unchanging. Lake Erie is assessed as Poor and Deteriorating, although there are a mix of trends happening in the Lake Erie basin.



See Appendix 3 for Tracking Progress: An Alternate Perspective.

3. Nine Great Lakes Indicators and 44 Sub-Indicators used to Assess and Report on the State of the Great Lakes

GLWQA General Objectives	Indicators	Sub-Indicators
Objective 1: Be a source of safe, high-quality drinking water	Drinking Water	Treated Drinking Water
Objective 2: Allow for swimming and other recreational use, unrestricted by environmental quality concerns	Beaches	Beach Advisories
Objective 3: Allow for human consumption of fish and wildlife unrestricted by concerns due to harmful pollutants	Fish Consumption	Contaminants in Edible Fish
Objective 4: Be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain	Toxic Chemicals	Toxic Chemical Concentrations
		Toxic Chemicals in Sediment
		Toxic Chemicals in Great Lakes Whole Fish
		Toxic Chemicals in Great Lakes Herring Gull Eggs
		Atmospheric Deposition of Toxic Chemicals
Objective 5: Support healthy and productive wetlands and other habitats to sustain resilient populations of native species	Habitat and Species	Coastal Wetland Amphibians
		Coastal Wetland Birds
		Coastal Wetland Fish
		Coastal Wetland Invertebrates
		Coastal Wetland Plants
		Coastal Wetlands: Extent and Composition
		Aquatic Habitat Connectivity
		Phytoplankton
		Zooplankton
		Benthos
		Diporeia
		Prey Fish
		Lake Sturgeon
		Walleye
		Lake Trout
		Fish Eating and Colonial Nesting Waterbirds
Objective 6: Be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem	Nutrients and Algae	Nutrients in Lakes
		Cladophora
		Harmful Algal Blooms
		Water Quality in Tributaries
Objective 7: Be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes	Invasive Species	Impacts of Aquatic Invasive Species
		Dreissenid Mussels
		Sea Lamprey
		Terrestrial Invasive Species
Objective 8: Be free from the harmful impact of contaminated groundwater	Groundwater	Groundwater Quality
Objective 9: Be free from other substances, materials or conditions that may negatively impact the chemical, physical or biological integrity of the Waters of the Great Lakes	Watershed Impacts and Climate Trends	Forest Cover
		Land Cover
		Watershed Stressors
		Hardened Shorelines
		Tributary Flashiness
		Human Population
		Precipitation Amounts
		Surface Water Temperature
		Ice Cover
		Water Levels
		Baseflow Due to Groundwater

4. Indicator Assessment Process

What is an Indicator?

An indicator is a piece of evidence, (e.g. data or measures) that informs about current conditions. Watching the evidence over time gives an indication of trends. Doctors use specific measures such as blood pressure and temperature to assess one's health. To assess large, complex ecosystems such as the Great Lakes, environmental indicators are a useful and accepted approach. Great Lakes indicators are used to:

- Assess conditions and track changes in the ecosystem;
- Understand existing and emerging issues;
- Guide programs and policies needed to prevent or address harmful environmental problems; and,
- Provide information to set priorities for research and program implementation.

Reporting on a suite of Great Lakes indicators produces a big picture perspective on the condition and trends of the complex ecosystem. Indicators have been used to report on Great Lakes ecosystem components since the first State of the Lakes Ecosystem Conference (SOLEC) in 1994.

Why Do We Assess?

When the region became industrialized, the Great Lakes bore the brunt of poor environmental management. However, with the signing of the first GLWQA in 1972, much effort has been made to improve environmental conditions resulting in many successes, but more work is needed. Policies, regulations and programs are in place to address the complex problems that impact the lakes.

Tracking ecosystem conditions is valuable in order to determine if progress towards achieving environmental goals and objectives for the Great Lakes has been made. Are management actions working? Are environmental conditions getting better or worse? To answer questions like these, various components of the ecosystem must be monitored. Using this information, Canada and the United States report on the state of the Great Lakes every three years as part of a commitment under the GLWQA. It is important to remember that the ecosystem is large and complex and it can sometimes take years for the lakes to respond to restoration activities.

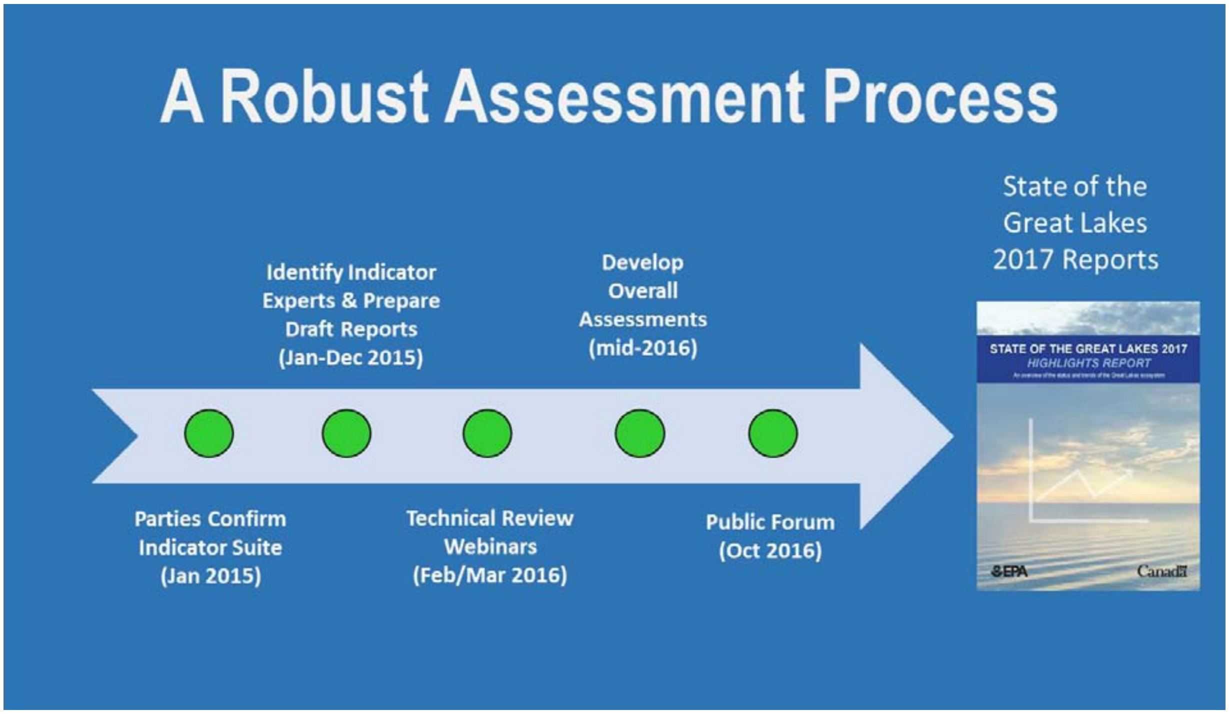
How Do We Assess?

A suite of nine comprehensive, science-based ecosystem indicators, supported by 44 sub-indicators, are used to assess how the Great Lakes are doing. Some indicators are supported by multiple sub-indicators while others are supported by only one sub-indicator. Ecosystem indicators are rated in relation to status using terms of **Good**, **Fair** and **Poor**; and trends using terms of **Improving**, **Unchanging** and **Deteriorating**. Each 3-year reporting cycle, experts prepare assessments using data that in most cases comes from long-term monitoring programs. For this report, the most current available data, generally from 2011 to 2014, have been added to the long-term data. Over 180 experts representing more than 30 different agencies and organizations from Canada and the U.S. contributed to the preparation of the indicators. The *State of the Great Lakes 2017 Highlights Report* is a summary of the information found in the sub-indicator reports which are included in their entirety in the *State of the Great Lakes 2017 Technical Report.* For more information on the assessment approach and definitions, refer to the section in this report entitled, Example Assessments – How are they Done?

State of the Great Lakes Reporting – A Robust Process

The State of the Great Lakes reporting work is led by the EI&R Task Team under the Science Annex (Annex 10) of the GLWQA.

The Great Lakes indicator suite has been reviewed and improved each reporting cycle in order to deliver an improved, updated and representative indicator suite that reports on the state of the Great Lakes in a comprehensive, understandable and scientific manner and allows for informed decision-making in the Great Lakes Basin. The reviews also aim to build consensus on indicators among federal, state, provincial and local management organizations. This consensus is necessary to ensure that all relevant data are being collected, analyzed, and reported in an effective manner as no single organization has the resources or mandate to examine the conditions of the entire Great Lakes ecosystem.



The State of the Great Lakes reporting cycle began in 2014 with a review of the indicators including consideration of comments from various experts and organizations such as the International Joint Commission. In January of 2015, the Parties agreed to nine indicators of ecosystem health to report against the nine General Objectives of the GLWQA. These sub-indicators are in turn supported by 44 sub-indicators.

Next, the sub-indicator authors were identified. Over 100 sub-indicator authors and 80 contributors, representing over 30 agencies and organizations, prepared sub-indicator descriptions and draft assessment reports in 2015[1].
A series of scientific confirmation webinars were held in February and March 2016 to ensure scientific integrity and confidence in the individual sub-indicator assessments and the draft overall indicator assessments.

[1] The EI&R Task Team asked scientists (federal, provincial, state, academia, and others) with knowledge of specific Great Lakes issue areas or ecosystem components to draft or revise a description (the document that guides the content for each sub-indicator report) and a report (assessment of status and trends and ecosystem condition) for each of these sub-indicators. These descriptions and reports are reviewed or prepared by authors at the beginning of each reporting cycle to ensure a comprehensive assessment of the conditions of the Great Lakes ecosystem. As part of this process, future considerations and recommendations were included in the descriptions where possible, i.e. reference to nearshore components, consideration of Chemicals of Mutual Concern, etc. IJC recommendations from the Great Lakes Ecosystem Indicator Project Report (June 2014) and the Recommended Human Health Indicators for Assessment of Progress on the GLWQA (June 2014), where feasible and appropriate, were also considered in updating the descriptions.

Part of the review also included considering ways to streamline the suite of indicators for reporting on the state of the Great Lakes. The "indicator categories" previously used are now referred to as "indicators"; prior reference to "indicators" will now be referred to as "sub-indicators". For this reporting cycle (2016-2017), there are 44 sub-indicators that support the nine high-level indicators. These nine high-level indicators are aligned to the General Objectives of the Agreement; however some General Objectives are broader than the current sub-indicators aligned to them. Therefore, further refinement of these indicators may be necessary in the future.

A series of scientific confirmation webinars were held in February and March 2016 to ensure scientific integrity and confidence in the individual sub-indicator assessments and the draft overall indicator assessments.

The draft indicator assessments were presented at the Great Lakes Public Forum in October 2016. The Forum provided an opportunity for the United States and Canada to discuss and seek public comment on the draft state of the lakes assessments. The draft indicator and supporting sub-indicator assessments were then finalized and form the basis of this technical report and the *State of the Great Lakes 2017 Highlights Report*. For more information on the Forum visit: https://binational.net/2016/11/25/glpf-fpgl-2016-presentations-videos/.

Confidence in the Assessments

By involving hundreds of experts and the public from the Great Lakes community, there is high confidence in the indicator assessments. Over 150 subject matter experts participated in the scientific confirmation webinars. These webinars evaluated draft environmental sub-indicator reports used to assess the status of the Great Lakes Basin as well as reviewed the compiling of the sub-indicators into overall indicator assessments. Draft status and trend assessments for sub-indicators and indicators were prepared using binational readily available data and best professireplacement onal judgment. For more information about data quality see Appendix 1.

In addition to the scientific confirmation review, hundreds of public participants saw the presentation of the draft assessments at the Public Forum and via an online webinar. All the authors of the sub-indicator reports also had an opportunity to complete a technical review of the draft Highlights report in December of 2016. A red-flag review, the last step in the review process, was completed prior to releasing the *State of the Great Lakes 2017 Highlights Report* to ensure there were no critical errors. This red-flag review was sent to GLWQA stakeholders and Great Lakes experts.

Example Assessments – How are they Done?

Status:

GOOD FAIR POOR

INDICATOR	SUB-INDICATOR	GREAT LAKES BASIN	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	LAKE ERIE	LAKE ONTARIO
High-Level Indicator 1	Sub-indicator A	Unchanging	Unchanging	Improving	Unchanging	Unchanging	Improving
	Sub-indicator B	Improving	Improving	Improving	Improving	Unchanging	Unchanging
	Sub-indicator C	Unchanging	Improving	Unchanging	Unchanging	Unchanging	Unchanging
	Sub-indicator D	Improving	No lake was assessed separately Great Lakes Basin assessment is Fair and Improving				
	Sub-indicator E	Improving	Unchanging	Unchanging	Unchanging	Improving	Improving
	Sub-indicator F	Undetermined	Undetermined	Undetermined	Undetermined	Undetermined	Undetermined

Identifying binational assessments for each high-level indicator and General Objective is a multi-step process.

The authors are asked to assess a status and trend for the Great Lakes Basin as well as each lake for their respective sub-indicators. In some cases, the author is unable to make a determination for each lake (see Sub-indicator D) and may only be able to assess the whole Great Lakes Basin.

The status rankings are Good, Fair and Poor and are denoted by the colours green, yellow and red respectively. There is one additional ranking for status called Undetermined and it is denoted by a grey colour.

The trend rankings are Improving, Unchanging, Deteriorating and Undetermined - denoted by the words in each of the coloured cells. See the Status and Trend definitions in Appendix 2.

The Great Lakes Basin assessment for each sub-indicator should correspond with an average, of sorts, of the five individual lake assessments. Best professional judgement by the authors is also an important part of determining the overall Great Lakes Basin assessment for each sub-indicator.

Status:

GOOD	FAIR	POOR

INDICATOR	SUB-INDICATOR	GREAT LAKES BASIN	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	LAKE ERIE	LAKE ONTARIO
High-Level Indicator 1	Sub-indicator A	Unchanging	Unchanging	Improving	Unchanging	Unchanging	Improving
	Sub-indicator B	Improving	Improving	Improving	Improving	Unchanging	Unchanging
	Sub-indicator C	Unchanging	Improving	Unchanging	Unchanging	Unchanging	Unchanging
	Sub-indicator D	Improving	No lake was assessed separately Great Lakes Basin assessment is Fair and Improving				
	Sub-indicator E	Improving	Unchanging	Unchanging	Unchanging	Improving	Improving
	Sub-indicator F	Undetermined	Undetermined	Undetermined	Undetermined	Undetermined	Undetermined

Overall Assessment = FAIR and UNCHANGING

An overall assessment for "High-Level Indicator 1" needs to be determined. This overall assessment is calculated by using a simple tally method of all the lake assessments from the six sub-indicators.

In this example, there are 10 Good status assessments (the green boxes), 19[2] Fair assessments (the yellow boxes), and 1 Poor assessment (the red box). There are 13[3] Improving trends, 12 Unchanging trends, 0 Deteriorating trends and 5 Undetermined trends. The Overall assessment for this high-level indicator would be Fair and Unchanging-Improving, since there are equal or near equal trend determinations of Unchanging and Improving.

Undetermined status and/or trends are included in the determination of the assessments if data are insufficient to make a status assessment or because of a variety of trends being seen. However, in the case where Undetermined was used by the authors as a result of no data, then these "Undetermined" assessments are not used in the tallying process.

[2] In the case where only an overall Great Lakes Basin sub-indicator assessment is provided by the authors, for the purpose of calculating the overall indicator assessment, the Great Lakes Basin assessment is also applied to each lake basin in the tallying exercise.
[3] Ibid

5. State of the Great Lakes

This chapter includes the nine high level indicator assessment followed by the supporting sub-indicator assessments. These indicators are used to report on progress towards achieving the General Objectives of the Great Lakes Water Quality Agreement.

Drinking Water

Status: Good   Trend: Unchanging

Nearly 30 million Americans and the majority of the 11 million Canadians living in the basin get their drinking water from the Great Lakes.

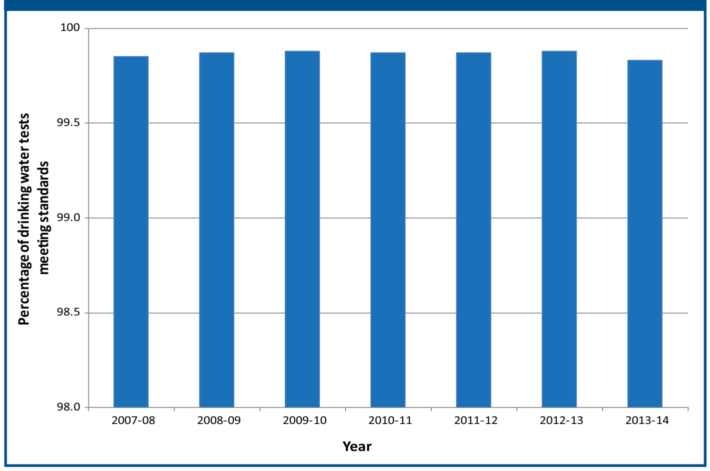
The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should be a source of safe, high-quality drinking water"*

Assessment Highlights

The Drinking Water indicator shows that the status of treated drinking water in both Canada and the U.S. is **Good** and the trend is **Unchanging** since the last report in 2011. This shows that the Great Lakes continue to be a high-quality source of drinking water; however, as with all source waters, water from the Great Lakes must be treated to make it safe to drink.

Ontario and U.S. state agencies have different ways of analyzing and reporting on the quality of treated drinking water, however, both compare microbial, radiological and chemical parameters in treated drinking water to health-based standards. In the Province of Ontario, almost 60% of the population gets their drinking water from the Great Lakes and treated water tests met Ontario Drinking Water Quality Standards 99.83% - 99.88% of the time from 2007 to 2014. In the U.S., 95 - 97% of the U.S. population living within the Great Lakes Basin, or approximately 27 million people, were serviced with drinking water that met all applicable health-based drinking water quality standards from 2012 to 2014.

Percentage of Canadian Drinking Water Tests Meeting Standards



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Treated Drinking Water	No lake was assessed separately Great Lakes Basin assessment is **Good** and **Unchanging**				

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Treated Drinking Water

Overall Assessment
Status: Good
Trend: Unchanging
Rationale: The overall quality of source water and treated water in the Ontario portion of the Great Lakes Basin is good. Throughout the period 2007 – 2014, Ontario's source water monitoring network rarely found source water chemical contaminant levels above Ontario drinking water quality standards (ODWQS), and never found source water radiological contaminant levels above ODWQS. From 2005 – 2014, the percentage of treated water test results that exceeded ODWQS was consistently low.

Overall, over 95% of the total human population living in the Great Lakes States of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin are served by compliant water supply systems that met health-based drinking water quality standards for years 2012, 2013 and 2014. The trend is "unchanging" with no significant increase or decrease in treated drinking water quality based on calculated indices of 98.6% (2012), 97.4% (2013) and 97.8% (2014) for the Great Lakes States.

Lake-by-Lake Assessment
Individual lake basin assessments were not prepared for this report.

Sub-Indicator Purpose
The purposes of this sub-indicator are to:

- Assess chemical, microbial and radiological contaminant levels in drinking water;
- Evaluate the potential for human exposure to drinking water contaminants; and,
- Evaluate the efficacy of policies and technologies to ensure safe drinking water.

Ecosystem Objective
Treated drinking water supplies should be free from harmful chemical, microbial and radiological contaminants and be safe to drink.

This sub-indicator best supports work towards General Objective #1 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be a source of safe, high-quality drinking water.

Ecological Condition
Even good quality source water requires treatment to make it safe to drink. To lower the risk of source water contamination reaching consumers' taps, and to keep drinking water treatment costs as low as possible, continual efforts should be made to decrease microbial, chemical and radiological contamination of source water.

Ontario
The Ontario Ministry of the Environment and Climate Change provided the data for the Canadian component of this report. The Ministry's Drinking Water Surveillance Program (DWSP) provided source water data and the Ministry's Drinking Water Management Division provided treated drinking water data. DWSP is a scientific, voluntary program run in partnership with municipalities and First Nations. Drinking Water Management Division has lead responsibility for program and operational activities related to the protection and provision of safe drinking water in Ontario, from source to tap. The source water data is from select municipal residential and First Nation drinking water systems. The treated water data is from all municipal residential drinking water systems, and therefore represents the vast majority of water consumed by Ontarians; note however that it does not include data from private water systems and small non-municipal systems. Both the source water data and the treated water data are from systems whose sources include not only the Great Lakes, but also inland lakes, rivers and groundwater.

This report compares source water and drinking water sample results to the Ontario Drinking Water Quality Standards (ODWQS). The ODWQS are Ontario's human health standards for microbial, chemical and radiological parameters in treated drinking water.

Source Water

Good quality source water is an important part of the drinking water safety net. Drinking water sources in the Great Lakes Basin include the Great Lakes, inland lakes, rivers and groundwater. Potential contaminants of drinking water sources include microbes, chemicals and radioactive substances. Source water must be treated to make it safe to drink. Generally, surface water requires more extensive treatment than groundwater.

Table 1 presents source water results from DWSP for thirteen parameters and a radiation screening test. The Ontario portion of the sub-indicator report compares source water contaminant levels to treated water quality standards.The first twelve parameters (arsenic to uranium) are chemical parameters. They were chosen because they have occurred at high concentrations in source water in the U.S. or Canada, or because they represent a class of contaminants (atrazine for pesticides and microcystin-LR for algal toxins). The thirteenth parameter, tritium, is a radiological parameter and was included to examine potential impacts from the nuclear power industry. The radiation screening test determined whether any other radiological parameters exceeded ODWQS. Source water monitoring did not include microbial parameters. In general, microbes account for a significant portion of all occurrences of parameter levels above ODWQS.

The number of drinking water systems whose source water data is summarized in Table 1 ranged from 118 in 2007 (116 municipal residential systems and 2 First Nations systems) to 109 in 2014 (106 municipal residential systems and 3 First Nations systems). In the period 2007 – 2014, the only parameters that had source water concentrations greater than ODWQS were fluoride, lead, selenium, trichloroethene and nitrilotriacetic acid. Whenever high levels of a given parameter occurred in more than one year, they were always repeat occurrences at the same one or two drinking water systems. The high concentrations of fluoride, lead, selenium and trichloroethene occurred in groundwater and the high concentrations of nitrilotriacetic acid occurred in surface water. The high fluoride, lead and selenium concentrations were caused by naturally occurring geologic deposits. In total, from 2007 – 2014, seven drinking water systems (6% of systems) had occurrences of source water concentrations greater than ODWQS. There are no atrazine results for 2012 – 2014 because DWSP did not monitor pesticides in that period.

In summary, the percentage of drinking water systems with source water chemical concentrations greater than ODWQS was low in the period 2007-2014. No radiological parameters were found at levels above ODWQS. Ontario's source water quality is good.

Treated Water

Figure 1 presents treated water test results for the period 2004 – 2014. Results are from all of Ontario's municipal residential drinking water systems. The number of municipal residential systems in Ontario ranged from 729 in 2004 to 665 in 2014, due mainly to amalgamation of systems. Since 2005-06, the percentage of tests meeting ODWQS has remained steady in the range 99.83% - 99.88%. Ontario's treated drinking water quality is good.

Table 2 presents a breakdown by parameter type of the percentage of test results from municipal residential systems meeting ODWQS. The percentage of tests that met standards was higher for microbial parameters than for chemical parameters. All radiological tests met standards. Disinfection byproducts are included in the chemical parameter category. A significant percentage of the chemical parameter exceedances of ODWQS (disinfection by-products for example) were caused by water treatment, and are not a reflection of the ecological health of source water.

United States

The information provided by the United States for this report focuses on finished, or treated, drinking water. In the United States, the Safe Drinking Water Act Reauthorization of 1996 requires all drinking water utilities to provide yearly water quality information to their consumers. To satisfy this obligation, U.S. water utilities produce an annual Consumer Confidence/Water Quality Report (CC/WQR). These reports provide information regarding source water type (i.e., surface water, groundwater); the availability of source water assessments; and, a brief summary of drinking water systems' susceptibility to:

- Potential sources of contamination;
- The water treatment process;
- Contaminants detected in finished drinking water;
- Violations that occurred; and,
- Other relevant information.

Records of the number and type of health-based violations are also recorded in the nationwide U.S. EPA Safe Drinking Water Information System (SDWIS). Health-based violations in the U.S. include violations of: a Maximum Contaminant Level (MCL) (the highest level of a contaminant that is allowed in drinking water); a Maximum Residual Disinfectant Level (MRDL) (the highest level of a disinfectant allowed in drinking water); and, Treatment Technique (TT) (a required process intended to reduce the level of contaminants in drinking water). (SOGL 2011 Report, Drinking Water Quality, Pg. 235)

In 2012, the total human population living in Great Lakes Basin counties in the States of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin was 26,857,596 and was served by a total of 4,292 water supply systems. It is important to note that not everyone living in a boarder county in which the Great Lakes Basin boundary goes through gets Great Lakes water, therefore, these population numbers are not representative of the number of people who draw their drinking water from the Great Lakes.

97.1% of the total population had drinking water meeting all applicable health-based drinking water quality standards with 94.2% of the water supply systems in compliance with drinking water quality regulations.

The overall treated drinking water index was 98.6%.

The range of calculated indices for treated drinking water quality was 95.9% (Wisconsin) and 99.4% (Indiana). The overall calculated index of 98.6% corresponds to a status of “Good” because at least 95% of person months for all health-based standards for drinking water were met for 2012.

Similarly in 2013, the total human population living in the Great Lakes Basin counties of the eight Great Lakes States was 26,319,447 and was served by a total of 4,238 water supply systems. 95.7% of the total population had drinking water meeting all health-based drinking water quality standards with 94% of the water supply systems in compliance with drinking water quality regulations.

The range of calculated indices was between 93.9% (Illinois) and 99.8% (Minnesota and Pennsylvania) for 2013. The overall treated drinking water index of 97.4%, calculated in “person-month violations” relative to “person-months” with no violations, corresponds to a status of “Good” for 2013.

In 2014, the total human population living in the Great Lakes Basin counties of the eight Great Lakes States is 26,672,882 and is served by a total of 4,148 water supply systems. 95.4% of the total population had drinking water that met all health-based drinking water quality standards with 93.8% of the water supply systems in compliance with drinking water regulations.

The range of calculated indices was between 94% (Ohio) and 99.8% (Pennsylvania) for 2014. The overall calculated index is 97.8% with a status of “Good” for treated drinking water quality in Great Lakes States in 2014.

Figure 2 shows overall person-months minus the sum of person-month violations/overall person months. Figure 3 shows the average % that community drinking water systems and population did not have any health based violations in U.S. Great Lakes counties.

Conversely, Figure 4 is a comparative breakdown by Great Lakes States of the total number of human population impacted by drinking water quality exceedances in Great Lakes states in 2012, 2013, and 2014. On average, 255 or 6% of the total water supply systems in the Great Lakes states incurred health-based system violations that are caused by exceedances in either chemical, microbiological, radiological, disinfection-by-products, and treatment technique parameters in years 2012, 2013, and 2014. Figure 5 is a percentage breakdown by type of drinking water quality exceedances resulting in water supply system violations for years 2012, 2013 and 2014 in Great Lakes States.

Linkages

Following is a brief discussion of other Great Lakes sub-indicators that can influence drinking water quality. In general, the quality of treated drinking water can be linked with other sub-indicators and may be negatively impacted by the demands of an ever increasing human population.

The Groundwater Quality sub-indicator is important because many municipalities obtain their drinking water from groundwater. Water Quality in Tributaries is important because some municipalities use tributaries as their drinking water source and because tributaries are the main route by which contaminants reach the Great Lakes. Related to this sub-indicator are the sub-indicators Precipitation Amounts in the Great Lakes Basin, Watershed Stressors, Forest Cover, Land Cover and Tributary Flashiness because these sub-indicators influence the potential for contaminants to wash into tributaries and to reach drinking water intakes in tributaries and in the Great Lakes. Harmful Algal Blooms can cause algal toxin contamination of drinking water sources, and by extension the related sub-indicators of Nutrients in Lakes and Surface Water Temperature are important to drinking water quality. Atmospheric Deposition of Toxic Chemicals and Toxic Chemical Concentrations (Open Water) can influence toxics concentrations at drinking water intakes.

This sub-indicator also links directly to the other human health related sub-indicators including Beach Advisories and Contaminants in Edible Fish.

Comments from the Author(s)

It would be beneficial for both the United States and Canada to continue efforts in arriving at an agreed-upon and standardized methodology in assessing drinking water quality in the Great Lakes for comparability of metrics. Assessment of drinking water quality status and trend is the same as previous reporting.

Assessing Data Quality (Ontario)

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		X				
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Assessing Data Quality (U.S.)

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		X				
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		X				
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				

6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report			X*			
Clarifying Notes: * = U.S. EPA is aware of inaccuracies and underreporting of some data in the U.S. EPA Safe Drinking Water Information System. U.S. EPA is working with the states to improve the quality of the data.						

Acknowledgments

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Last Updated

State of the Great Lakes 2017 Technical Report

	2007	2008	2009	2010	2011	2012	2013	2014
Arsenic	100%	100%	100%	100%	100%	100%	100%	100%
Atrazine	100%	100%	100%	100%	100%	---	---	---
Barium	100%	100%	100%	100%	100%	100%	100%	100%
Fluoride	99%	99%	99%	99%	99%	99%	99%	99%
Lead	99%	99%	100%	100%	99%	100%	100%	100%
Microcystin-LR	100%	100%	100%	100%	100%	100%	100%	100%
Nitrilotriacetic acid	100%	98%	100%	100%	100%	100%	100%	100%
Nitrate	100%	100%	100%	100%	100%	100%	100%	100%
Nitrite	100%	100%	100%	100%	100%	100%	100%	100%
Selenium	99%	99%	99%	99%	99%	99%	99%	99%
Trichloroethene	97%	99%	98%	98%	98%	98%	98%	99%
Uranium	100%	100%	100%	100%	100%	100%	100%	100%
Tritium	100%	100%	100%	100%	100%	100%	100%	100%
Other radiological	100%	100%	100%	100%	100%	100%	100%	100%

Table 1. Percentage of drinking water systems where DWSP source water results for select parameters met Ontario Drinking Water Quality Standards.

Source: Ontario Ministry of the Environment and Climate Change, Drinking Water Information Management System

Parameter Type	2010-11	2011-12	2012-13	2013-14
Microbial	99.90%	99.89%	99.90%	99.85%
Chemical	99.67%	99.69%	99.76%	99.68%
Radiological	100.00%	100.00%	100.00%	100.00%
Total	**99.87%**	**99.87%**	**99.88%**	**99.83%**

Table 2. Breakdown by parameter type and year of the percentage of drinking water test results from municipal residential systems meeting Ontario Drinking Water Quality Standards.

Sources:

Ontario Ministry of the Environment and Climate Change, *Chief Drinking Water Inspector Annual Report, 2013 – 2014*, https://archive.org/details/annualreport201200onta22405_201508

Ontario Ministry of the Environment and Climate Change, *Chief Drinking Water Inspector Annual Report, 2012 – 2013*, https://archive.org/details/annualreport201200onta22405

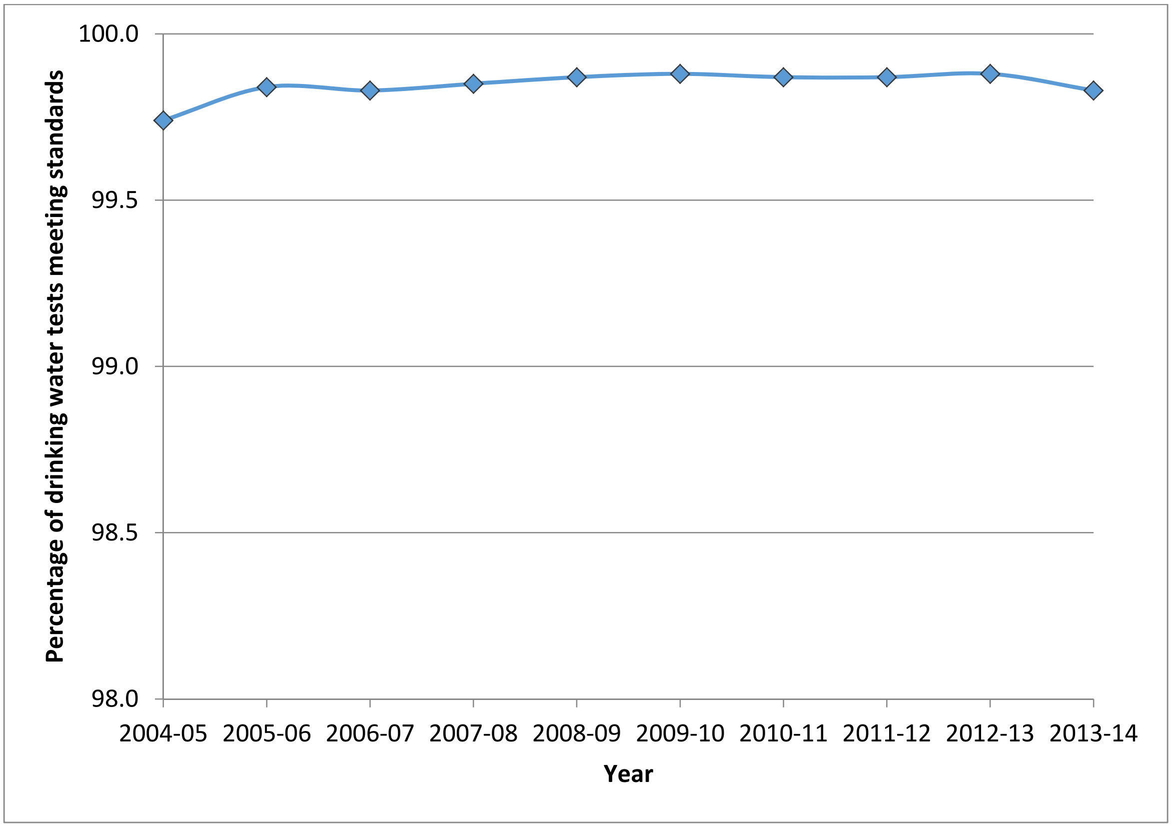


Figure 1. Trend in percentage of treated drinking water tests meeting Ontario Drinking Water Quality Standards, for municipal residential drinking water systems.
Sources:
Ontario Ministry of the Environment and Climate Change, *Chief Drinking Water Inspector Annual Report, 2013 – 2014*, https://archive.org/details/annualreport201200onta22405_201508
Ontario Ministry of the Environment and Climate Change, *Chief Drinking Water Inspector Annual Report, 2010 – 2011*, https://archive.org/details/annualreport201000snsn21683

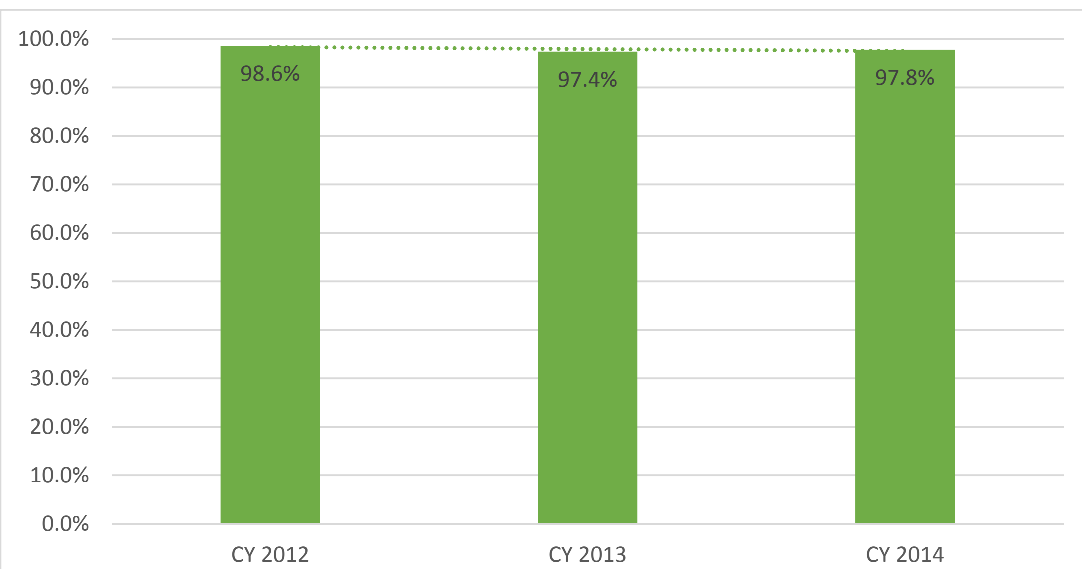


Figure 2. Overall person-months minus the sum of person-month violations/overall person months
Source: U.S. EPA Safe Drinking Water Information System

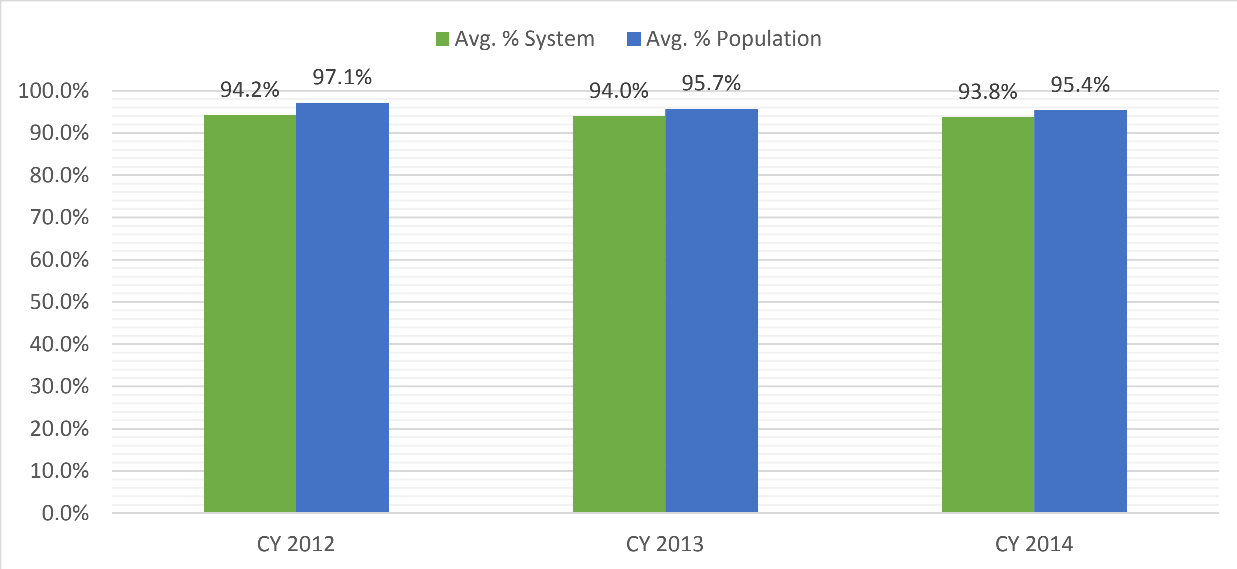


Figure 3. Average % community drinking water systems and population that did not have any health based violations in U.S. Great Lakes counties.
Source: U.S. EPA Safe Drinking Water Information System

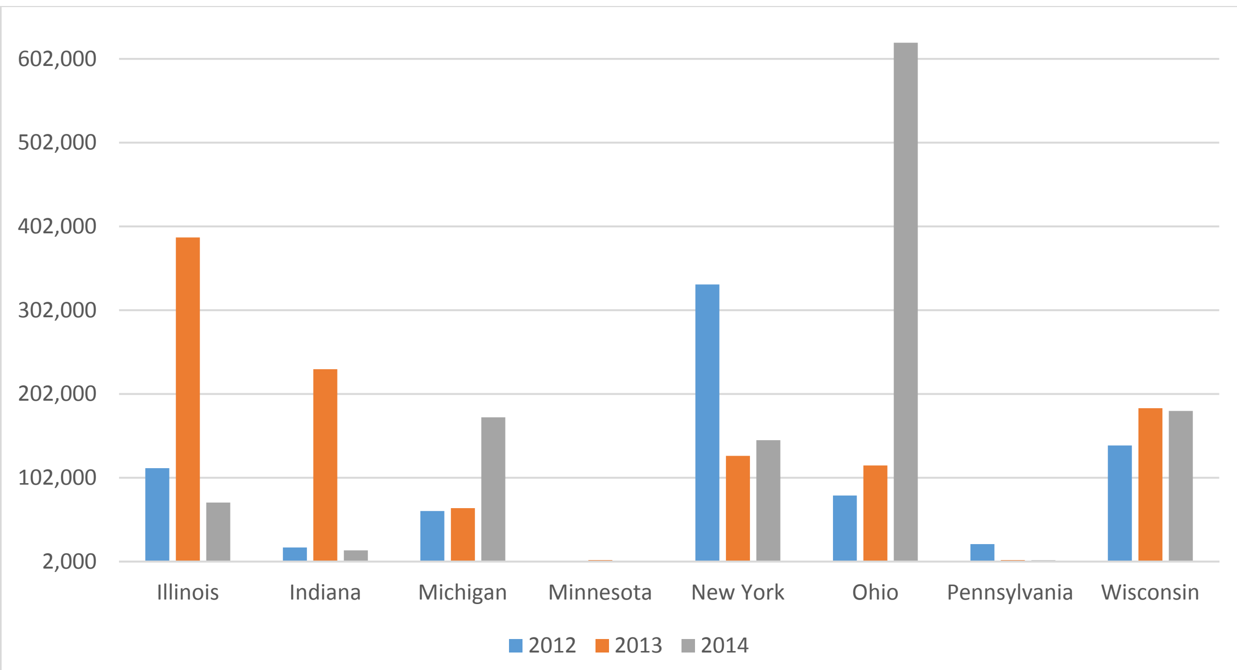


Figure 4. Comparative breakdown of total number of human population living in Great Lakes States impacted by drinking water quality exceedances in 2012, 2013 and 2014.
Source: U.S. EPA Safe Drinking Water Information System

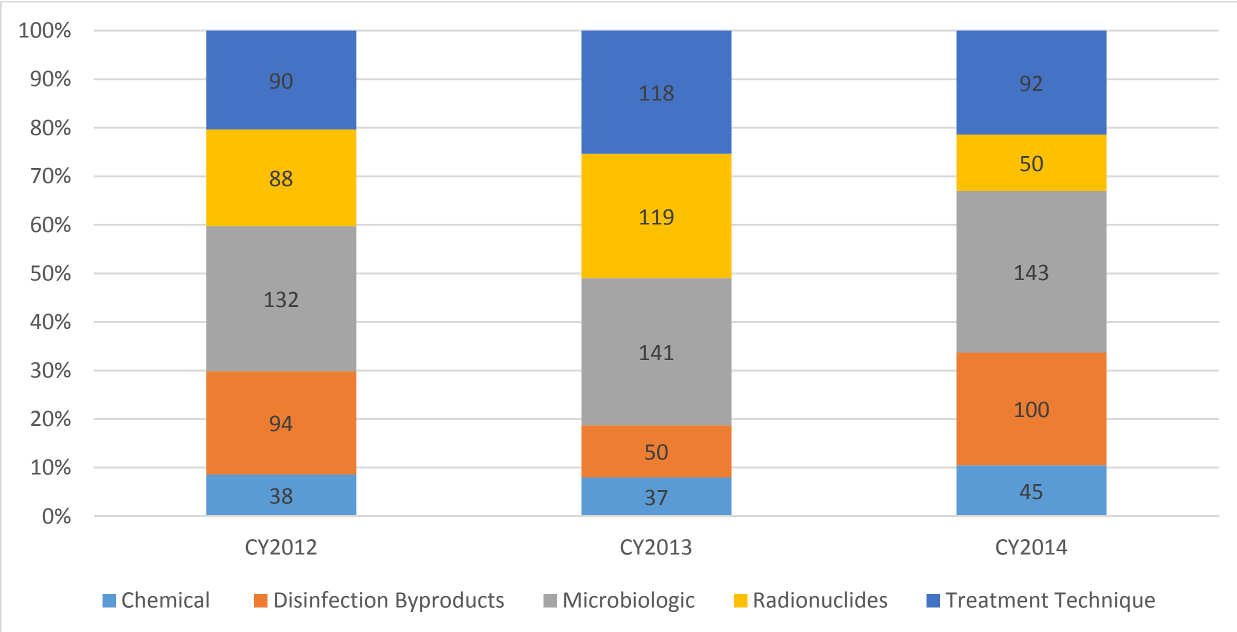
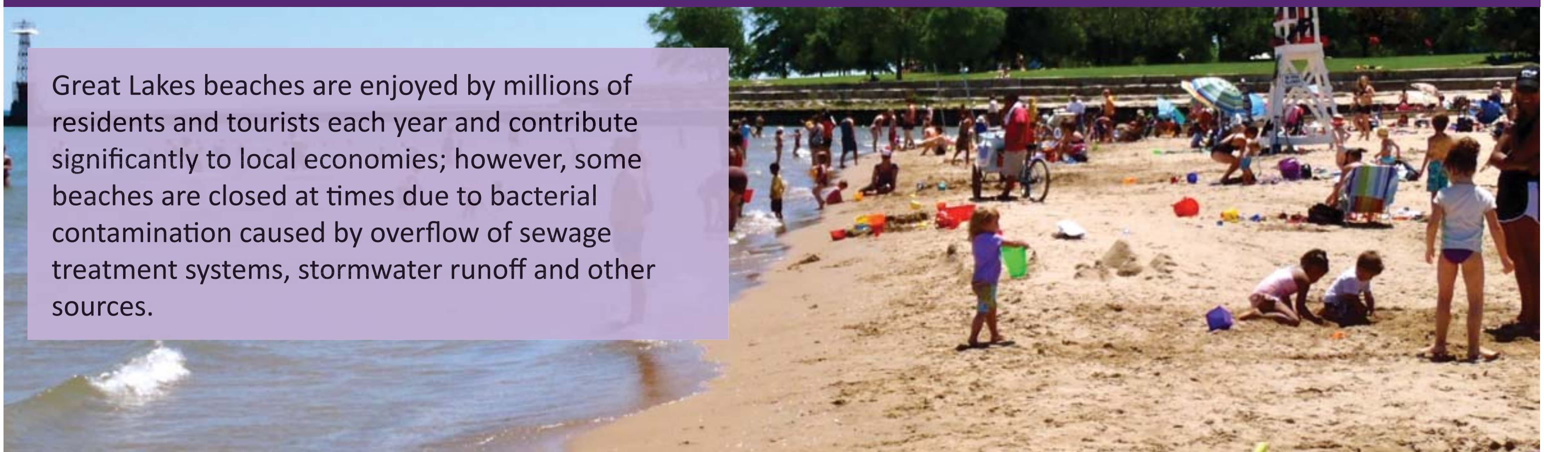


Figure 5. Percentage of health based exceedances caused by chemical, microbiological, radiological, disinfection by-products and treatment technique parameters.
Source: U.S. EPA Safe Drinking Water Information System

Beaches

Status: Fair to Good   Trend: Unchanging



Great Lakes beaches are enjoyed by millions of residents and tourists each year and contribute significantly to local economies; however, some beaches are closed at times due to bacterial contamination caused by overflow of sewage treatment systems, stormwater runoff and other sources.

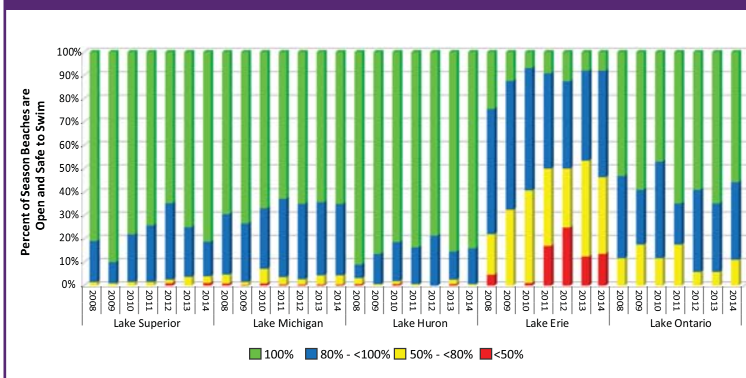
The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should allow for swimming and other recreational use, unrestricted by environmental quality concerns"*

Assessment Highlights

The overall status of Beaches is **Fair** to **Good** and the trend is **Unchanging** since 2011. The Beaches indicator shows that many monitored beaches in the Great Lakes are safe for swimming and recreational use throughout most of the swimming season.

The U.S. and Canada use different bacterial standards or criteria to determine when a beach is unsafe for swimming or other recreational activities. The Ontario standards are more stringent and therefore Ontario often has more beach health advisories issued. Approximately 1,000 beaches along the Great Lakes shoreline are monitored for the fecal bacteria indicator *E. coli* each year. Over the 2011 to 2014 time period, the percentage of days that monitored Canadian Great Lakes beaches met Ontario bacterial standards for swimming averaged 78%. The U.S. Great Lakes beaches monitored during this same time period were open and safe for swimming 96% of the time on average. However, the status of Lake Erie beaches in Canada and the U.S. has deteriorated from the previous 2008 to 2010 reporting period. Sources of *E. coli* for all of the Great Lakes can include wastewater treatment plants, runoff from the land after a heavy rainfall, improperly working septic systems, and even large flocks of gulls.

U.S. Great Lakes Beaches: Percent of Season Open By Lake



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Beach Advisories	Unchanging	Unchanging	Unchanging	Deteriorating	Unchanging

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Beach Advisories

Overall Assessment

Status: Fair-Good
Trend: Unchanging
Rationale: The percentage of days that monitored U.S. Great Lakes beaches that were open and safe for swimming during 2011-2014 is an average of 96% of the swimming season. The trend shows slightly deteriorating conditions from 97% in 2008-2010. The percentage of days that monitored Canadian Great Lakes beaches met Ontario bacterial standards for swimming during the 2011--2014 period is an average of 78%. Differences in the percentage of open and posted beaches between the U.S. and Canada may reflect differing posting criteria.

Lake-by-Lake Assessment

Lake Superior

Status: Good
Trend: Unchanging
Rationale: During 2011 through 2014, the percentage of days that U.S. Lake Superior monitored beaches were open and safe for swimming is an average of 98% of the swimming season. The trend shows slightly deteriorating conditions from 99% in 2008-2010. Efforts to identify and remediate sources of contamination continue to be conducted at Lake Superior beaches. In Canada, during 2011 through 2014, the percentage of days that monitored Lake Superior beaches were open and safe for swimming is an average of 89% of the swimming season. The trend shows slightly improving conditions, from 88% in 2008-2010.

Lake Michigan

Status: Good
Trend: Unchanging
Rationale: During 2011 through 2014, on average, the percentage of days that Lake Michigan monitored beaches were open and safe for swimming is an average of 97% of the swimming season. The trend shows unchanging conditions from 97% in 2008-2010. Efforts to identify and remediate sources of contamination continue to be conducted at Lake Michigan beaches.

Lake Huron

Status: Good
Trend: Unchanging
Rationale: During 2011 through 2014, the percentage of days that U.S. monitored Lake Huron beaches were open and safe for swimming is an average of 99% of the swimming season. The trend shows unchanging conditions from 99% in 2008-2010. Efforts to identify and remediate sources of contamination continue to be conducted at Lake Huron beaches. In Canada, during 2011 through 2014, the percentage of days that monitored Lake Huron beaches were open and safe for swimming is an average of 82% of the swimming season. The trend appears to be slightly deteriorating from 83% in 2008-2010.

Lake Erie

Status: Poor
Trend: Deteriorating
Rationale: During 2011 through 2014, the percentage of days that U.S. monitored Lake Erie beaches that were open and safe for swimming is an average of 75% of the swimming season. The trend shows deteriorating conditions from 85% in 2008-2010. Efforts continue to be conducted to identify and remediate sources of contamination at Lake Erie beaches. In Canada, during 2010 through 2014, the percentage of days that Lake Erie monitored beaches were open and safe for swimming is an average of 69% of the swimming season. The trend appears to be deteriorating from 78% in 2008-2010.

Lake Ontario
Status: Fair-Good
Trend: Unchanging
Rationale: During 2011 through 2014, the percentage of days that U.S. monitored Lake Ontario beaches were open and safe for swimming is an average of 94% of the swimming season. The trend shows slightly improving conditions from 93% in 2008-2010. Efforts continue to be conducted to identify and remediate sources of contamination at Lake Ontario beaches. In Canada, during 2011 through 2014, the percentage of days that Lake Ontario monitored beaches were open and safe for swimming is an average of 77% of the swimming season. The trend appears to be improving from 75% in 2008 – 2010.

Sub-Indicator Purpose

- To assess the number of days that Great Lakes beaches are open and safe for swimming by assessing the health-
  related swimming posting (advisories or closings) days for recreational areas (beaches).
- To infer potential harm from pathogens to human health through body contact with nearshore recreational waters.

Ecosystem Objective

Waters should be safe for recreational use. Waters used for recreational activities involving body contact should be substantially free from pathogens, including bacteria, parasites, and viruses, that may harm human health. This indicator supports Annexes 1 and 2 of the GLWQA (2012).

Ecological Condition

Measure

Please note that for consistency, all results from 1999-2006 for Great Lakes beaches have been recalculated and reassessed based on the new beach sub-indicator reporting method presented in the last 2011 report. Beach advisories are now calculated based on the number of days a monitored beach is open and safe for swimming during the summer season rather than assessing the percentage of monitored and non-monitored beaches that are open 95% of the swimming season. Only those beaches that are monitored by beach safety programs are included in the analysis. It should also be noted that the statistics have changed from the 2011 *State of the Great Lakes* report due to the new reporting methods used in this report, i.e. previous reports may have shown a higher percentage of beaches that were open for swimming and meeting bacterial standards.

The measure is the percentage of days in the beach season that monitored Great Lakes beaches are open and safe for swimming. For example, a sentence stating "93% of beaches were open and safe for swimming" does not indicate that the beaches were open 93 days of the season; it indicates that the beaches were, on average, open and safe for swimming 104 days out of the 112 days in the swimming season (i.e. 93%). The beach season is generally from the Memorial Day/Victoria Day weekend to Labor Day; however, some health units/counties vary so all beach days that are reported on by counties and health units will be used.

Endpoint

For each Canadian lake basin, the status will be considered GOOD if 80% or more of the beach season for monitored Great Lakes beaches are open and safe for swimming. If only 70-79.9% of beaches are open and safe for swimming during the Canadian beach season, then the status will be considered FAIR; if less than 70% of beaches are open and safe for swimming during the Canadian beach season, then the status will be considered POOR.

For each U.S. lake basin, the status will be considered good if 90% or more of the monitored Great Lakes beaches are open and safe for swimming. If only 80 – 89% of beaches are open and safe for swimming, then the status will be considered FAIR; if less than 80% of beaches are open and safe for swimming, then the status will be considered POOR.

Background

Beach monitoring is conducted primarily to detect bacteria that indicate the possible presence of disease-causing microbes (pathogens) from fecal pollution. People swimming in water contaminated with pathogens can contract diseases of the gastrointestinal tract, eyes, ears, skin, and upper respiratory tract. When monitoring results reveal elevated levels of indicator bacteria, the state or local government/health units issue a beach advisory or closure notice until further sampling shows that the water quality is meeting the applicable water quality standards.

A health-related advisory day is one that is based upon elevated levels of *E. coli*, or other indicator organisms, as reported by county health departments (U.S.), Boards of Health (Ontario), or municipal health departments in the Great Lakes Basin. *E. coli*, Enterococci, and other microorganisms are measured in beach water samples because they act as indicators for the potential presence of pathogens which could harm human health through body contact with nearshore recreational waters.

The Ontario provincial standard is 100 *E. coli* colony forming units (cfu) per 100 mL, based on the geometric mean (GM) of a minimum of one sample per week from each of at least 5 sampling sites per beach (Recreational Water Protocol, 2014). The Beach Management Protocol states that beaches of 1000 meters of length or greater require one sampling site per 200 meters, with a minimum of 5 samples taken at each site (Beach Management Guidance Document, 2014). In some cases local Health Units in Ontario have implemented a more frequent sampling procedure than is outlined by the provincial government. When *E. coli* levels exceed the standard, beach waters are posted as unsafe for the health of bathers until further sampling shows that the water quality is meeting the applicable water quality standards. The average swimming season in Ontario begins at the end of May and continues until the first weekend in September, but some health units may have a longer or shorter season than the norm. The difference in the swimming season length, the number of beaches sampled each season, as well as the frequency of sampling are all factors that may skew the final result of the percent of beaches open and safe for swimming throughout the season.

In the U.S., the U.S. Environmental Protection Agency (U.S. EPA) suggests the use of a Beach Action Value (BAV) to make beach advisory or closure decisions. Any single sample above the BAV could trigger a beach notification until another sample below the BAV is collected. U.S. EPA's recommended BAVs are outlined in U.S. EPA's Recreational Water Quality Criteria (RWQC) which were revised in December, 2012, in accordance with the Beaches Environmental Assessment and Coastal Health (BEACH) Act. The revised criteria reflect the latest scientific knowledge and are designed to protect the public from exposure to harmful levels of pathogens while participating in water-contact activities.

U.S. EPA's revised RWQC correspond to two different illness rates that states must select and apply at their inland and coastal recreation waters. U.S. EPA suggests that a state's chosen criterion illness rate be used to determine the corresponding BAV. Based on an estimated illness rate of 36 per 1,000 primary contact recreators, EPA recommends a BAV of 235 *E. coli* cfu per 100 mL or 70 Enterococci cfu per 100 mL. Based on an estimated illness rate of 32 per 1,000 primary contact recreators, EPA recommends a BAV of 190 *E. coli* cfu per 100 mL or 60 Enterococci cfu per 100 mL (U.S. EPA Recreational Water Quality Criteria 2012). The State of Michigan uses 130 *E. coli* cfu per 100 mL as a 30-day GM, and a maximum of 300 *E. coli* cfu per 100 mL based on the GM of three or more samples taken during the same sampling event at representative locations within a defined sampling area, to make beach notification decisions.

U.S. EPA is authorized by the BEACH Act to award grants to coastal and Great Lakes states, territories and eligible tribes to help local authorities monitor their coastal and Great Lakes beaches and notify the public of water quality conditions that may be unsafe for swimming. Great Lakes beach managers are able to regularly monitor beach water quality and advise bathers of potential risks to human health when water quality standards for bacteria are exceeded. When levels of fecal indicator bacteria exceed a state's BAV, swimming at beaches is prohibited or advisories are issued to inform beachgoers that swimming may be unsafe. The swimming season starts Memorial Day weekend and ends on Labor Day. The U.S. EPA provides publicly-accessible data about beach closings and advisories for U.S. coastal beaches at its Beach Advisory and Closing On-line Notification (BEACON) system at: http://www2.epa.gov/waterdata/beacon-20-beach-advisory-and-closing-online-notification (U.S. EPA BEACON).

Status of Great Lakes Beach Advisories

Since the last reporting period, the percentage of U.S. Great Lakes beaches open and safe for swimming has deteriorated slightly (Figure 1). Overall, the percentage of monitored Great Lakes beaches that were open and safe for swimming during 2011-2014 was an average of 96% (percent of beach days open and not under an action). The trend appears to be slightly deteriorating from 97% in 2008-2010.

The percentage of U.S. beaches open the entire swimming season (100% of the time) during 2011 to 2014 was 64% (Figure 3). This shows a deteriorating trend from 70% in 2008-2010. The percentage of U.S. Great Lakes beaches open 80% or more of the swimming season during 2011–2014 was 92% overall. This shows a slightly deteriorating trend from 94% during the 2008 – 2010 reporting cycle.

The percentage of Lake Superior U.S. beaches open the entire (100%) swimming season from 2011-2014 was 73% (Figure 5). This shows a decreasing trend from 83% in 2008-2010. The percentage of U.S. Lake Superior beaches open 80% or more of the swimming season during 2011–2014 was 97% overall. This shows a slightly deteriorating trend from 99% during the 2008 – 2010 reporting cycle.

The percentage of Lake Michigan beaches open the entire (100%) swimming season from 2011-2014 was 64% (Figure 7). This shows a decreasing trend from 70% in 2008-2010. The percentage of Lake Michigan beaches open 80% or more of the swimming season during 2011-2014 was 96% overall. This shows an unchanging trend from 96% during the 2008-2010 reporting cycle.

The percentage of Lake Huron U.S. beaches open the entire (100%) swimming season from 2011-2014 was 83% (Figure 8). This shows a decreasing trend from 86% in 2008-2010. The percentage of U.S. Lake Huron beaches open 80% or more of the swimming season during 2011–2014 was 99% overall. This shows a slightly improving trend from 98% during the 2008 – 2010 reporting cycle.

The percentage of Lake Erie U.S. beaches open the entire (100%) swimming season from 2011-2014 was 9% (Figure 10). This shows a deteriorating trend from 14% in 2008-2010. The percentage of U.S. Lake Erie beaches open 80% or more of the swimming season during 2011–2014 was 50% overall. This shows a deteriorating trend from 68% during the 2008 – 2010 reporting cycle.

The percentage of Lake Ontario U.S. beaches open the entire (100%) swimming season from 2011-2014 was 61% (Figure 12). This shows an improving trend from 53% in 2008-2010. The percentage of U.S. Lake Ontario beaches open 80% or more of the swimming season during 2011–2014 was 90% overall. This shows an improving trend from 86% during the 2008 – 2010 reporting cycle.

The percentage of days that monitored Canadian Great Lakes beaches met bacterial standards for swimming during the 2011--2014 period is an average of 78%. The trend appears to be slightly deteriorating from 79% in 2008-2010 (Figure 2). This analysis is based on the number of days within a swimming season that beaches are open and safe to swim. Note that this report focuses on the actual number of days that a beach is open AND safe to swim, so results are slightly different than the overall health unit reports. Due to a delay in receiving results from beach water sampling, beaches are sometimes not posted by health units on days that a beach would actually be unsafe to swim at. Since the *E .coli* geometric data is viewed after the season is complete, this report focuses on those beach days in a swimming season that are actually safe to swim over the entire swimming season. The target for this sub-indicator report for each lake basin, and for the entire Great Lakes Basin, is that the aggregate of monitored beaches will meet bacteria standards for swimming 95% or greater of the available beach days in the U.S. and 80% or greater of the available beach days in Canada.This distinction better reflects the difference in standards for issuing beach advisories/posting between the U.S. and Canada. The number of days that each beach was open and safe to swim at was calculated based on this standard to provide a consistent analysis with the past State of the Great Lakes (previously known as SOLEC) report. All data prior to 2008 has been recalculated and reassessed based on the Ontario Public Health standards used in this report to provide consistency. The original data set included only those beaches monitored throughout the beach season; therefore there has been no change in the type of reporting for Canadian beaches. All Canadian health units with beaches residing on the Great Lakes provided their 2011-2014 beach data for this report.

The percentage of all Canadian beaches open the entire (100%) swimming season from 2011-2014 was 26% (Figure 4). This shows a slightly improving trend from 25% in 2008-2010. The percentage of Canadian Great Lakes beaches open 80% or more of the swimming season during 2011–2014 was 58% overall. This shows a deteriorating trend from 61% during the 2008 – 2010 reporting cycle. Note that beach posting data from 3 health units was missing in the 2008-2011 analysis for the 2011 SOLEC report, but has now been added to the overall database, which could reflect different statistics from the prior 2011 report.

The percentage of Lake Superior Canadian beaches open the entire (100%) swimming season from 2011-2014 was 51% (Figure 6). This shows a decreasing trend from 56% in 2008-2010. The percentage of Canadian Lake Superior beaches open 80% or more of the swimming season during 2011–2014 was 76% overall. This shows a slightly deteriorating trend from 77% during the 2008 – 2010 reporting cycle. The number of beaches monitored in along Lake Superior on the Canadian side has been reduced in 2013 and 2014 which may be part of the reason for deteriorating beach conditions.

The percentage of Lake Huron Canadian beaches open the entire (100%) swimming season from 2011-2014 was 36% (Figure 9). This shows an improving trend from 32% in 2008-2010. The percentage of Canadian Lake Huron beaches open 80% or more of the swimming season during 2011–2014 was 65% overall. This shows a deteriorating trend from 71% during the 2008 – 2010 reporting cycle.

The percentage of Lake Erie Canadian beaches open the entire (100%) swimming season from 2011-2014 was 9% (Figure 11). This shows a deteriorating trend from 20% in 2008-2010. The percentage of Canadian Lake Erie beaches open 80% or more of the swimming season during 2011–2014 was 36% overall. This shows a deteriorating trend from 59% during the 2008 – 2010 reporting cycle.

The percentage of Lake Ontario Canadian beaches open the entire (100%) swimming season from 2011-2014 was 17% (Figure 13). This shows an improving trend from 13% in 2008-2010. The percentage of Canadian Lake Ontario beaches open 80% or more of the swimming season during 2011–2014 was 56% overall. This shows an improving trend from 48% during the 2008 – 2010 reporting cycle.

Annual variability in weather, the number of beaches monitored, and the length of the swimming season may affect the variability in days open and safe to swim during each swimming season. Comparisons of the frequency of beach postings between Canada and the U.S. will be limited due to the use of different water quality criteria in the Great Lakes.

Linkages

Beach postings may be the result of pressures including bacterial loadings from tributaries and extreme precipitation events. Improved wastewater treatment in response to these pressures may reduce the number of beach postings. Implementation of best management practices and green infrastructure to reduce the volume of storm water runoff may also decrease the number of beach advisories.

Currently, it is difficult to report on beach advisories as they related to Harmful Algal Blooms (HABs). It is quite expensive to test for toxic cyanobacteria. Some health units are noting that a bloom is present while testing for *E. coli*; however, without specialized tests, it would be difficult to determine if the algae is toxic. Beach advisories/closures as a result of HABs/algal blooms may be a future component of this report but for this sub-indicator it will track the percentage of days that beaches are open and safe for swimming during the beach season based on *E. coli* levels.

Comments from the Author(s)

Annual variability in the data may result from the variability in monitoring frequencies among beach management entities and variations in reporting, and may not be solely attributable to actual increases or decreases in levels of bacterial indicators. In addition, annual variability of weather may affect the variability in bacterial counts.

Additional point and non-point source pollution at coastal areas due to population growth and increased land use may result in additional beach postings, particularly during wet weather conditions. Unless contaminant sources are reduced or removed (or new sources introduced), Great Lakes beach sample results generally contain similar bacteria levels after events with similar meteorological conditions (primarily wind direction and the volume and duration of rainfall). If episodes of poor recreational water quality can be associated with specific events (such as meteorological events of a certain threshold), then forecasting for episodes of elevated bacterial counts may become more accurate.

Recent genomics research from Dr. Tom Edge at Environment Canada may also become an increasingly important technique in the beach analysis area. Ongoing research with the Genomics Research and Development Initiative (GRDI) has found genomic techniques which can be used to discover new DNA markers for bacteria found in the gut of seagulls (Environment Canada, 2015). This is a promising cost-effective and targeted solution to measure seagull fecal contamination in water samples in the near future and then better target the sources of *E. coli* in the Great Lakes.

There may be new indicators and new detection methods available through current research efforts occurring binationally in both public and private sectors and academia. Although currently a concern in recreational waters, viruses and parasites are difficult to isolate and quantify, and feasible measurement techniques have yet to be implemented. Although considered reliable indicators of potential harm to human health, the presence of *E. coli* and/or Enterococcus may not necessarily be related to fecal contamination.

New rapid detection methods are beginning to be used at several Great Lakes locations to provide the public with real time beach water quality information. The City of Racine Health Department is using the rapid quantitative Polymerase Chain Reaction (qPCR) method for *E. coli* at North Beach, along with the 18 hour culture method (Colilert), to validate the method. Racine was the first entity in the Great Lakes to use the rapid qPCR method for *E. coli*. The Wilmette, Illinois Water Utility and Milwaukee, Wisconsin Health Department have also done some culture/qPCR comparative testing for *E. coli* at some of their beaches. Various entities in Michigan are also beginning to use the rapid qPCR method for *E. coli* along with Colilert. EPA's Office of Research and Development in Cincinnati, Ohio has assisted Michigan Department of Environmental Quality (MDEQ) by providing training to multiple health departments in the state. Although this approach is feasible for beach water quality monitoring, it is very expensive.

This sub-indicator was updated in 2015 to more closely reflect the impacts to human health. Non-monitored beaches will no longer be included in the measure for this sub-indicator as they had been in the U.S. prior to 2011. Non-monitored beaches were originally entered into U.S. databases as open and safe for swimming for 100% of the beach season because the lack of monitoring resulted in no postings. This assumption that non-monitored beaches were always safe for swimming may have resulted in an overstatement of the safety of Great Lakes beaches in SOLEC reports prior to 2011.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				

6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				
Clarifying Notes: Although data obtained from the U.S. and Canada are comparable in terms of quality of data from the source (#5), the data is NOT comparable in terms of actual beach postings since each country uses different posting criteria.						

Acknowledgments
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Information Sources

Great Lakes beach data provided by U.S. EPA
http://watersgeo.epa.gov/beacon2/

Canadian Great Lakes Beach data provided by the following Ontario Health Units with beaches residing along the Great Lakes: Algoma; Chatham Kent; Durham Region; Elgin St. Thomas; Grey Bruce; Haliburton Kawartha Pine Ridge District; Halton Region; Hamilton; Hastings and Prince Edward Counties; Huron County; Kingston; Lambton County; Niagara Region; North Bay Parry Sound District; Peel Region; Simcoe Muskoka District; Sudbury & Distruct; Thunder Bay District; Toronto; Windsor-Essex County

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Figure 2. Overview of beach days that Canadian monitored Great Lakes beaches are open and safe for swimming from 2006-2014.
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Figure 3. Overview of beach days that U.S. beaches were open and safe to swim between 2000-2014.
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Figure 5. Overview of Lake Superior U.S. beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.
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Figure 6. Overview of Lake Superior Canadian beach days where beaches were open and safe to swim during the swimming season between 2005 – 2014 **Insufficient data prior to 2005.*
Source: Data collected from Ontario Health Units located along the Great Lakes (see Health Units listed in information source section), 2015.

Figure 7. Overview of Lake Michigan beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.
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Figure 8. Overview of Lake Huron U.S. beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.
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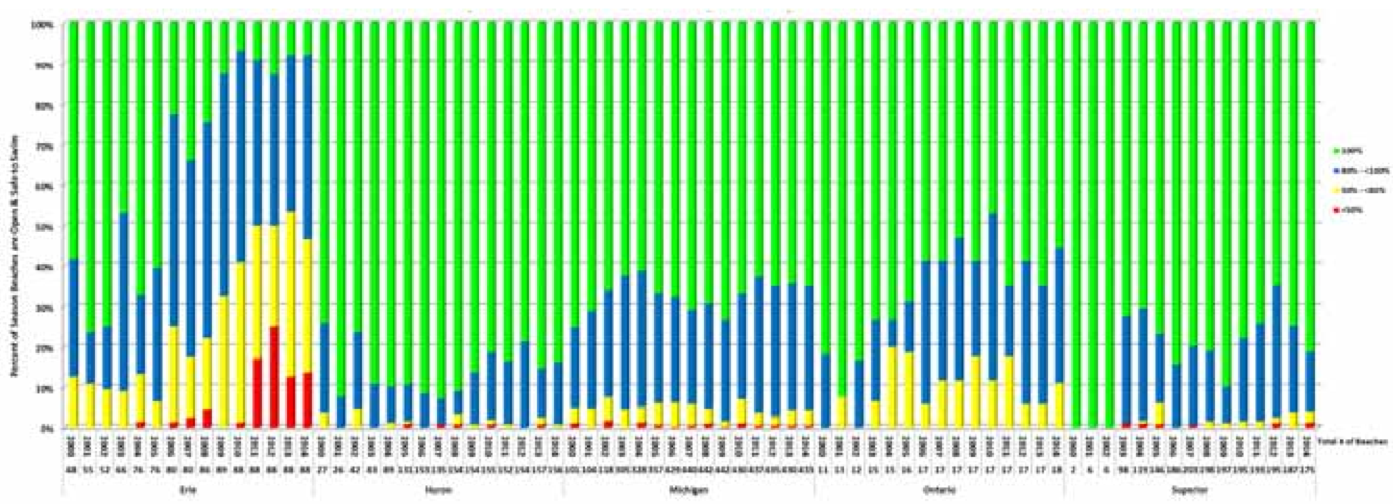


Figure 1. Percentage of beach days that U.S. monitored Great Lakes beaches are open and safe for swimming from 2000-2014.
Green represents the percentage of beaches that were open 100% of the swimming season; blue represents the percentage of beaches that were open between 80-<100%% of the swimming season; yellow represents the percentage of beaches that were open 50-<80% of the swimming season; and red represents the percentage of beaches that were open less than 50% of the swimming season.
Source: Data collected from U.S. states and reported to U.S. EPA's Beach Advisory and Closing On-Line Notification (BEACON) system.

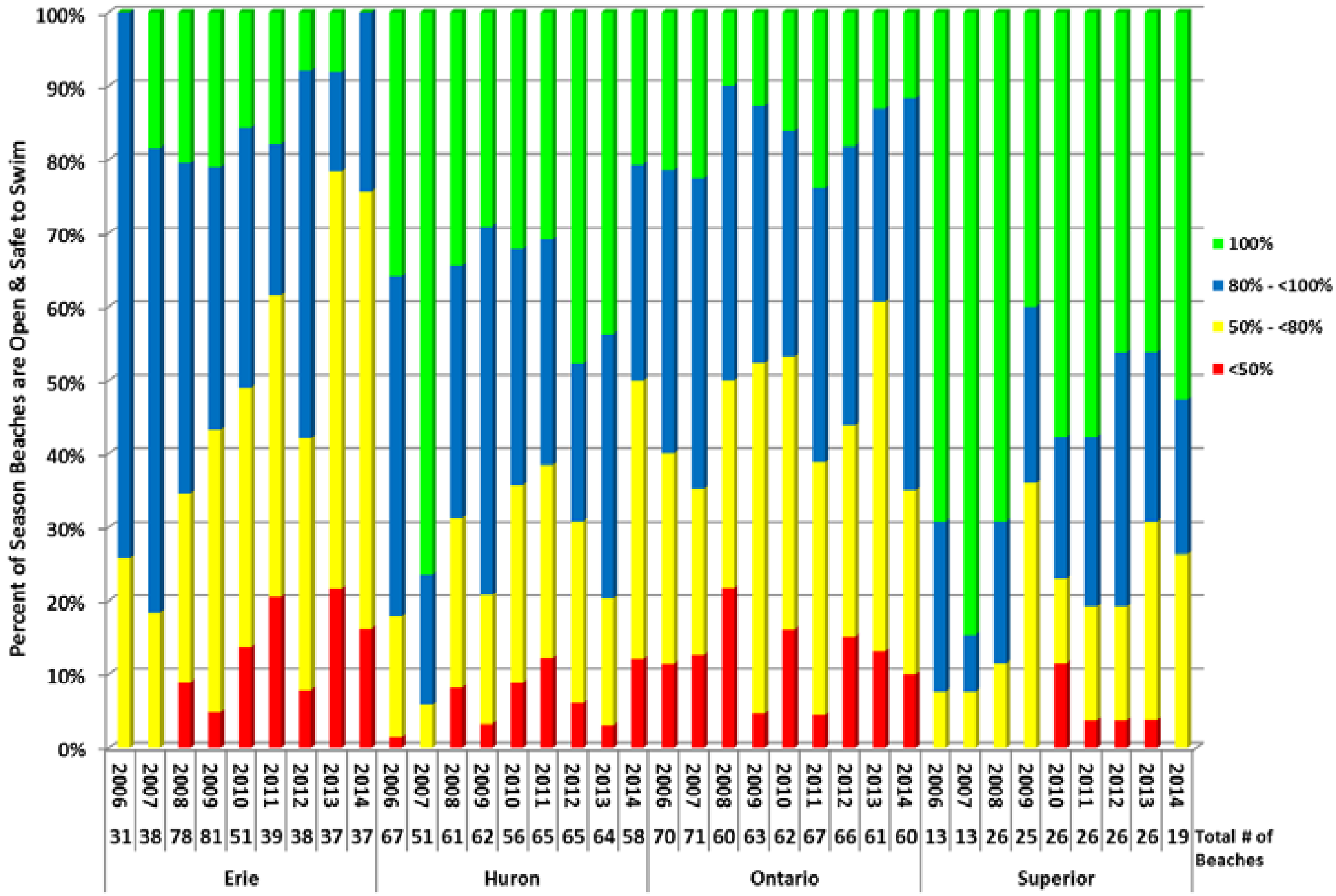
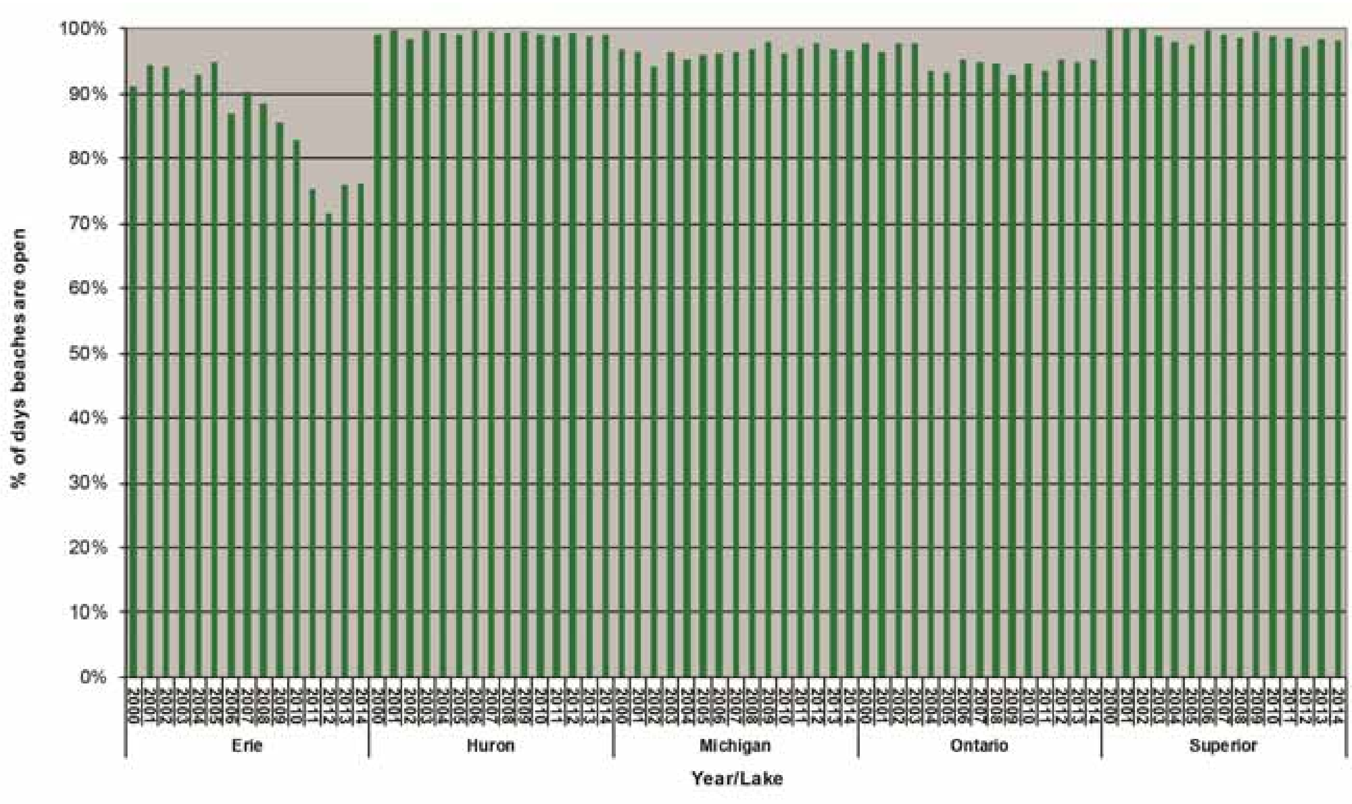


Figure 2. Overview of Canadian beach days where beaches were open and safe to swim between 2006 – 2014 within each lake basin swimming season.

Green represents the percentage of beaches that were open 100% of the swimming season; blue represents the percentage of beaches that were open between 80-<100% of the swimming season; yellow represents the percentage of beaches that were open 50-<80% of the swimming season; and red represents the percentage of beaches that were open less than 50% of the swimming season.

For example, in 2014, in Lake Ontario, 11% of monitored beaches were open 100% of the swimming season, which is approximately 7 monitored beaches.

Source: Data collected from Ontario Health Units located along the Great Lakes (see Health Units listed in information source section), 2015.



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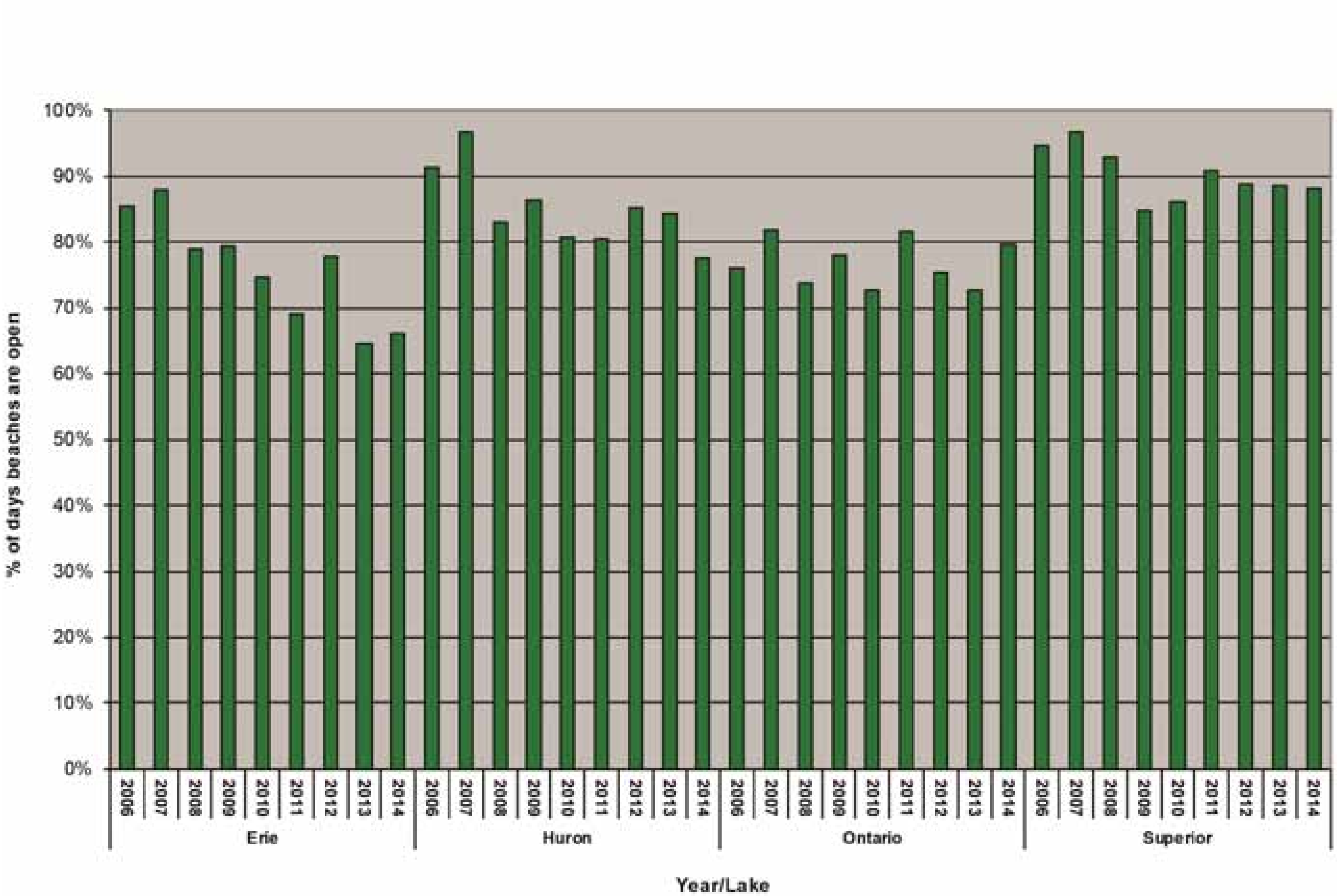

Figure 4. Percentage of beach days that Canadian monitored Great Lakes beaches are open and safe for swimming from 2006-2014.

Source: Data collected from Ontario Health Units located along the Great Lakes (see Health Units listed in information source section), 2015.

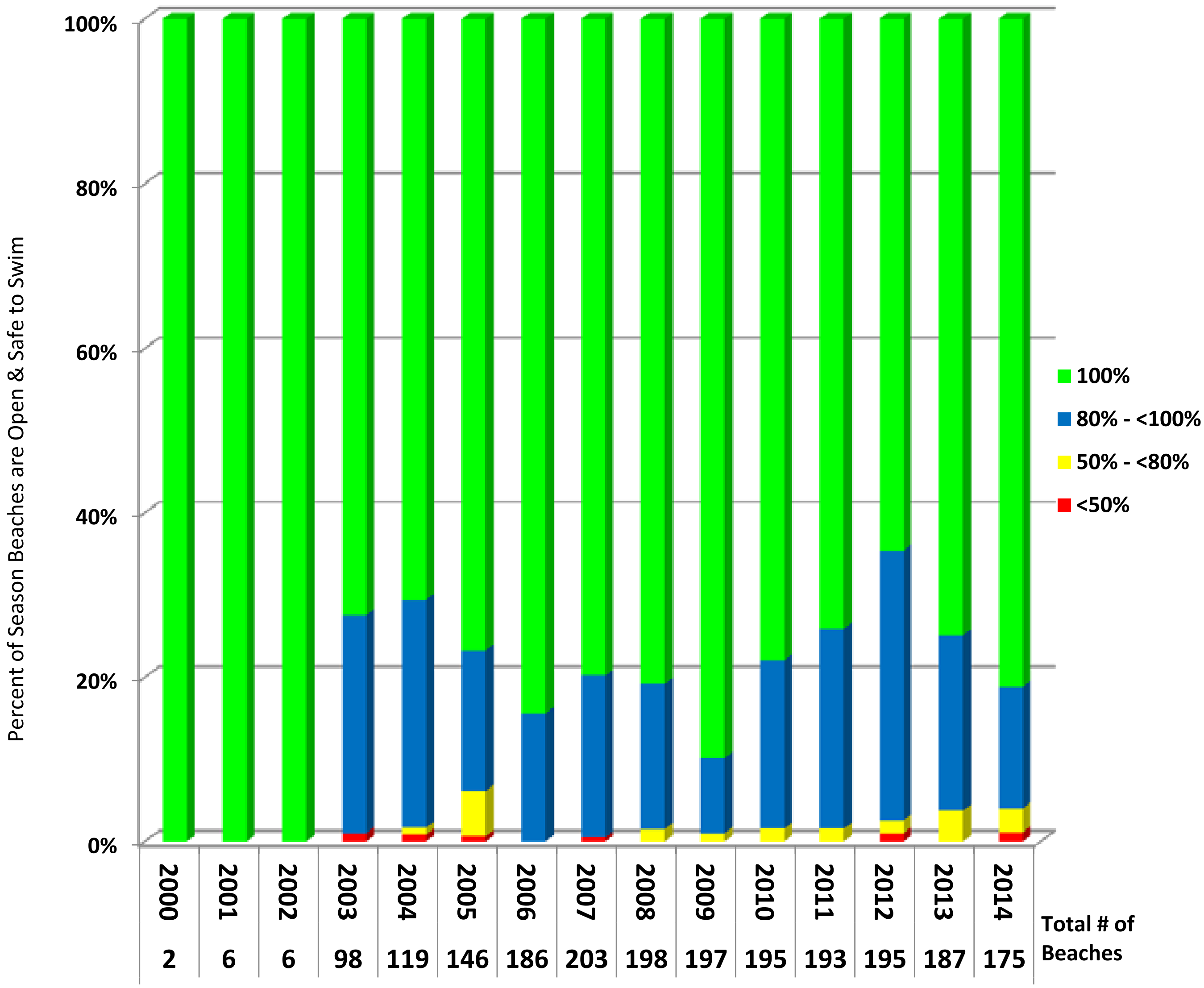

Figure 5. Overview of Lake Superior U.S. beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.
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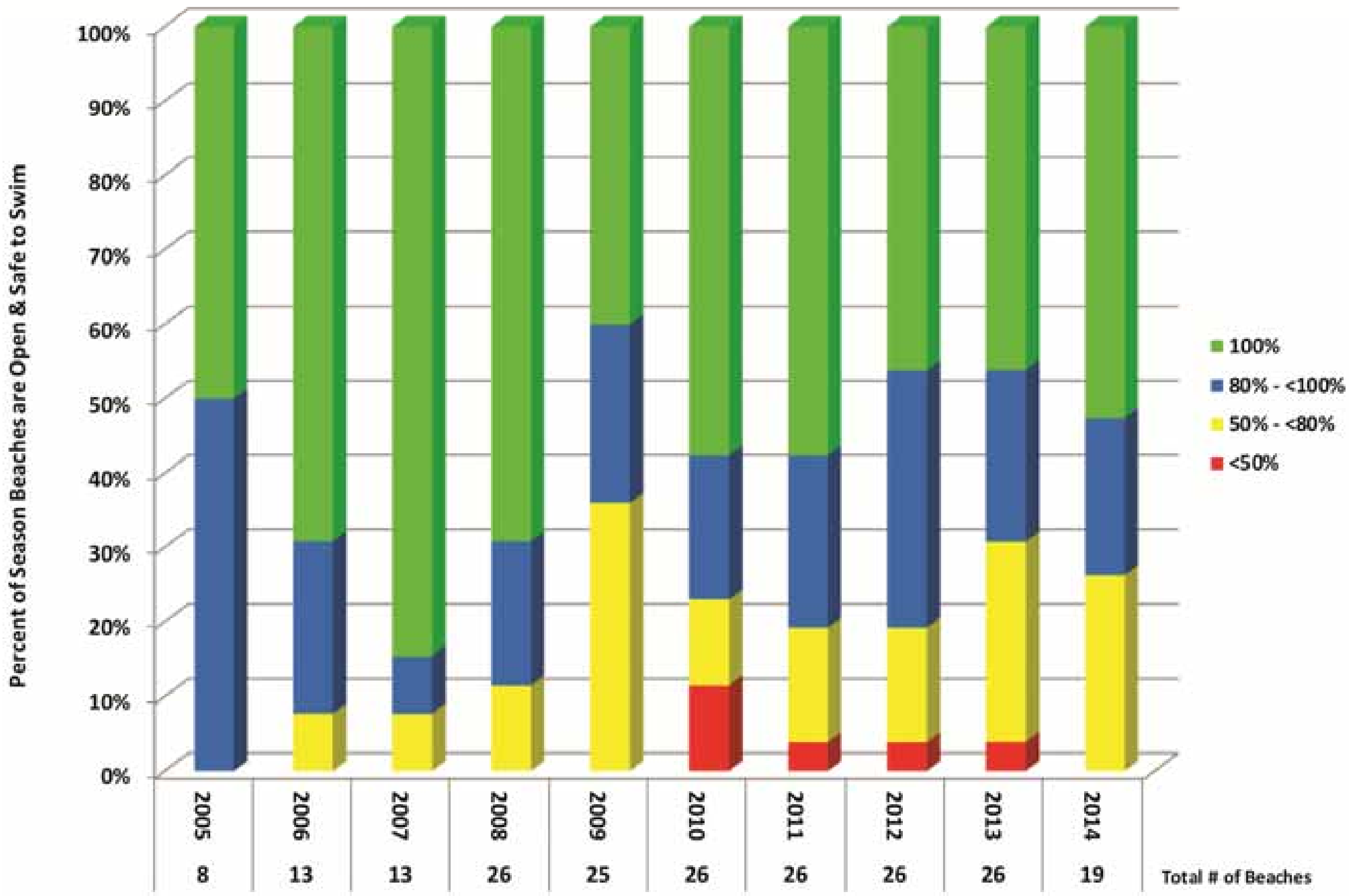


Figure 6. Overview of Lake Superior Canadian beach days where beaches were open and safe to swim during the swimming season between 2005 – 2014 **Insufficient data prior to 2005.*
Source: Data collected from Ontario Health Units located along the Great Lakes (see Health Units listed in information source section), 2015.

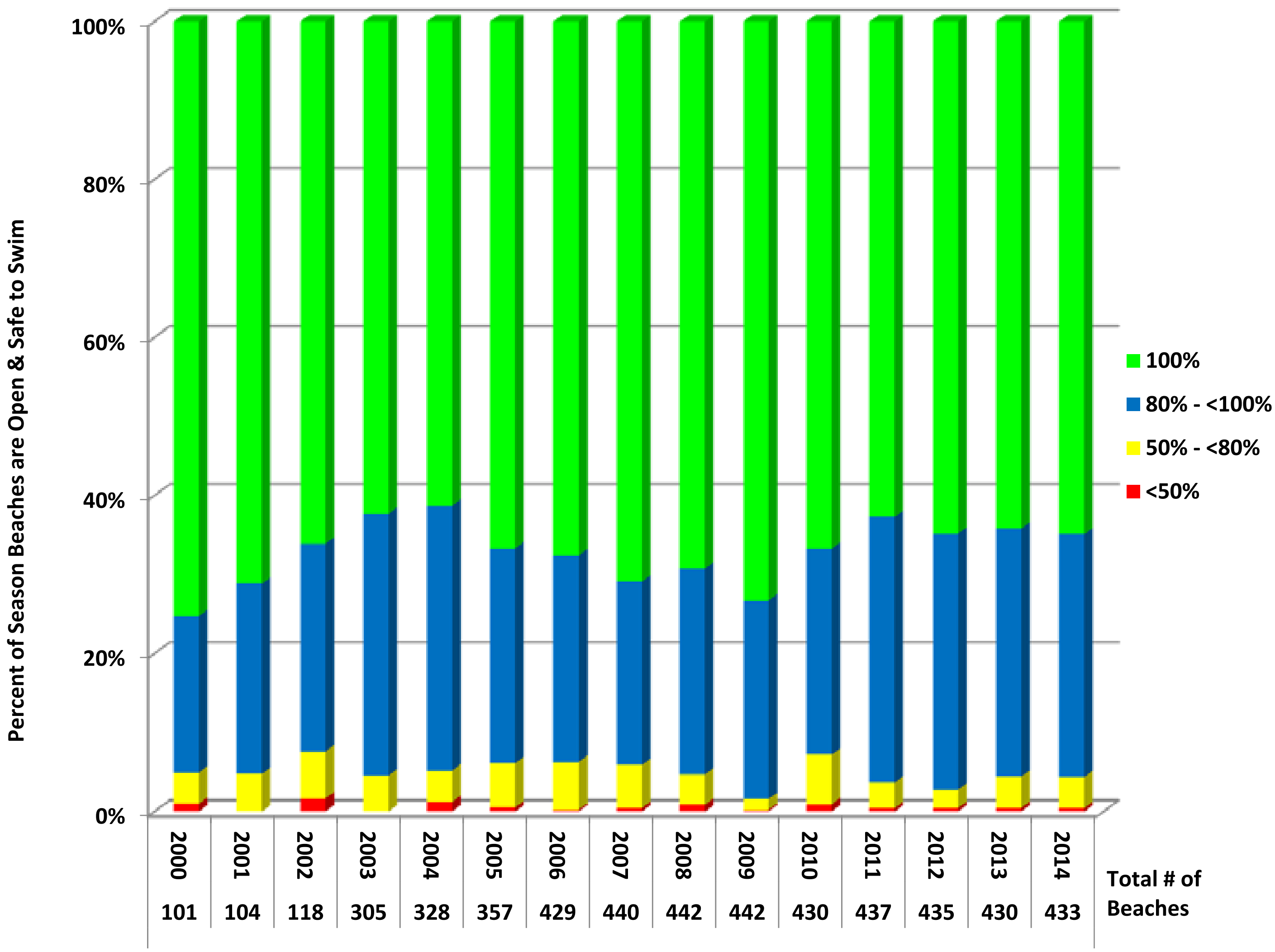


Figure 7. Overview of Lake Michigan beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.

Source: Data collected from U.S. states and reported to U.S. EPA's Beach Advisory and Closing On-Line Notification (BEACON) system.

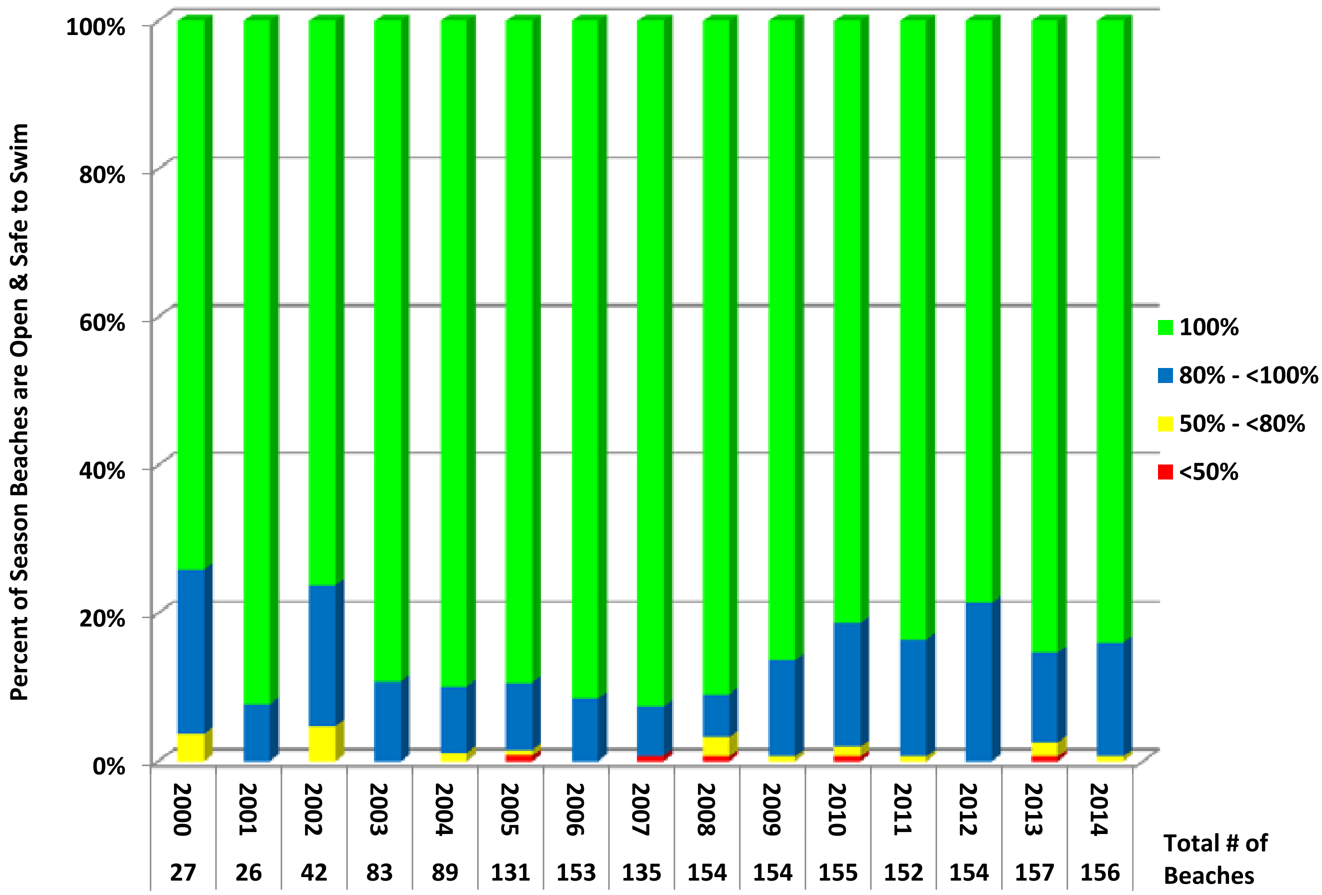
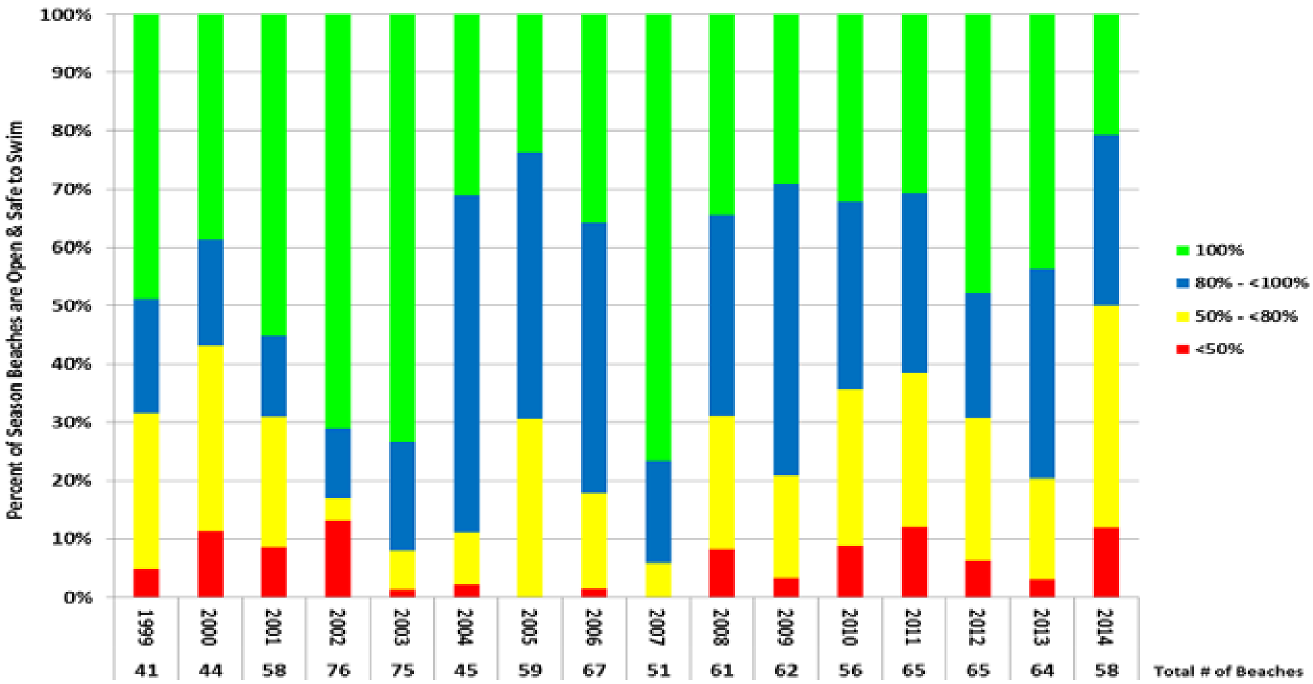


Figure 8. Overview of Lake Huron U.S. beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.
Source: Data collected from U.S. states and reported to U.S. EPA's Beach Advisory and Closing On-Line Notification (BEACON) system.



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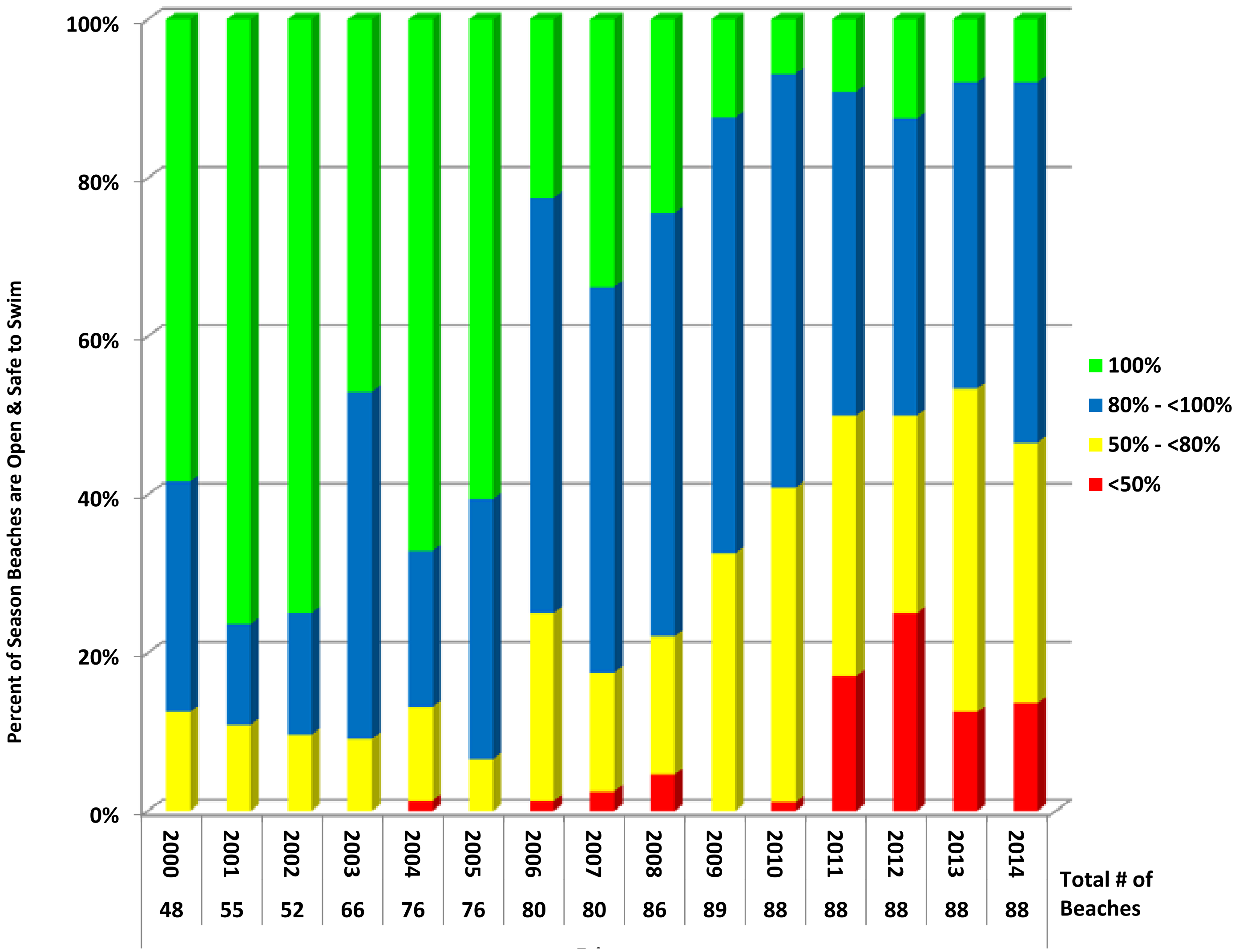

Figure 10. Overview of Lake Erie U.S. beach days where beaches were open and safe to swim during the swimming season between 2000 – 2014.
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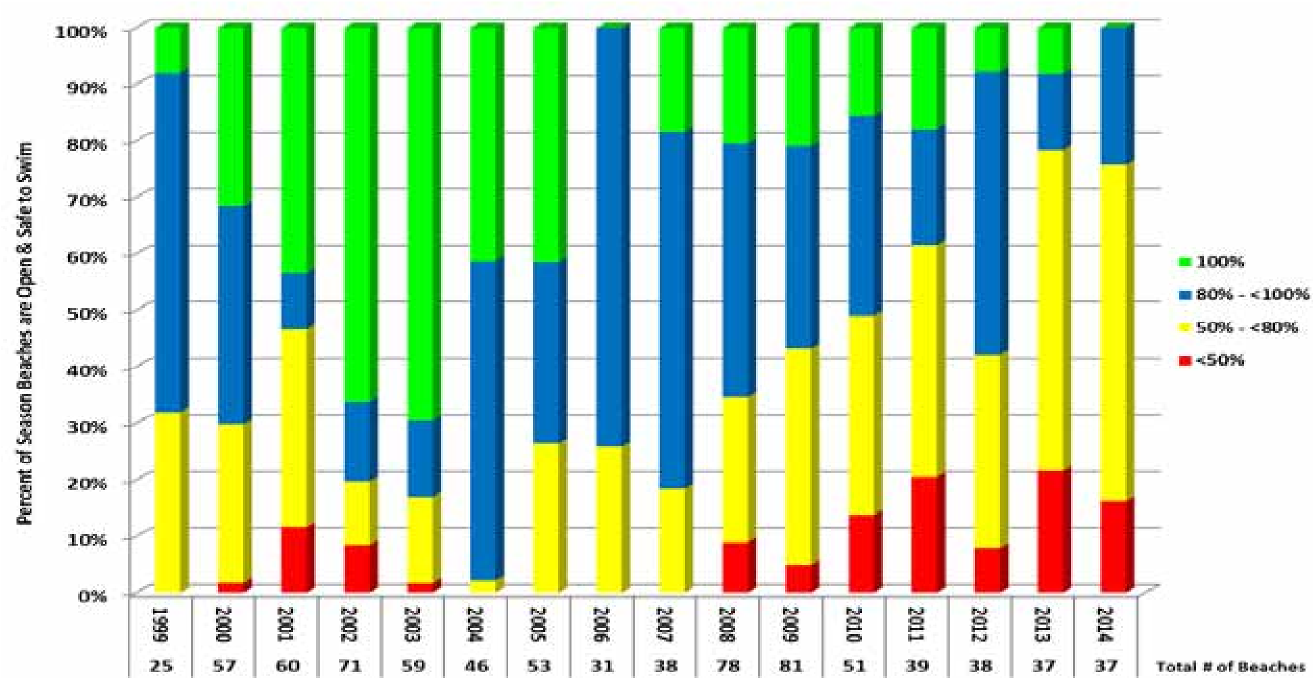

Figure 11. Overview of Lake Erie Canadian beach days where beaches were open and safe to swim during the swimming season between 1999 – 2014.
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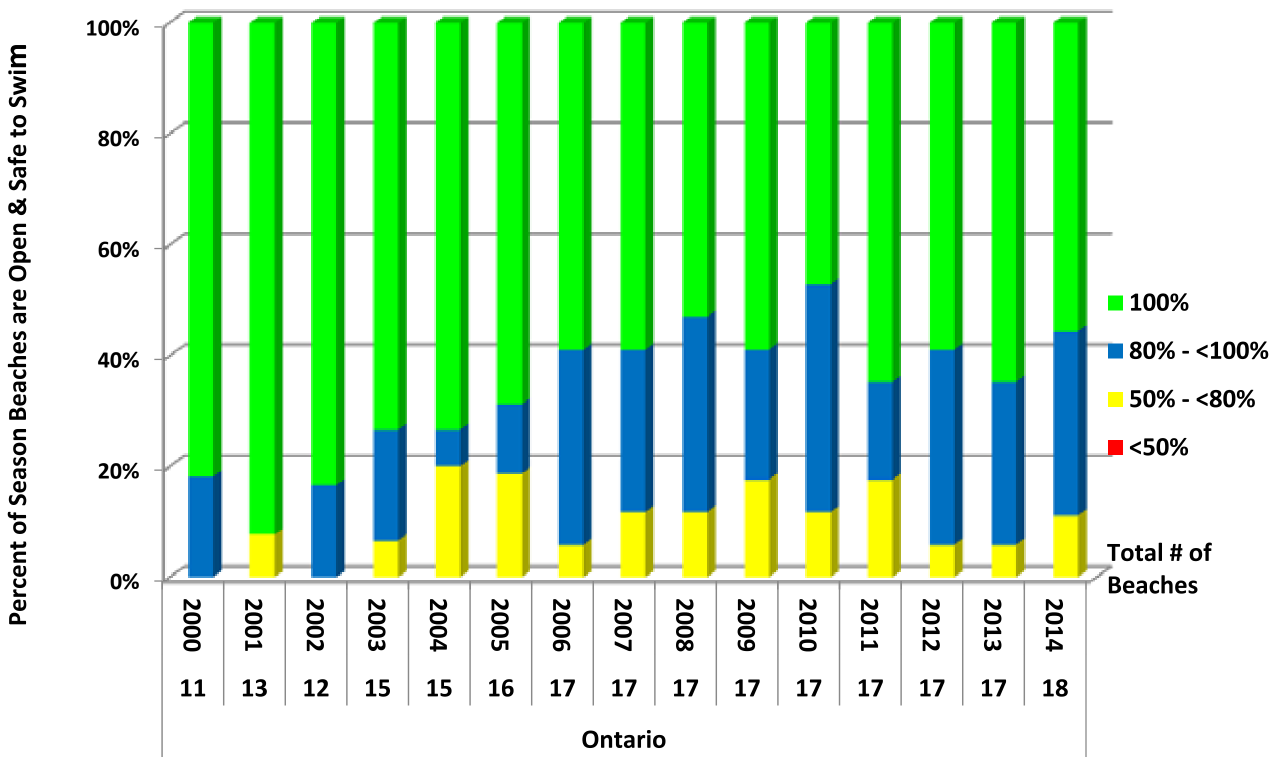

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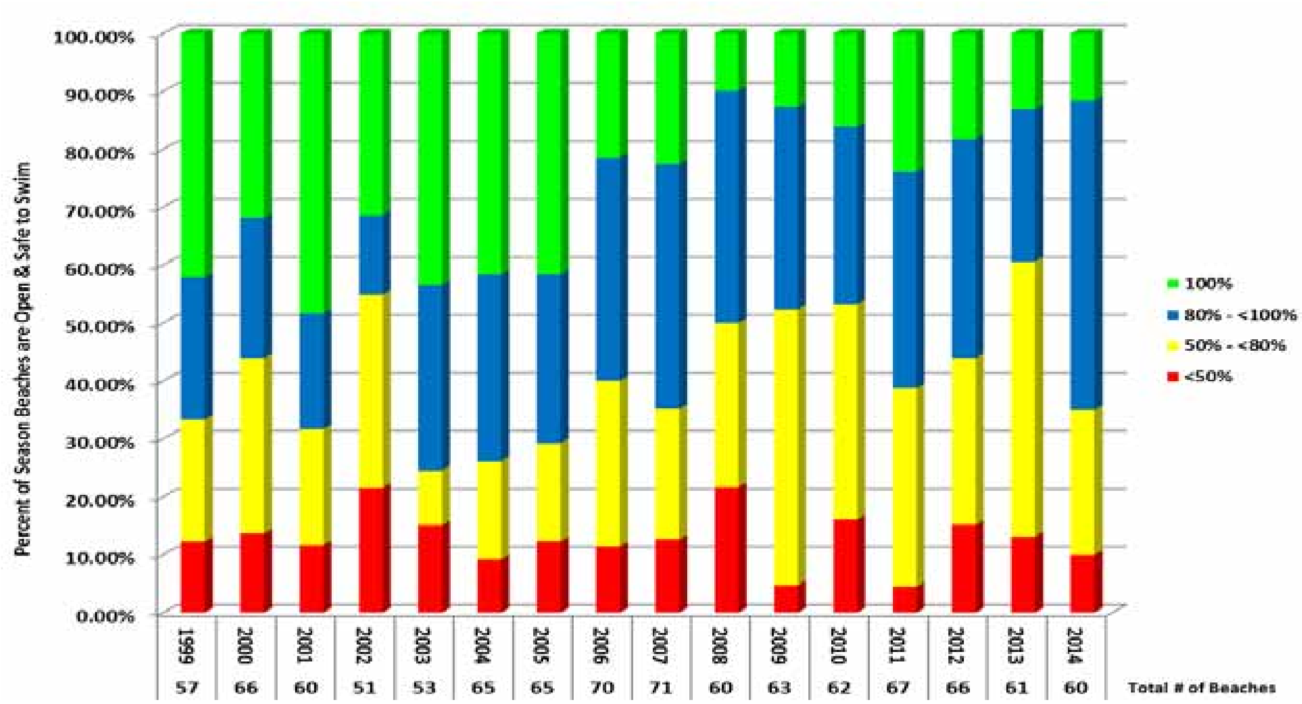
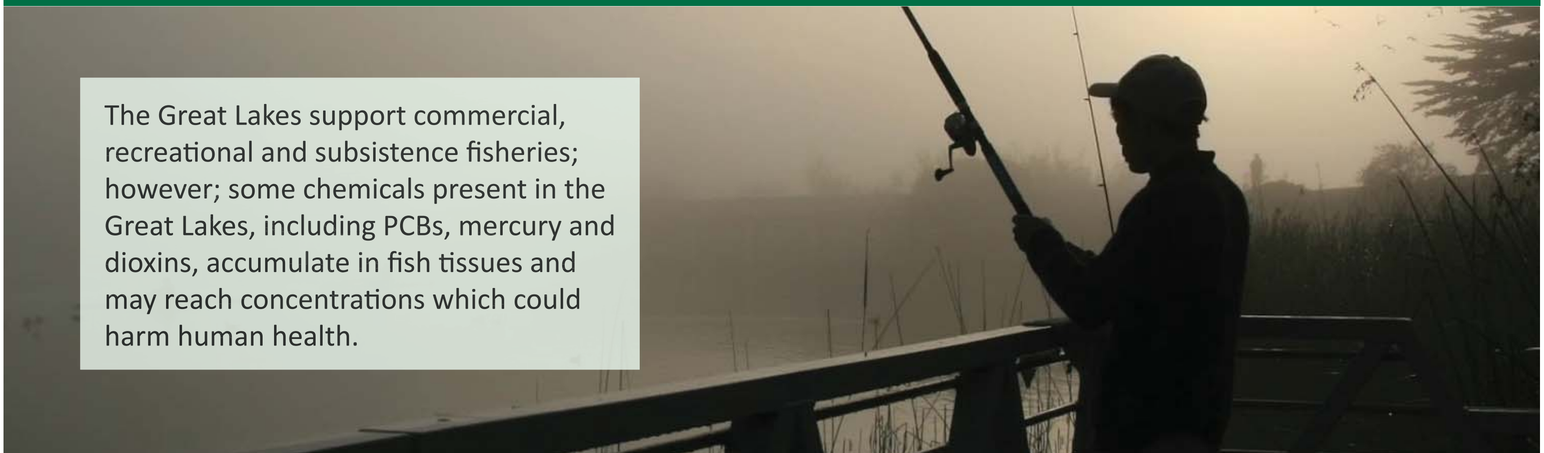


Figure 13. Overview of Lake Ontario Canadian beach days where beaches were open and safe during the swimming season between 1999 – 2014.
Source: Data collected from Ontario Health Units located along the Great Lakes (see Health Units listed in information source section), 2015.

Fish Consumption

Status: Fair   Trend: Unchanging



The Great Lakes support commercial, recreational and subsistence fisheries; however; some chemicals present in the Great Lakes, including PCBs, mercury and dioxins, accumulate in fish tissues and may reach concentrations which could harm human health.

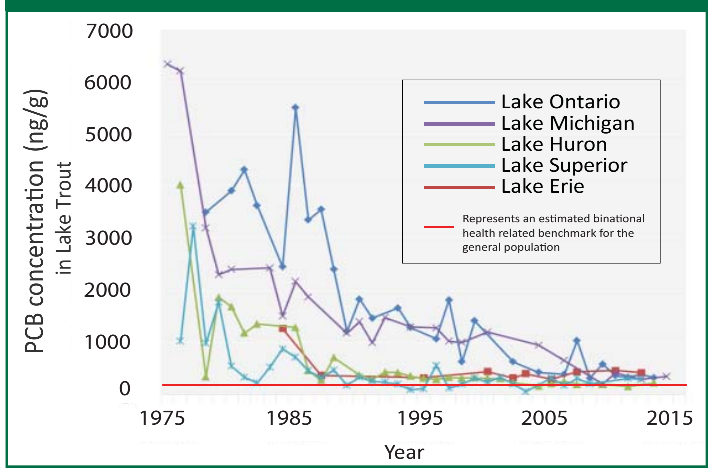
The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should allow for human consumption of fish and wildlife unrestricted by concerns due to harmful pollutants"*

Assessment Highlights

The Fish Consumption indicator reveals that in all the Great Lakes contaminants in edible portions of fish have declined over time. However, in Lakes Erie and Huron, recent concentrations of PCBs and mercury are stable or slightly increasing. The status of contaminants in edible portions of fish is assessed as **Fair** and the trend is **Unchanging** since last reported in 2011.

Contaminants causing consumption restrictions of Great Lakes fish typically include PCBs, mercury, and dioxins. PCBs drive the majority of fish consumption advice in both the U.S. and Canada. PCB levels in edible portions of fish tissue have decreased by 90% in some cases, but are still above consumption benchmarks. Mercury levels have generally declined over the last four decades and, depending on the fish species and lake, are lower than most fish consumption advisory benchmarks. However, in Lakes Erie and Huron, PCBs and mercury have remained stable or are slightly increasing. Non-legacy contaminants, such as Perfluorooctanesulfonic acid or PFOS (a stain repellent), continue to be a monitoring priority and will be included in future State of the Great Lakes reporting as necessary. Additional stressors such as warming waters and invasive species will likely continue to complicate the cycling of contaminants in the Great Lakes and may impact the levels of contaminants in fish.

PCBs in Edible Fish Tissue Have Declined But Are Still Above Guidelines



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Contaminants in Edible Fish	Unchanging	Improving	Unchanging	Deteriorating	Improving

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Contaminants in Edible Fish

Overall Assessment
Status: Fair
Trend: Unchanging
Rationale: Concentrations of major contaminants responsible for fish consumption advisories (PCB and Hg) in the edible portions of Great Lakes fish are generally either decreasing or have been stable in recent years. PCBs are responsible for the majority of fish consumption advice in all of the Great Lakes. PCB levels appear to have declined in Lakes Ontario and Michigan fish in recent years; however, they appear to be stable in Lake Huron and Lake Superior fish, and slightly increasing in Lake Erie fish. Overall, PCB levels in edible portion of Great Lakes fish have declined substantially (more than 90% in some cases) since its ban in the late 1970s. However, their current levels are still above certain advisory benchmarks. A slowdown in declines and oscillating pattern in temporal trends of fish contaminant levels are normal and further decreases in PCB levels in coming years can be expected. Depending on fish species and lake, mercury levels are declining, stable or weakly increasing; however, they are lower than most fish consumption advisory benchmarks and do not appear to be of major concern. Recent levels of any other legacy contaminant or known contaminants of emerging concern typically do not result in restrictions on fish consumption. Other stressors, such as invasive species, can alter food web structure and contaminant dynamics by recycling historically deposited contaminants which may affect future fish contaminant trends. The overall status and trend for this indicator is a mix of both short and longer time scales. The status is assessed through a comparison of current concentrations to an advice category while the trend is assessed by the long term data set and the statistical significance of that trend.

Lake-by-Lake Assessment
Lake Superior
Status: Fair
Trend: Unchanging
Rationale: There have been substantial improvements in PCB and mercury levels in Lake Superior fish over time; however, the levels appear to be stable in the recent years. Toxaphene is still present in some Lake Superior fish, albeit cause only a few, minor restrictions (between 1 and 4 meals per month). About 41.5% of the advisories for the Canadian waters of the Great Lakes are still restrictive (<8 meals per month) (OMOECC 2015).

Lake Michigan
Status: Fair
Trend: Improving
Rationale: Historically, PCB levels in fish from Lake Michigan were the worst among the Great Lakes. However, substantial declines over time have resulted in levels close or near to the other lakes in more recent years. Both PCBs and mercury appear to be mostly declining and continue to be the contaminants most responsible for driving fish consumption advisories.

Lake Huron
Status: Fair
Trend: Unchanging
Rationale: Lake Huron fish experienced declines in both PCBs and mercury during the 1970s and 1980s; however, levels of mercury and, to a certain extent, PCBs appear to be stable since that time. Disturbances in the food web structure of Lake Huron due to invasive species may have contributed to the slower declines in the recent years. About 42% of the advisories for the Canadian waters of the Great Lakes are still restrictive (<8 meals per month) (OMOECC 2015).

Lake Erie
Status: Fair
Trend: Deteriorating
Rationale: Concentrations of PCBs and mercury have been historically lower in Lake Erie fish compared to the other Great Lakes. However, there appears to be slightly increasing trends, specifically for mercury and PCBs,

which have been confirmed through detailed statistical analyses of the monitoring data (Bhavsar et al. 2010, Azim et al. 2011, French et al. 2011, Sadraddini et al. 2011). Alteration of the Lake Erie food web by invasive species, such as dreissenid mussels and round goby, has likely impacted the contaminant levels in Lake Erie fish. About 60% of the advisories for the Canadian waters of the Great Lakes are still restrictive (< 8 meals per month) (OMOECC 2015).

Lake Ontario
Status: Fair
Trend: Improving
Rationale: Similarly to Lake Michigan, PCB levels in fish from Lake Ontario were historically among the worst in the Great Lakes. However, substantial declines over time have resulted in almost similar or, in some cases, lower levels compared to the other lakes in the recent times. Both PCBs and mercury appear to be mostly declining. About 58.4% of the advisories for the Canadian waters of the Great Lakes are still restrictive (< 8 meals per month) (OMOECC 2015).

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess levels of compounds that pose a risk to human health and infer the potential harm through the consumption of Great Lakes fish. Special emphasis will be paid to compounds that are incorporated into fish consumption advisories such as persistent, bioaccumulative, and toxic (PBT) compounds including mercury and polychlorinated biphenyls (PCBs) in fillets of Great Lakes fish.

Ecosystem Objective
Fish in the Great Lakes ecosystem should be safe to eat. Consumption should not be limited by contaminants originated from human activities.

This sub-indicator best supports work towards General Objective #3 of the 2012 Great Lakes Water Quality Agreement (GLWQA) which states that the waters of the Great Lakes should "allow for human consumption of fish and wildlife unrestricted by concerns due to harmful pollutants"

History and Background
Both the U.S. and Canadian agencies monitor contaminants in edible portions of Great Lakes fish to provide advice on safe consumption. This sub-indicator assesses the status of the ecosystem by comparing contaminant concentrations in fish to levels that result in consumption advice. The outcome is then used to relate the ecosystem status to General Objective #3 of the GLWQA.

Fish contaminant monitoring data included in this assessment include those produced annually by Ontario's Fish Contaminant Monitoring Program, individual State monitoring programs, and results of the 2010 Great Lakes Human Health Fish Tissue Study. In 2009, U.S. EPA's Great Lakes National Program Office's Great Lakes Fish Monitoring and Surveillance Program eliminated the edible fish analysis portion of its program, refocused its efforts on identifying emerging contaminants in whole fish, and therefore, could not contribute new data to this sub-indicator. The analysis for this sub-indicator was limited to fish species that are of interest for human consumption as well as are good indicators of contaminants of concern (i.e., PCB and mercury). Five selected fish species were Lake Trout, Walleye, Lake Whitefish, Coho Salmon, and Chinook Salmon. Fish contaminant levels can be influenced by age, and thereby size, of fish. To prepare spatial and temporal trends, narrow size ranges of 55-65 cm for Lake Trout, Coho Salmon and Chinook Salmon, and 45-55 cm for Walleye and Lake Whitefish were considered. Samples included in the analysis for this sub-indicator were selected to provide the widest temporal and spatial scale for results. This broad scale approach was accomplished by soliciting data generated by the Province of Ontario, the 8 Great Lakes State monitoring programs, and U.S. EPA's 2010 Great Lakes Human Health Fish Fillet Tissue Study.

<u>Ontario's Fish Contaminant Monitoring Program</u>
Ontario started monitoring contaminants in fish in the late 1960s. Ontario's Fish Contaminant Monitoring Program was formally established in 1976, and the first fish consumption advisories were issued in 1977. Staff from the Ontario Ministry of Natural Resources and Forestry and Ministry of the Environment and Climate Change collect the fish, which are then analyzed by the Ministry of the Environment and Climate Change for a variety of substances, including mercury, PCBs, mirex, DDT, dioxins, and contaminants of emerging concern (e.g., polybrominated diphenyl ethers (PBDEs), perfluoroalkyl acids (PFAAs)). The results are used to develop the Guide to Eating Ontario Fish, which give size-specific consumption advice for each species and location tested. The 2015-2016 edition of the

Guide to Eating Ontario Fish gives advice to anglers, subsistence fishers and their families, and First Nations and Métis communities in determining which fish species and what size caught from Ontario water bodies can be consumed to minimize exposure to toxins. The Guide compiles information for more than 2,300 locations around the Province of Ontario, including about 60 regions covering the Canadian waters of the Great Lakes.

Great Lakes Human Health Fish Tissue Study
U.S. EPA's Office of Water, Great Lakes National Program Office, and Office of Research and Development are collaborating to conduct the Great Lakes Human Health Fish Tissue Study. The Great Lakes Human Health Fish Tissue Study was initiated in 2010 under the Agency's National Coastal Condition Assessment (NCCA), and it is the first statistically based study of fish contamination in the Great Lakes. Fish samples were collected from 157 randomly selected sites throughout the five Great Lakes, and fillet tissue samples were analyzed for mercury, PCBs, PBDEs, and PFAAs. The fillet samples were also analyzed for omega-3 fatty acids. Results for PFAAs were published in 2014. Other results are expected to be reported in 2016. This study is being repeated, beginning in 2015.

Great Lakes Consortium for Fish Consumption Advisories
The Great Lakes Consortium for Fish Consumption Advisories (Consortium) is a collaboration of fish advisory program managers from government health, water quality, and fisheries agencies in the eight U.S. states bordering the Great Lakes. The purpose of the Consortium is to share information about contaminants found in fish of the Great Lakes region, evaluate human health effects of those contaminants, and develop protocols and methods for determining fish consumption advice and communications. The Consortium has its roots in a taskforce formed in the early 1980s. Consortium membership is fluid but typically includes representatives from the eight U.S. states bordering the Great Lakes - Indiana, Illinois, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin. The following goals for fish consumption advisories guide the continuing work of the Consortium: (1) use credible and understandable science; (2) minimize the potential for toxic contaminant exposure; (3) maintain the health benefit of fish consumption; and (4) present the information in a manner that will result in voluntary compliance. Member states provided contaminant concentration data for this sub-indicator.

Measure
Since the 1970s, there have been declines in the levels of many PBT contaminants in the Great Lakes basin due to bans on their use and/or production and restrictions on emissions. However, because of their ability to bioaccumulate and persist in the environment, PBT contaminants continue to be a significant concern. Historically, elevated levels of a variety of contaminants including PCB, mercury, dioxins/furans, mirex and toxaphene have restricted consumption of Great Lakes fish. However, concentrations of many PBTs, including toxaphene and mirex, have declined to levels that they can be eliminated from regular monitoring to prioritize resources for other purposes such as monitoring contaminants of emerging concern or CECs (Gandhi et. al 2014, 2015). Monitoring of CECs, such as perfluoroalkyl acids (PFAAs) and polybrominated diphenyl ethers (PBDEs), continues to be a priority for Provincial, State, and Tribal programs as concentrations and toxicity of these compounds continue to be assessed for inclusion into advice. At this time, however, risks due to the identified CECs do not exceed those from PCBs and mercury. For this assessment, PFAAs were considered, but PBDEs were omitted because fish consumption is not considered the primary route of exposure at present, their levels appear to have declined in fish fillets by 46–74% between 2006/07 and 2012, and although they will remain in-use in existing consumer items for a while, their accumulation in fish will not be substantial (Gandhi et al. 2017a, Lorber 2008).

Ecological Condition
PCB
Level of total PCB in fish ranged from a few hundred to thousands of nano grams per gram (ng/g) during the 1970s (Figure 1). In many cases, these historical levels were higher than the advisory benchmark of about 2000 ng/g (Table 1). PCBs were banned during the late 1970s, which spurred declines in their environmental levels. PCB concentrations have declined substantially over the four decades in all of the Great Lakes (Figure 1). The declines varied by fish type and lake, but were as much as >90% in many cases. Recent PCB levels in selected sizes of fish from the five Great Lakes are <500 ng/g.

Scientific studies conducted between the 1980s and 2000s highlighted greater toxicity of PCBs, which resulted in lower advisory benchmarks over time. At present, the advisory benchmarks for severe restriction on fish consumption (i.e., not more than 1-2 meals per month) are about 200 ng/g, an order of magnitude lower. As such, despite substantial declines in the fish PCB levels, PCBs continue to be of concern for health of humans consuming the Great Lakes fish.

Although PCBs appear to be declining in many cases, especially for Lakes Ontario and Michigan where fish PCB levels were historically the highest, in Lakes Erie, Huron and Superior, either a stable or slightly increasing trend is emerging. Although a greater variability and slower declines at lower levels are typical and other stressors (e.g., invasive species, climate change) may be contributing to the stable/increasing trends, no substantial declines in PCB for Lakes Erie, Huron and Superior since the late 1980s are worrisome.

Mercury

Mercury concentrations in fish historically exceeded fish consumption advisory benchmarks more frequently (Figure 2). The levels have generally declined over the last four decades, and the concentrations in the selected sizes of fish from the five Great Lakes are now below 0.2-0.3 µg/g (Figure 2). These levels would allow at least 4-8 meals per month consumption for the sensitive population (Table 1).

Walleye can be considered among the best indicator species for mercury. The monitoring data show that the mercury levels continue to decline in Lakes Ontario, Michigan and Superior. However, similar to PCB, the levels appear to be stable or slightly increasing for Lakes Erie and Huron. A stabilizing trend for mercury in Lake Superior fish is also evident from the monitoring data collected for Lake Trout and Chinook Salmon.

PFAAs

Emerging contaminants, such as perfluoroalkyl acids (PFAAs), in edible portion of Great Lakes fish continue to be a priority for monitoring and surveillance for the Great Lakes States and the Province of Ontario. Minnesota is investigating the sources of perfluoroalkyl acids in Minnesota fish, and has site-specific advice for where fish have been tested for elevated perfluorooctane sulfonic acid (PFOS). Similarly, elevated levels of PFOS were found in fish at five Ontario locations, for which site-specific advice has been issued. A recent publication on PFAAs from the National Coastal Conditions Assessment and the National Rivers and Streams Assessment identified that PFOS was the most dominant PFAA found in their samples and that Maximum PFOS concentrations were 127 and 80 ng/g in urban river samples and Great Lakes samples, respectively (Stahl, et al. 2014). However, concentrations of PFOS in common Great Lakes fish species do not result in advisories that would be more restrictive compared to those due to PCBs or mercury (Gandhi et al. 2017b). For this reason, a detailed assessment was not conducted for PFAAs this year, but shall be considered in the future reports as necessary.

Toxaphene

Recent research into the levels of toxaphene in Great Lakes fish have resulted in the recommendation that routine monitoring of toxaphene be discontinued (Gandhi et. al. 2014). At present, for the Canadian waters of the Great Lakes, toxaphene causes minor (7%) restrictions only for Lake Superior fish. However, the hazard posed by toxaphene might have been masked by the presence of more dominant contaminants that drive advisories, such as PCBs and mercury. A study conducted by OMOECC simulated advisories that excluded the presence of other contaminants and focused only on toxaphene. The result of this study found that advisories became more restrictive in only a small percentage of Lakes Superior, Huron, and Ontario samples and not at all for Lake Erie (Gandhi et al. 2014). Lake Michigan was not included in this OMOECC study. The results of this research identified that toxaphene is less of a concern than the dominant contaminants that drive consumption advice, such as PCBs and mercury, from the perspective of health risk to humans through fish consumption. For this reason, toxaphene will no longer be reported in this sub-indicator.

Mirex

Mirex has been traditionally a concern for only Lake Ontario fish due to historical discharges from large-scale manufacturing to Lake Ontario via the Niagara and Oswego Rivers. Long-term monitoring data gathered by the Province of Ontario show that the majority of measurements for mirex and photomirex in fish were below detection in all lakes except Lake Ontario, and that the concentrations in Lake Ontario decreased by approximately 90% between 1975 and 2010 (Gandhi et al. 2015). The decreasing trends and current levels of mirex suggest that routine monitoring for this chemical be replaced with periodic surveillance (Gandhi et al. 2015). The half-lives of mirex and photomirex have decreased in recent years indicating an expedited recovery, possibly in response to remedial actions. Gandhi et al. (2015) predicts that within 15 years, mirex and photomirex levels in Lake Ontario fish will allow for consumption of at least 8 meals per month, and that the presence of other chemicals, such as PCBs and mercury, are a greater contributor to the current advice. For this reason, mirex will no longer be reported in this sub-indicator.

Omega-3 Fatty Acids

Omega-3 Information, Research, and Future work

Fish contain beneficial nutrients such as Omega-3 fatty acids, high quality lean protein, minerals and vitamins. Omega-3 fatty acids have been identified as important for development of the young brain, lowering the risk of Alzheimer disease, decelerating the aging of the brain and more. It is important to consider both the risk of contaminants and the benefits of fatty acids when choosing fish for consumption. Contaminants of concern are generally greater in older fish and Omega-3 fatty acids are highest in cold water species. One can gain the most benefit while minimizing the risk by consuming a variety of smaller cold-water fish and by following the appropriate consumption advisory.

Omega-3 fatty acids are polyunsaturated fatty acids (PUFA) with three nutritionally important fats: α-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). Humans are unable to synthesize Omega-3 fatty acids in the body, but can obtain them through diet. ALA is generally found in plant oils, while EPA and DHA are commonly found in fish oils and seaweed and phytoplankton. Benefits of consuming Omega-3 fatty acids include improved cognitive ability and cardiovascular health. However, the benefit of Omega-3 fatty acids through the consumption of Great Lakes fish may not outweigh the risk of exposure to toxic chemicals, such as mercury and PCBs. Research regarding the risk and benefit relationship of consuming fish is ongoing. Researchers are attempting to add to this body of knowledge through 1) generation of fatty acid data for Great Lakes fish species, currently a significant gap, 2) comparing those fatty acid levels to contaminant concentrations, and 3) ultimately incorporating into fish consumption advice (Neff et. al. 2014, Turyk et. al 2012, Williams et. al 2014).

In more recent years, State and Provincial governments responsible for issuing consumption advice have shifted their attention towards both the risks and benefits of consuming Great Lakes fish when setting advisories. At present, this is achieved qualitatively by assessing both the contaminant burden of fish and their levels of fatty acids. While more monitoring data are needed to understand the levels of fatty acids in Great Lakes fish, there are evidences that Great Lakes fish can be a good source of beneficial long chain polyunsaturated fatty acids. For example, recent assessments by U.S. EPA's Office of Science and Technology, and the Province of Ontario indicate that concentrations of EPA and DHA in common species from the Great Lakes increase with fish length (Figure 3). This is supported by a recent assessment of 13 Wisconsin sport fish which found that fish length was positively correlated with total fatty acid for all of the fish assessed but that the correlation was not positive for any individual species (Williams et. al. 2014). Additionally, the study showed that of the species assessed, salmonids generally contained the highest total fatty acids while percids and centrarchids contained the lowest concentrations, and that diet was a better predictor of fatty acid concentration than taxonomic family (Williams et al. 2014).

EPA and DHA content is generally higher in fatty, large fish; however, these fish also typically contain greater levels of PCBs (Neff et al. 2014a). Limited data have indicated that EPA and DHA content in Lake Erie fish are comparable to some commercially-sourced fish and shellfish such as Yellowfin Tuna, shrimp, Pacific Cod, halibut, lobster and scallops (Neff et al. 2014a). Based on concurrent measurements of contaminants and fatty acids, it was concluded that consumption of certain Lake Erie fish within the limits of the fish advisories can be a good supplemental source of PUFA (Neff et al. 2014a). Further, cooking generally has little effect on Omega-3 fatty acid content of fish (Neff et al. 2014b). As such, cooking fish on a grill to let fat and associated organic contaminants such as PCB drip away is a good approach to enhance benefits over risk of eating Great Lakes fish. More comprehensive fatty acid and contaminant data are needed to provide consumption advice that not only considers the risk of consuming Great Lakes fish, but also the benefits.

Future reporting of this sub-indicator will continue to focus on beneficial compounds, such as fatty acids in species of fish most consumed by Great Lakes citizens and may allow for comparison of risks and benefits of fish consumption and tracking of concentrations of these compounds over time. As noted in the Guide to Eating Ontario Fish 2015-2016, "it is clear that fish consumption can present both benefits and risks. So the real question is: do the benefits of eating fish outweigh the risks to our health? Well, it depends. This is because various factors such as the contaminant of concern, its level in fish, and the levels of various nutrients (e.g., Omega-3 fats, vitamins) in fish vary widely from one fish species and size to another, and are location-specific. Although scientific studies have begun to evaluate the health benefits against the risks of eating contaminated fish, our understanding is still very limited due to differences in the benefits of various nutrients and health risks from different contaminants. This makes it challenging to compare benefits and risks in every case. Because of the current limitations, the advice in this guide continues to be based only on contaminant risk…" (from http://www.ontario.ca/environment-and-energy/guide-eating-ontario-fish). Future reports would continue to show the change in contaminant levels in fish and may also show the benefit of consuming Great Lakes fish resulting in a more comprehensive assessment of "fish-ability."

Linkages

Sources of chemical contaminants, and their cycling through the ecosystem, vary among the lakes. Therefore, it is important to have an understanding of how contaminants arrive to the Great Lakes and ultimately into fish species through diet, in addition to the presence of contaminants and their potential harm. This sub-indicator can easily be linked to all the other sub-indicators in the Toxic Chemicals indicator.

Comments from the Author(s)

At present, PCBs, mercury, and chlordane are the only PBT chemicals that have uniform fish advisory protocols across the U.S. Great Lakes Basin. The U.S. Great Lakes Sport Fish Advisory Task Force is currently drafting additional uniform PBT advisories in order to limit confusing the public that can result from issuing varying advisories for the same species of fish across the basin.

There are differences in the way fish samples are analyzed for contaminants and consumption advisories are developed in the U.S. and Canada. This means that the data and advisories cannot be directly compared between the two countries. For this sub-indicator, more consistent data generated by the Province of Ontario for fish from the Canadian waters of the Great Lakes (1 provincial agency versus 8 states) were mostly utilized for Lakes Ontario, Erie, Huron and Superior, while data generated by the U.S. agencies were utilized for Lake Michigan. Since large bodied fish considered in this assessment have large home ranges and likely move across the border, utilization of only Ontario data for Lakes Superior, Huron, Erie and Ontario should not be a major concern. A comparison of the recent contaminant levels to the corresponding advisory benchmarks has been provided by considering similarities in the benchmarks used by the agencies on both sides of the border.

An increased focus on emerging contaminants is occurring in monitoring programs in the U.S. and Canada. While U.S. EPA's Great Lakes National Program Office no longer collects or analyzes sport fish fillets, the Office has instituted an Emerging Contaminants Surveillance Program in whole fish that looks to identify the presence or absence of emerging contaminants of interest and will inform State monitoring and advisory programs. The first year of this program was in 2011, and results are being shared through various outlets, including State of the Great Lakes reporting (previously known as SOLEC), as they are received.

The Ontario Ministry of the Environment and Climate Change continues to monitor contaminants of long term concern such as PCBs, dioxins/furans, mercury and organochlorine pesticides. During the last decade, the Province has started analyzing some contaminants of emerging concern for the Great Lakes environment such as polybrominated diphenylethers (PBDEs), perfluoroalkyl acids (PFAAs) and polychlorinated naphthalene (PCNs) in selected fish samples.

It should be noted that the analysis presented in this sub-indicator report is cursory and a more in-depth data analysis of the monitoring data is recommended to draw a firm conclusion on contaminant trends. Monitoring data for the connecting channels of the Great Lakes were not considered as fish captured from the channels could be migratory and the data may not reflect the local conditions.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada		x				

6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

Acknowledgments
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Information Sources
OMOECC Guide to Eating Ontario Fish – www.ontario.ca/fishguide
State Monitoring & Advisory programs – http://fishadvisoryonline.epa.gov/Contacts.aspx
Site Specific PFAA Advice, Minnesota - http://www.health.state.mn.us/divs/eh/fish/eating/sitespecific.html

GLHHFTS - http://www2.epa.gov/fish-tech/studies-fish-contamination
Leanne Stahl, U.S. Environmental Protection Agency, OST
Baline Snyder, TetraTech
Chip McCarty, Computer Sciences Corporation
John Wathen, U.S. Environmental Protection Agency, OST

State Data included in this sub-indicator
Tom Hornshaw, Illinois Environmental Protection Agency
Candy Schrank, Wisconsin Department of Natural Resources
Jim Stahl, Indiana Department of Environmental Management
Joe Bohr, Michigan Department of Environmental Quality

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List of Tables

Table 1. Consumption limits set by the Guide to Eating Ontario Sport Fish (based on Health Canada TDIs) and the Sport Fish Advisory Taskforce. Source: Ontario Ministry of the Environment and Climate change and Great Lakes Sport Fish Advisory Task Force (PCB Protocol 1993, Mercury Protocol 2007
* Women of childbearing age and children under 15

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Figure 1. Total PCB concentrations (ng/g) in five species from the Great Lakes. Lake Michigan measurements were for skin-on fillets, while skin-removed fillets for the other lakes.
Source: Ontario Ministry of the Environment and Climate Change and U.S. Environmental Protection Agency.
Figure 2. Total mercury concentrations (µg/g) in five species from the Great Lakes. Lake Michigan measurements were for skin-on fillets, while skin-removed fillets for the other lakes.
Source: Ontario Ministry of the Environment and Climate Change and U.S. Environmental Protection Agency.
Figure 3. EPA + DHA (mg/g) compared to the length (cm) of common species from the Great Lakes.
Source: Ontario Ministry of the Environment and Climate Change and U.S. Environmental Protection Agency.

Last Updated

State of the Great Lakes 2017 Technical Report

Meals per month	PCB (ug/g)			Hg (ug/g)		
	Sensitive*	Sensitive**	General**	Sensitive*	Sensitive**	General**
32	0 - .05	<.026	<.026	0 <=.05	<0.06	<0.15
16		.026-.053	.026-.053		0.06-0.12	0.15-0.3
12		.053-.070	.053-.070		0.12-0.16	0.3-0.4
8		.070-.105	.070-.105	>0.05 <= .11	0.16-0.25	0.4-0.6
4	.06 - .2	.105-.211	.105-.211	.0.11 <= .22	0.25-0.5	0.6-1.2
2			.211-.422			1.2-1.8
1	.21 - 1.0		.422-.844	>.22 <= 0.95		
0.5	1.1 - 1.9					
0 (do not eat)	>1.9	>.211	>.844	>0.95	>0.5	>1.8

*Sport Fish Advisory Consortium Protocol
**Ontario Ministry of the Environment and Climate Change

Table 1. Consumption limits set by the Guide to Eating Ontario Sport Fish (based on Health Canada TDIs) and the Sport Fish Advisory Taskforce. Source: Ontario Ministry of the Environment and Climate change and Great Lakes Sport Fish Advisory Task Force (PCB Protocol 1993, Mercury Protocol 2007
* Women of childbearing age and children under 15

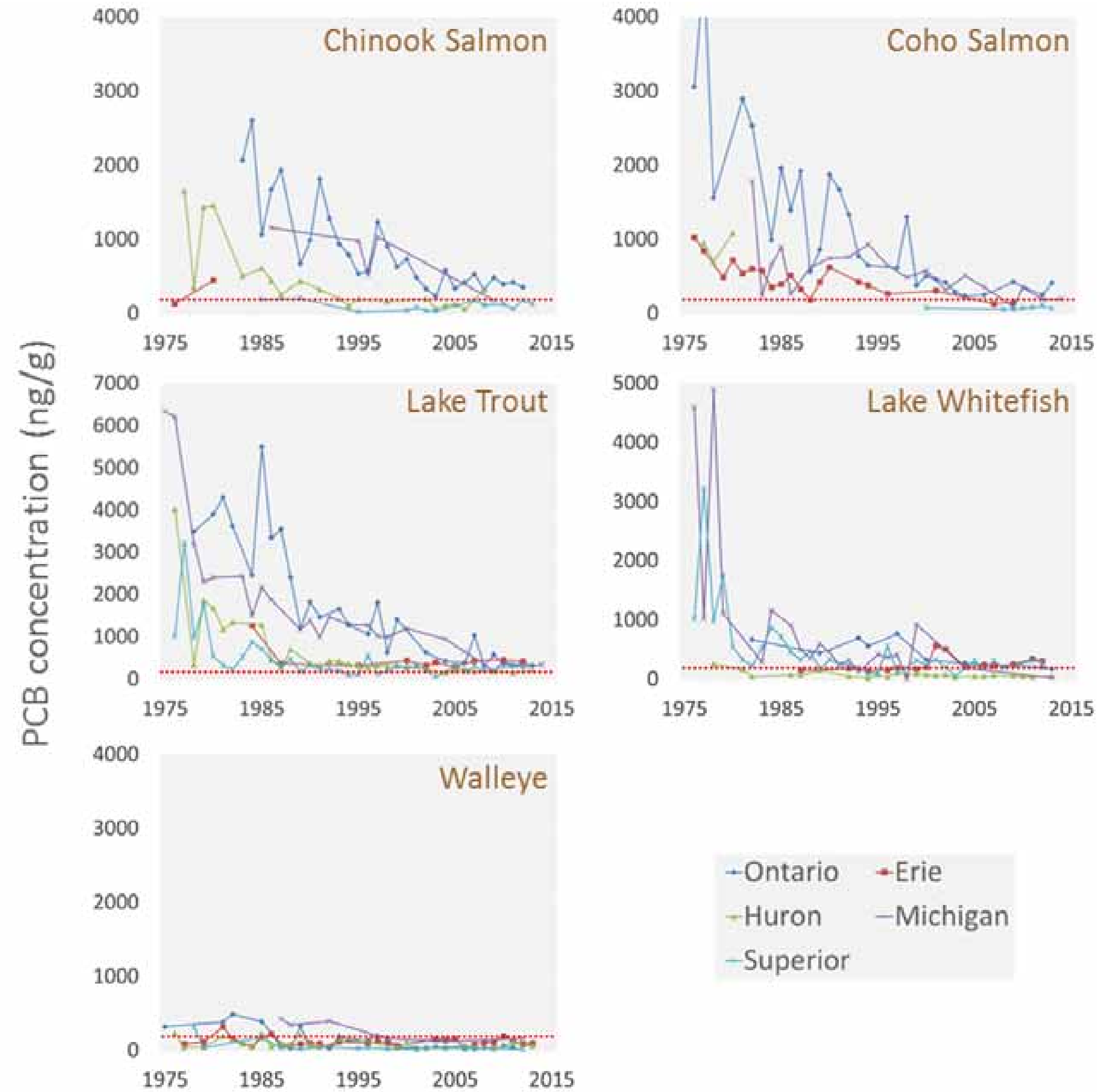


Figure 1. Total PCB concentrations (ng/g) in five species from the Great Lakes. Lake Michigan measurements were for skin-on fillets, while skin-removed fillets for the other lakes. Dashed red lines represent an estimated bi-national health related benchmark for the general population.
Source: Ontario Ministry of the Environment and Climate Change and U.S. Environmental Protection Agency.

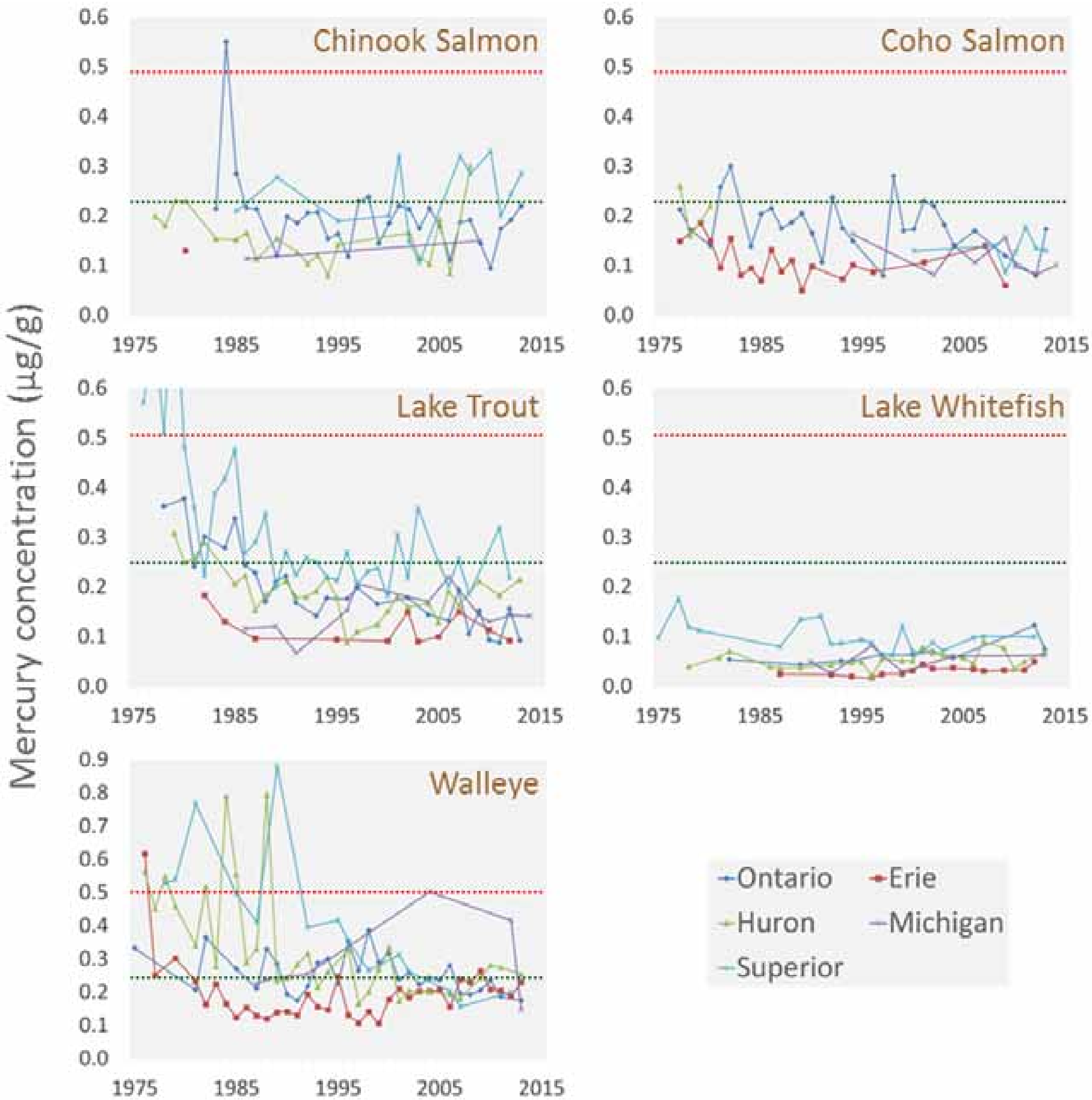


Figure 2. Total mercury concentrations (µg/g) in five fish species from the Great Lakes. Lake Michigan measurements were for skin-on fillets, while skin-removed fillets for the other lakes. Dashed red and green lines represent an estimated binational health related benchmark for the general and sensitive populations, respectively (see Table 1). Source: Ontario Ministry of the Environment and Climate Change, and U.S. Environmental Protection Agency.

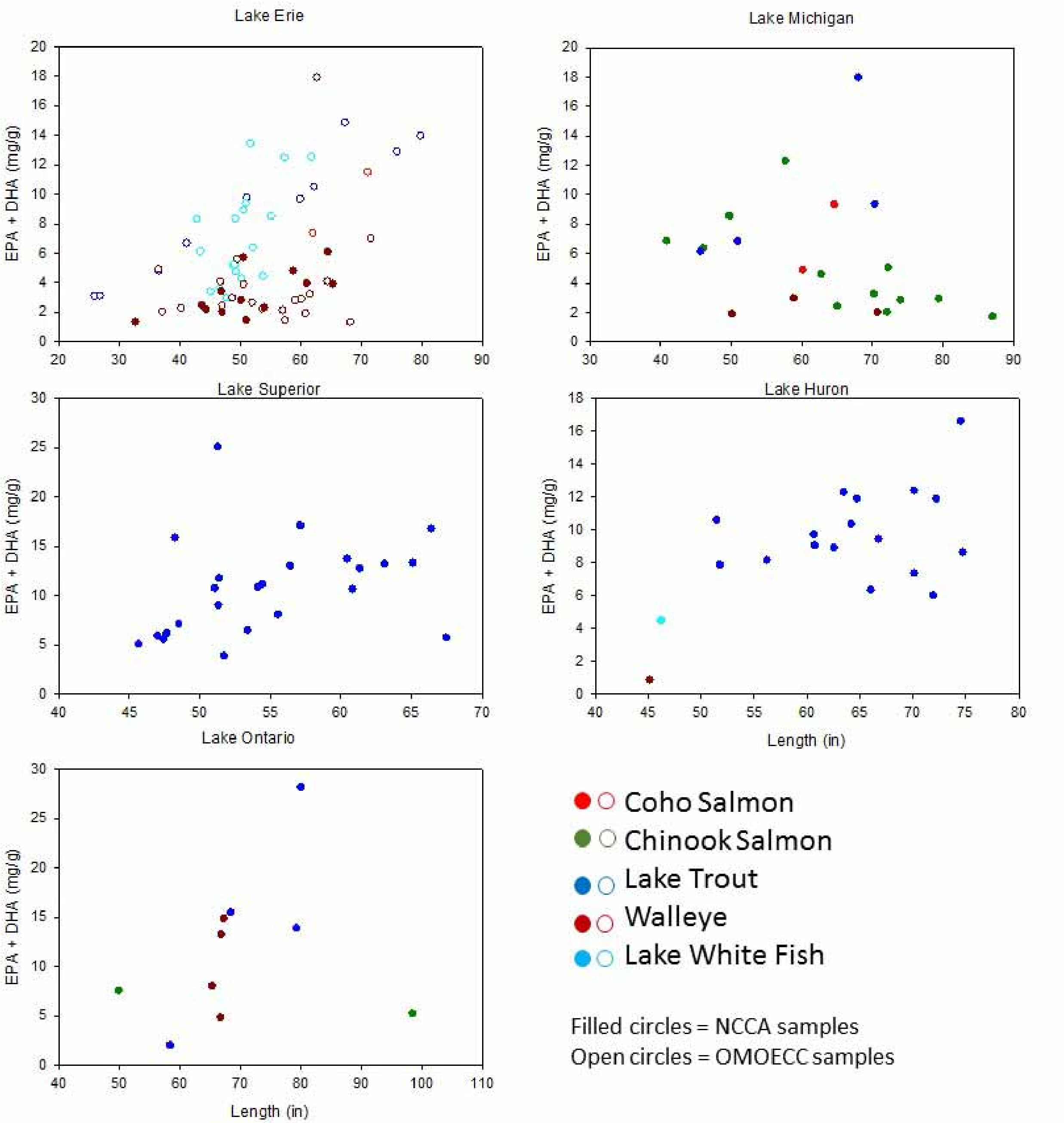
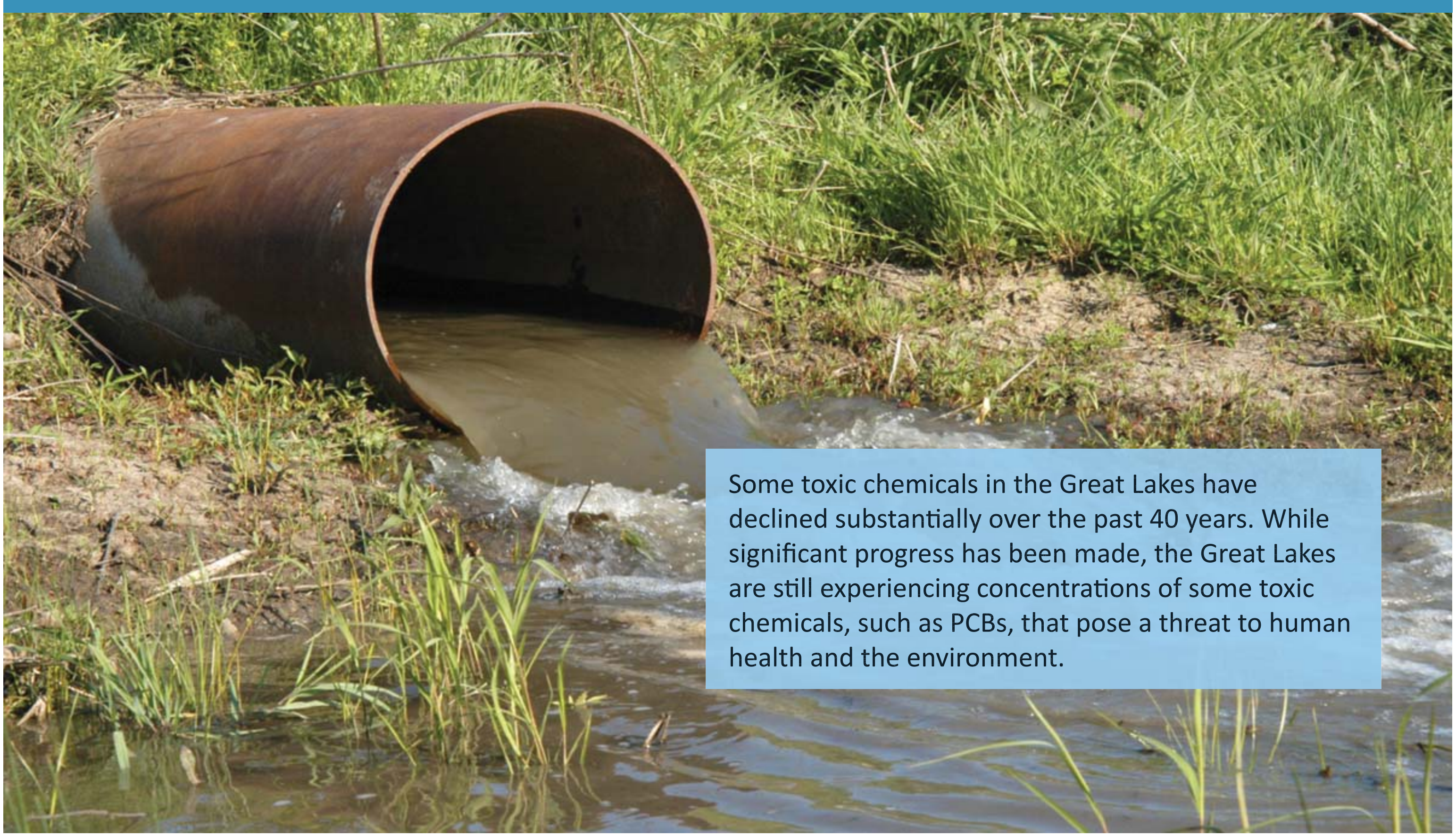


Figure 3. EPA + DHA (mg/g) compared to the length (cm) of common species from the Great Lakes. Source: Ontario Ministry of the Environment and Climate Change and U.S. Environmental Protection Agency

Toxic Chemicals

Status: Fair   Trend: Unchanging to Improving

The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain"*



Some toxic chemicals in the Great Lakes have declined substantially over the past 40 years. While significant progress has been made, the Great Lakes are still experiencing concentrations of some toxic chemicals, such as PCBs, that pose a threat to human health and the environment.

Toxic Chemicals

Assessment Highlights

The Toxic Chemicals indicator shows that nearly all older and regulated or banned chemicals, generally referred to as legacy contaminants and include Polychlorinated Biphenyls (PCBs) and mercury, have decreased over the past 40 years. In general, non-legacy compounds, such as Polybrominated Diphenylethers (PBDEs), have shown slow declines in recent years, although some replacements for these compounds are increasing in the environment. Overall, the status of Toxic Chemicals is **Fair** and the trend is **Unchanging** to **Improving**.

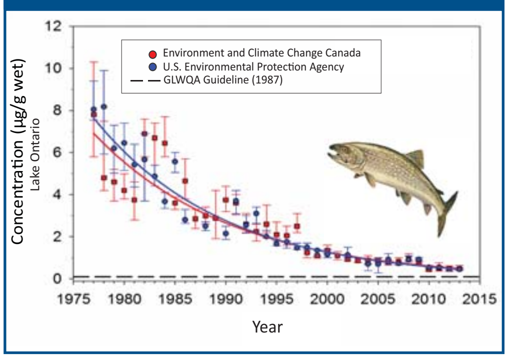
In the offshore waters of the Great Lakes, the long-term trends for many contaminants, such as PCBs and PBDEs, show declines to lower levels and little or no change in the more recent trend, although concentrations are higher in the lower lakes. There are however, occasional exceedances of water quality objectives and criteria for PCBs.

Contaminant levels in Great Lakes whole fish and Herring Gull eggs have decreased significantly since the 1970s. Although declines are being seen, concentrations of some compounds, like PCBs and PBDEs, may still exceed environmental quality guidelines or objectives. Localized areas of highly contaminated sediment in Areas of Concern (AOCs) and hazardous waste sites may continue to act as sources of these and other contaminants to the lakes. Residual sources of PCBs remain in the Great Lakes Basin and throughout the world. PCBs and other chemicals can be carried by air currents from within and outside the basin to the Great Lakes; therefore, atmospheric deposition will remain a significant source of PCBs and other contaminants for decades into the future.

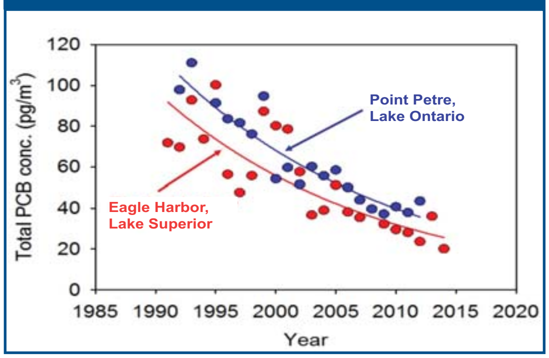
The Toxic Chemicals indicator includes data from several long-term monitoring programs. These programs have been tracking a wide variety of chemicals including mercury, PCBs and PBDEs in the environment for years, and in some cases, decades. The number of substances being monitored is increasing and evolving, thereby improving our base of knowledge to lead to more robust assessments; including chemicals such as current-use pesticides, pharmaceuticals and personal care products.

Refer to the *State of the Great Lakes 2017 Technical Report* for chemicals monitored in the Great Lakes.

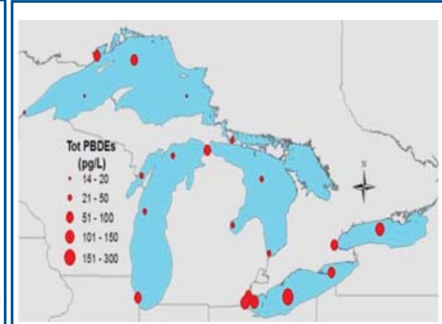
PCBs in Whole Fish are Decreasing



PCBs in Air are Decreasing



PBDEs are Higher in Lakes Erie and Ontario



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Toxic Chemical Concentrations	Improving	Unchanging	Unchanging	Unchanging	Unchanging
Toxic Chemicals in Sediments	Unchanging	Unchanging	Unchanging	Improving	Improving
Toxic Chemicals in Great Lakes Whole Fish	Unchanging	Improving	Unchanging	Unchanging	Improving
Toxic Chemicals in Great Lakes Herring Gull Eggs	Improving	Improving	Improving	Unchanging	Unchanging
Atmospheric Deposition of Toxic Chemicals	No lake was assessed separately Great Lakes Basin assessment is **Fair** and **Improving**				

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Toxic Chemical Concentrations

Open water

Overall Assessment
Status: Good
Trend: Unchanging
Rationale: Legacy contaminants that are persistent, bioaccumulative and/or toxic have decreased in Great Lakes waters. The long-term trends for many legacy contaminants including mercury show declines to lower levels and little or no change in the more recent record. Occasional exceedances of water quality objectives are observed for total PCBs. The number of compounds being monitored is increasing, thereby improving our base of knowledge.

Lake-by-Lake Assessment

Lake Superior

Status: Good
Trend: Improving
Rationale: In general, the status of Lake Superior is good, but has the highest concentrations of certain compounds such as a-HCH, g-chlordane, lindane and toxaphene which accumulate in the cold, deep waters of Lake Superior, and once present, are slow to disappear due to their persistence and the long water residence time. These compounds are showing declining concentrations over the long term but no change in recent years. Other compounds are showing no trends, and there are no statistically significant increasing trends for any monitored compounds. Lake Superior shows among the lowest concentrations for a suite of new compounds, including perfluorinated surfactants and brominated flame retardants.

Lake Michigan

Status: Good
Trend: Unchanging
Rationale: Fewer data are available for Lake Michigan because Environment and Climate Change Canada has only conducted three campaigns on this lake. The data indicate unchanging conditions for many compounds (declining for dieldrin) and no exceedances of available water quality guidelines are observed. Additional data for a suite of compounds is being made available by the U.S. EPA and will be included in future State of the Great Lakes (previously known as SOLEC) sub-indicator reports.

Lake Huron

Status: Good
Trend: Unchanging
Rationale: Lake Huron has some of the lowest concentrations of many contaminants due to few sources and it is less subject to atmospheric deposition and retention of persistent compounds due to its geographical location. Some evidence of increasing PAHs is observed in Georgian Bay, although concentrations are low and no guidelines are exceeded at the monitored locations. Mercury and several important legacy organochlorines are showing declining trends.

Lake Erie

Status: Fair
Trend: Unchanging
Rationale: Lake Erie displays relatively high concentrations of certain legacy organochlorines and industrial by-products due to its location downstream of historic sources. Some PAHs are also highest in Lake Erie. Current use pesticides are in general highest in Lake Erie and in its monitored tributaries. In the most recent surveys, no exceedances of available water quality guidelines were observed. Observed variability is highest in Lake Erie for most monitored parameters and few trends are discernible. A significant decline in total mercury is noted in the eastern basin only.

Lake Ontario

Status: Fair

Trend: Unchanging

Rationale: Due to its position downstream of the other Great Lakes and in a highly populated region, relatively high concentrations of some contaminants such as PAHs are observed in Lake Ontario. Other compounds indicative of consumer product sources (e.g., PBDEs, perfluorinated compounds) are also highest here. An increase in total PAHs and some industrial compounds is observed. Several organochlorines are declining, as they are in the other Great Lakes.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess the concentration of toxic chemicals in Great Lakes waters; to infer the potential for impairment to the quality of the waters of the Great Lakes by harmful pollutants; to infer progress toward virtual elimination of chemicals of mutual concern; to inform the risk assessment of toxic chemicals and the development of risk management strategies; to inform the development of environmental quality guidelines; and to report on environmental response (i.e., progress) toward the achievement of targets identified in action plans and risk management strategies for toxic chemicals in the Great Lakes Basin.

Ecosystem Objective

This sub-indicator best supports work towards General Objective #4 of the 2012 Great Lakes Water Quality Agreement (GLWQA) which states that the Waters of the Great Lakes should "be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain."

Ecological Condition

Measure

This sub-indicator assesses the current status of toxic chemicals and will track whether concentrations are decreasing, staying the same, or increasing in Great Lakes waters over time. The chemicals of interest include toxic chemicals of current and future concern. The monitoring data will be used to assess the progress and effectiveness of pollution prevention and control measures for chemicals of mutual concern as identified in Annex 3 of the GLWQA. The monitoring data will also be used.to inform the selection of additional compounds of mutual concern under Annex 3. The sub-indicator will primarily report offshore data because these are the focus for monitoring trends; the status for this sub-indicator will consider the nearshore for those areas where the information is available (see data limitations section).

A suite of compounds is monitored on the CSMI rotation schedule (i.e., once every five years). The number of stations sampled varies by lake. In Canada, additional sampling is conducted for compounds that are not bioaccumulative at stations located within the Great Lakes as well as high risk watersheds from which tributaries may convey sources of toxic chemicals to the Great Lakes.

Endpoints

The target or endpoint for this sub-indicator will have been met when the Waters of the Great Lakes are free from pollutants in quantities or concentrations that could be harmful to human health, wildlife or aquatic organisms, through direct exposure or indirect exposure through the food chain. Status will be determined on a case-by-case basis taking a weight-of-evidence approach in making an expert assessment, including the number of compounds that are detectable and/or are below water quality guidelines (such as the CCME Water Quality Guidelines for the Protection of Aquatic Life, GLWQA Specific Objectives and Lake Ecosystem Objectives, or other Great Lakes agency water quality guidelines, where available) and the relative effect of the compound, if known. Progress will be determined based on whether trends of the toxic chemicals are positive or negative, the rate of change in the concentrations, and by the number of chemicals which are doing so.

Programs and Methods

The status of toxic chemicals in open waters of the Great Lakes is monitored by the Canadian and United States federal governments. Environment and Climate Change Canada (ECCC) conducts ship-based cruises to collect water quality samples as part of its Great Lakes Surveillance Program. Since 2004, this has included monitoring for toxic chemicals using a specialized and improved technique that permits the accurate detection of low concentrations that may also be used for the determination of temporal trends. Monitoring is generally conducted during spring cruises as this timing has been determined to be optimal to establish annual maxima for many legacy compounds (Williams et al. 2001), although summer concentrations are used to detect maximum concentrations for current-use pesticides. From 2004 to 2013, monitoring (for contaminants) was conducted on each lake every two or three years. Since 2013, monitoring is coordinated with the Cooperative Science and Monitoring Initiative (CSMI), so that work is focused on one of the Great Lakes in each year. Monitoring in Lake Michigan over the same time period has been conducted jointly by the parties and using ECCC techniques. Monitoring for contaminants of emerging concern (CECs) is now conducted in Lake Michigan by Clarkson University under grant from the U.S. EPA. Additional data from 18 stations distributed throughout all five of the Great Lakes were collected as part of a binational sampling effort in 2011 – 2012, using a technique to concentrate very large sample volumes (100-200 L) onto resin columns (Venier et al. 2014). These data permit the assessment of the status of additional compounds that may not otherwise be detected in smaller samples.

All major Great Lakes regions (nearshore, offshore and major embayments) are monitored. Due to inherently high ship and laboratory costs, sample sizes are in general quite small, limiting our ability to assess all nearshore areas. The status of contaminants in the Great Lakes is performed using all recent data and trends are based on data collected since 2004 because laboratory and field techniques improved greatly at that time. A large suite of parameters is routinely monitored in the Great Lakes. Table 1 lists the parameters and indicates those that are detected in more than 10% of samples for each of the lakes.

Organochlorines Pesticides and Industrial Byproducts

Organochlorine pesticides have been banned, restricted or discontinued but many remain ubiquitous in the Great Lakes. Overall, the most abundant organochlorines present in Great Lakes waters are alpha-HCH, dieldrin and lindane. Concentrations of alpha-HCH and gamma-HCH (Lindane; Figure 1) are highest in Lake Superior and dieldrin is highest in Lake Michigan although recent data show highest concentrations in the western basin of Lake Erie. Due to its large surface area, cold water temperature and long retention time, Lake Superior is most susceptible to accumulation of these compounds. All three of these compounds are declining over time. The decreasing trend for lindane is dramatic (Figure 2). The voluntary removal of lindane was announced by the Canola Council of Canada in 1998 (National Round Table on the Environment and the Economy, 2001). In 2006, the U.S. EPA banned the agricultural use of lindane and in 2009 the production and agricultural use of lindane was banned under the Stockholm Convention. Figure 2 demonstrates that the in-lake concentrations responded to these reductions with declines observed in each of the Great Lakes (statistically significant in lakes Erie and Ontario) since our measurements began in 2004.

For the industrial byproducts, the most abundant are hexachlorobenzene (HCB) and hexachlorobutadienne (HCBD). Concentrations are highest in the lower Great Lakes (lakes Erie and Ontario) because sources have historically been greater in the more industrial regions and these compounds are not as subject to atmospheric transport. Increasing trends are observed for both compounds in most lakes, although the trends are statistically significant ($p<0.05$) only for HCB in Lake Huron and the east basin of Lake Erie, and for HCBD in Lake Ontario.

Polychlorinated biphenyls (PCBs)

Despite being banned in 1977 in the United States and Canada, PCBs continued to be used and stored. While inventories have been reduced over the past several decades, PCBs continue to be detected throughout the Great Lakes. Concentrations of total PCBs are observed according to the following spatial trend: Ontario ≈ Erie > Huron ≈ Michigan > Superior ($p < 0.001$; Venier et al. 2014). Within each lake, spatial distributions indicate higher concentrations in harbours and nearshore regions compared to offshore waters. The highest individual concentrations are observed in the western basin of Lake Erie and concentrations decrease as waters flow to the central and eastern basin. PCB concentrations in Lake Michigan waters are higher in Green Bay and near Chicago compared to the offshore. In Lake Huron, concentrations are highest in Saginaw Bay and offshore concentrations are lower and appear to decline from south to north within the main body of the lake. There is no temporal trend in total PCBs since 2004, although we know from sediment core data (see Toxic Chemicals in Sediment sub-indicator) and fish tissue data (see Toxic Chemicals in Great Lakes Whole Fish sub-indicator) that concentrations have declined over the past four decades. The Ontario Provincial Water Quality Objective of 1 ng/L is used as a benchmark and it has been exceeded in some years in Lake Erie and Hamilton Harbour (Lake Ontario). The most recent data (Venier et al. 2014) demonstrate the above-noted spatial distribution but no exceedances of the benchmark are observed. There is no trend in total PCBs since 2004 in Great Lakes waters.

Polycyclic aromatic hydrocarbons (PAHs)

The most abundant PAHs observed in Great Lakes waters include naphthalene, phenanthrene, fluoranthene, fluorene and pyrene. Higher molecular weight PAHs are less frequently detected because they tend to be less soluble in water and partition instead to sediment. Concentrations of total PAHs (the sum of 17 individual PAH compounds) are highest in lakes Erie and Ontario, intermediate in lakes Huron and Michigan, and lowest in Lake Superior. This spatial distribution follows the pattern of usage, with more intense industry and urbanization observed in the lower Great Lakes. Generally stable conditions or increases are observed for PAHs. The sum of the 17 PAHs (i.e., total PAHs) are unchanged in most lakes although statistically significant increases are observed for Lake Ontario and Georgian Bay, largely driven by increasing naphthalene and fluorene concentrations. In an urban setting, PAHs were found to be contributed to Lake Ontario predominantly via tributary loading; therefore, source reductions must ultimately come from non-point sources (Melymuk et al. 2014).

Mercury

Concentrations of total (i.e., whole water) mercury are highest in Lake Erie and significantly lower in offshore waters of the other Great Lakes (Figure 3). The Canadian Council of Ministers of the Environment (CCME 1999) guideline for mercury in water (26 ng/L for the protection of aquatic life) has not been exceeded although concentrations in the western basin of Lake Erie in 2009 (mean 13.2 and maximum 18.2 ng/L) approached the guideline. Higher concentrations of mercury have been noted in Lake Erie previously (Dove et al. 2011), due to the historic presence of chlor-alkali and other industries in the St. Clair River – Detroit River interconnecting channel.

The overall decline in mercury from historic high levels is supported by long-term measurements in fish and sediment (for example, see the Toxic Chemicals in Great Lakes Whole Fish and Toxic Chemicals in Sediment sub-indicator reports). Mercury in water declined significantly between 2003 and 2009 (Dove et al. 2011); however, since that time, this decline may have slowed or halted (see Figure 4). During this period the lower Great Lakes (Erie and Ontario) have also recently experienced either flat or weak increasing trends of mercury in fish (Bhavsar et al. 2010, Toxic Chemicals in Whole Fish sub-indicator report). The increase of mercury in fish, without a concurrent increase in water, implies that changes in mercury cycling may be occurring in the lower lakes.

In-Use Pesticides

Currently used pesticides have been monitored in the Great Lakes since about 1994 and in high priority tributaries federally since about 2002, including suites of compounds known as acid herbicides, neutral herbicides and organophosphorus insecticides (Struger et al. 2004). More recently, additional compounds such as glyphosate and carbamates are also monitored due to dramatic increases in their usage. Organophosphorus insecticides are rarely observed in offshore waters and this monitoring has been discontinued. The most commonly observed compounds are atrazine, metolachlor and 2,4-D. In Great Lakes waters, concentrations at the monitored locations have not exceeded CCME guidelines, indicating good status, and no temporal trends are observed. Concentrations of these compounds are highest in the lower Great Lakes (i.e., lakes Erie and Ontario), with maximum concentrations generally observed in the western basin of Lake Erie (e.g., for glyphosate). In tributaries, concentrations tend to be highest in agricultural and urban areas, although there has been a marked recent decline in the concentrations of urban pesticides in Ontario streams, primarily due to enhanced pesticide regulation at the provincial level (Todd and Struger 2014). Pesticide concentrations in monitored tributaries indicate occasional (at some sites, routine) exceedance of guidelines (e.g., 2,4-D, atrazine, metolachlor, chlorpyrifos) and the widespread presence of a longer list of pesticide compounds (Struger, pers. comm., Struger et al. 2016). The cumulative effect of chronic exposure to pesticide mixtures is a gap requiring attention.

Toxaphene

Toxaphene is not routinely monitored but its discussion is merited due to its relevance to the Great Lakes. Toxaphene was banned almost 40 years ago, and its use in the Great Lakes Basin was minimal, but atmospheric transport and deposition, combined with its high persistence and retention in cold environments, has resulted in its presence at relatively high concentrations in both Great Lakes water (Muir et al. 2006) and fish (Xia et al. 2012). Concentrations of toxaphene are highest in Lake Superior compared to the other lakes, where it is responsible for approximately 7% of the fish consumption advisories (Ontario Ministry of the Environment and Climate Change, 2015). Toxaphene concentrations in all the lakes are declining, with a modeled half-life of 9.2 years in Lake Superior (Xia et al. 2011). Similar rates of decline have been observed in Great Lakes fish (Xia et al. 2012); it may take 30 years for Lake Superior lake trout tissue concentrations to decline to concentrations observed in the other Great Lakes (Xia et al. 2011).

Flame Retardants

Recent work conducted on each of the Great Lakes sampled for polybrominated diphenyl ethers (PBDEs), and other flame retardants (Venier et al. 2014). The results showed higher concentrations in the lower Great Lakes and the spatial patterns were consistent with consumer products as a primary source (Figure 5). PBDE congener patterns reflected the Penta-BDE and Deca-BDE mixtures. Alternative brominated flame retardants were detected, reflecting the wide usage of these replacement products for the commercial Penta-BDE mixture. Dechlorane Plus and hexabromocyclododecane (HBCCD) concentrations were highest in Lake Ontario, reflecting manufacturing sources and usage patterns. The ubiquity of flame retardants reflects their widespread usage in commercial products, and it will remain important to continue risk assessment activities, monitor ambient levels and to track progress if and when the use of these compounds is regulated.

Additional Compounds of Concern

Additional compounds that are of potential concern including perfluorinated compounds (PFCs; a group of highly persistent surfactants), bisphenol A (contained in some plastics) and triclosan (an antibacterial agent in consumer products) are being monitored in the Great Lakes and high risk watersheds as part of the Government of Canada's Chemicals Management Plan. Results for PFCs are consistent with patterns of consumer product sources, with higher concentrations noted near urban regions (Gewurtz et al. 2013). Information about these compounds is shared promptly with risk assessment and risk management agencies in order that decision making is based on the most recently available, best science.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Toxic Chemicals in Great Lakes Whole Fish – interpretation of status and trends is conducted jointly to determine the degree of concordance between the information sources – for example to determine if temporal trends observed in fish are due to water quality changes or due to biological mediation.
- Toxic Chemicals in Sediment – longer-term trends of Great Lakes toxics may be discerned from retrospective analyses in sediment cores. Trends of high molecular weight PAHs may be more accurately monitored in sediments; a disadvantage is that it may take a very long time to be able to track progress.
- Atmospheric Deposition of Toxic Chemicals – water quality data are required for the calculation of fluxes, and temporal data are required to interpret trends in atmospheric concentrations and changes in deposition rates.

Comments from the Author(s)

The assessment of organic contaminants in water can be challenging given the relatively complex field and laboratory requirements. However, water can provide a stable medium for the assessment of organic contaminants which otherwise may be more challenging in other media (e.g. for compounds having short residence times in air, those not bioaccumulating in fish tissue or binding to sediment, or those undergoing transformations or biogeochemical cycling in the environment). The assessment of contaminants in Great Lakes offshore waters is a viable means to determine long-term trends for compounds that are relevant for management and ecosystem health. It is also an important medium to consider in conjunction with information about contaminants in air, sediment and biological media.

Several of the environmental quality guidelines that were previously available for legacy organic contaminants have been withdrawn. The Canadian Council of Ministers of the Environment has withdrawn guidelines for a-HCH and PCBs in favour of the use of fish and sediment guidelines as these compounds are hydrophobic and/or bioaccumulative. There is therefore a lack of benchmarks against which to gauge the lakes' status. Despite the dearth of guidelines, the assessment of toxic contaminants is important as the current status represents an important means of assessing exposure for biota and the offshore temporal data series provide a means of assessing trends.

The concentrations of many legacy organic contaminants are low in the offshore waters of the Great Lakes, are reduced from historical maxima, and are currently changing slowly. The realignment of the monitoring schedule with the CSMI will result in less frequent data collection for these compounds, and this is warranted. For new compounds requiring surveillance, and for those requiring more frequent assessment due to more rapid change, the schedule may not follow the CSMI in order to effect adequate monitoring.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	×					
2. Data are traceable to original sources	×					
3. The source of the data is a known, reliable and respected generator of data	×					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	×					
5. Data obtained from sources within the U.S. are comparable to those from Canada	×					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	×					
Clarifying Notes: The data incorporated here are directly comparable across the Great Lakes; additional U.S. data are currently being gathered and will be incorporated into future Great Lakes (previously known as SOLEC) sub-indicator reports.						

Acknowledgments

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List of Tables and Figures

Table 1. Legacy organic contaminants monitored in Great Lakes surface water for Environment and Climate Change Canada's Great Lakes Surveillance. Parameters are monitored during spring cruises from dissolved (filtered) large volume (16 – 24 L) samples using clean techniques. Those detected in more than 10% of samples are indicated with an "×".
Source: Environment and Climate Change Canada

Figure 1. Spatial distribution of dissolved lindane (gamma hexachlorocyclohexane) in the Great Lakes. Data are the most recent available spring, surface data for all stations.
Source: Data are from Environment and Climate Change Canada's Great Lakes Surveillance

Figure 1. Temporal changes of dissolved Lindane in the Great Lakes. Data are spring, surface data at offshore stations. Boxes show central median and 25% and 75% values, whiskers show 1.5x interquartile range.
Source: Data are from Environment and Climate Change Canada's Great Lakes Surveillance

Figure 2. Temporal changes of total mercury in the Great Lakes. Data are a) Great Lakes spring, surface data from offshore stations and b) Lake Erie spring, surface data from all stations by basin. Lake Erie west basin data for are scaled using the left-hand vertical axis and central and east basin data are scaled using the vertical axis on the right. Boxes show central median and 25% and 75% values, whiskers show 1.5x interquartile range. Temporal trends indicate declines in all of the lakes (not statistically significant for Georgian Bay) with the exception of Lake Erie, where there is no significant change.
Source**:** Data are from Environment and Climate Change Canada's Great Lakes Surveillance.

Figure 4. Spatial distribution of total mercury in the Great Lakes. Data are the most recent available spring, surface data for all stations.
Source: Data are from Environment and Climate Change Canada's Great Lakes Surveillance
Figure 5. Spatial distribution of the concentrations of total PBDEs, pg/L.
Source: Vernier et al.

Last Updated

State of the Great Lakes 2017 Technical Report

Parameter	Lake Superior	Lake Michigan	Lake Huron	Georgian Bay	Lake Erie	Lake Ontario
Organochlorines						
Alpha-Chlordane	×	×			×	×
Alpha-Endosulfan		×	×		×	×
Alpha-HCH	×	×	×	×	×	×
Beta-Endosulfan	×	×			×	×
Dieldrin	×	×	×	×	×	×
Gamma-chlordane					×	×
Lindane	×	×	×	×	×	×
Mirex						
o'p'-DDT						
Octachlorostyrene						
p'p'-DDD					×	×
p'p'-DDE					×	×
p'p'-DDT						
Industrial byproducts						
Hexachlorobenzene	×	×	×	×	×	×
Hexachlorobutadiene					×	×
Pentachlorobenzene	×	×	×	×	×	×
Polychlorinated biphenyls[1]	×	×	×	×	×	×
Polycyclic Aromatic Hydrocarbons (PAHs)						
Acenaphthene		×	×		×	×
Acenaphthylene					×	×
Anthracene					×	×
Benzo(a)anthracene					×	×
Benzo(a)pyrene					×	
Benzo(b,k)fluoranthene					×	×
Benzo(e)pyrene					×	×
Benzo(ghi)perylene						
Chrysene	×				×	×
Dibenzo(ah)anthracene						
Fluoranthene	×	×	×	×	×	×
Fluorene	×	×	×	×	×	×
Indeno(1,2,3-cd)pyrene					×	
Napthalene	×	×	×	×	×	×
Perylene		×				
Phenanthrene	×	×	×	×	×	×
Pyrene	×	×	×		×	×

Table 1. Legacy organic contaminants monitored in Great Lakes surface water for Environment and Climate Change Canada's Great Lakes Surveillance. Parameters are monitored during spring cruises from dissolved (filtered) large volume (16 – 24 L) samples using clean techniques. Those detected in more than 10% of samples are indicated with an "×".
Source: Environment and Climate Change Canada

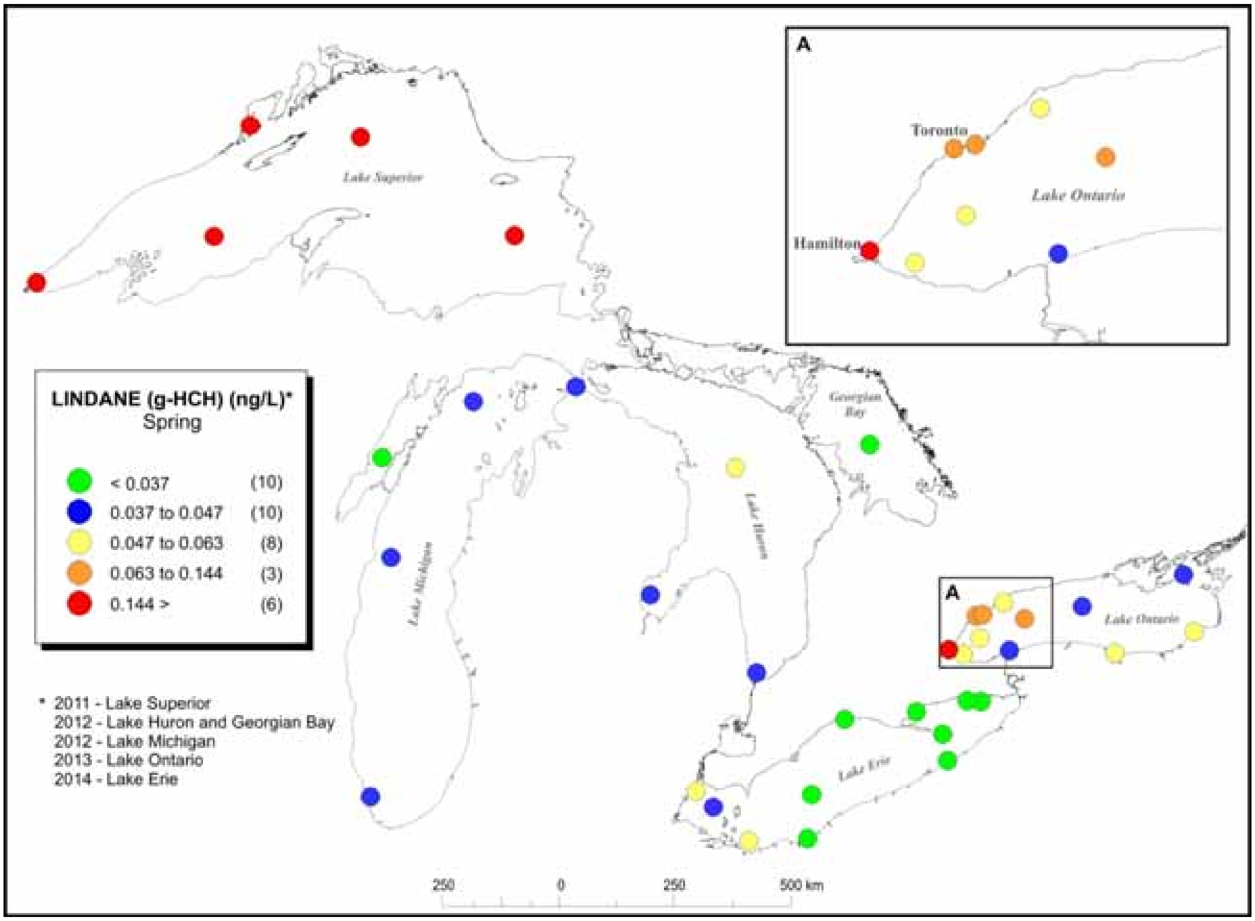

Figure 1. Spatial distribution of dissolved lindane (gamma-HCH) in the Great Lakes. Data are the most recent available spring, surface data for all stations. The year of sampling is provided below the legend, and the number of samples in each category is shown in parentheses in the legend.
Source: Data are from Environment and Climate Change Canada's Great Lakes Surveillance

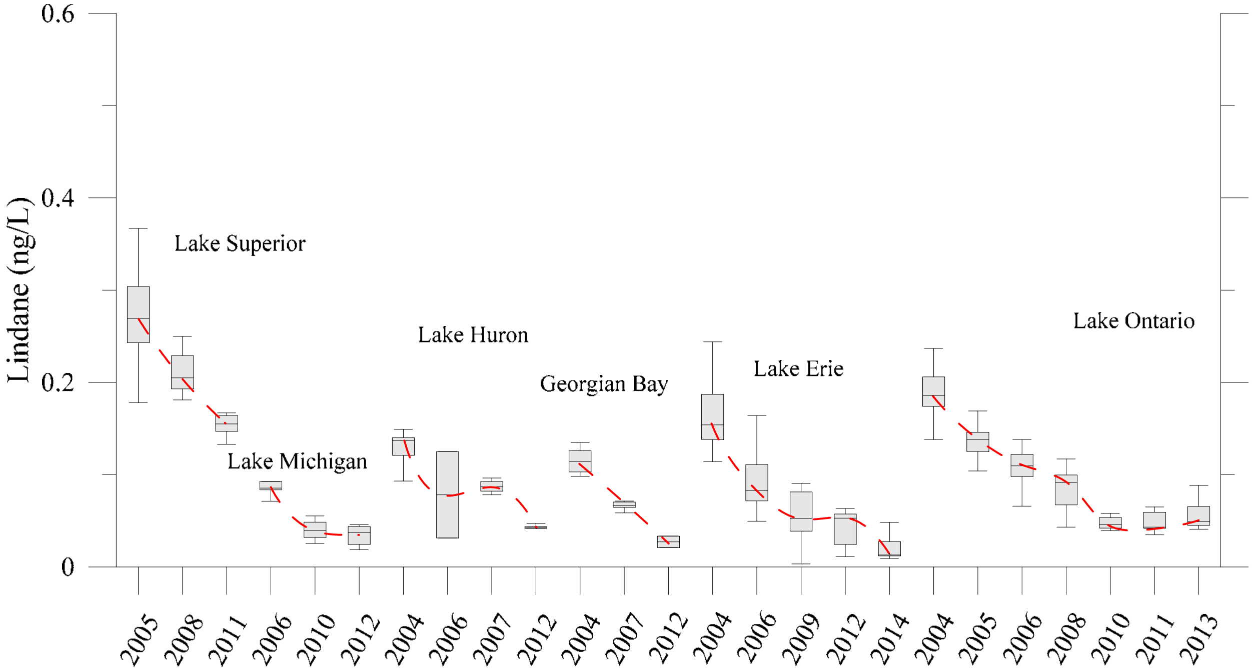

Figure 3. Temporal changes of dissolved Lindane (gamma-HCH) in the Great Lakes. Data are spring, surface data at offshore stations. Boxes show central median and 25% and 75% values, whiskers show 1.5x interquartile range. Source**:** Data are from Environment and Climate Change Canada's Great Lakes Surveillance

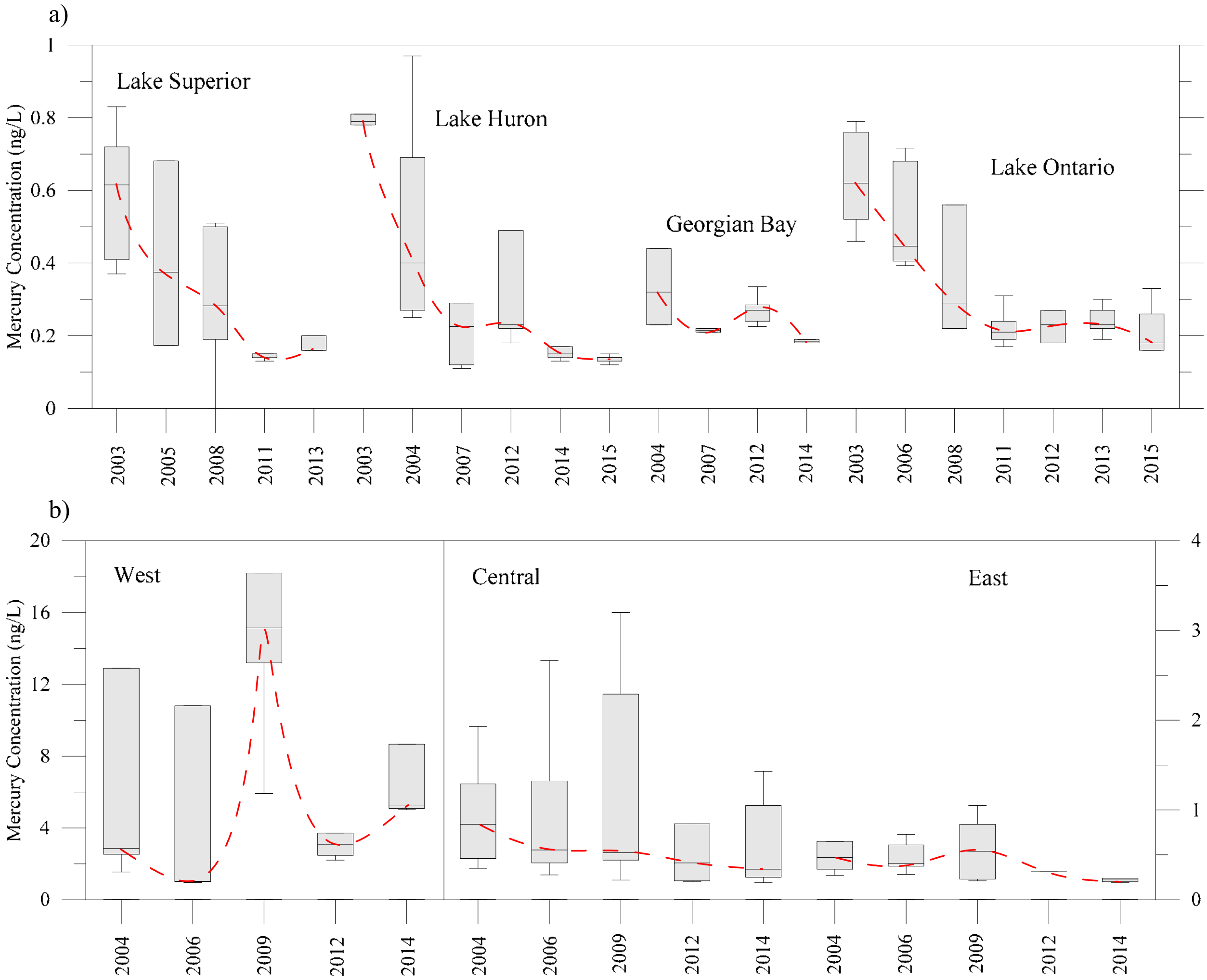

Figure 4. Temporal changes of total mercury in the Great Lakes. Data are a) Great Lakes spring, surface data from offshore stations and b) Lake Erie spring, surface data from all stations by basin. Lake Erie west basin data for are scaled using the left-hand vertical axis and central and east basin data are scaled using the vertical axis on the right. Boxes show central median and 25% and 75% values, whiskers show 1.5x interquartile range. Temporal trends indicate declines in all of the lakes (not statistically significant for Georgian Bay) with the exception of Lake Erie, where there is no significant change.
Source: Data are from Environment and Climate Change Canada's Great Lakes Surveillance

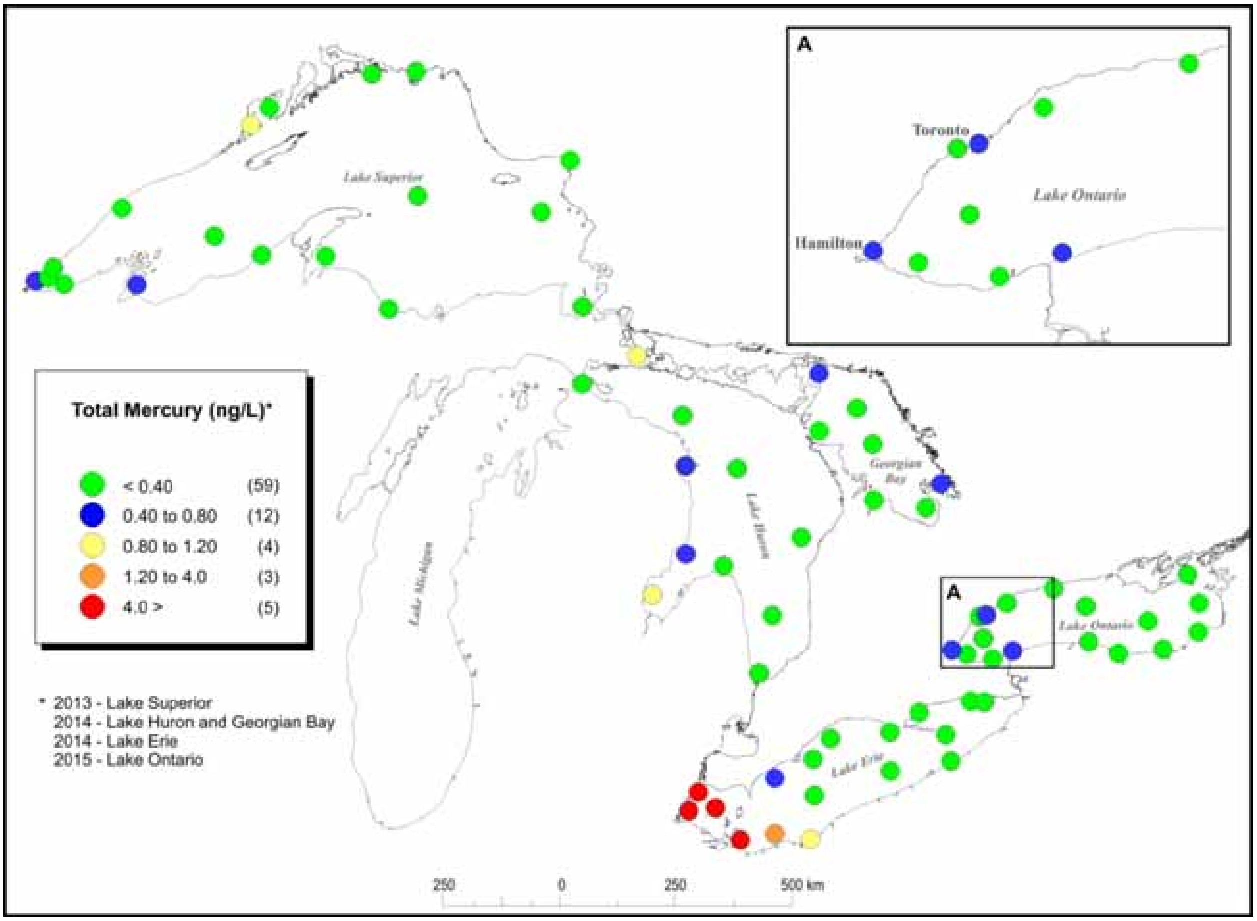

Figure 4. Spatial distribution of total mercury in the Great Lakes. Data are the most recent available spring, surface data for all stations. The year of sampling is provided below the legend, and the number of samples in each category is shown in parentheses in the legend.
Source: Data are from Environment and Climate Change Canada's Great Lakes Surveillance

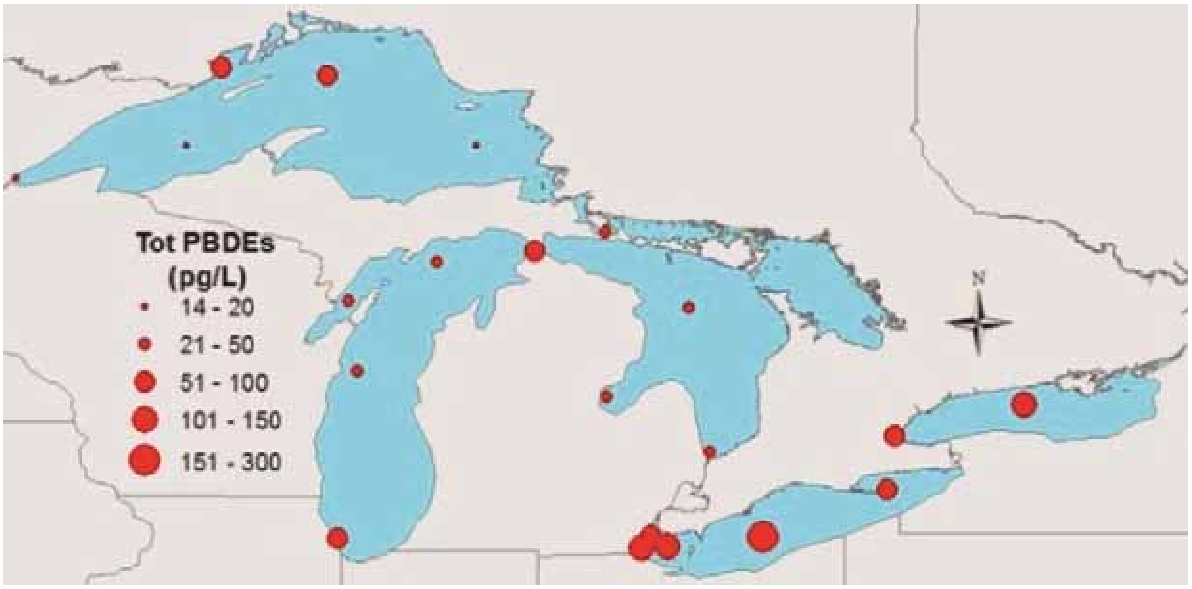

Figure 5. Spatial distribution of the concentrations of total PBDEs, pg/L.
Source: Vernier et al.

Sub-Indicator: Toxic Chemicals in Sediment

Overall Assessment
Status: Fair
Trend: Improving
Rationale: Legacy contaminants that are persistent, bioaccumulative and/or toxic have decreased in Great Lakes sediment. Long term trends for many legacy contaminants including mercury exhibit declines or no change. Legacy compounds including PCBs and DDT are generally below Canadian Council of Ministers of the Environment (CCME) sediment quality guideline values while other contaminants including polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) and polybrominated diphenyl ethers (PBDEs) exhibit some exceedances of guidelines, particularly in Lake Ontario. Emerging and new contaminants are of increasing concern as many exhibit trends toward increasing concentrations and need to be studied further to determine acceptable limits.

Lake-by-Lake Assessment

Lake Superior

Status: Good
Trend: Unchanging
Rationale: Lake Superior is the largest, coldest and deepest of the Great Lakes. Greater contaminant cycling times and lower rates of volatilization have resulted in lower rates of decrease in concentrations for some legacy contaminants, compared to the other Great Lakes. However, typical offshore deep-water sediment contaminant concentrations are very low, with atmospheric deposition as the primary source. While still exhibiting the highest toxaphene concentrations in the Great Lakes, these levels have declined by an order of magnitude since their peak in the 1980s. Concentrations of some metals exceed the strictest sediment quality guidelines due to the geochemistry of the watershed (pre-Cambrian shield) and historical regional sources associated with mining and smelting. While the concentration of some of brominated flame retardants (BFRs) including BDE 209, Dechlorane 604 and decabromodiphenylethane (DBDPE) are the lowest in the Great Lakes, they are increasing in concentration with doubling times of 7-24 years, 5-38 years and 5-16 years, respectively (Guo 2015).

Lake Michigan

Status: Fair
Trend: Unchanging
Rationale: Lake Michigan sediment is assessed for State of the Great Lakes reporting (previously known as SOLEC) for the first time. Lake Michigan consists of a cold, deep and forested northern basin, and a more urbanized southern basin. Atmospheric deposition is a primary source of most contaminants in sediments due to the lake's large surface area; however, inputs from tributaries and other local sources are also important (Lepak et al. 2015, Zhang et al. 2009, Eisenreich and Strachan 1992). Some chemicals exhibit elevated concentrations in sediment, in areas such as Green Bay, at sites on the eastern shores of the lake, and/or in the southern basin. Mercury concentrations are highest in Green Bay with higher contributions from industrial and watershed-derived sources (Lepak et al. 2015). Concentrations of some flame retardants are highest in Lake Michigan compared to the upper Lakes (lower Great Lakes not assessed), with the highest levels in the southeast portion of the lake and near Sleeping Bear Dunes (Guo 2015). PCBs concentrations are declining – albeit very slowly - in Lake Michigan sediments with halving times between 32 to 179 years (Li et al. 2009). PFCs that have replaced the more well-known PFOS and PFOA are now being found at comparable levels in Lake Michigan sediments (Codling et al. 2014).

Lake Huron

Status: Good
Trend: Unchanging
Rationale: Lake Huron is similar to Lake Superior from a sediment contamination viewpoint, as the lake is large, cold and deep with atmospheric deposition as the primary source of most contaminants. Typical sediment contaminant concentrations are very low; however PCDD/Fs, nickel and copper concentrations are above guidelines in areas

of Spanish Harbour and the Whalesback Channel due to local historical industrial/mining activity. Very low sedimentation rates negatively impact natural recovery in the area. As with Superior, concentrations of some metals exceed the strictest guidelines; the natural geochemistry of the watershed (pre-Cambrian shield) is a factor.

Lake Erie

Status: Fair
Trend: Improving
Rationale: Lake Erie exhibits a definitive spatial gradient in contamination with decreasing concentrations from the western basin to the eastern basin, and from the southern area to the northern area of the central basin. This spatial distribution in Lake Erie is influenced by industrial activities in the watersheds of major tributaries, including the Detroit and St. Clair Rivers which, along with the Maumee, hydrodynamically impacts the southern shoreline, while sediment quality in the eastern basin continues to be classified as excellent. Lake wide decreases in sediment for legacy contaminants are impressive with declines of greater 50% for mercury, PCBs, hexachlorobenzene (HCB), DDT and lead (Table 1). Government initiatives and remedial actions have effectively diminished point sources across the Great Lakes Basin. Lake Erie has the highest sedimentation rate of the Great Lakes and as a result has the largest declines in bottom sediment legacy contaminant concentrations. Mean trace metal concentrations remain above the CCME federal threshold effects level (TEL) for all three basins; however, exceedances in the probable effects level (PEL) are rare.

Lake Ontario

Status: Fair
Trend: Improving
Rationale: Lake Ontario continues to exhibit the poorest sediment quality of all the Great Lakes. The greatest frequency and magnitude of exceedances of the CCME sediment quality guidelines is for PCDD/Fs. This legacy contamination issue is the result of historical industrial activities in the Niagara River watershed and the influence of sources in the upstream lakes; however, current levels of PCDD/F contamination represent a 53 percent decline from peak levels in the 1970s. Mercury continues to have PEL exceedances in offshore depositional areas while realizing a decline of 94% lakewide. Trends in most legacy chemicals in Lake Ontario point toward improvement in sediment quality over time. While most BFR concentrations are low, dechlorane plus, also a result of historical industrial activity in the Niagara River watershed is several orders of magnitude higher in Lake Ontario, compared to the other lakes. Most BFR concentrations are not declining in concentration.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess the concentrations of toxic chemicals in sediments throughout the Great Lakes; to infer the potential for impairment to the quality of sediment of the Great Lakes by harmful pollutants; to infer progress toward virtual elimination of chemicals of mutual concern; to inform the risk assessment of toxic chemicals and the development of risk management strategies; to inform the development of environmental quality guidelines; and to report on environmental response (i.e., progress) toward the achievement of targets identified in action plans and risk management strategies for toxic chemicals in the Great Lakes basin.

Ecosystem Objective

This sub-indicator best supports work towards General Objective #4 of the 2012 Great Lakes Water Quality Agreement (GLWQA) which states that the Waters of the Great Lakes should "be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain."

Ecological Condition

Measure

The purpose of this sub-indicator is to assess the temporal trends and spatial distributions of toxic chemicals in sediment from the five Great Lakes. Each Lake will have a selection of chemicals assessed over several chemical classes. The chemicals that will be assessed may include hexachlorobenzene (HCB), polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), dioxins, lead and mercury as well as PBDEs and brominated flame retardants and other emerging compounds. The sub-indicator report will include results of monitoring and surveillance activities for toxic chemicals of current and future concern as well as current literature on contaminants in Great Lakes sediment. The monitoring data will be used to inform the selection of chemicals of mutual concern for Annex 3 of the GLWQA as well as monitor to assess the progress and effectiveness of pollution prevention and control measures for those compounds.

As a sub-indicator of temporal trends the concentrations of toxic chemicals in sediment cores at selected sites within the Great Lakes will be measured at intervals appropriate for detecting trends in lakes with low sedimentation rates (e.g. 10 years). Sampling for each lake will follow the Cooperative Science Monitoring Initiative (CSMI) schedule. The chemicals of interest include chemicals of current and future concern which may be harmful to the Great Lakes ecosystem.

The sediment concentrations will be depicted using the standard tables and figures showing the change in concentration at different depths. Temporal trends may also be depicted using estimated fluxes to sediments for each core section.

As a sub-indicator of spatial trends, the concentrations of toxic chemicals in surficial sediments will be measured at similar intervals as those for temporal trends. Sampling will usually follow the CSMI schedule. Sampling locations will include not only the depositional zones of the lakes, but also nearshore locations. Surficial sediments may either represent the top three centimetres in Lakes Michigan, Erie and Ontario, and the top 1 centimetres in Lakes Superior and Huron, or a homogenized sample collected with a ponar.

Endpoints

The target or endpoint for this sub-indicator will have been met when the sediments of the Great Lakes are free from pollutants in quantities or concentrations that could be harmful to human health, wildlife or aquatic organisms, through direct exposure or indirect exposure through the food chain. Status of surficial sediment (spatial distribution) will be determined by comparison with existing sediment quality criteria (e.g. the Canadian Council of Ministers of the Environment's Canadian Sediment Quality guidelines Probable Effect Level) where they exist or where no sediment quality guidelines exist on a case-by-case basis taking a weight-of-evidence approach in making an expert assessment, including the number of compounds that are detectable and/or are below sediment quality guidelines (where available) and the relative effect of the compound, if known. Status of temporal trends will be determined by measuring the upper segment of the core to be compared to the sediment quality guidelines. Progress will be determined based on whether trends of the toxic chemicals are positive or negative, the rate of change in the concentrations, and by the number of chemicals which are doing so.

Status of Contaminants in Sediment

Sediments in the Great Lakes generally represent a primary sink for contaminants, but can also act as a source through resuspension and subsequent redistribution. Burial in sediments also represents a primary mechanism by which contaminants are sequestered and prevented from re-entering the water column. A new Environment and Climate Change Canada initiative (2014) which samples Great Lake sediment according to the CSMI schedule will provide a more extensive (spatially and temporally) assessment for both the connecting channels and the Great Lakes for future State of the Great Lakes (previously known as SOLEC) reports.

Comparisons of surficial sediment contaminant concentrations with sub-surface maximum concentrations indicate that contaminant concentrations have generally decreased by more than 35 per cent, and, in some cases, by as much as 80 per cent over the past four decades (Table 1).

Sediment concentrations can also be assessed against guideline values established for the protection of aquatic biota, e.g., Canadian Sediment Quality Guidelines Probable Effect Level (PEL, CCME 1999). These guidelines can be applied as screening tools in the assessment of potential risk, and for the determination of relative sediment quality concerns.

Mercury and Metals

The spatial distribution of mercury contamination in Great Lakes sediments generally represents those of other toxic compounds, including other metals and organics such as PCBs, as accumulation of a broad range of contaminants on a lake-by-lake basis can be the result of common sources. The highest concentrations of mercury in sediments of Lakes Michigan, Erie and Ontario are observed in offshore depositional areas characterized by fine-grained sediments (figure 1). Contaminant concentrations are generally correlated with particle size; hence the distribution of mercury is not only a function of loadings and proximity to sources, but of substrate type and bathymetry. Mercury contamination is generally quite low in Lakes Huron, Michigan, Superior, and more recently Lake St. Clair, with higher concentrations in Lake Ontario and the western basin of Lake Erie (Marvin et al. 2004). There is a gradient in contamination in Lake Erie toward decreasing concentrations from the western basin (mean 370 ng/g) to the central basin (230 ng/g) to the eastern basin (100 ng/g). The spatial distribution in Lake Erie is influenced by industrial activities in the watersheds of major tributaries, including the Detroit River, and areas along the southern shoreline (Marvin et al. 2004). Sources and loadings of mercury to Lake Huron appear to have been reduced to the point that no apparent spatial pattern exists. Current sediment contamination is substantially lower than peak levels that occurred in the mid – 1950s through the early 1970s for all of the lakes with concomitant reductions of connecting channels including the Niagara, lower Detroit and upper St. Clair Rivers, all of which are associated with historical mercury contamination; these areas were also intensively industrialized and were primary sources of a variety of persistent toxics to the open lakes, including PCBs. A more recent study conducted in 2012 through 2014 (Lepak et al. 2015) is consistent with earlier studies, showing:

- a wide total mercury concentration range across Great Lakes sediments;
- lowest total mercury concentrations observed offshore in Lakes Huron and Superior and higher concentrations in western Lake Erie and in Lake Ontario; and
- regional increases in mercury concentration relative to those offshore in Lake Michigan (Green Bay) and Lake Superior sediment (Thunder Bay and near the St. Louis River).

For metals, PEL guideline exceedances were frequent in Lake Ontario for lead, cadmium and zinc. Guideline exceedances (PEL) were rare in all of the other lakes, with the exception of lead in Lake Michigan where the PEL (91.3 µg/g) was exceeded at over half of the sites.

PCBs

PCB results from Li et al. (2009), conducted during a similar time period to the study by Burniston et al. (2011), found a 30% reduction in PCB concentration across the Great Lakes compared to results from (Eisenreich (1987)), with the greatest decrease occurring in Lake Ontario. The comparison of PCB totals to historical studies is confounded by changes in analytical methodology. Comparing surficial sediment (lakewide average) with subsurface maxima using similar analytical techniques may provide more representative results. Reductions for PCBs across the Great Lakes comparing lakewide average of surficial sediment with sub surface maxima ranged from 5% in Lake Michigan to 85% in Lake Ontario. For PCBs, while decreased production contributes to this reduction, based on recent research on congener distribution patterns in sediments of the Great Lakes the decreased concentrations may also be the result of the loss of light congeners due to repeated resuspension of surficial sediment, desorption of light congeners and subsequent evaporation (in Lake Michigan; (Li et al. 2009)) or by anaerobic reductive dechlorination (in Lake Ontario; (Li et al. 2009)). Because of differences in toxicity between congeners the latter could reduce the toxicity of the PCBs (Li et al. 2009) First order half-lives ($t_{1/2}$) vary from 44.9 years (Lake Huron) to 9.7 years (Lake Superior), see Table 2, with shorter half-lives found at sites (Ontario, Erie, Superior) closer to tributary sources and thus more responsive to PCB source reductions (Li et al. 2009). Sites that were influenced with sediment resuspension and bioturbation were not included in the table as these processes tend to homogenize the sediment thereby distorting the buried profile (Hornbuckle et al. 2006). There were no PEL (277 ng/g total PCBs) guideline exceedances for PCBs in any of the Great Lakes sediments.

Flame Retardants

Flame retardants (FRs) are heavily used globally in the manufacturing of a wide range of consumer products and building materials. The FRs have been found to be bioaccumulating in Great Lakes fish and in breast milk of North American women. While industrial discharges may not be responsible for ongoing contamination, modern urban/industrial centres can act as diffuse sources of current inputs. Studies of sediment core profiles of PBDEs in Lake Ontario suggest that accumulation of these chemicals has recently peaked, or continues to increase (Marvin et al. 2007; Shen et al. 2010). The Lake Ontario BDE profile indicates a leveling off of accumulation in the past decade, presumably as a result of voluntary cessation of production of these compounds in North America. However other contemporary studies have shown total PBDEs, and in particular the deca-substituted BDE 209 are continuing to increase across all five Great Lakes, with doubling times ranging from 4 years to 74 years. BDE209 was produced in the U.S. as late as 2014, but still remains in many products and is the predominant congener in sediment, accounting for over 90% (Guo, 2015; Zhu and Hites, 2005) of measured PBDEs. This is of concern because BDE209 can degrade in biota and sediment to more toxic BDEs (Gauthier et al, 2008). A study of the upper lakes by Guo (2015) found the highest surficial concentrations for both total PBDE and BDE209 concentrations were in Lake Michigan (especially southeast and Sleeping Bear Dunes), and Lake Huron (especially Saginaw Bay and North Channel) and were comparable to Lake Erie concentrations, but lower than Lake Ontario.

Other FRs such as dechlorane plus (*anti* and *syn*) and related compounds Dec604 Dec602 are found at low levels throughout the upper Great Lakes but are more elevated in Lake Erie and an order of magnitude higher in Lake Ontario (Figure 2; data source: Lakes Superior, Michigan, Huron (Guo 2015)); Lake Erie Environment and Climate Change Canada; Lake Ontario (Yang et al. 2011 and 2012) however levels have shown a leveling off in recent years (Figure 3), data source: Shen et al. 2010). Most FRs increased significantly after 1920 and have leveled off or decreased since 2000, but Dec604 and DBDPE are still increasing. Spatially, in the upper Great Lakes, PBDEs and 1,2-Bis(2,4,6-tribromophenoxy)ethane (BTBPE) dominate in both southern and northern Lake Michigan, especially the southeast portion of the lake and the sites near Sleeping Bear Dune. Despite these trends, maximum concentrations of many FRs remain well below maximum concentrations of contaminants such as DDT and PCBs observed in past decades.

Perfluoroalkyl Compounds

Perfluoroalkyl Compounds (PFCs) are a broad range of substances that have attracted much scientific and regulatory interest in recent years as a result of their detection globally in humans and wildlife. PFCs are routinely detected in precipitation and air in urban and rural environments. These compounds have a myriad of applications, but have been primarily used as soil and liquid repellents for papers, textiles and carpeting. Production of PFCs as stain repellents in carpets historically exceeded $1 billion annually.

Two classes of PFCs, the perfluoroalkyl sulfonate acids (PFSAs), particularly perfluorooctane sulfonate (PFOS), and the perfluorocarboxylates, particulary perfluorooctanoic acid (PFOA), are the most commonly measured PFCs in sediment and sediment cores; these compounds are highly stable and persistent in the environment, and are potentially toxic. In surficial sediments concentrations of perfluorobutane sulfonate (PFBS) and perfluorobutanoic acid (PFBA) are now occurring at concentrations comparable to those of the PFCs which they replaced (PFOS and PFOA) (Codling et al. 2014). PFCs have been detected in environmental samples far from urban areas, including remote areas such as the Canadian Arctic. The physical and chemical properties of PFCs are different from many other semi-volatile pollutants as they have both hydrophilic and hydrophobic properties. While persistent and bioaccumulative, PFCs can be transported in both the aqueous and non-aqueous phase. As well PFCs in bottom sediment may diffuse to the surface and become bioavailable. These properties significantly influence their pathways through the environment.

Concentrations of PFCs in sediments of Great Lakes tributaries are highest in urbanized and/or industrialized watersheds. In general levels of perfluoroalkyl sulfonate acids and PFOS in tributaries (Environment Canada 2009) and open waters of the Great Lakes are slightly higher than the perfluorocarboxylates with the highest levels of PFCs generally found in areas of Lake Ontario and the western end of Lake Erie and the Detroit River corridor (Environment Canada 2009). There is a gradient toward increasing PFC contamination from the upper Great Lakes (Superior and Huron) to the lower Great Lakes (Erie and Ontario) for both tributary and open-lake sediments. Concentrations of PFCs in open-lake sediments are driven not only by proximity to sources, but physical processes and bathymetry as well. The highest PFC concentrations in open-lake sediments were found in Lake Ontario. The spatial distributions of PFCs in Lake Ontario are fairly consistent across the lake, which is primarily due to lake currents that evenly distribute suspended particles and across the three major depositional basins.

The spatial distributions of PFCs in Great Lakes sediments are heavily influenced by shoreline-based urban and industrial activities, which in some cases stand in contrast to distributions of legacy contaminants such as PCBs. These results suggest that large urban areas can act as diffuse sources of PFCs associated with modern industrial and consumer products.

Carbazoles

Polyhalogenated carbazoles are an emerging contaminant that has been shown to be persistent and likely toxic. While some congeners are a byproduct of halogenated indigo dye production there are likely other anthropogenic or natural sources (Parette et al. 2015). A sediment study of Lakes Michigan, Superior, and Huron by Guo (2015) found a total of 26 polyhalogenated carbazoles (PHCs) plus carbazole which is a concern because carbazole and its derivatives have been found to be carcinogenic and mutagenic in animal studies. Most of the halogenated carbazoles were detected in more than 50% of Lake Michigan surficial grab sediment samples, and in less than 25% of the samples from Lakes Superior and Huron. In all three lakes, concentrations of individual PHCs ranged widely from below detection limit to 261 ng/g (Figure 4). Compared to PBDEs (excluding BDE209), halogenated carbazoles concentrations were generally 1–3 orders of magnitude higher, and concentrations of several PHCs were comparable with BDE209. Time trends varied from significantly increasing with time (carbazole and 1368-TeCC) to increasing since 1950s (fluxes of dibromo- and tribromo-carbazoles) to decreasing since 1900s (1368-TeBC and some mixed halogenated carbazoles) (Guo 2015).

Other Chemicals

Other contaminants are increasingly found in the sediments of the Great Lakes, including industrial chemicals, hormones, steroids, and pharmaceuticals and personal care products (PPCP). A recent study (Guo 2015) of pesticides in sediments of lakes Michigan, Superior, and Huron shows concentrations for atrazine and simazine are increasing exponentially. Assessment of the occurrence and fate of newer compounds has been incorporated into sediment assessment studies.

Research is required to determine what impact emerging contaminants have on the ecosystem of the Great Lakes, including developing PELs for the top priority emerging contaminants.

Linkages

Sediment contamination affects both water quality and aquatic dependent life. Sediment can be a source of mercury and other toxic chemicals to enter the water column. These chemicals are components of the Toxic Chemicals and the Habitat and Species indicators including “Toxic Chemical Concentrations” and “Atmospheric Deposition of Toxic Chemicals”.

Comments from the Author(s)

Efforts to control inputs of historical contaminants have resulted in decreasing contaminant concentrations in the Great Lakes open-water sediments for many of the legacy chemicals. However, chemicals such as FRs, current-use pesticides, and pharmaceuticals and personal care products (PPCP) may represent emerging issues and potential future stressors to the ecosystem. These results corroborate observations made globally, which indicate that large urban centers act as diffuse sources of chemicals that are heavily used to support our modern societal lifestyle.

Long-term research and monitoring programs are valuable tools for demonstrating effectiveness of remedial actions and management initiatives, as well as acting as indicators of emerging issues. Enhanced Canadian Great Lakes studies now include the regular sampling of sediment to be collected following the CSMI schedule. The Great Lakes Sediment Surveillance Program is a complimentary program in the U.S. Comparison of contaminant results between studies and across lakes is currently difficult because of differences in sampling designs, sampling locations, and analytical procedures. Changes in contaminant deposition cannot be detected over time frames less than the temporal resolution of the surficial sediment samples, which can be from 3 to 220 years.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					

3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				

Acknowledgments

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	Lake Superior	Lake Huron	Lake Michigan	Lake Erie	Lake Ontario	Lake St.Clair
Mercury	0	64	49	60	94	86
PCBs	45	9	5	51	85	97
PCDD/Fs	NA	NA	NA	NA	53	NA
HCB	NA	NA	NA	78	40	97
DDT	NA	93	NA	60	60	95
Lead	10	43	NA	71	65	75

Table 1. Estimated percentage declines in sediment contamination in the Great Lakes (1970 – 2015) based on comparison of surface sediment concentrations with maximum concentrations at depth in sediment cores.
Source: Environment and Climate Change Canada; Lepak (2015); Li (2006); Marvin (2004)

Lake	Location	Peak year	Half-life ($t_{1/2}$), Years
Superior	SU22	1993	9.7±7.9
Michigan	LM41[b]	1979	31.7±14.3
Huron	HU12[b]	1981	44.9±1.0
Erie	ER37	1981	16.6±2.2
Ontario	ON-30	1973	11.0±1.0
Ontario	ON-40	1963	17.0±4.4

[a] The first order $t_{1/2}$ values at other sampling locations cannot be obtained due to insufficient numbers (<3) of data points (SU08, SU12, SU16, HU38, HU48) or severe sediment mixing (ER09).
[b] The top segment was excluded in $t_{1/2}$ calculation at these sites.

Table 2. First order half-life (t1/2) of PCBs in sediments of the Great Lakes[a]
Source: Li et al. 2009

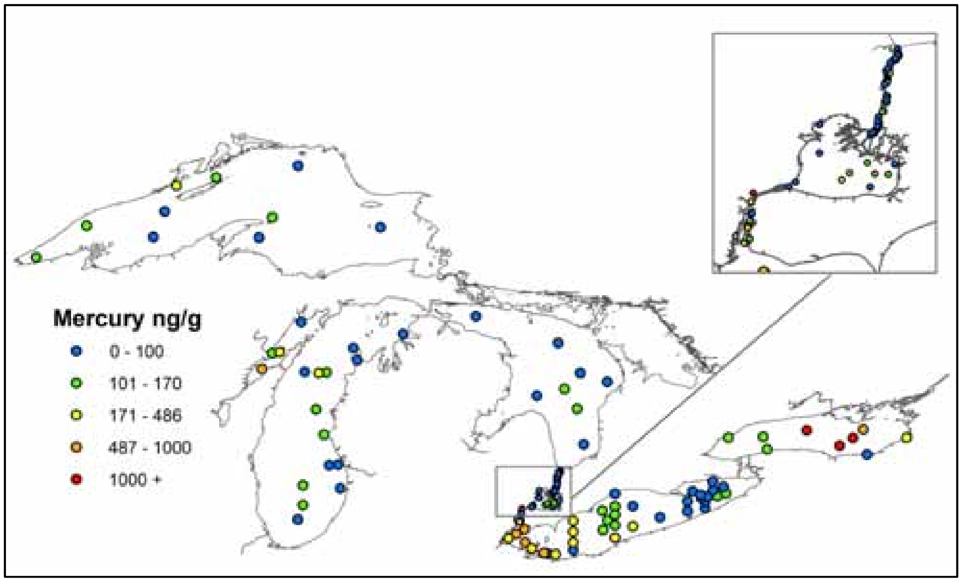

Figure 1. Spatial distribution of mercury contamination in surface sediments in open-lake areas and tributaries of the Great Lakes, sampled 2012-14 Sources: St. Clair River, Lake St. Clair, Detroit R. and Lake Erie -Environment and Climate Change Canada; Lakes Superior, Huron, Michigan, Ontario- Lepak 2015 Source: Environment and Climate Change Canada and Lepak 2015

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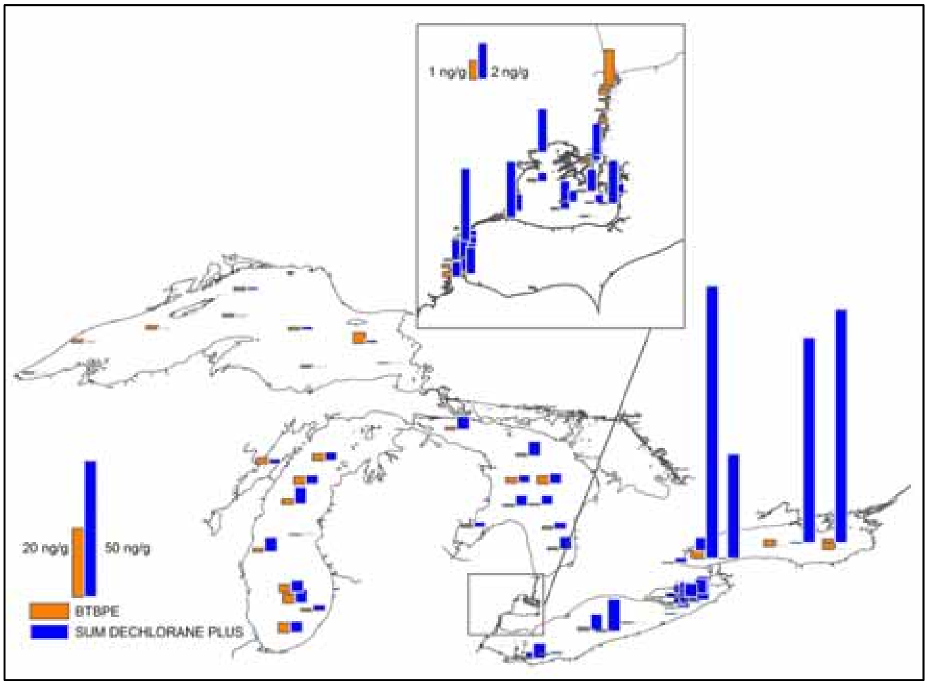

Figure 2.Spatial distribution of BTBPE and dechlorane plus (sum of syn and anti) in Great Lake sediment (sampled in 2010-2014).
*S*ource: Lakes Superior, Michigan and Huron-Guo (2015); St. Clair River, Lake St. Clair, Detroit R. and Lake Erie - Environment and Climate Change Canada; Lake Ontario -Yang et al. 2011 and 2012

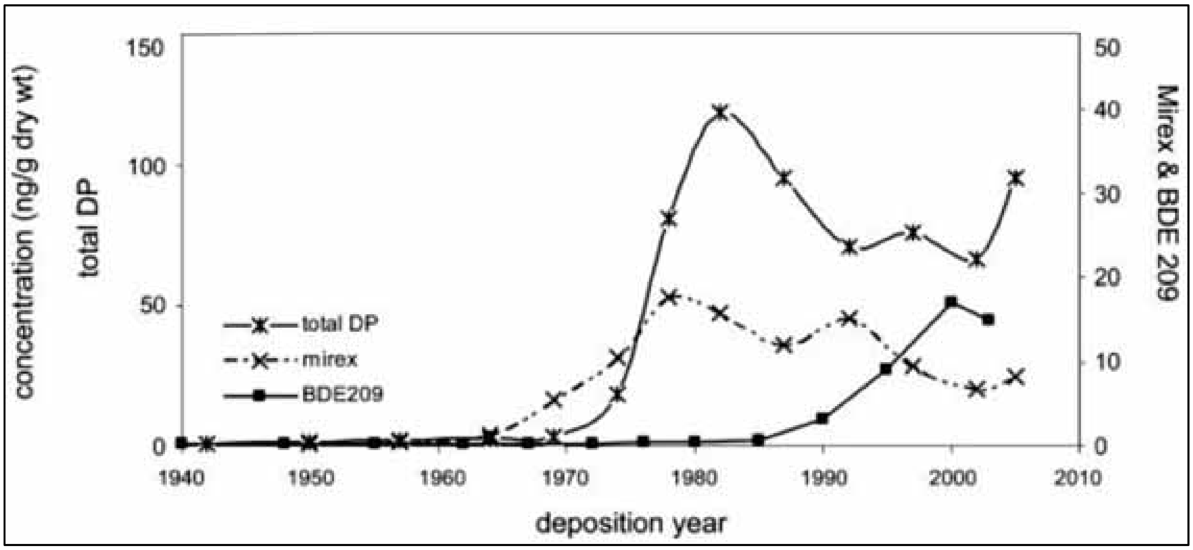

Figure 3. Temporal trend of total (syn + anti) Dechlorane plus; BDE209 and mirex in a Lake Ontario core.
Source: Shen et al. 2010

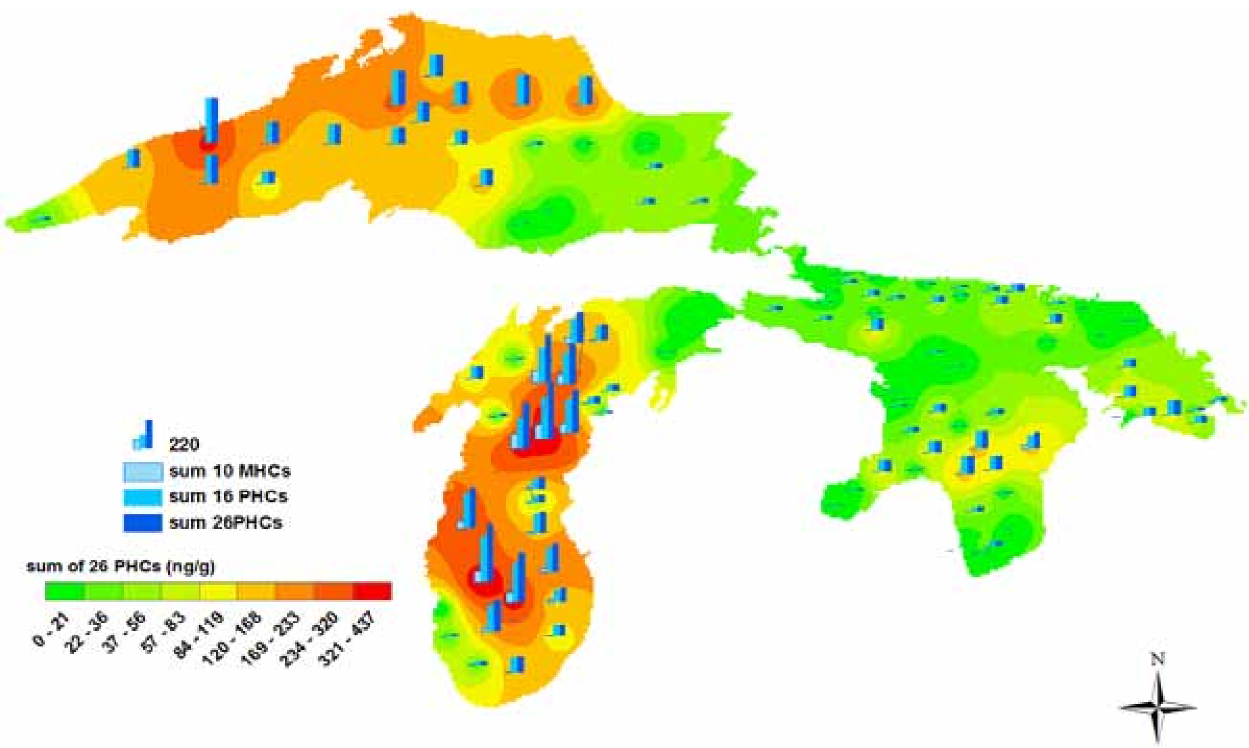

Figure 4. Spatial distribution of PHC concentrations (ng/g dw) in Ponar Grab sediment samples from Lakes Michigan, Superior, and Huron.
Source: Guo 2015

Sub-Indicator: Toxic Chemicals in Great Lakes Whole Fish
Lake Trout/Walleye

Overall Assessment
Status: Fair
Trend: Improving
Rationale: The assessment of status and trend incorporates multiple contaminants, from multiple species, in all 5 of the Great Lakes over time. A new approach has been applied in an attempt to better reflect the multiple variables in determining the overall assessment of condition and trend for this sub-indicator. A Mean Deviation Ratio (MDR) has been calculated for TeBDE, HxBDE, PeBDE, Total Mercury, Total PCB, Total DDT, and PFOS. Based upon this new approach, the overall condition for toxic chemicals in whole fish is fair and conditions are improving over a 15-year period (1999-2013) (Figure 1). Due to the change in assessment methodology from the previous report, results are not directly comparable. However, it should be noted that individual chemical concentrations are continuing to trend in similar ways to the previous report. The resulting shift in status and trend of the 2016 sub-indicator is a result of the revised Mean Deviation Ration methodology.

Lake-by-Lake Assessment
Lake Superior
Status: Fair
Trend: Unchanging
Rationale: In Lake Superior, the status of toxic chemicals in fish is assessed as Fair and this condition has remained Unchanged over a 15-year period (1999-2012) (Figure 2). The MDR plot for Lake Superior appears to vary significantly over the period of monitoring with a large shift upward in 2000. The addition of PBDEs to monitoring programs in 2000 resulted in an increased MDR score due to exceedances of targets for these compounds (Figure 2). Toxaphene continues to be measured at higher concentrations in Lake Trout from Lake Superior than in trout from the other Great Lakes.

Lake Michigan
Status: Fair
Trend: Improving
Rationale: Conditions of toxic chemicals in fish from Lake Michigan are assessed as Fair and conditions have improved over a 15-year period (1999-2013) (Figure 3). Of the U.S. monitored lakes, Lake Michigan often has the highest concentrations of monitored contaminants in Great Lakes. A recent assessment of the most abundant compounds measured in whole body fish from the Great Lakes, identified that organochlorine pesticides and total PCB are the dominant contributors (~75%) to the contaminant burden of Lake Michigan lake trout.

Lake Huron
Status: Fair
Trend: Unchanging
Rationale: The current status of toxic chemicals in whole fish from Lake Huron is assessed as Fair and this condition remains Unchanged over a 15-year period (1999-2013) (Figure 4). The MDR appears to be increasing since 2006; however, basin wide changes to food webs in Lake Huron have resulted in reduced growth rates in Lake Trout. The result of these changes has been the inclusion of older fish in the composite samples measured by the U.S. EPA. Since older fish generally contain higher levels of bioaccumulative contaminants, the recent increases are likely a result of this phenomenon. The issue has been identified and will be taken into account in future monitoring.

Lake Erie
Status: Fair
Trend: Unchanging
Rationale: Conditions for this sub-indicator in Lake Erie are assessed as Fair and conditions remain Unchanged over a 15-year period (1999-2013) (Figure 5). While on average, based on MDR, the condition in Lake Erie are

unchanged; however, it is important to note that mercury levels in fish from the western basin of the lake continue to increase. Observed levels are still below the objectives of the 1987 GLWQA, but are approaching levels that may be of concern.

Lake Ontario
Status: Fair
Trend: Improving
Rationale: In Lake Ontario, conditions for this sub-indicator are assessed as Fair, based on MDR, and they have improved over a 15-year period (1999-2013) (Figure 6). Of the binationally monitored lakes, Lake Ontario often has the highest concentrations of monitored contaminants in the Great Lakes; however, levels are stable or slowly declining in Lake Trout.

Sub-Indicator Purpose
The purpose of this sub-indicator is to describe temporal and spatial trends of bioavailable contaminants in representative open water fish species from throughout the Great Lakes; to infer the effectiveness of remedial actions related to the management of critical pollutants; and to identify the nature and describe the trends of new and emerging pollutants of concern.

Ecosystem Objective
Great Lakes waters should be free of toxic substances that are harmful to fish and wildlife populations. This sub-indicator best supports work towards General Objective #4 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should “be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain.”

Ecological Condition
Background and Methods
Long-term (greater than 25 years), basin-wide monitoring programs that measure whole body concentrations of contaminants in top predator fish (Lake Trout and/or Walleye) are conducted by both the U.S. Environmental Protection Agency (U.S. EPA) Great Lakes National Program Office through the Great Lakes Fish Monitoring and Surveillance Program, and the Fish Contaminants monitoring and surveillance activities covered under Environment and Climate Change Canada’s (ECCC) Fresh Water Quality Monitoring Program. These monitoring programs aim to identify risks posed from contaminants to fish and their wildlife consumers as well as to monitor trends in time as a measure of progress towards Ecosystem Objectives. The *Toxic Chemicals in Great Lakes Whole Fish* sub-indicator is included in the Toxic Chemicals indicator assessment for the Great Lakes since long-term trends of contaminants in biota provide valuable insights into the relative abundance of bioaccumulative contaminants in the environment. Fish integrate their exposure to contaminants over time and across their range and thus provide a broader assessment of environmental exposure than would a water sample taken at a single location at a point in time. Bioaccumulative contaminants are also found at higher concentrations in biota than they are in water, allowing for more accurate and cost effective determination of levels in the environment. It is important to note, however, that contaminant levels in biota represent not just quantities of contaminants in the water, but are the result of the integration of many biological, chemical and physical interactions (e.g. bioaccumulation and biomagnification processes, variations in diet and growth rates).

Fish Collection and program design
Environment and Climate Change Canada reports annually on contaminant burdens in similarly aged Lake Trout (4+ through 6+ year range) and Walleye (Lake Erie) as well as in Rainbow Smelt (*Osmerus mordax*), a common forage species. The U.S. EPA monitors contaminant burdens in similarly sized Lake Trout (600-700 mm total length) and Walleye (Lake Erie, 400-500 mm total length) annually from alternating locations by year in each lake. Monitoring stations for both ECCC and U.S. EPA are shown in Figure 9. Additional differences between the ECCC and U.S. EPA programs include measurement of contaminants in individual fish (ECCC) and measurement of composite samples (U.S. EPA). Additionally, U.S. EPA has shifted to collecting Lake Trout in the eastern basin of Lake Erie, Environment and Climate Change Canada does not collect samples in Lake Michigan, and individual program contaminant lists are not identical, Table 1. Despite these differences in collection and analysis, trends and interpretation are very similar. Trends were deemed significant if the slope of the regression model applied to

annual median or means were greater or less than zero at $\alpha = 0.05$. Contaminant concentrations and trends are compared to available criteria, see Table 2. In previous reports, binational criteria identified in the 1987 Great Lakes Water Quality Agreement (GLWQA) were used for trend analysis. The GLWQA was renegotiated in 2012 and the resulting document no longer includes ecological objectives for specific contaminants. In the absence of binational targets in the 2012 GLWQA, contaminant concentrations will be compared to the 1987 GLWQA criteria where applicable. The GLWQA, first signed in 1972, renewed in 1978, and amended in 1987 and 2012, expresses the commitment of Canada and the United States to restore and maintain the chemical, physical and biological integrity of the Great Lakes Basin ecosystem.

More information on the monitoring programs can be found at the following websites:
http://www.epa.gov/glnpo/monitoring/fish/index.html and
http://www.ec.gc.ca/scitech/default.asp?lang=en&n=828EB4D2-1

Lake and Basin wide assessments (Mean Deviation Ratio)

The Mean Deviation Ratio (MDR) is a simple and effective communication tool with a public audience that allows multiple variables to be considered to answer a single question, "What is the status of chemicals of concern in Great Lakes whole fish?" This new approach is responsive to changes in concentration in the environment over time and is reflective of real conditions. The MDR can be easily revised as additional chemical information is available and / or criteria / guidelines are developed. For a more detailed description of the MDR methodology, please see the indicator description for this sub-indicator.

Condition assessment
State of the Great Lakes reporting (previously known as SOLEC) assesses the condition for each sub-indicator as POOR, FAIR, or GOOD. To assess condition of this sub-indicator, the variance in the estimated MDR for each lake/year was carried through all steps of the calculation. The average variance for the previous 10 years was then converted to an estimate of the standard deviation for the MDR for each lake. In the plots, the value of 1 (i.e. on average contaminants are present at the levels of their guidelines) was bounded on either side by 1 standard deviation. This central band was deemed to represent FAIR condition as any MDR residing in this zone would overlap 1 when variance is considered. Values above and below the central band were deemed to represent POOR and GOOD condition respectively as MDR in these zones would be greater than one standard deviation from 1.

Toxic Chemicals in Great Lakes Whole Fish
Basin Wide Summary
Since the late 1970s, concentrations of persistent organic pollutants such as polychlorinated biphenyls (PCBs) and organochlorine pesticides (OC_{pest}) in most monitored fish species have declined. Long term mercury trends show varied results across the basin where, although still below the target established in the 1987 GLWQA, levels are still increasing in the Western Basin of Lake Erie. Certain OC_{pest} do not have environmental targets/objectives for levels in whole fish or where targets exist, concentrations have remained below criteria values (Table 2). For these reasons, chlordane, dieldrin, mirex in all lakes except Lake Ontario and toxaphene in all lakes except Lake Superior are not included in this sub-indicator report. Recent monitoring and surveillance for emerging and emerged chemicals have produced a significant amount of data for compounds designated as Chemicals of Mutual Concern (CMCs) under Annex 3 of the 2012 Great Lakes Water Quality Agreement. Examples of emerged chemicals include polybrominated diphenyl ethers (PBDEs) and perfluorooctane sulphonate (PFOS) while examples of emerging chemicals include siloxanes, nonylphenol, and brominated flame retardant replacement products. Through the Annex 3 process, new chemicals designated as CMCs will be incorporated into monitoring and surveillance programs, when applicable. In general, the levels of regulated compounds are slowly declining or have stabilized in the tissues of Great Lakes top predatory fish. Basin wide, the changes are often lake-specific as they are dependent, in part, on the physio-chemical characteristics of the contaminants, hydrological characteristics of the lake, and the biological composition of the fish community and associated food webs. Despite these declines, concentrations of some compounds, like PCBs and PBDEs continue to exceed environmental quality guidelines and/or objectives.

The results of an assessment of all organic contaminants and mercury measurements in whole body Lake Trout and Walleye generated by Environment and Climate Change Canada and the U.S. Environmental Protection Agency (U.S. EPA) between the years 2008 and 2012 showed that the so called "legacy" contaminants, PCBs and OC_{pest}

comprised approximately 2/3 of the contaminant burden of Lake Trout and Walleye in the Great Lakes, Figure 7, (McGoldrick et al. 2015). This may seem surprising considering the long-term decline of PCBs and OC_{pest} observed since monitoring began in the 1970s; however, it is likely a reflection of the relative quickness with which newer chemicals are regulated or phased-out before large environmental inventories are built up in waste streams or other compartments (i.e. sediments). Newer classes of contaminants, PBDEs, PFCs, siloxanes, and other flame retardants, comprise the majority of the remaining contaminant burden measured in Great Lakes fish.

Chemical specific summaries

Total polychlorinated biphenyls (PCBs)
Total PCB (Arochlor 1254) concentrations in Great Lakes top predator fish have continuously declined since their phase-out in the 1970s (Figure 10). Median PCB concentrations in Lake Trout in Lakes Superior, Michigan, Huron, and Ontario and Walleye in Lake Erie continue to decline; however, they are still above the target of 0.1 µg/g ww in the 1987 amendment to the GLWQA. Concentrations are highest in Lake Michigan, followed by Lakes Ontario, Huron, Erie, and Superior. Log-linear regression of PCB concentrations over time show the continued long-term annual declines of 4-5% in Lake Trout from Lake Superior and 4-9% in Lakes Huron, 8% in Lake Ontario while PCBs in Lake Erie Walleye are declining by 2-3% per year. PCB levels reported by the U.S. EPA for Lake Trout from Lake Huron appear to have increased temporarily between 2003 and 2012, Figure 8. However, in depth investigations of fish from this area have shown that fish in Lake Huron are growing at a slower rate, potentially as a result of invasive species and decreased food availability, which has resulted in an increase in the age of the fish being used in the U.S. composite samples. Age has a positive correlation to observed concentrations of contaminants in fish and likely explains the increase in PCB levels. This interpretation is supported by the ECCC data which does not show an increasing trend and is based on PCB concentrations from fish of similar ages (4-6). Data collected since the last State of the Great Lakes (SOGL) sub-indicator report (–2011-2014), show that total PCB concentrations in composited Rainbow Smelt measured by Environment and Climate Change Canada were all less than 0.05 µg/g ww in Lake Superior and all less than 0.1 µg/g in Lake Ontario. In the remaining Canadian lakes, 91% and 83% of total PCB measured in Rainbow Smelt were below 0.1 µg/g ww in Lakes Huron and Erie, respectively. In 2016, PCBs were designated as a Chemical of Mutual Concern by the Parties, Canada and the United States of America, through the GLWQA.

Dichlorodiphenyltrichloroethane (DDT) and metabolites
The concentration of sumDDT, the sum of opDDT and its metabolites, opDDD and opDDE, in Great Lakes top predator fish have continuously declined since the use of the chemical was banned in 1972. Average concentrations measured since the last sub-indicator report (2010-2014) remain well below the 1987 amendment to the GLWQA target of 1.0 µg/g ww across the basin (Figure 11). Exceedances of the 1.0 µg/g target were infrequent and occurred only in Lakes Superior, Huron, and Ontario. The increased variability in the Environment and Climate Change Canada data relative to the U.S. EPA is a result of the difference between analyzing individual fish (ECCC) and the analysis of composited samples (U.S. EPA). Composited samples represent an average of the fish used to make the composite and are generally less variable.

Total mercury
Observed concentrations of mercury have been variable spatially across the basin and between the monitoring programs operated by ECCC and the U.S. EPA over the last 2 reporting cycles of State of the Great Lakes reporting. The 2011 report indicated increasing trends of mercury in fish collected from Lakes Superior, Erie, and Huron and stable concentrations in lakes Ontario and Michigan. Continued monitoring and surveillance of mercury by ECCC and the U.S. EPA have provided insight into these trends (Figure 12). Two segment linear piecewise regression of the ECCC dataset show that declines in mercury ceased in the late 1980s in Lakes Superior and Huron and the early 1990s in Lakes Erie and Ontario. Following the change points in each lake, mercury levels have not changed in lakes Huron and Ontario and appear to be increasing in Lakes Superior and Erie. In Lake Superior, the high variability of observed mercury concentrations from 2002-2010 seem to have returned to more typical levels and while the recent trend lines are increasing, their slopes are not statistically different than zero. As with PCBs, mercury levels reported by the U.S. EPA for Lake Trout from Lake Huron appear to be increasing as a result of older fish being included in the U.S. EPA composite samples. U.S. EPA has since revised its compositing methodology to age samples prior to compositing to keep similarly aged fish together. The increasing trend of mercury in Walleye from the western basin of Lake Erie is still present in data collected by ECCC (Figure 12). Since

1993, levels of mercury in Walleye from the west basin of Lake Erie have been increasing at 3.4% per year. While the underlying mechanisms causing this increase are not presently known with certainty, the increases in the last three years are coincident with a resurgence of large algal blooms in the west basin of the lake. These blooms and resulting anoxia in the hypolimnion could be creating favourable conditions for the creation of methyl-mercury, the bioaccumulative form of mercury.

Similar temporal patterns in mercury concentrations are also observed in Rainbow Smelt, a common forage fish for many fish and birds in the Great Lakes Basin (Figure 18). Continued monitoring of mercury levels in fish from all the lakes is warranted to adequately assess the future risk to wildlife consumers of fish in the Great Lakes Basin, especially in areas where levels appear to be increasing. Mercury was designated as a Chemical of Mutual Concern by the Parties, Canada and the United States of America, through the GLWQA.

Mirex

Mirex is only measured at significant levels in fish from Lake Ontario due to historical releases in the Niagara River and other locations within the lake's watershed. Average concentrations for Lake Ontario whole Lake Trout, between 2008 and 2012, was approximately 0.7 µg/g ww while the levels in the other four lakes range between <0.005 and 0.03 µg/g ww over the same time range (McGoldrick et al. 2015). Log-linear regression of mirex concentrations in Lake Trout from Lake Ontario with time show that levels have declined at a rate of ~13% per year since 2000. According to the guidelines listed in the 1987 Amendment of the GLWQA, mirex should be "substantially absent" from Great Lakes fish. The lack of a numerical target for mirex makes it difficult to incorporate into the MDR calculation and for this reason it was not included in the assessment.

Toxaphene

Decreases in toxaphene concentrations have been observed throughout the Great Lakes in all media following its ban in the mid-1980s (Xia et al. 2012). Concentrations of toxaphene are substantially higher in Lake Superior, where average concentrations from 2008-12 were 231 ng/g ww as compared to the other lakes which ranged from 25-78 ng/g ww (McGoldrick et al 2015). The high levels of toxaphene in Lake Superior, relative to the other Great Lakes, likely reflects the importance of atmospheric transport as a source of toxaphene to the Great Lakes Basin, the importance of atmospheric deposition as a source of contaminants to Lake Superior, and the cold temperatures, slow sedimentation rates and long residence time of the lake (James et al. 2001; Muir et al. 2004; Swackhamer et al. 1998). There are currently no defined ecological objectives for this compound in the Great Lakes and thus it was not incorporated into the MDR calculation in this sub-indicator.

Polybrominated Diphenyl Ethers (PBDEs)

The production and use of three popular commercial formulations of PBDE have or are being voluntarily phased out by industry in North America. The phase out of the more toxic penta- and octa-BDE compounds, started in 2004, continued through 2012. In a national survey of PBDE concentrations in top predator fish from lakes across Canada, the highest concentrations were observed in fish from the Great Lakes and >95% of the PBDE compounds in the fish were tetra-, penta-, or hexa-BDEs (Gewurtz et al. 2011). Federal Environmental Quality Guidelines (FEQG) have been developed by Environment and Climate Change Canada for these three homologue groups which are meant to provide targets for acceptable environmental quality, assess the significance of observed concentrations, and to measure the success of risk management activities. Average concentrations of BDE 47 (TeBDE) in all 5 lakes remain below the FEQ guidelines of 44 ng/g ww and are generally declining across the basin (Figure 13). Average concentrations of BDE 99 + 100 (PeBDE) in all 5 lakes remain above the FEQ guidelines of 1.0 ng/g ww and are declining in Lakes Ontario, Huron, and Michigan and have mixed trends in Lakes Superior and Erie (Figure 14). Average concentrations of BDEs 153 + 154 (HxBDE) are below the FEQ guidelines of 4.0 ng/g ww in Lakes Superior and Erie and above the guideline in Lakes Michigan, Huron and Ontario. Average concentrations of Total BDEs (tetra + penta + hexa) were highest in Lake Ontario, followed by Lakes Superior, Michigan, Huron and Erie. Ratios of TeBDE: PeBDE: HxBDE in each of the lakes were similar and on average 6:3:1. A publication of the U.S. EPA data set since the previous State of the Great Lakes indicates that this ratio may be shifting toward higher brominated congeners in recent years and that the cause for this shift has not been clearly identified to date (Crimmins et al. 2010). PBDEs were designated as a Chemical of Mutual Concern by the Parties, Canada and the United States of America, through the GLWQA.

Perfluorinated acids

Perfluorooctane sulfonate (PFOS) is a synthetic substance belonging to a larger class of organic fluorochemicals that are either partially or completely saturated with fluorine. PFOS, perfluorocarboxylates and their precursors are used primarily in water, oil, soil, and grease repellents for paper and packaging, carpets, and fabrics, as well as in aqueous film forming foam (AFFF) for fighting fuel fires. PFOS was voluntarily phased-out of production by their primary supplier in 2002. However, PFOS use in Canada and the U.S. continues due to specific use exemptions. Average concentrations of PFOS are generally above the FEQ guideline of 4.6 ng/g ww in all 5 Great Lakes (Figure 16). PFOS observed in both the U.S. EPA and ECCC programs show similar patterns and trends and concentrations appear to be declining at most locations, although these declines are statistically significant only in Lakes Ontario (since 2002), Huron, and Michigan (Figure 16). Change-point analysis of the longest time series available (Lake Ontario) identified the year 2002 as the point that the slope of relationship between PFOS and year changed. Interestingly, 2002 is the year of the production phase-out by the primary manufacturer in the U.S. PFOA and PFOS were designated as a Chemical of Mutual Concern by the Parties, Canada and the United States of America, through the GLWQA.

Additional Emerging Contaminants

Both the U.S. and Canadian monitoring and surveillance programs have invested in the identification and quantification of emerging chemicals through the Great Lakes Restoration Initiative in the U.S. and Canada's Chemicals Management Plan. The compounds summarized in the following paragraphs have been newly identified or data have only recently become available, thus status and trend statements are not possible at this time. However, the authors do feel it is important to highlight this work and if warranted, these compounds may appear in future State of the Great Lakes sub-indicator reports on toxic chemicals in whole fish. It is also important to note that surveillance for emerging chemicals is an essential part of both countries' programs. Identification of new compounds are reported out in peer reviewed literature, State of the Lakes Reports, and many other information outlets. Recent publications identifying New Fluorinated Surfactant Contaminant (Chu et al. 2016) and Novel Polyfluorinated Compounds (Fakouri Baygi et al in press) are just two examples of emerging chemical identification and surveillance in the Great Lakes.

Polychlorinated alkanes (PCAs) or Chlroinated Paraffins

This group of chemicals are complex mixtures of compounds classified by the length of the alkane chain and are used as additives in lubricants, metal cutting fluids, paints and plastics and they have flame retardant properties. A recent study on the levels of PCAs in fish from Canadian lakes showed that fish from the Great Lakes had higher levels of the medium chain (C14-C17) PCAs (MCPCAs) than short chain (C10-C13) PCAs (SCPCAs) (Saborido Basconcillo, Backus et al. 2015). The levels of MCPCAs were very similar at approximately 12 ng/g in fish from Lakes Ontario, Erie and Huron and 4 ng/g in Lake Superior. In these same fish, SCPCAs were measured to be between 3 and 5 ng/g. Short Chain Polychlroinated Alkanes (SCPCAs) were were designated as a Chemical of Mutual Concern by the Parties, Canada and the United States of America, through the GLWQA.

Hexabromocyclododecane (HBCDD)

HBCDD is a high production flame retardant used mainly in polystyrene foams and is believed to have been used as a replacement alternative to PBDEs. Levels of α-HBCDD, the dominant isomer present in fish tissues, assessed by Environment and Climate Change Canada, in Lake Trout from Lake Ontario averaged 4.7 ng/g ww in samples collected between 2008 and 2012. The levels observed were on the higher end of the range reported in a previous study of HBCDD at the same location in Lake Ontario (Ismail, Gewurtz et al. 2009); and lower than concentrations identified in eels collected from Dutch freshwaters (van Leeuwen and de Boer 2008). HBCDD was designated as a Chemical of Mutual Concern (CMC) by the Parties, Canada and the United States of America, through the GLWQA and has been added to the routine monitoring lists of both U.S. and Canadian monitoring programs as a result.

Nonylphenol and nonylphenol ethoxylates (NPEs)

NPEs are common ingredients in detergents, emulsifiers and dispersing agents in household, industrial and agricultural products, and waste water treatment plant effluents are a primary route of release to the environment (Kannan, Keith et al. 2003). The average concentration of NPE identified by Environment and Climate Change Canada in Lake Trout from Lake Ontario was 14 ng/g ww (McGoldrick et al. 2015). The average was within the range of concentrations reported in fish tissues from rivers in Michigan U.S. (Keith, Snyder et al. 2001), and Lake Biwa in Japan (Tsuda, Takino et al. 2000). NPEs were considered as a Chemicals of Mutual Concern by the Annex

3 Subcommittee (C3) of the GLWQA but was not nominated by the Great Lakes Executive Committee.

Siloxanes
Siloxanes are high production volume chemicals that are common ingredients in many personal care products, cosmetics, as well as industrial cleaning fluids and dry cleaning (Environment Canada 2008a, Environment and Canada and Health Canada 2008b, Environment Canada and Health Canada 2008b, Horii and Kannan 2008, Wang, Moody et al. 2009) and are known by their shortened form of D4, D5, and D6. These compounds have been measured in fish from the Great Lakes by Environment and Climate Change Canada in recent years (McGoldrick et al. 2014). In general, concentrations of D5 are higher in Great Lakes whole fish than D4 or D6 and D5 is highest in Lake Ontario (140 ng/g), followed by Superior (76 ng/g), Erie (34 ng/g) and Huron (16.5 ng/g). On a mass concentration basis, D5 is also among the top 10 most abundant compounds measured in Great Lakes Lake Trout or Walleye (McGoldrick et al 2015).Currently, there are no ecosystem objectives for siloxanes and they are not being considered as a CMC by Annex 3 of the GLWQA.

Linkages
Contaminant levels in Lake Trout and Walleye are dependent on complex biological and physiochemical interactions both within and outside of the Great Lakes Basin as these apex predators integrate contaminant inputs from water, air, sediment, and their food sources. A changing climate and associated changes to precipitation and wind currents will alter the influx of contaminants from sources outside of the basin and may alter food webs and the contaminant transfer through them. Aquatic invasive species also alter food webs and change energy and contaminant dynamics in the lakes. They also may introduce new pathways by which sediment contaminant pools could be mobilized and transferred to fish. Many new contaminants of concern are components of consumer products, personal care products, or pharmaceuticals, as a result, wastewater treatment effluents are an important source of contamination which is growing along with the human population of the basin.

Comments from the Author(s)
Environmental specimen banks containing tissue samples are a key component of both the U.S. and Canadian monitoring programs, allowing for retrospective analyses of newly identified chemicals of concern to be able to develop long term trends in the short-term.

The importance of changes in the food webs of the Great Lakes are becoming much more important to understand and quantify. For example, the declines of zooplankton populations in Lake Huron are suspected to be the cause for slower growing Lake Trout and higher chemical concentrations for PBTs as a result. Food web assessments for chemical transfer fatty acid content and fatty acid ratios (Crimmins et. al. in prep) are ongoing in in the U.S. to assist in the interpretation of chemical results and trends.

The authors have made efforts to improve the statistical rigor of this sub-indicator report through the inclusion of error bounds on estimated concentrations and trends through time. The authors have also focused on contaminants with defined environmental targets, guidelines and/or thresholds to put observed concentrations in context with risk to the environment. Other improvements to statistical rigor, such as, better methods to characterize dataset with censored values (i.e. non-detects) should be investigated and incorporated in future reports on this sub-indicator.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					

4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Acknowledgments
Authors:
Daryl McGoldrick, Environment and Climate Change Canada
Mandi Clark, Environment and Climate Change Canada
Elizabeth Murphy, United States Environmental Protection Agency

Information Sources:
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We would like to acknowledge all the State, Tribal, and Provincial partners that contribute samples and information to the monitoring and surveillance programs in both the United States and Canada.

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Data available upon request from authors or U.S. data can be accessed at:
http://www.epa.gov/cdx/

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lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

Figure 15. Mean HxBDE concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

Figure 16. Mean PFOS concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency
Figure 17. Average concentrations of total mercury (dots) measured in composite samples of Rainbow Smelt by Environment Canada. Lines show the three year moving average. Note that most rates of change are not significantly different from zero base on p-values >0.05.
Source: Environment and Climate Change Canada

Last Updated
State of the Great Lakes 2017 Technical Report

Compound or Class	Agency		Great Lake				
	Environment and Climate Change Canada	US EPA	Ontario	Erie	Huron	Michigan	Superior
4-n-octylphenol (OP)	X		X				
4-nonlyphenol monoethoxylate (NP1EO)	X		X				
4-nonylphenol (NP)	X		X				
4-nonylphenol diethoxylate (NP2EO)	X		X				
Hexabromocyclododecane (α-, γ-HBCD)	X		X				
Polychlorinated naphthalenes (PCN)[1]	X		X				
tris(2-butoxyethyl) phosphate (TBOEP)	X		X	X			
Chlorinated alkanes (short and medium chain)	X		X	X	X		X
Decamethylcyclopentasiloxane (D5)	X		X	X	X		X
Dodecamethylcyclohexasiloxane (D6)	X		X	X	X		X
Dodecamethylpentasiloxane (L5)	X		X	X	X		X
Hexamethylcyclotrisiloxane (D3)	X		X	X	X		X
Octamethylcyclotetrasiloxane (D4)	X		X	X	X		X
Perfluorooctane sulfonamide (PFOSA)	X		X	X	X		X
Perfluorooctanoic acid (PFOA)	X		X	X	X		X
Chlordane (α-, γ-)	X	X	X	X	X	X	X
Dieldrin	X	X	X	X	X	X	X
Heptachlor epoxide	X	X	X	X	X	X	X
Hexachlorobenzene (HCB)	X	X	X	X	X	X	X

Compound or Class	Agency		Great Lake				
	Environment and Climate Change Canada	**US EPA**	**Ontario**	**Erie**	**Huron**	**Michigan**	**Superior**
Hexachlorocyclohexane (α-, γ-HCH)	X	X	X	X	X	X	X
Mercury	X	X	X	X	X	X	X
Mirex	X	X	X	X	X	X	X
p,p'-dichlorodiphenyldichloroethane (DDD)	X	X	X	X	X	X	X
p,p'-dichlorodiphenyldichloroethylene (DDE)	X	X	X	X	X	X	X
p,p'-dichlorodiphenyltrichloroethane (DDT)	X	X	X	X	X	X	X
Perfluorodecanesulfonate (PFDS)	X	X	X	X	X	X	X
Perfluorodecanoic acid (PFDA)	X	X	X	X	X	X	X
Perfluorododecanoic acid (PFDoA)	X	X	X	X	X	X	X
Perfluorononanoic acid (PFNA)	X	X	X	X	X	X	X
Perfluorooctanesulfonate (PFOS)	X	X	X	X	X	X	X
Perfluorotridecanoic acid (PFTrA)	X	X	X	X	X	X	X
Perfluoroundecanoic acid (PFUnA)	X	X	X	X	X	X	X
Polybrominated diphenyl ethers (PBDE)[1]	X	X	X	X	X	X	X
Polychlorinated biphenyls (PCB)	X	X	X	X	X	X	X
Endrin		X	X	X	X	X	X
cis-nonachlor		X	X	X	X	X	X
Endosuflan (I, II)		X	X	X	X	X	X
Endosulfan sulfate		X	X	X	X	X	X

Compound or Class	Agency		Great Lake				
	Environment and Climate Change Canada	US EPA	Ontario	Erie	Huron	Michigan	Superior
Hexachlorocyclohexane (β-, δ-HCH)		X	X	X	X	X	X
Octachlorostyrene		X	X	X	X	X	X
Oxychlordane		X	X	X	X	X	X
Total Dioxin TEQ (Mammal)		X	X	X	X	X	X
Toxaphene (Camphechlor)		X	X	X	X	X	X
trans-nonachlor		X	X	X	X	X	X
Chemicals detected greater than 10 % frequency identified through monitoring and surveillance programs							

Table 1. Chemicals detected greater than 10 % frequency identified through Monitoring and Surveillance
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

Contaminant	Criteria Source	Criteria type	Value (ng/g ww)
TetraBDE (TeBDE)	Environment Canada Federal Environmental Quality Guidelines	Wildlife Diet	44
PentaBDE (PeBDE)	Environment Canada Federal Environmental Quality Guidelines	Wildlife Diet	1.0
HexaBDE (HeBDE)	Environment Canada Federal Environmental Quality Guidelines	Wildlife Diet	4.0
PFOS	Environment Canada Federal Environmental Quality Guidelines	Mammalian Diet	4.6
Total PCBs	1987 GLWQA amendment	Wildlife Diet	100 (0.1 µg/g)
Total DDT	1987 GLWQA amendment	Wildlife Diet	1000 (1.0 µg/g)
Total Mercury	1987 GLWQA amendment	Wildlife Diet	500 (0.5 µg/g)

Table 2. Contaminant criteria for environmental monitoring and surveillance programs
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

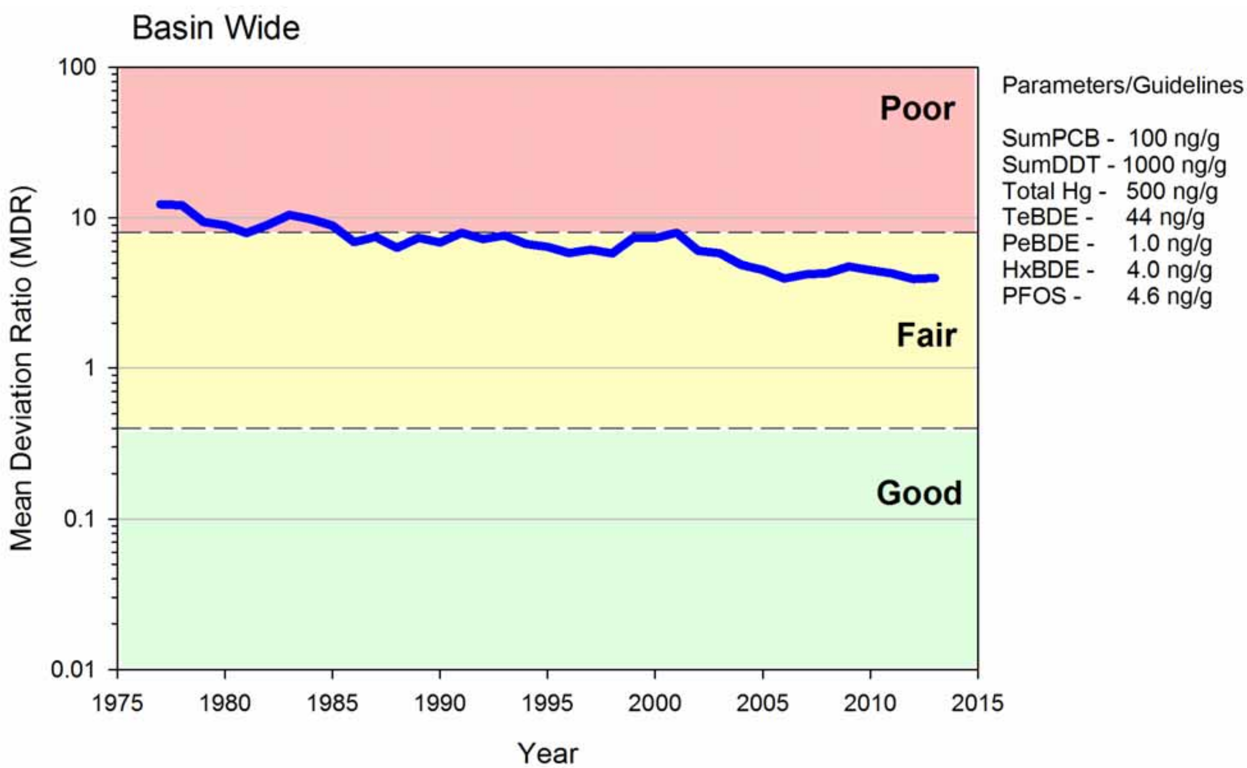


Figure 1. Mean Deviation Ratio for the Great Lakes Basin.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

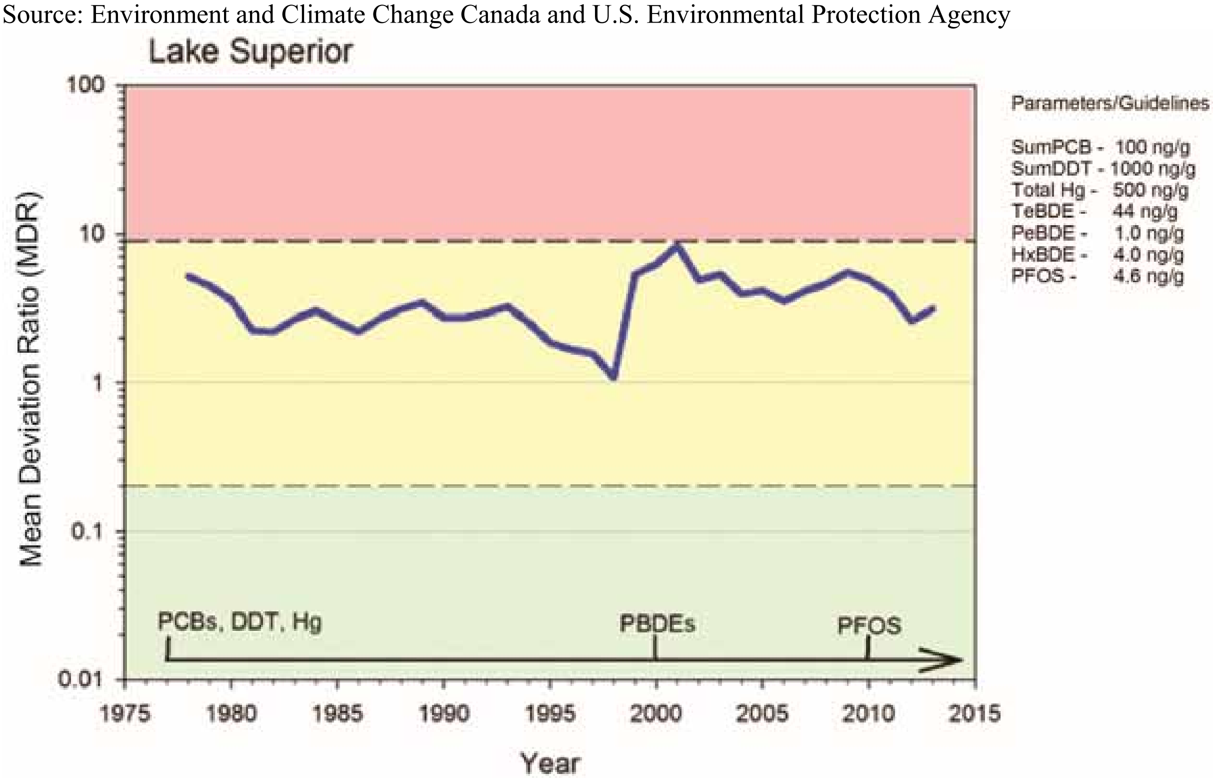


Figure 2. Mean Deviation Ratio for Lake Superior.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

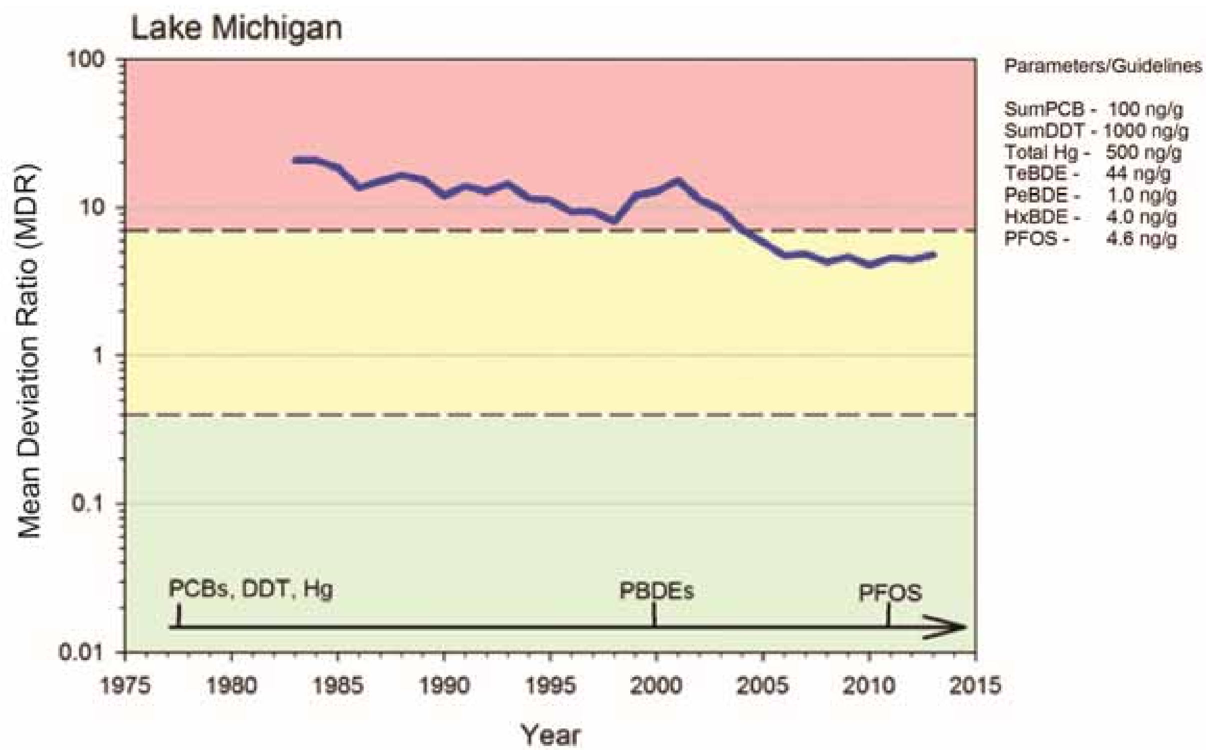


Figure 3. Mean Deviation Ratio for Lake Michigan.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

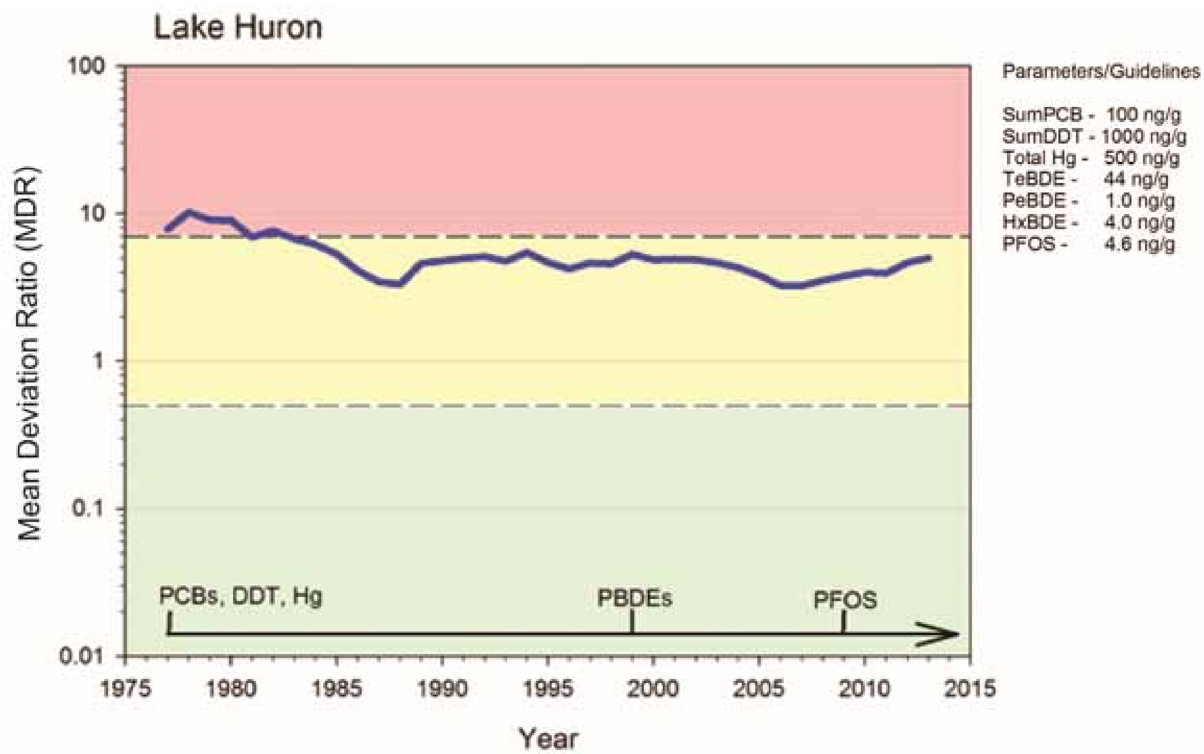


Figure 4. Mean Deviation Ratio for Lake Huron.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

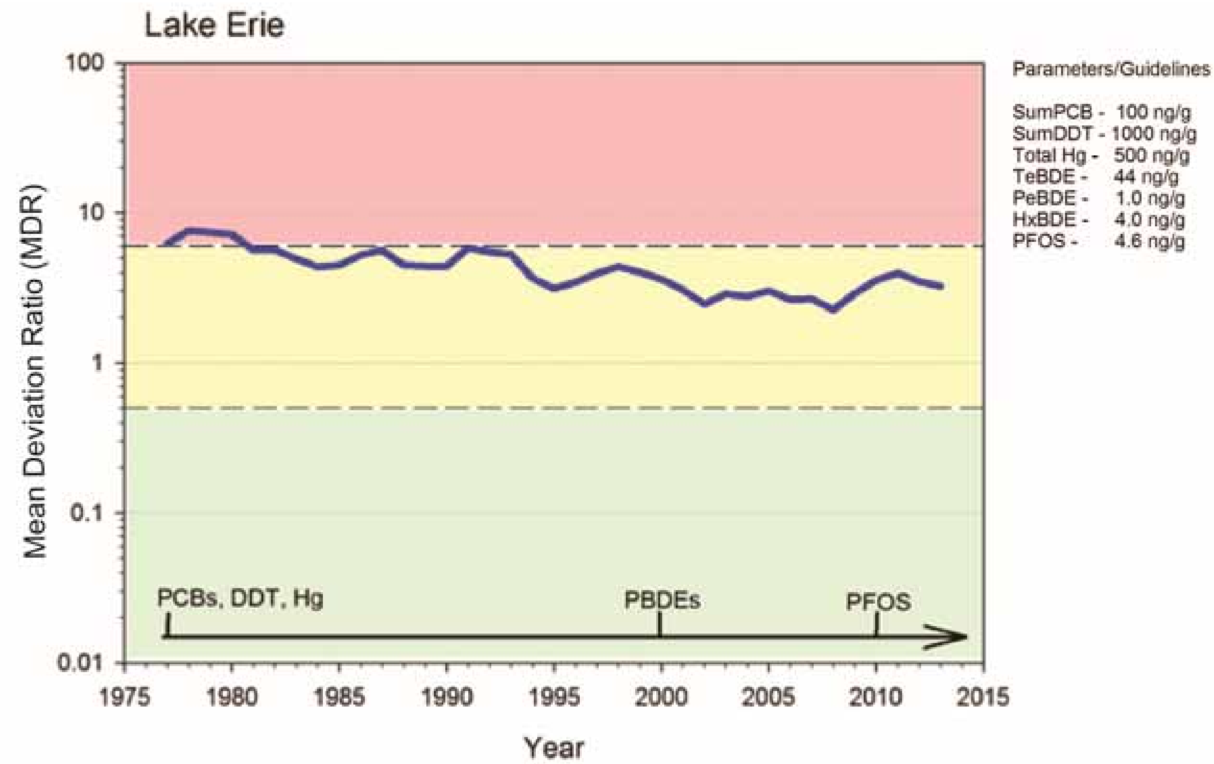


Figure 5. Mean Deviation Ratio for Lake Erie.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

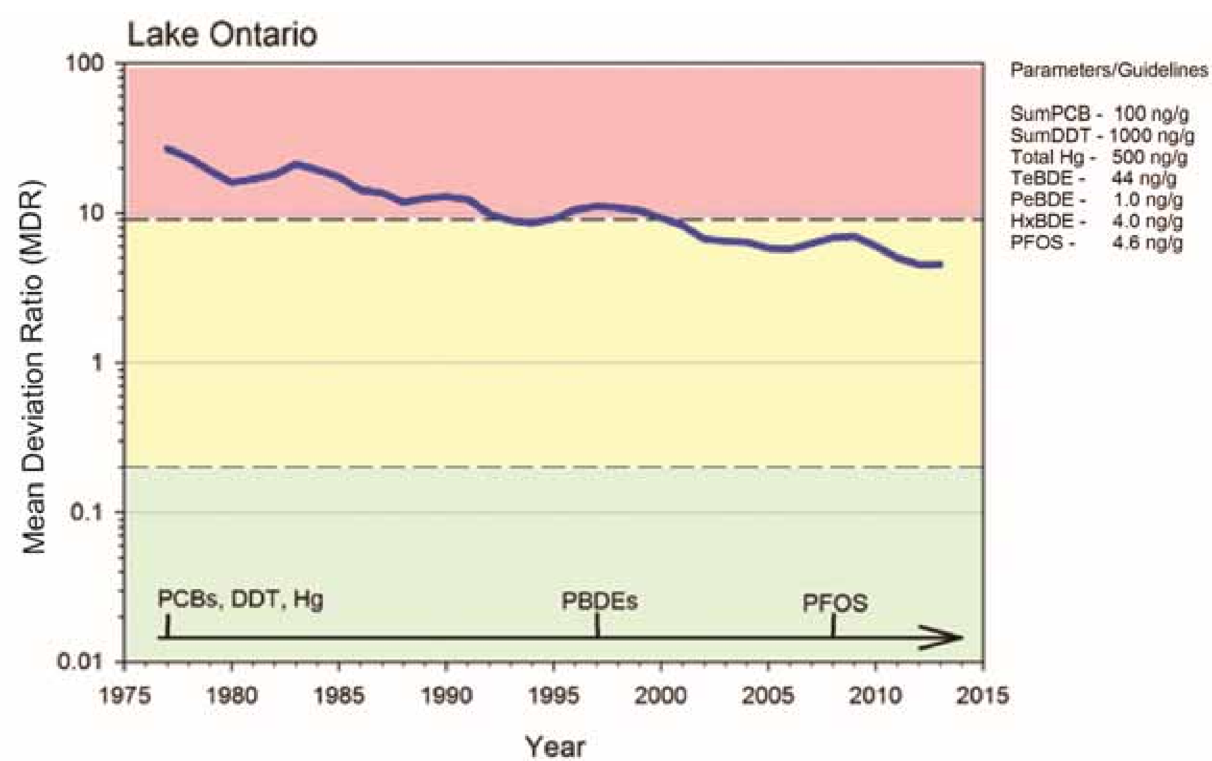


Figure 6. Mean Deviation Ratio for Lake Ontario.

Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

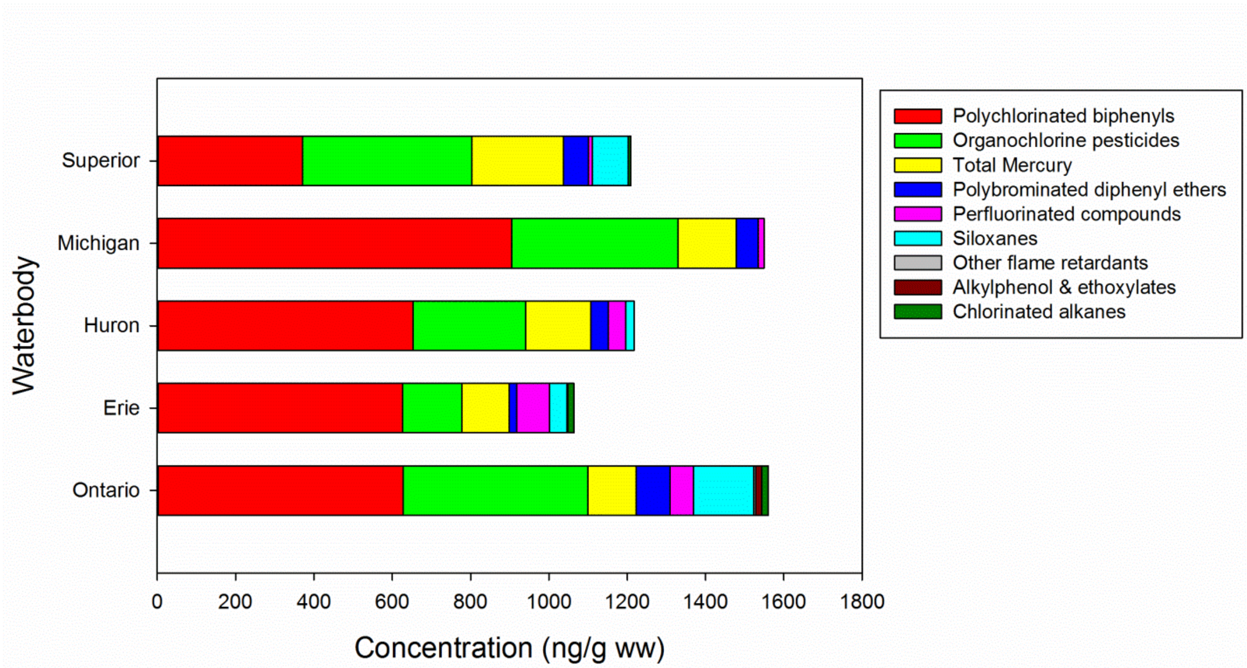


Figure 7. Basin wide chemical contribution to body burden of whole top predator fish.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

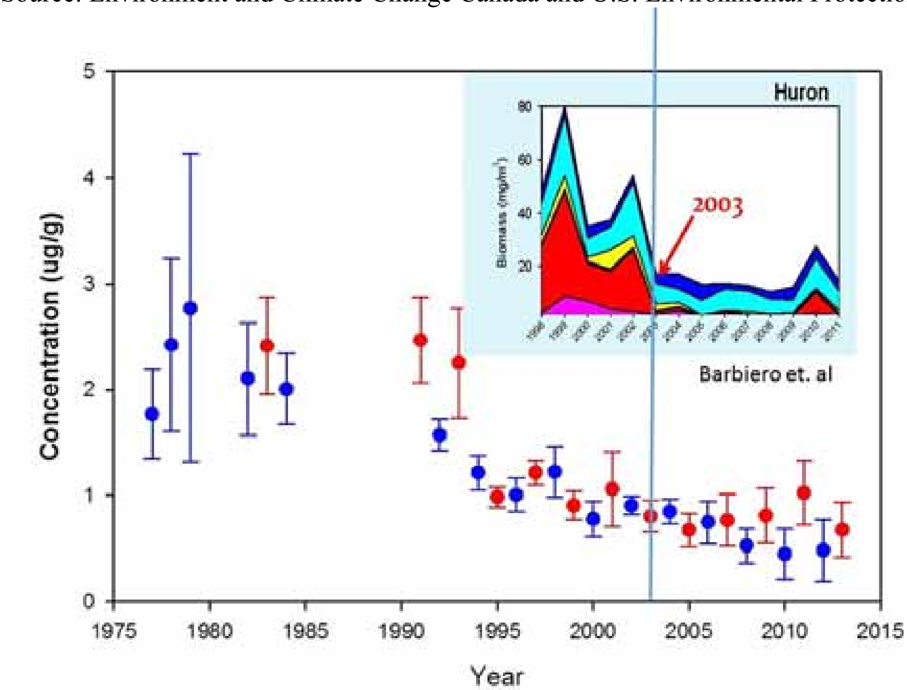


Figure 8. Total PCB concentration trend in Lake Huron Lake Trout and zooplankton biomass in Lake Huron over time.
Source: U.S. Environmental Protection Agency and Barbiero et al.

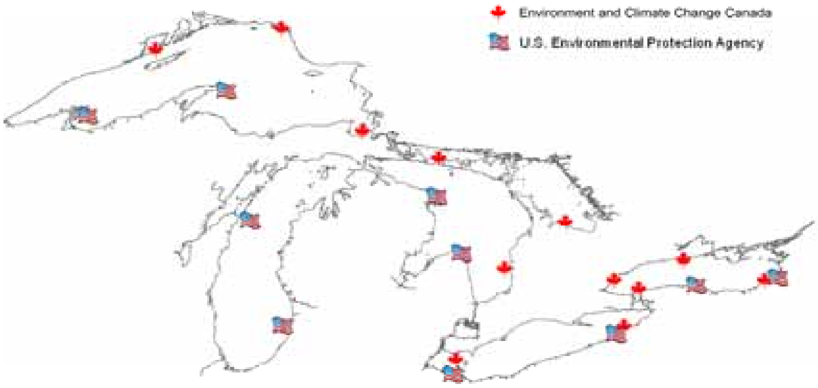


Figure 9. Map of Great Lakes showing Environment and Climate Change Canada and U.S. Environmental Protection Agency monitoring stations for fish contaminants.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

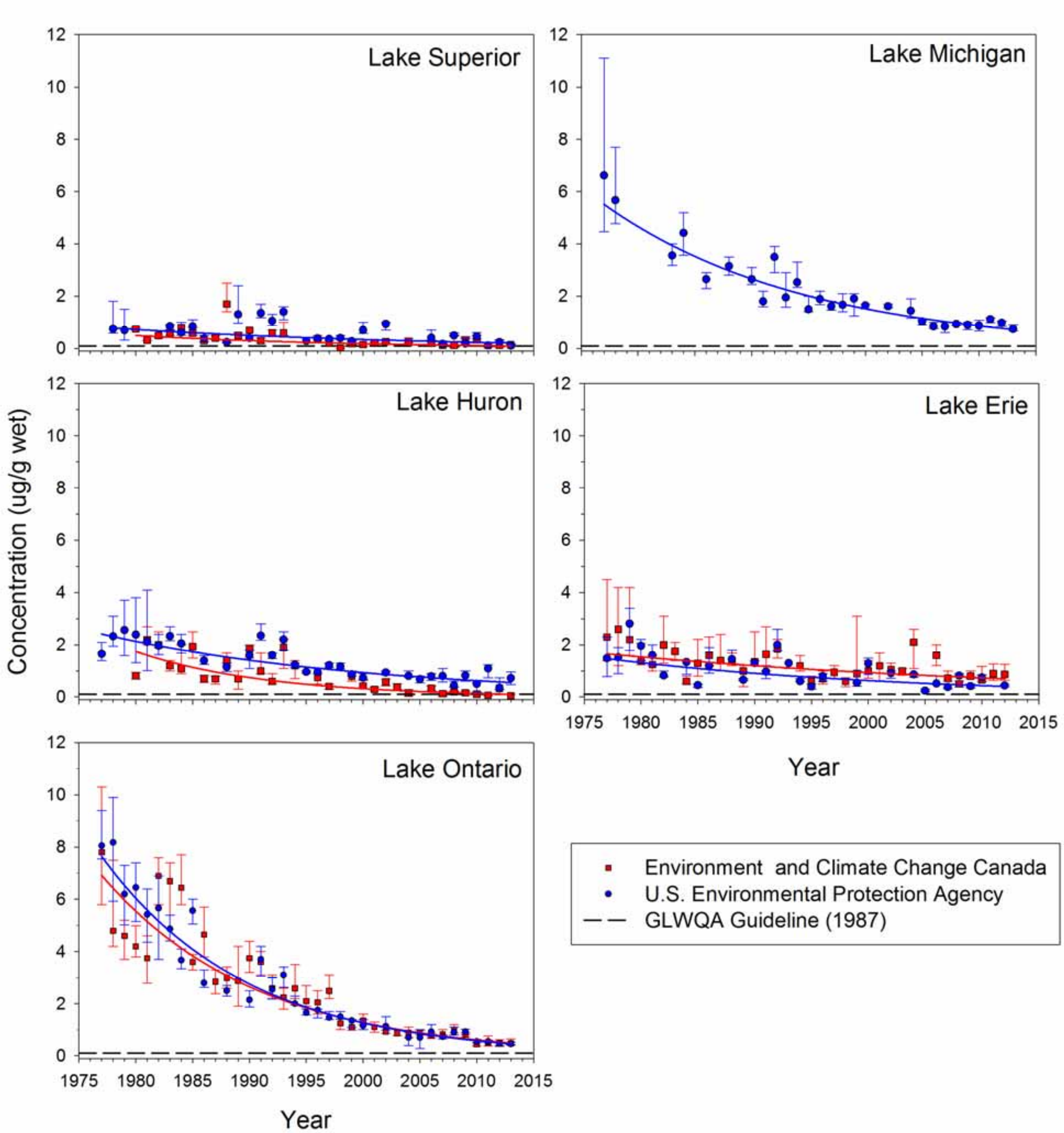


Figure 10. Total PCB concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

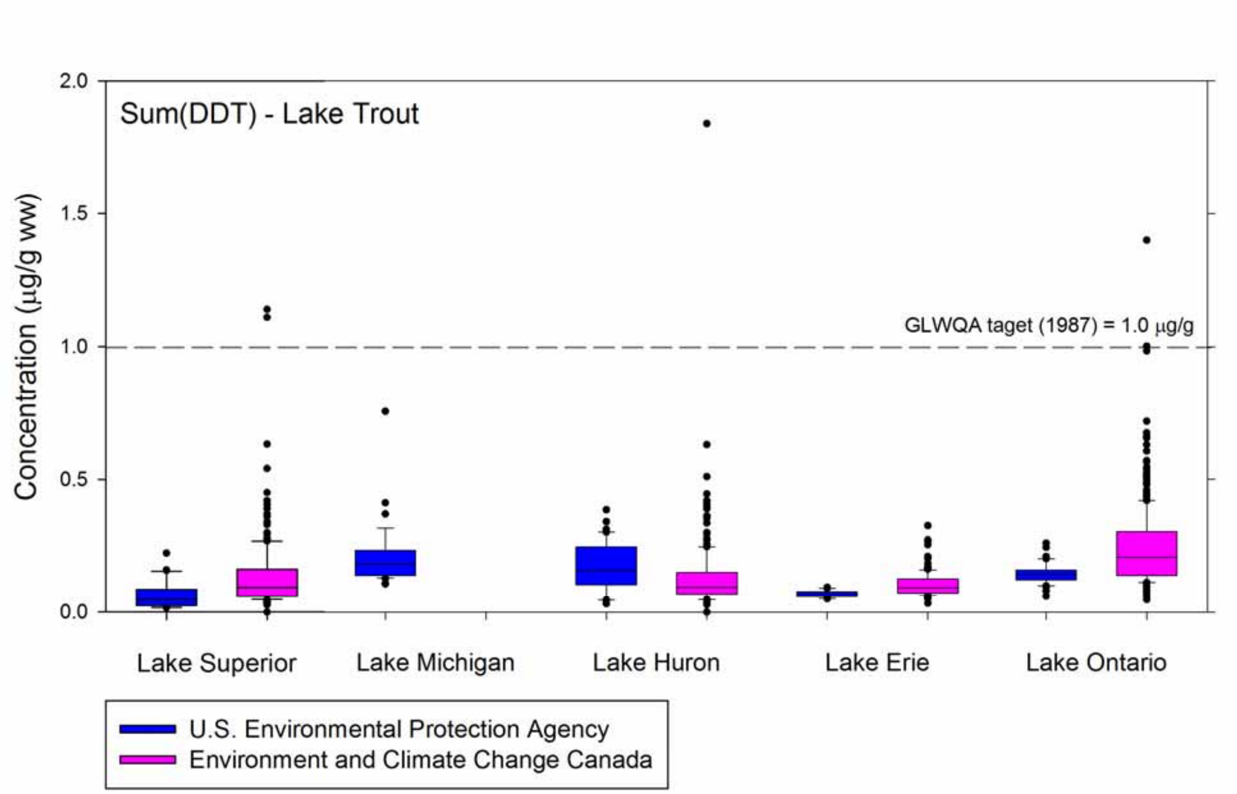


Figure 11. Total DDT (DDD + DDE + DDT) for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes, 2012.
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

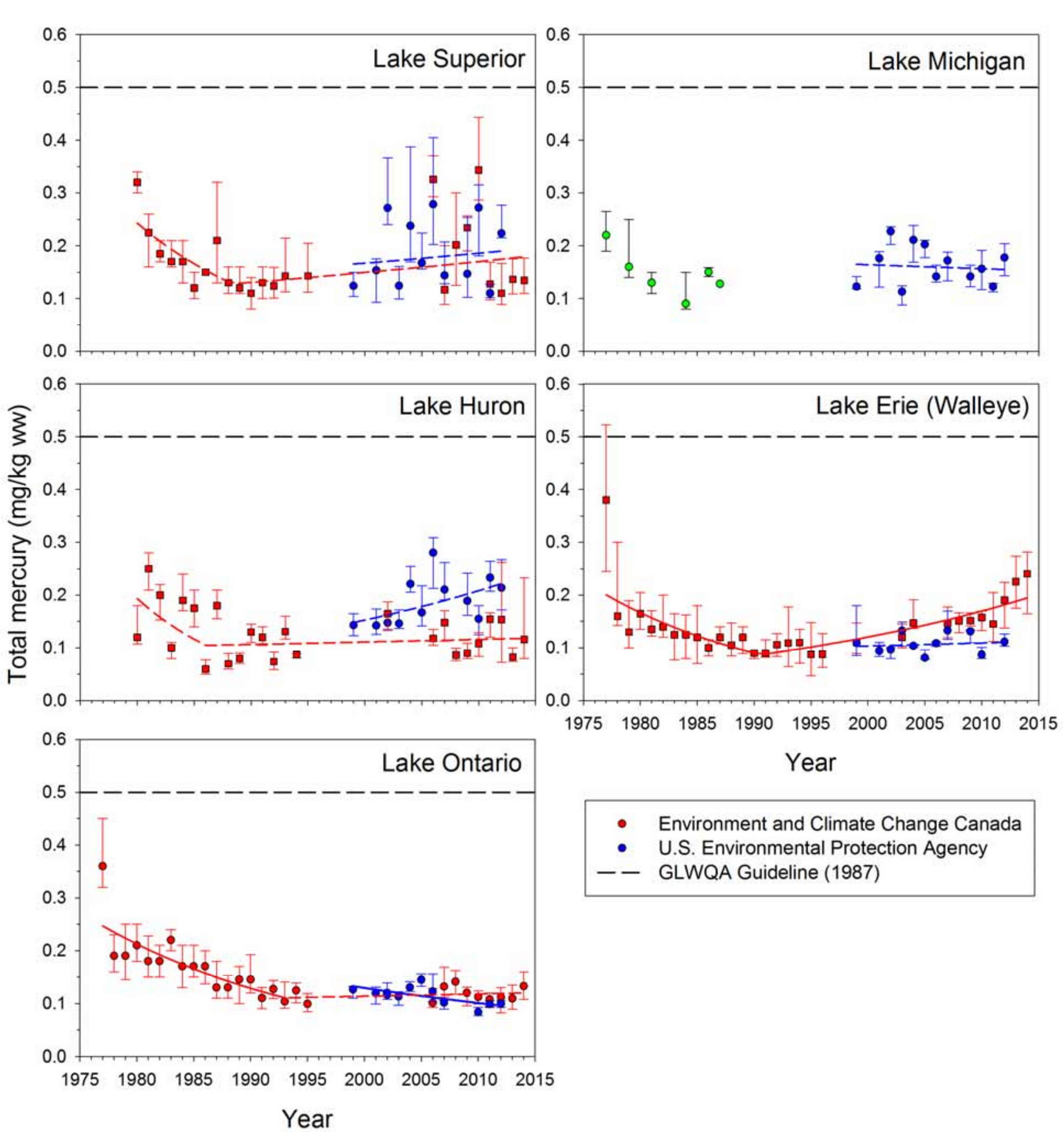


Figure 12. Total mercury concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada, U.S. Environmental Protection Agency

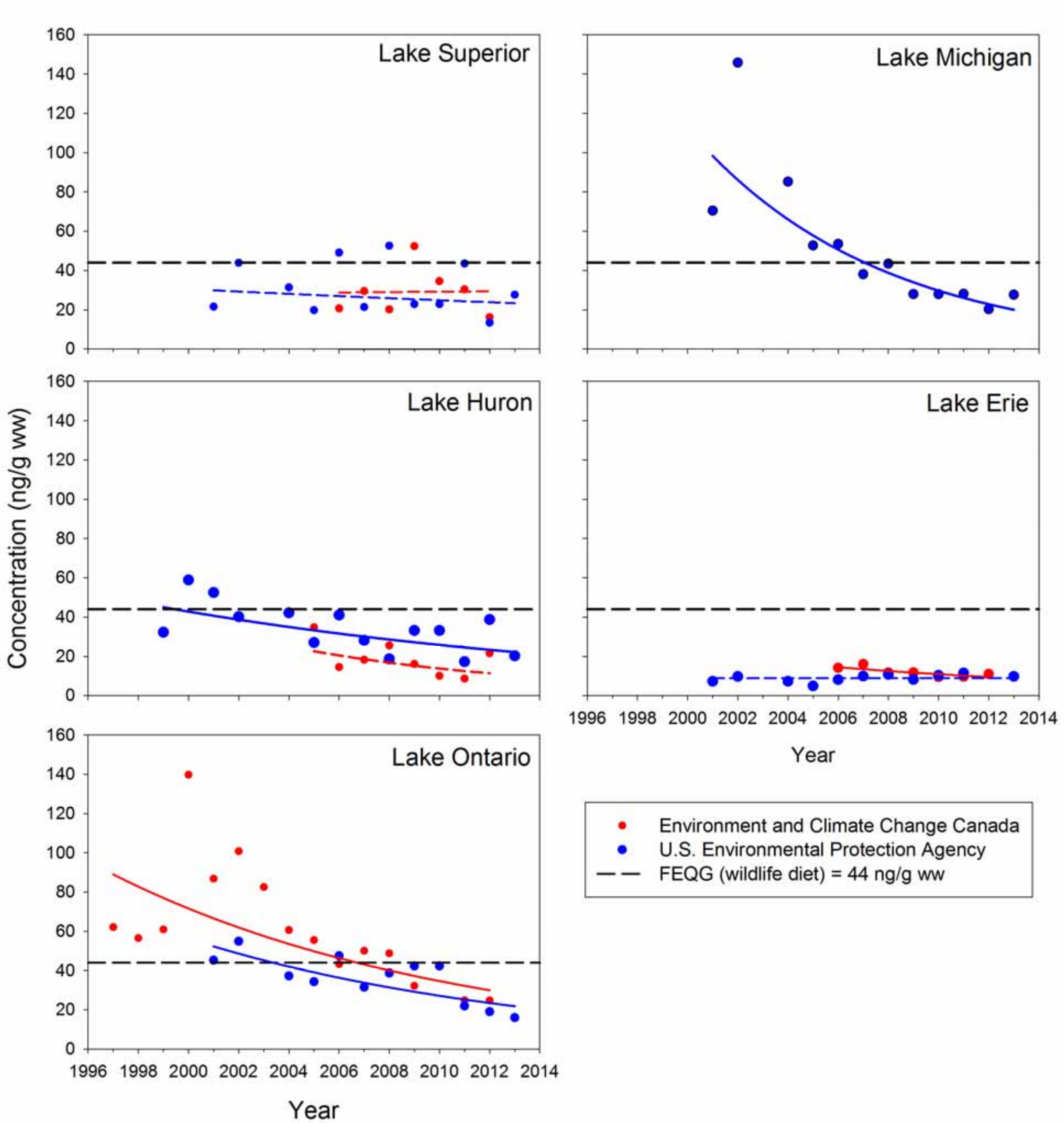


Figure 13. Mean TeBDE concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero (α = 0.05).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

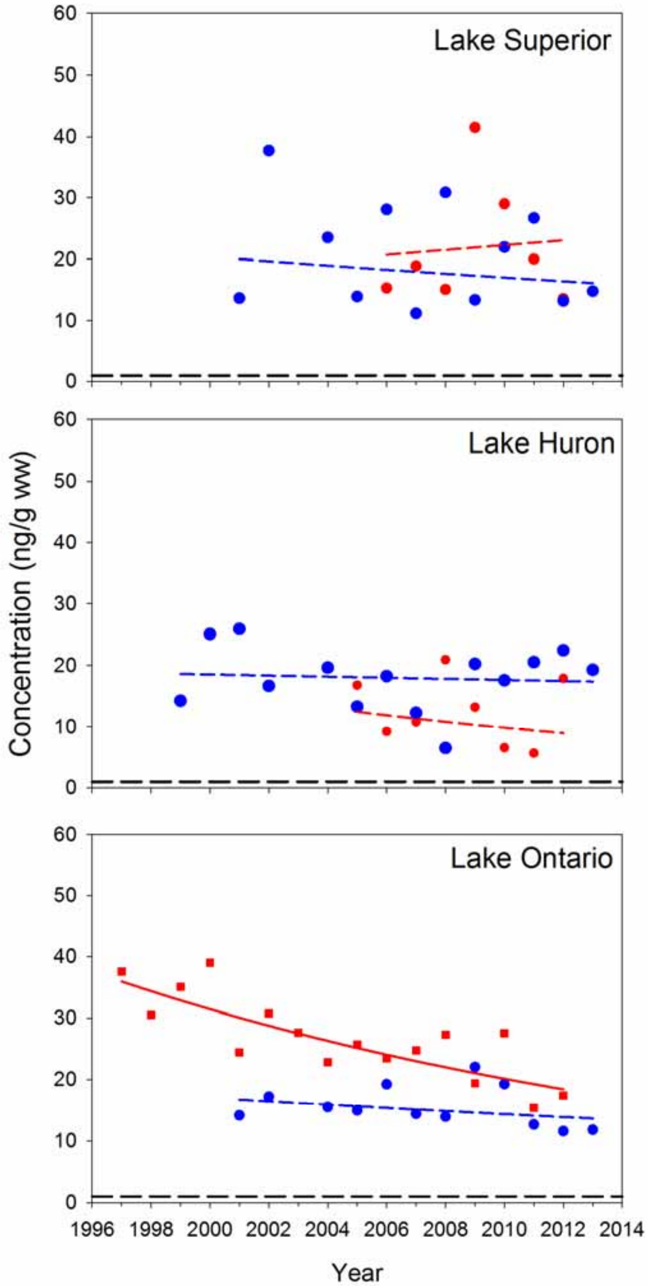
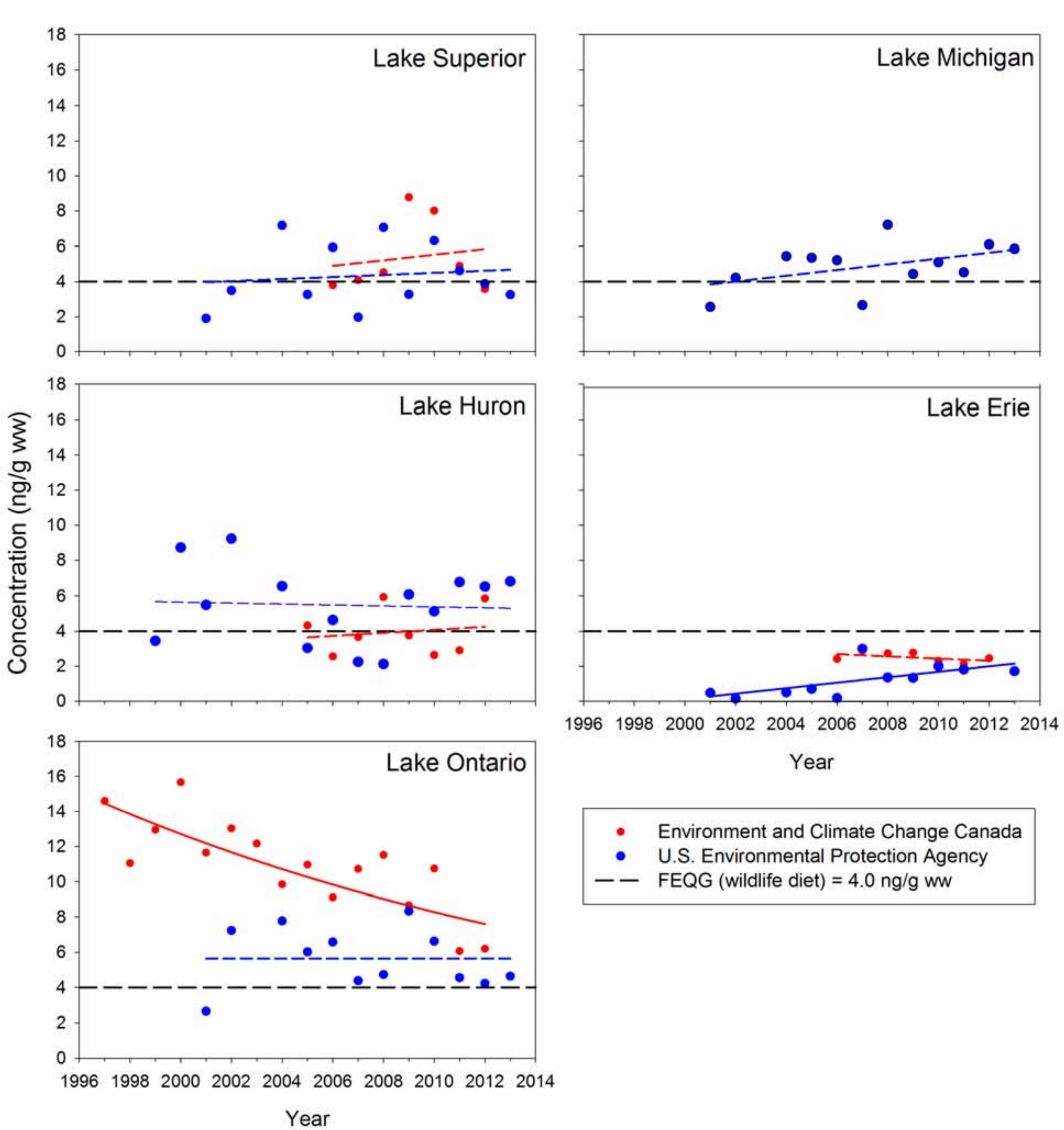


Figure 14. Mean PeBDE concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency



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Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

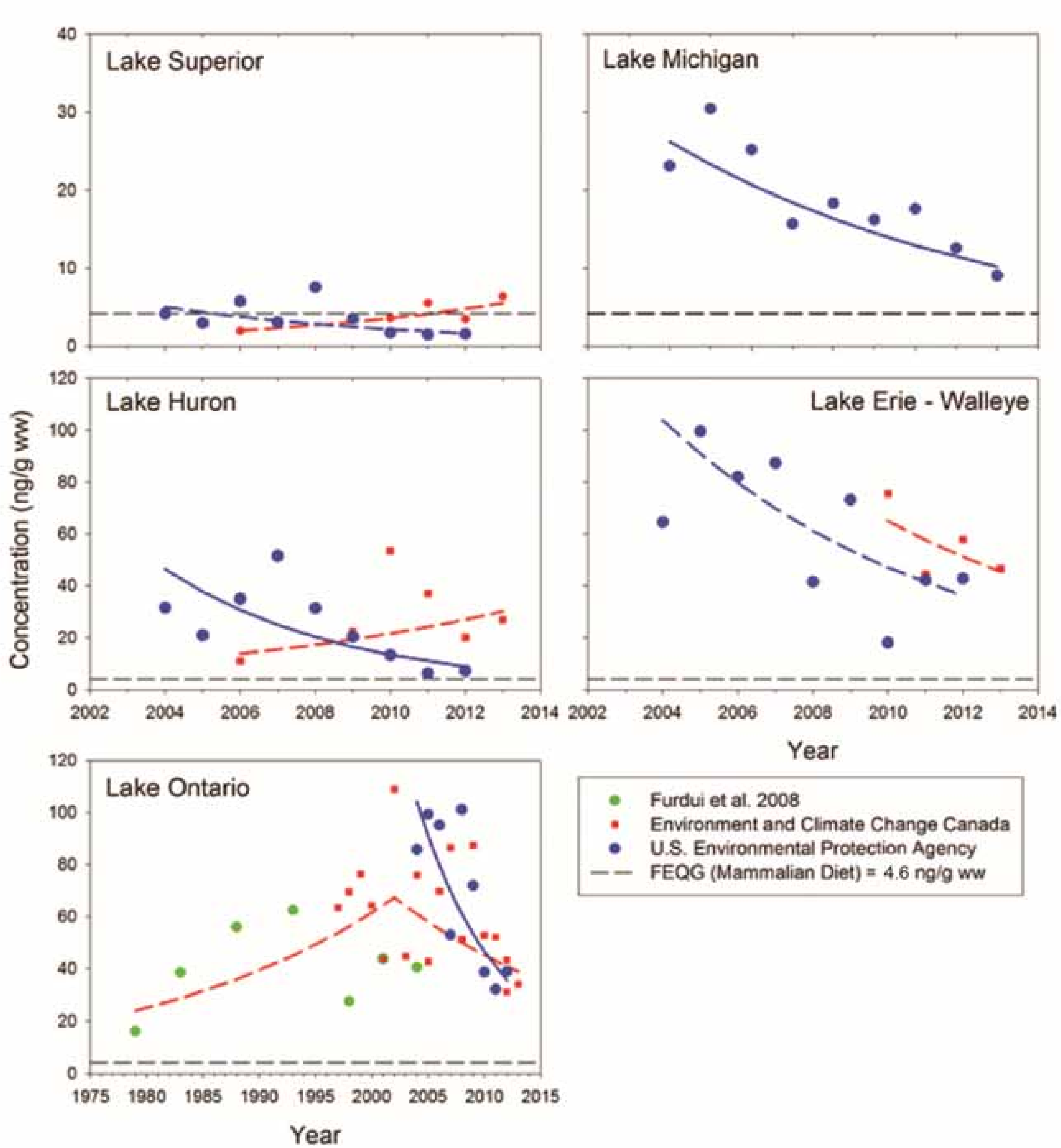

Figure 16. Mean PFOS concentrations for individual (Environment and Climate Change Canada) and composited (U.S. Environmental Protection Agency) whole body Lake Trout or Walleye (Lake Erie) collected from each of the Great Lakes. Figures with dashed trend lines are shown where slopes are not statically different than zero. Solid lines denote slopes that are statistically greater or less than zero ($\alpha = 0.05$).
Source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

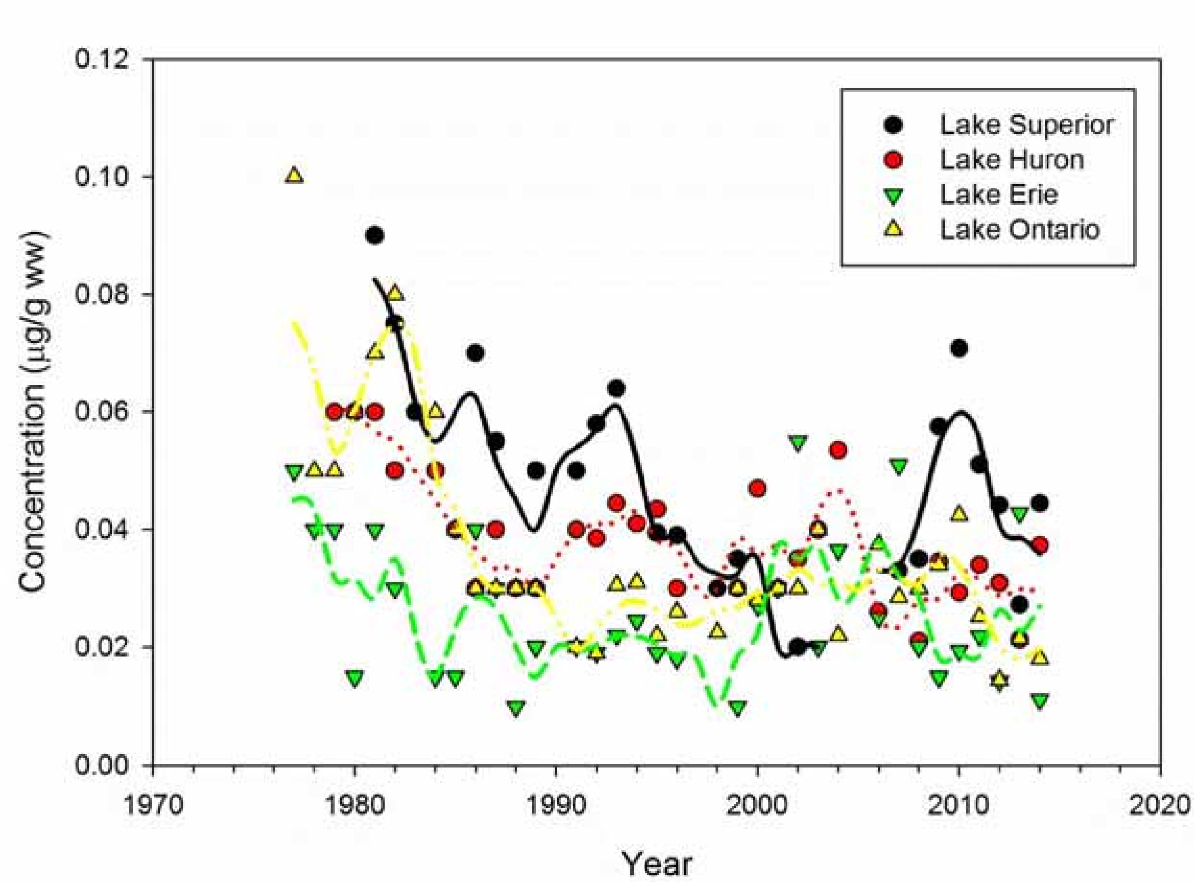

Figure 17. Average concentrations of total mercury (dots) measured in composite samples of Rainbow Smelt by Environment Canada. Lines show the three year moving average.
Source: Environment and Climate Change Canada

Sub-Indicator: Toxic Chemicals in Great Lakes Herring Gull Eggs

Overall Assessment
Status: Good
Trend: Improving
Rationale: The long term trends (1974 to present) of virtually all legacy contaminants (PCBs, dioxins and furans, organochlorine pesticides) are declining. The short term trends, those over the last decade, are a mixture of some showing significant declines but others showing no significant change. Non legacy compounds, however, like fully substituted polybrominated diphenyl ethers (e.g. BDE-209), syn- and anti-Dechlorane Plus (DDC-CO), and Hexabromocyclodoecane (HBCDD) have increased in recent years. Perfluorinated sulfonates (PFSAs) have declined over time, but some perfluorinated carboxylic acids (PFCAs) have increased from 1990 to 2010 in eggs from some gull colonies.

Lake-by-Lake Assessment

Lake Superior
Status: Good
Trend: Improving
Rationale: The traditional legacy contaminants, DDE, SUM PCBs and TCDD, have declined significantly in long term (1974-2013) and short term (2000-2013). Mercury has declined significantly in the long term but neither it, nor SUM BDE, has declined significantly in the short term. BDE-209, HBCDD, and DCC-CO have increased from 2006/08 to 2012. At the Agawa Rocks colony, SUM PFCA have increased from 1990 to 2010.
Refer to Figure 2 for more detail on the long- and short-term trends by compound and water body.

Lake Michigan
Status: Good
Trend: Improving
Rationale: The traditional legacy contaminants, DDE, SUM PCBs and TCDD, have declined significantly both since the 1970s (1974-2013) and in the last decade (2000-2013). Mercury has declined significantly in the long term but neither it, nor SUM BDE, has declined significantly in the short term. BDE-209, HBCDD, and DCC-CO have increased from 2006/08 to 2012.

Lake Huron
Status: Good
Trend: Improving
Rationale: The traditional legacy contaminants, DDE, SUM PCBs and TCDD and mercury have declined significantly since the 1970s (1974-2013) and in the last decade (2000-2013). No significant change for SUM BDE in the short-term. BDE-209, HBCDD, and DCC-CO have increased from 2006/08 to 2012, while SUM PFCAs have increased from 1990 to 2010 from the Detroit River colony.

Lake Erie
Status: Fair
Trend: Unchanging
Rationale: The legacy contaminants, DDE, SUM PCBs, TCDD and mercury, have all declined significantly since the 1970s (1974-2013). However, none of them, as well as SUM BDEs has declined significantly in the last decade (2000-2013). SUM PFCA have increased from 1990 to 2010 from the Detroit River and Niagara Falls colonies.

Lake Ontario
Status: Fair
Trend: Unchanging
Rationale: The legacy contaminants, DDE, SUM PCBs, TCDD and mercury, have all declined significantly since the 1970s (1974-2013). However, none of them, as well as SUM BDEs has declined significantly in the last decade. SUM PFCA have

increased from 1990 to 2010 from Toronto Harbour and Niagara River colonies. BDE-209, HBCDD, and DCC-CO have increased from 2006/08 to 2012.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess concentrations of chemical contaminants in a representative fish eating colonial waterbird, and it will be used to infer the impact of these contaminants on the physiology of the colonial waterbird.

This sub-indicator will assess the current toxic chemical concentrations and trends in representative colonial waterbirds (gulls, terns, cormorants and/or herons) on the Great Lakes; infer and measure the impact of contaminants on the health (i.e. the physiology and breeding characteristics) of the waterbird populations; and assess ecological and physiological endpoints in representative colonial waterbirds on the Great Lakes. It can be used to describe temporal and spatial trends of bioavailable contaminants in representative biota throughout the Great Lakes; to infer the effectiveness of remedial actions related to the management of critical pollutants; and to document and describe the trends of chemicals of emerging concern.

Ecosystem Objective

Tracking progress of fish-eating colonial waterbirds on the Great Lakes toward an environmental condition in which there is no difference in contaminant levels and related biological endpoints between birds on and off the Great Lakes. As part of this sub-indicator, contaminant levels are also measured in herring gull eggs to ensure that levels continue to decline.

This sub-indicator best supports work towards General Objective #4 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain."

Ecological Condition

Although there are Great Lakes wildlife species that are more sensitive to contaminants than Herring Gulls, and colonial nesting waterbird species in general, there is no other species which has the historical dataset that the Herring Gull does. As contaminant levels continue to decline (if they do), the usefulness of the Herring Gull as a biological indicator species may lessen (due to its reduced sensitivity to low levels of contamination) but its value as a chemical indicator will remain and probably increase - as levels become harder and harder to measure in other media. It is an excellent accumulator tracker since many of the above biological measures are correlated with contaminant levels in their eggs. In other colonial waterbirds, there are similar correlations between contaminant levels in eggs and various biological measures. Contaminant levels in eggs of other colonial waterbirds are usually correlated with those in Herring Gulls. Adult Herring Gulls nest on all the Great Lakes and the connecting channels and remain on the Great Lakes year-round. Because their diet is usually made up primarily of fish, they are an excellent terrestrially nesting indicator of the aquatic community. The Herring Gull egg contaminants dataset is also the longest running continuous (annual) contaminants dataset for wildlife in the world. The chemical related sub-indicators showing long-term trends of contaminants in biota provide valuable insight into the relative abundance of contaminants in the vicinity of fish and waterbird populations. They represent not just contaminants in water, but offer insight into how chemicals get into and move throughout the food web.

Contaminant Burdens

Annual concentrations of legacy compounds, such as organochlorine pesticides, PCBs, PCDFs/PCDDs and other organic contaminants, and mercury and other metals are measured in Herring Gull eggs from 15 sites from the Great Lakes Herring Gull Monitoring Program, and 5 sites from the Michigan Department of Environmental Quality (Figure 1) from throughout the Great Lakes (U.S. and Canada). The Herring Gull eggs are collected in a similar fashion between the two programs, and similar contaminant analyses are performed; the main difference between the two programs is the frequency of egg collection. On a less routine basis, measurements of brominated and non-brominated flame retardants, and perfluorinated sulfonates (PFSAs) and perfluorinated carboxylic acids (PFCAs) are also analyzed.

At all colonies of Herring Gulls monitored in the Great Lakes Herring Gull Monitoring Program (Environment and Climate Change Canada), concentrations of PCBs, PCDD/Fs and organochlorine pesticides have fallen dramatically since the 1970s (de Solla et al. 2016; Table 1). The range in concentrations of PCBs (Aroclor 1254:1260 1:1 equivalents) was between 50.1 and 165.6 µg/g among the 10 colonies monitored in the early 1970s, whereas by 2013 the maximum concentration was 14.8 µg/g (Table 1). By 2013, of the TCDD, PCBs and the most prevalent OC pesticides, concentrations in 2013 ranged between

3.3% and 20.1% of the concentrations from the year they were first measured (Table 1). In general, trends in contaminant burdens followed an exponential decline from the 1970s to 2013, i.e., the rate of decline is proportional to concentrations (Figure 2; Table 3). Although generally the declines were consistent with a first order exponential decay model, the rates of decline in POPs in Herring Gull eggs were generally lower in later years, and for many colonies, concentrations have stabilized in the last few years. When all colonies were pooled, the mean half-lives for POPs ranged from 5.5 to 13.7 years for PCBs, TCDD and the six organochlorine pesticides (Table 3). For ΣPCBs, the half-lives ranged from 9.9 to 24.3 years among colonies, with Middle Island having the longest half-life. Overall, Middle, Granite and Gull islands (Lakes Erie, Superior and Michigan, respectively) had the longest half-lives for POPs.

Although the Clean Michigan Initiative-Clean Water Fund (CMI-CWF; Michigan Department of Environmental Quality) have not monitored Herring Gulls for long as the Great Lakes Herring Gull Monitoring Program, there have been some declines in PCBs and OC pesticides. PCBs, *p,p*'-DDE and total mercury had declined from 2002/06 to 2008/12 for colonies from Lake Michigan and Lake Huron, and one colony from Lake Erie (Table 2). Generally, concentrations for the subset of colonies from the MDEQ were within the range for the 15 colonies of the GLHGMP.

These declines in legacy POPs are consistent with compounds whose production ceased in the 1970s; however the temporal trends in other compounds whose production continued in the 2000s or later show different trajectories. For example, PBDEs in Herring Gull egg from 6 colonies generally showed rapid increases from 1982 to 2000, no further increasing trend from 2000 to 2006, and then declines by 2012 (Figure 3; Letcher et al. 2015). Conversely, full brominated PBDEs (e.g. BDE-209), syn- and anti-Dechlorane Plus (DDC-CO), and Hexabromocyclodoecane (HBCDD) have increased from 2006 to 2012 (Figure 3; Letcher et al. 2015).

Contaminant burdens varied among the 15 GLHGMP colonies, with concentrations generally highest in colonies with substantial urban or industrial influences nearby or upstream. Using the methodology of Weseloh et al. (2006), where colonies were ranked from most to least contaminated for legacy POPs using fish flesh criteria as weighting factors; the 15 colonies were ranked for the 2013 data. Overall, Herring gull eggs from Fighting Island (Detroit River), Middle Island (Western Lake Erie), Toronto Harbour and Hamilton Harbour (Lakes Ontario), and Channel Shelter Island (Lake Huron) were the most contaminated for legacy POPs. Conversely, the colonies from Eastern Lake Erie and Western Lake Ontario tended to be the most contaminated for perfluorinated sulfonates (PFSAs) and perfluorinated carboxylic acids (PFCAs; Figure 4; Letcher et al. 2015).

Assessment of Health of Colonial Waterbirds

The health of colonial waterbirds, particularly in relation to contaminant burdens or exposure, has been assessed at a number of colonies, primarily in Areas of Concern. Contaminant burdens were examined in eggs of herring gulls and double-crested cormorants (*Phalacrocorax auritius*) collected from colonies in the vicinity of the Spanish Harbour Area of Concern in Recovery (Lake Huron) and compared to reference colonies in 2011 and 2012. Concentrations of TCDD, PCBs, and mercury, were low in eggs and were not notably elevated in the Area in Recovery (AiR) relative to the reference colonies, and were considered to be below those associated with adverse effects on reproduction. Recent egg burdens appeared to be markedly lower to concentrations measured in earlier time periods (Hughes et al. 2014b). Similarly, Reproduction and development were examined in herring gulls and common terns (*Sterna hirundo*) breeding within the St. Marys River Area of Concern (Lake Huron) in 2011 and 2012. Freshly-laid eggs were collected from colonies within the AOC and from reference sites were artificially incubated in the laboratory and assessed for embryonic viability, incidence of embryonic deformities, contaminant burdens and other biochemical endpoints. Overall, embryonic viability of herring gulls and common terns was high at AOC colonies. Frequencies of embryonic deformities were comparable between AOC colonies and reference colonies for both species, were not associated with exposure to dioxin-like PCBs and dioxins, which did not differ between AOC and reference sites. Contaminants were not sufficiently elevated in embryos to adversely impact the reproductive success and development of herring gulls and common terns foraging in the St. Marys River AOC (Hughes et al. 2014a).

Breeding success of the Black-crowned Night-Heron (*Nycticorax nycticorax*) was examined at a colony on Turkey Island in the Detroit River Area of Concern (AOC) and an upstream non-AOC reference colony on Georgian Bay in 2009 and 2011. Breeding success was lower in night-herons from the AOC compared to the reference colony in both study years; at the AOC colony in 2009, productivity was below a range of thresholds considered to be typical for a stable population. Despite higher concentrations found overall at the AOC colony, concentrations of PCBs, other organochlorines and PBDEs in eggs and liver of nestlings were below concentrations associated with adverse reproductive effects. Mercury concentrations in eggs and livers of nestlings from the AOC colony were comparable to concentrations at the reference colony and were below those associated with adverse reproductive effects. Reduced breeding success in 2009 was likely not due to elevated concentrations of contaminants historically associated with the AOC, but likely to other stressors, such as predation, weather and disturbance. At both colonies, concentrations of DDT, PCBs and mercury in eggs and nestling livers exceeded tissue residue guidelines (Hughes et al. 2013).

Variable DNA microsatellites were used to screen for mutations in Double-crested Cormorants (*Phalacrocorax auritus*) families from two colonies in Hamilton Harbour AOC (Lake Ontario) and Mohawk Island (Lake Erie) Microsatellite mutation rates were 6 times higher at the Hamilton Harbour site closest to the industrial sources of Polycyclic Aromatic Hydrocarbons (PAHs) than the other Hamilton Harbour site, and both were higher than the reference colony (King et al. 2014). A Phase I metabolite of the PAH benzo[a]pyrene was identified in bile and liver from Hamilton Harbour cormorant chicks suggesting that these cormorants are exposed to and metabolizing PAHs, highlighting their potential to have caused the observed mutations (King et al. 2014).

The health of Herring Gulls is also being assessed at Thunder Bay (Lake Superior) and Hamilton Harbour AOCs. Periodic measurements are made of biological features of gulls and other colonial waterbirds known to be directly or indirectly impacted by contaminants and other stressors. These include (but are not limited to): clutch size, eggshell thickness, hatching and fledging success, size and trends in breeding population, various physiological biomarkers including vitamin A, immune and thyroid function, stress (corticosterone) and growth hormone levels, liver enzyme induction, PAH levels in bile and porphyrins and genetic and chromosomal abnormalities. Additional monitoring considerations include: tracking porphyria, vitamin A deficiencies, and the evaluation of avian immune systems. Chemical burdens in eggs of colonial nesting waterbirds are assessed for temporal trends, and are compared to suitable reference sites.

Linkages

There are many linkages between the Toxic Chemicals in Great Lakes Herring Gull Eggs sub-indicator and many other sub-indicators within the Great Lakes (previously known as SOLEC) reporting suite. There is a link between Fish-Eating and Colonial Nesting Waterbirds and Toxic Chemicals in Whole Fish as well as with Lake Sturgeon, Lake Trout and Preyfish. Changes in fish productivity of the Great Lakes have been reflected in fish eating birds (Figure 5; Paterson et al. 2014); temporal changes in the energy density of forage fish eggs are reflected in those of both top predator fish (Lake Trout) and a fish-eating bird (Herring Gulls). A link has also been shown by Dr. Craig Hebert between contaminant levels in Herring Gull eggs and Ice Cover. There is a direct link between Herring Gull contaminants and endocrine disruption and, in terms of the health of Great Lakes fish-eating birds, between Herring Gulls and both botulism outbreaks and the occurrence of fish diseases.

Comments from the Author(s)

The bioavailability of POPs, and thus exposure to wildlife is not simply a function of the concentrations found in environmental matrices such as water, soil or sediment, but varies considerably with the myriad of factors that control the transport and fate of contaminants. Measurements of body burdens in waterbirds integrate the net effect of factors such as bioavailability, temperature, growth rates, food chain dynamics, and chemical partitioning behavior. One of the advantages of using colonial waterbirds as indicators is that their rates of elimination of body burdens for POPs are generally much faster than the rates of environmental degradation; hence changes in body burdens reflect changes in the bioavailability of POPs.

Degradation half-lives in sediment of the PCB congeners typically found in Herring Gull eggs range between 10 to 19 years in sediment (Sinkkonen and Paasivirta 2000). Conversely, the half-life of *p,p*'-DDE in Herring Gulls was estimated to be 264 days (Norstrom et al. 1986), with half-lives for PCBs likely to be similar. The half-lives of PCBs fed to ring doves ranged from 7 to 53 days (Drouillard and Norstrom 2001). Hence, Herring Gulls respond faster to inputs of POPs through their diet than the degradation rate of POPs in the general environment. Although there were dramatic declines in contaminant burdens of legacy POPs in Herring Gull eggs from the 1970s to 2013, not all of the changes in egg burdens were due solely to the elimination of the contaminants in the environment. Changes in food web components affect dietary exposure and hence body burdens of POPs in wildlife. By using ecological tracers, Hebert and Weseloh (2006) found that not only did Herring Gull diets and trophic level change at many Great Lakes colonies between 1974 and 2003, but when the effect of changing trophic level was removed, the rates of contaminant declines were reduced. Hence, a proportion of the declines were due to reductions in dietary exposure from feeding at lower trophic levels.

Also, contaminant concentrations in most colonially-nesting, fish-eating birds are at levels where gross ecological effects, such as eggshell thinning, reduced hatching and fledging success, and population declines, are no longer apparent. Greater reliance for detecting biological effects of contaminants is being put upon physiological and genetic biomarkers.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

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Source: Great Lakes Herring Gull Monitoring Program (Environment and Climate Change Canada)
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Table 3. Mean percent declines (SD), mean decay constants (SD) and mean half-lives (SD) for PCBs, organochlorine pesticides and 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) in Herring Gull eggs from 15 Great Lakes colonies from the first year of reporting to 2013 (with the exception of Fighting Island where the last year of reporting was 2010). Minimum and maximum values and associated colonies are also shown. Note that colonies identified with the smallest (minimum) decay constant also have the longest (maximum) half-life and vice versa.
Source: Great Lakes Herring Gull Monitoring Program (Environment and Climate Change Canada)

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Sites in green are the 15 colonies monitored annually by Environment and Climate Change Canada (Great Lakes Herring Gull Monitoring Program), and the sites in red are monitored periodically by the Michigan Department of Environmental Quality.
Source: de Solla et al., in press; unpublished data
Figure 2. Temporal changes (exponential models) in concentrations of PCBs (Aroclor 1254:1260 1:1 equivalents) and six organochlorine pesticides (µg/g, wet weight) and 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) (pg/g, wet weight) in Herring Gull eggs from the Great Lakes, 1974-2013. For each compound, data were reported for the two colonies that had the highest (●) and lowest (□) decay constants.
Source: de Solla et al. in press; unpublished data
Figure 3. Time-point comparisons over six years of the arithmetic mean of the sum concentrations of SUM 7PBDEs (BDE-28, -47, -100, -99, -154, -153 and -183), BDE-209, HBCDD and SUM 2DDC-CO concentrations in herring gull egg pools collected in 2006, 2008 and 2012 from Agawa Rock (Lake Superior), Gull Island (Lake Michigan), Channel-Shelter Island (Lake Huron), Chantry Island (Lake Huron), Weseloh Rocks (Niagara River, above the falls) and Toronto Harbor (Lake Ontario).
Source: Su et al. 2015.
Figure 4. Arithmetic mean concentrations of SUM 4 perfluorinated sulfonates (PFSAs) and SUM 9 perfluorinated carboxylic acids (PFCAs) and sampling locations of herring gull eggs in the North American Great Lakes.
Fourteen colonies sampled by Environment and Climate Change Canada as part of the Great Lakes Herring Gull Monitoring Program (GLHGMP) are marked with black dots, whereas five Clean Michigan Initiative-Clean Water Fund (CMI-CWF) U.S. colonies are marked with yellow dots.
Source: Letcher et al. 2015.
Figure 5. Energy density (kJ/g) trends for eggs of Lake Huron rainbow smelt (RS), 4–7 year old lake trout (LT), and herring gull eggs (HRG) collected from Chantry, Channel Shelter, and Double Island nesting colonies from 1989–2011. Solid, dotted, and dashed lines represent best fit least squares linear regression lines for lake trout, rainbow smelt, and herring gull egg data, respectively.
Source: Paterson et al. 2014.

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Lake	Colony	Year	PCB 1:1	*p,p'*-DDE	HE	Σ Chlordane	HCB	Mirex	Dieldrin	TCDD[1]
St Lawrence	Strachan I.	1986	35.79	7.44	0.06	0.22	0.07	0.94	0.16	57.0
		2013	5.33	0.65	0.01	0.03	0.01	0.12	0.02	4.8
Lake Ontario	Snake I.	1974	140.51	21.37	0.17	0.25	0.56	6.59	0.47	185.0
		2013	7.01	0.79	0.01	0.06	0.03	0.15	0.03	9.7
Lake Ontario	Leslie St. Spit	1974	165.56	23.32	0.14	0.17	0.60	7.44	0.46	60.0
		2013	8.78	1.48	0.02	0.13	0.03	0.20	0.08	11.2
Lake Ontario	Hamilton H	1981	79.33	11.10	0.12	0.72	0.23	1.94	0.26	50.0
		2013	7.05	0.83	0.01	0.06	0.02	0.10	0.03	6.6
Lake Erie	Port Colborne	1974	72.56	8.71	0.16	0.16	0.21	0.84	0.37	32.0
		2013	5.82	0.42	0.01	0.05	0.02	0.02	0.04	2.9
Lake Erie	Weseloh Rocks	1979	50.47	4.01	0.09	0.24	0.17	0.49	0.20	87.0
		2013	5.90	0.52	0.01	0.05	0.03	0.04	0.04	4.3
Lake Erie	Middle I.	1974	72.36	5.55	0.16	0.24	0.38	0.44	0.34	25.0
		2013	14.79	0.69	0.01	0.06	0.02	0.01	0.04	6.7
Detroit River	Fighting I.	1972	115.09	48.10	0.08	0.20	0.31	0.13	0.27	49.0
		2010	15.52	0.73	0.01	0.04	0.01	0.01	0.02	2.9
Lake Huron	Double I.	1974	56.34	13.83	0.16	0.40	0.30	0.52	0.53	28.0
		2013	4.14	0.47	0.04	0.17	0.02	0.03	0.02	4.2
Lake Huron	Chantry I.	1974	85.67	20.97	0.16	0.36	0.47	2.16	0.47	45.0
		2013	2.84	0.42	0.01	0.05	0.02	0.04	0.02	4.4
Lake Huron	Channel Shelter I.	1980	69.55	8.90	0.13	0.29	0.19	0.20	0.18	155.0
		2013	10.64	1.04	0.01	0.04	0.08	0.02	0.02	25.0
Lake Michigan	Gull I.	1977	111.60	27.76	0.26	0.89	0.12	0.21	0.72	58.0
		2013	7.49	1.00	0.02	0.13	0.03	0.02	0.06	3.2
Lake Michigan	Big Sister I.	1971	141.67	60.98	0.39	0.62	0.42	0.68	0.83	45.0
		2013	4.15	0.69	0.01	0.05	0.02	0.01	0.04	1.5
Lake Superior	Agawa Rocks	1974	50.07	14.19	0.13	0.38	0.29	0.76	0.42	79.0
		2013	3.38	0.34	0.02	0.07	0.02	0.02	0.03	3.0
Lake Superior	Granite I.	1973	75.43	25.25	0.06	0.08	0.21	1.35	0.35	14.0
		2013	3.15	0.40	0.01	0.06	0.02	0.02	0.03	3.0

[1]TCDD was not measured until 1981 at the earliest.

Table 1. Concentrations of PCBs and organochlorine pesticides (µg/g, wet weight) and 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) (pg/g, wet weight) in Herring Gulls eggs from the Great Lakes in the first and last years of reporting.
Source: Great Lakes Herring Gull Monitoring Program (Environment and Climate Change Canada)

Site	N		PCB (mg/kg)		*p,p'*- DDE (mg/kg)		TEQ (ng/kg)		Hg (mg/kg)	
	02/06	08/12	02/06	08/12	02/06	08/12	02/06	08/12	02/06	08/12
Lake Michigan										
Grand Traverse Bay	5	5	3.1	1.8	2.2	0.8	759	251	0.69	0.41
Lake Huron										
Saginaw Bay AOC	3	5	6.0	3.6	1.3	0.7	768	466	0.47	0.40
St. Marys River AOC	9	7	3.1	1.5	1.0	0.4	226	239	0.65	0.40
Lake Superior	10	6	3.4	2.1	1.5	0.7	200	305	0.82	0.50
Huron National Wildlife Refuge	2	3	3	1.5	1.5	0.5	391	188	0.72	0.45
Lake Erie										
River Raisin AOC	5	5	10.8	7.8	1.1	0.8	719	511	0.42	0.32
All non-AOC Sites Combined	25	15	3.4	1.9	1.6	0.7	219	314	0.75	0.43

Table 2. Concentrations of PCBs, *p,p*'-DDE, and toxic dioxin equivalents (TEQs) in Herring Gulls eggs from the American Great Lakes in the 2002 to 2006 and 2008 to 2012. Only a subset of the 10 colonies are listed here. Data in red are mean concentrations in 2008-12 that are significantly lower than those from 2002-06.
Source: Data from the Clean Michigan Initiative-Clean Water Fund (CMI-CWF; Michigan Department of Environmental Quality)

Year	PCB 1260	PCB 1:1	Σ PCBs	*p,p'*-DDE	HE	Σ Chlordane	HCB	Mirex	Dieldrin	TCDD
Mean	-93.66%	-91.05%	-65.17%	-94.42%	-89.25%	-72.74%	-88.61%	-95.15%	-90.15%	-88.84%
SD	0.04	0.05	0.13	0.04	0.06	0.21	0.11	0.04	0.05	0.07
Min	-82.10%	-79.55%	-39.08%	-87.14%	-77.17%	-23.63%	-57.16%	-87.23%	-80.40%	-73.28%
Max	-98.62%	-97.07%	-88.33%	-98.87%	-96.78%	-91.94%	-96.92%	-98.90%	-96.12%	-96.69%
Min Colony	Middle I	Middle I	Weseloh R	Weseloh R	Double I	Leslie St Spit	Channel Sh I	Strachan I	Weseloh R	Middle I
Max Colony	Big Sister I	Big Sister I	Big Sister I	Big Sister I	Big Sister I	Big Sister I	Fighting I	Big Sister I	Double I	Big Sister I
					Decay constant (λ)					
Mean	-0.116	-0.091	-0.054	-0.123	-0.063	-0.056	-0.140	-0.236	-0.075	-0.097
SD	0.029	0.025	0.010	0.056	0.019	0.020	0.045	0.343	0.017	0.028
Min λ	-0.056	-0.042	-0.029	-0.044	-0.039	-0.034	-0.072	-0.065	-0.055	-0.041
Max λ	-0.161	-0.128	-0.070	-0.244	-0.103	-0.110	-0.234	-1.334	-0.119	-0.146
Min Colony	Middle I	Middle I	Middle I	Channel Sh	Granite I	Granite I	Gull I	Gull I	Granite I	Middle I
Max Colony	Gull I	Chantry I	Strachan I	Fighting I	Strachan I	Hamilton H	Chantry I	Chantry I	Strachan I	Weseloh R
					Half-life (years)					
Mean	6.42	8.43	13.43	6.86	11.82	13.67	5.46	6.03	9.58	7.91
SD	2.06	3.24	3.43	3.28	3.16	3.72	1.77	3.10	1.87	3.07
Minimum	4.29	5.42	9.92	2.84	6.72	6.33	2.96	0.52	5.80	4.73
Maximum	12.41	16.35	24.27	15.63	17.77	20.24	9.57	10.67	12.63	16.95

Table 3. Mean percent declines (SD), mean decay constants (SD) and mean half-lives (SD) for PCBs, organochlorine pesticides and 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) in Herring Gull eggs from 15 Great Lakes colonies from the first year of reporting to 2013 (with the exception of Fighting Island where the last year of reporting was 2010). Minimum and maximum values and associated colonies are also shown. Note that colonies identified with the smallest (minimum) decay constant also have the longest (maximum) half-life and vice versa.

Source: Great Lakes Herring Gull Monitoring Program (Environment and Climate Change Canada)

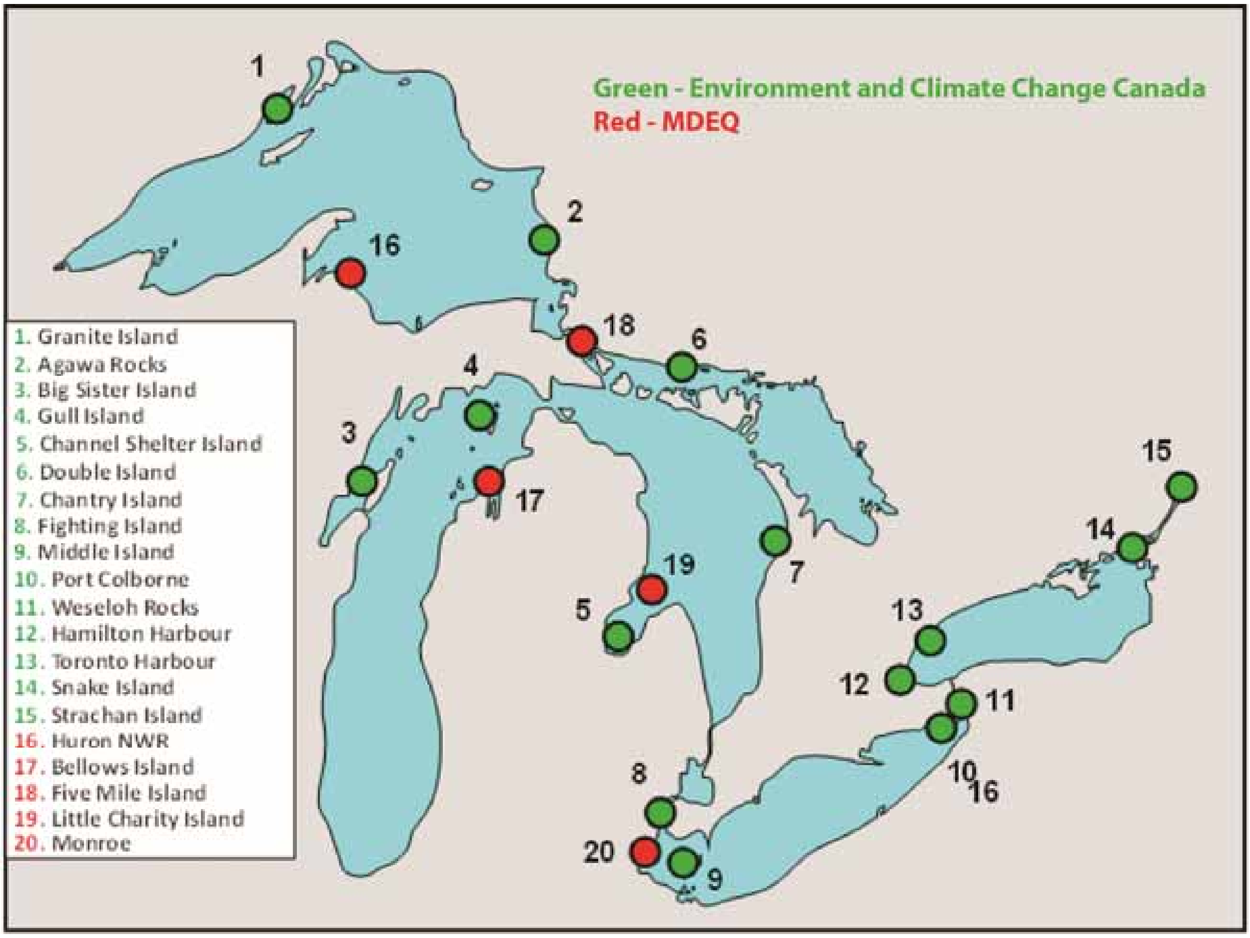

Figure 1. Herring Gull annual monitoring colonies in the Great Lakes and connecting channels, 1974-2013 for legacy compounds. Sites in green are the 15 colonies monitored annually by Environment and Climate Change Canada and Climate Change (Great Lakes Herring Gull Monitoring Program), and the sites in red are monitored periodically by the Michigan Department of Environmental Quality.
Source: de Solla et al. 2016; unpublished data

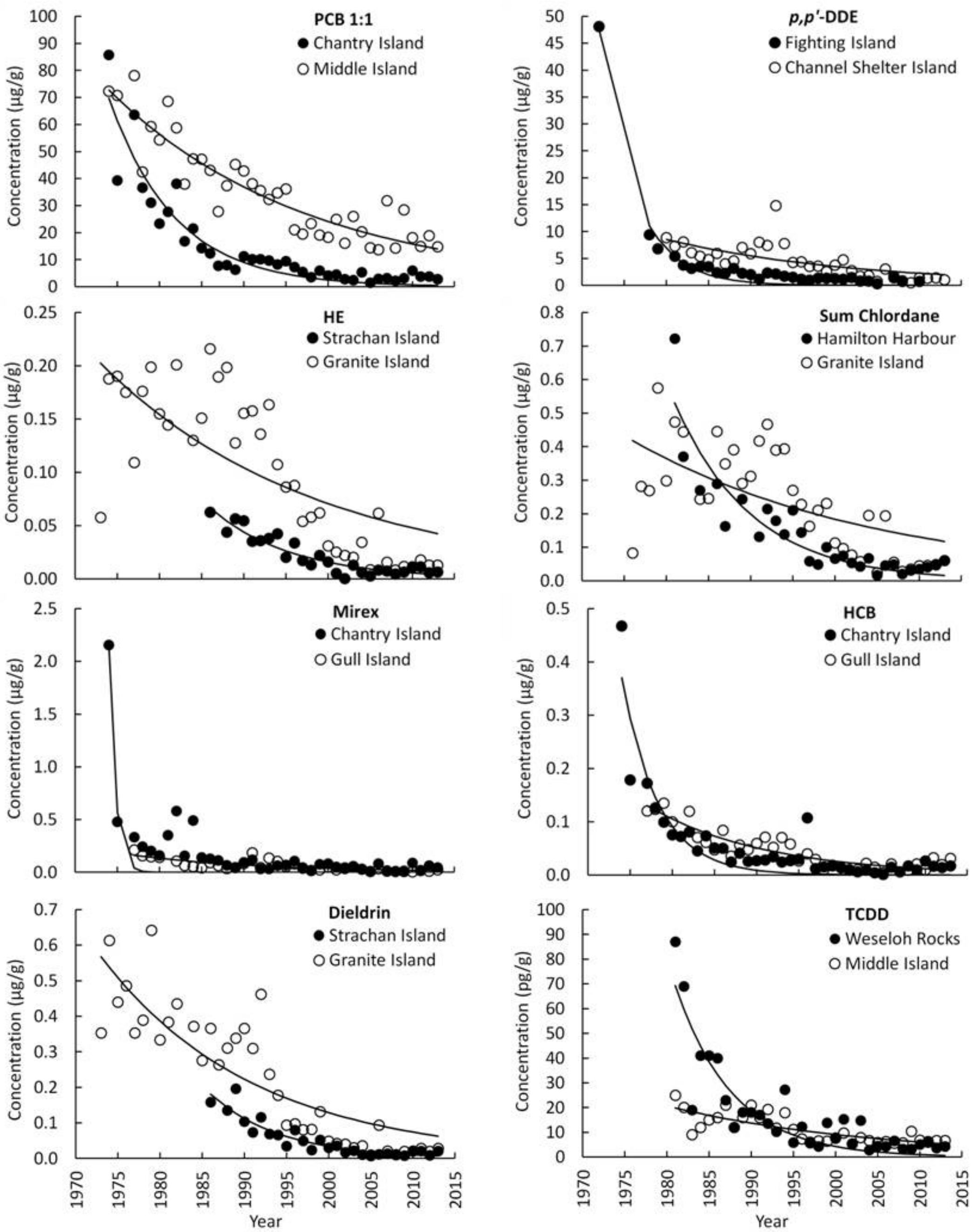

Figure 2. Temporal changes (exponential models) in concentrations of PCBs (Aroclor 1254:1260 1:1 equivalents) and six organochlorine pesticides (µg/g, wet weight) and 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) (pg/g, wet weight) in Herring Gull eggs from the Great Lakes, 1974-2013. For each compound, data were reported for the two colonies that had the highest (●) and lowest (□) decay constants.
Source: de Solla et al. in press; unpublished data

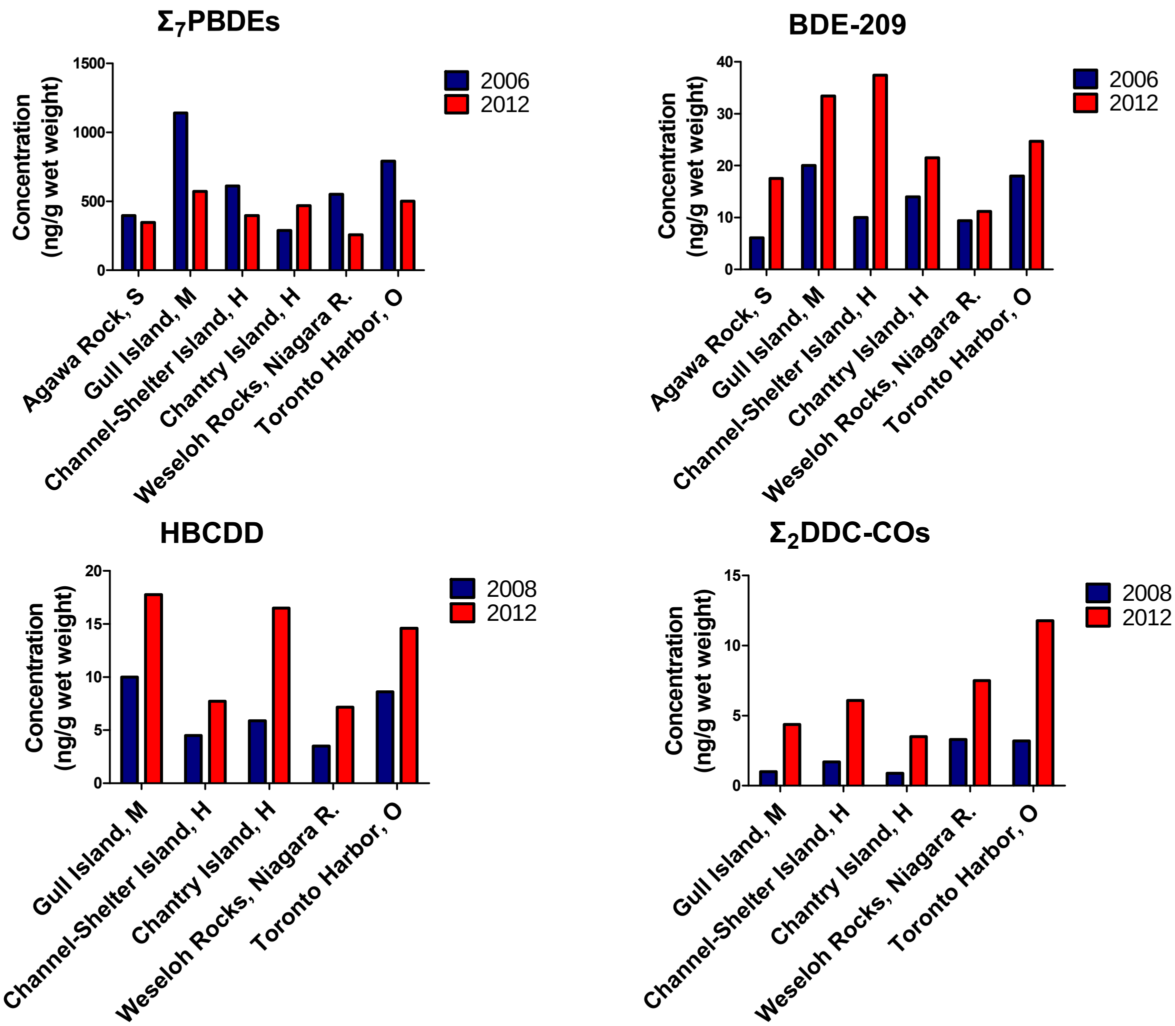

Figure 3. Time-point comparisons over six years of the arithmetic mean of the sum concentrations of SUM (Σ) 7PBDEs (BDE-28, -47, -100, -99, -154, -153 and -183), BDE-209, HBCDD and SUM (Σ) 2DDC-CO concentrations in herring gull egg pools collected in 2006, 2008 and 2012 from Agawa Rock (Lake Superior), Gull Island (Lake Michigan), Channel-Shelter Island (Lake Huron), Chantry Island (Lake Huron), Weseloh Rocks (Niagara River, above the falls) and Toronto Harbor (Lake Ontario).
Source: Su et al. 2015.

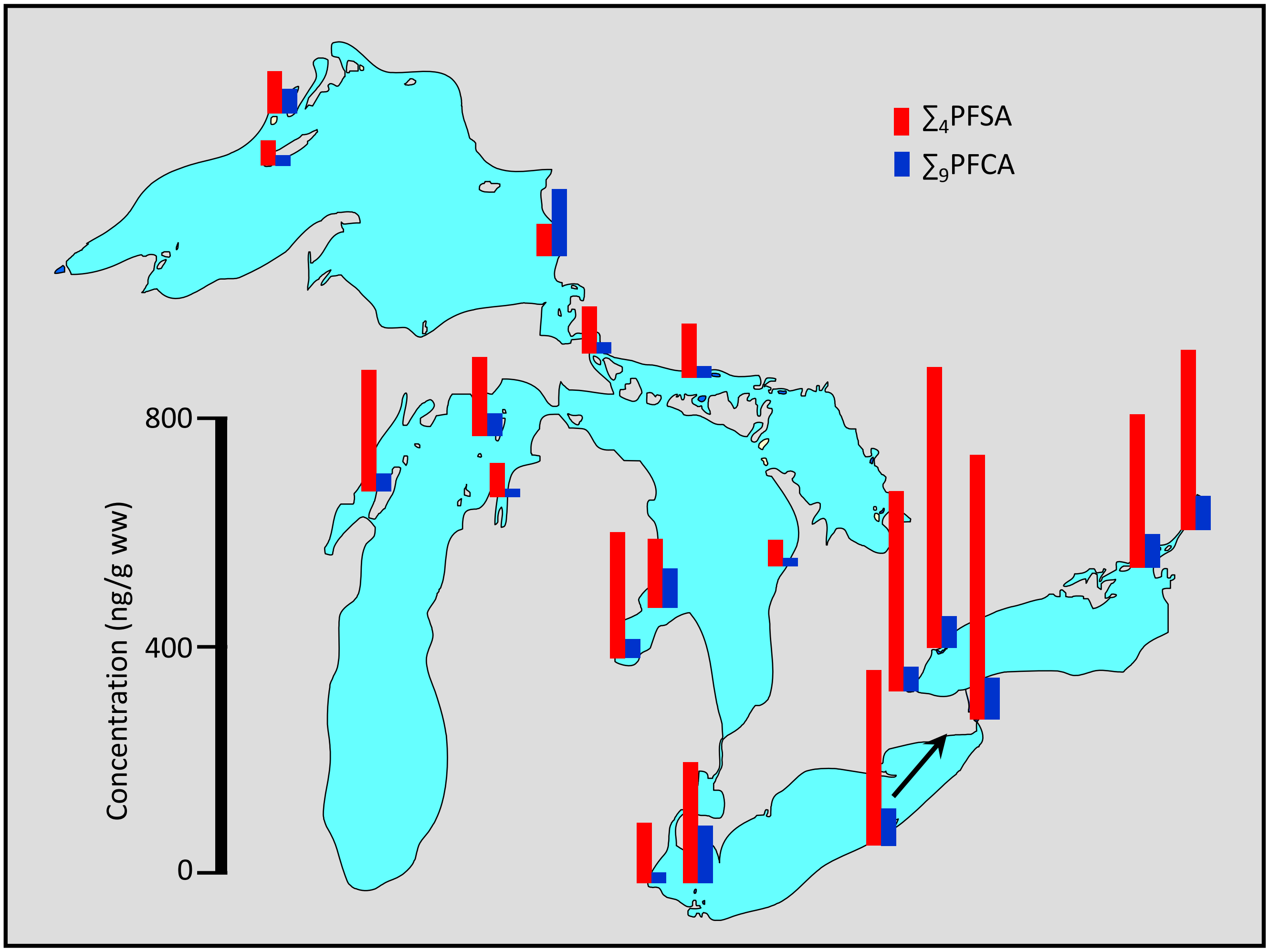

Figure 4. Arithmetic mean concentrations of SUM (Σ) 4 perfluorinated sulfonates (PFSAs) and SUM (Σ) 9 perfluorinated carboxylic acids (PFCAs) and sampling locations of herring gull eggs in the North American Great Lakes.
Burdens from fourteen colonies sampled by Environment and Climate Change Canada as part of the Great Lakes Herring Gull Monitoring Program (GLHGMP) and five Clean Michigan Initiative-Clean Water Fund (CMI-CWF) U.S. colonies are represented by bars for PFSAs and PFCAs.
Source: Source: Letcher et al. 2015.

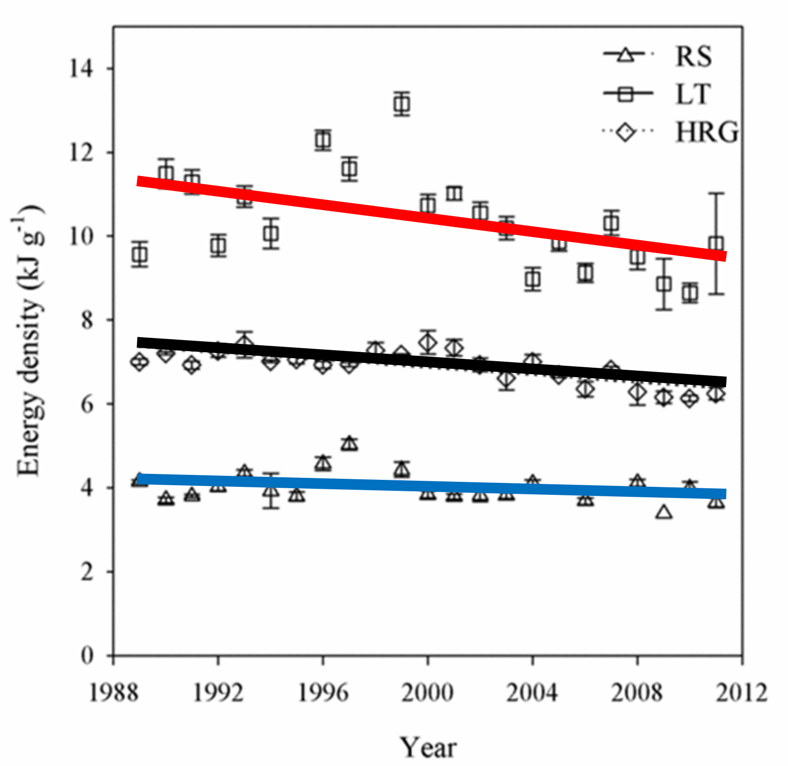

Figure 5. Time-point comparisons over six years of the arithmetic mean of the sum concentrations of SUM 7PBDEs (BDE-28, -47, -100, -99, -154, -153 and -183), BDE-209, HBCDD and SUM 2DDC-CO concentrations in herring gull egg pools collected in 2006, 2008 and 2012 from Agawa Rock (Lake Superior), Gull Island (Lake Michigan), Channel-Shelter Island (Lake Huron), Chantry Island (Lake Huron), Weseloh Rocks (Niagara River, above the falls) and Toronto Harbor (Lake Ontario). RS=Rainbow Smelt; LT=Lake Trout and HRG=Herring Gull Eggs
Source: Paterson et al. 2014.

Sub-Indicator: Atmospheric Deposition of Toxic Chemicals

Overall Assessment
Status: Fair
Trend: Improving
Rationale: Although levels of toxic chemicals in air are generally low, the large surface area of the Great Lakes results in significant atmospheric inputs (Eisenreich and Strachan 1992). While concentrations of some toxic chemicals are very low at rural sites, they are much higher in "hotspots" such as urban areas. Lake Michigan, Lake Erie, and Lake Ontario have greater inputs from urban areas. Eastern Lake Erie tends to show higher levels than at other remote sites, most likely since it is located closer to an urban area (Buffalo, NY) than the other master stations. It may also receive some influence from the East Coast of the U.S.

The overall trend for Atmospheric Deposition of Toxic Chemicals is improving for legacy chemicals, such as PCBs, although variations in trends were seen for different chemicals. Improving trends for PAHs, organochlorine pesticides, dioxins and furans; unchanging or slightly improving for mercury, PCBs, and PBDEs. Atmospheric deposition of toxic compounds to the Great Lakes is likely to continue into the future. The levels of compounds no longer in use, including many organochlorine pesticides, may decrease to undetectable levels. Atmospheric deposition of PCBs will continue for decades due to residual sources remaining worldwide. Slow or no decrease in concentrations of PAHs and metals may continue depending on further pollution reduction efforts or regulatory requirements. Although mercury and dioxin emissions have reduced over the past decade, elevated environmental levels are still observed.

Atmospheric deposition of chemicals of emerging concern, such as non-BDE flame retardants and other compounds that may currently be under the radar, could also serve as future stressors on the Great Lakes. Efforts are being made to screen for other chemicals of potential concern, with the intent of adding such chemicals to Great Lakes monitoring programs given available methods and sufficient resources.

Lake-by-Lake Assessment
Each lake was not specifically categorized for status and trend because of limited sample stations for each lake basin to allow for a lake-by-lake assessment. Site specific trends for many chemicals are available (Salamova et al. 2015). Calculated loadings for each lake, including trends over time, are also available (U.S. EPA and Environment Canada 2008 and Shunthirasingham et al. 2016).

Sub-Indicator Purpose
The purpose of this sub-indicator is to assess toxic chemicals in the atmosphere and precipitation in the Great Lakes region. The sub-indicator will infer potential impacts of toxic chemicals from atmospheric deposition on the Great Lakes aquatic ecosystem and progress toward virtual elimination of anthropogenic Chemicals of Mutual Concern (CMCs). The sub-indicator will also inform the risk assessment of potentially harmful chemicals and the development of risk management strategies for toxic substances, including the CMCs, persistent organic pollutants (POPs) and other harmful substances.

Ecosystem Objective
This sub-indicator is relevant to the General Objective #4 of the 2012 GLWQA that the waters of the Great Lakes "be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain." This sub-indicator is also relevant to Annex 3-Chemicals of Mutual Concern of the GLWQA, the purpose of which is to "reduce the anthropogenic release of chemicals of mutual concern, recognizing: (i) that chemicals of mutual concern released into the air, water, land, sediment, and biota should not result in impairment to the quality of the Waters of the Great Lakes; and (ii) the need to manage chemicals of mutual concern including, as appropriate, by implementing measures to achieve virtual elimination and zero discharge of these chemicals." The Annex 3 further calls for the Parties to (i) monitor and evaluate the progress and effectiveness of pollution prevention and control measures; (ii) exchange, on a regular basis, information on monitoring, surveillance…; (iii) identify and assess the occurrence, sources, transport, and impact of chemicals of mutual concern, including spatial and temporal trends in the atmosphere…; (iv) identify and

assess loadings … from the atmosphere; and (v) coordinating research, monitoring, and surveillance activities as a means to provide early warning for chemicals that could become chemicals of mutual concern.

Ecological Condition
The United States' Integrated Atmospheric Deposition Network (IADN) and Canada's Monitoring and Surveillance in the Great Lakes Basin (GLB) are the primary source of data for this sub-indicator report. IADN and GLB form a collaborative binational monitoring network that has been in operation since 1990, with five master monitoring stations, one near each of the Great Lakes, and several satellite stations (Figure 1). Since that time, over a million measurements of the concentrations of PCBs, pesticides, PAHs, flame retardants, and trace metals have been made at these sites. Concentrations of PBT chemicals are measured in the atmospheric gas and particle phases and in precipitation. Spatial and temporal trends of these concentrations and atmospheric loadings to the Great Lakes can be examined using these data. Data from other networks and surveillance studies are used here to supplement the IADN and GLB data, particularly for mercury, dioxins and furans.

PCBs
Atmospheric PCB concentrations are decreasing relatively slowly with halving times in the range of 9-40 years at Canadian sites (Shunthirasingham et al. 2016) and about 15 years at U.S. sites (Salamova et al. 2015); see Figure 2. There were no differences in the halving times of PCBs among the five U.S. sites and the three sites in Canada, suggesting a relatively homogeneous decrease rate in the Great Lakes region (Salamova et al. 2015; Shunthirasingham et al. 2016).

Although PCB production was banned in the early 1970s in North America, the slow decline in air concentrations can be attributed to volatilization from the lakes themselves (Khairy et al. 2015), from building sealants (Shanahan et al. 2015, and others), from drying sewage sludge (Shanahan et al. 2015, Yi et al. 2008), and from paints (Hu and Hornbuckle, 2010). In addition, there are continued emissions from older electrical and hydraulic equipment still in use and in the waste stream. Urban areas are believed to be the main sources of PCBs to rural regions (Buehler et al. 2001; Hafner and Hites 2003; Cleverly et al. 2007; Shunthirasingham et al. 2016).

Volatilization of PCBs from the lakes is also shown by an atmospheric loadings analysis (Shunthirasingham et al. 2016). The fluxes of total PCBs show increasing volatilization and decreasing gas absorption and wet deposition. Wet deposition constitutes a small portion of the fluxes. Wet deposition to Lakes Erie, Michigan, and Superior were not reported after 2006, and wet deposition to Lake Huron was not reported after 2008, due to precipitation concentrations reaching detection limits. Lake Erie continued to have absorbance fluxes significantly higher than for the other lakes, which may be due to influences from upstate New York and the East Coast (Hafner and Hites 2003).

Organochlorine Pesticides (OCPs)
Concentrations of OCPs that have been banned are generally declining in air in the Great Lakes Basin. Chlordanes, dieldrin, and DDT-related substances show halving times in the range of 7-13 years (Salamova et al. 2015). Concentrations of α-HCH and γ-HCH are decreasing rapidly in air, with halving times of 5 years at Canadian sites (Shunthirasingham et al. 2016) and about 4 years at U.S. sites (Salamova et al. 2015); see Figure 3. These are the most rapid halving times observed for any compound measured as part of IADN/GLB.

The insecticides, α-endosulfan and β-endosulfan, are still on the market, but they are slated for complete elimination in 2016. Even though endosulfan is currently in use, it is interesting that its vapour phase atmospheric concentrations around the Great Lakes are decreasing with halving times ranging from 7 to 13 years (Salamova et al. 2015, Shunthirasingham et al. 2016) (Figure 4). Based on estimated use rates of endosulfan in the U.S. from 1997 to 2009, Salamova et al. 2015, estimates that endosulfan has an atmospheric chemical degradation rate of about 4 years – which suggests that endosulfan is less persistent in the environment than related compounds.

The satellite station of Egbert, located between Lakes Ontario and Huron and surrounded by agricultural cropland, showed high concentrations of dichlorodiphenyltrichloroethanes (DDTs), dieldrin, γ-HCH (lindane), and endosulfan compared to the more remote master stations on Lakes Huron and Ontario. This observation was attributed to historical (DDTs, lindane, and dieldrin) and current (endosulfan) agricultural applications of these OCPs in the area. These observations suggest that agricultural areas are a source of OCPs to the lakes (Shunthirasingham et al. 2016). Isomer-specific data provide insights on the temporal trends and possible sources of specific compounds. The relative proportion of *o,p'*-DDT to *p,p'*-DDT in air has increased significantly at five U.S. sites and 2 Canadian sites over the last two decades (see Figure 5). It is suggested that dicofol (a pesticide manufactured from DDT), which has higher *o,p'*-/*p,p'*-DDT ratios than technical DDT, may now be a significant, additional source of DDT to the Great Lakes (Venier and Hites 2014; Shunthirasingham et al. 2016). The average ratio of the concentration of γ-HCH (lindane) versus the sum of the concentrations of γ-HCH + α-HCH did not vary significantly with time, but it did show an urban signature, suggesting that cities may be more important sources of these compounds than previously suspected.

Loadings calculations up to 2010 suggest that the atmosphere is a source of endosulfan and *p,p'*-DDT to the lakes and that the lakes are a source of *p,p'*-DDE to the atmosphere (Shunthirasingham et al. 2016).

Flame Retardants

The concentrations of halogenated flame retardants have been measured in IADN/GLB samples since January 2005. Specifically, the atmospheric concentrations of polybrominated diphenyl ethers (PBDEs) and eight alternative halogenated flame retardants [pentabromoethyl benzene (PBEB), hexabromobenzene (HBB), 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (TBB), *bis*(2-ethylhexyl)-tetrabromophthalate (TBPH), *syn*-Dechlorane Plus (*syn*-DP), *anti*-Dechlorane Plus (*anti*-DP), 1,2-*bis*(2,4,6-tribromophenoxy)ethane (TBE), and decabromodiphenylethane (DBDPE)] were measured in each IADN sample. The levels of almost all of these flame retardants, except for PBEB, HBB, and DP, were significantly higher in Chicago, Cleveland, and Sturgeon Point. The concentrations of PBEB and HBB were relatively high at Eagle Harbor and Sturgeon Point, respectively, for unknown reasons, and the concentrations of DP were relatively high at Cleveland and Sturgeon Point, the two sites closest to this compound's production site in Niagara Falls, New York.

These data were analyzed using a multiple linear regression model to determine significant temporal trends in these atmospheric concentrations, and some of these data are shown in Figure 6 (Liu et al. 2016). The concentrations of PBDEs were decreasing at the urban sites at Chicago and Cleveland, but were generally unchanging at the remote sites, Sleeping Bear Dunes and Eagle Harbor. GLB data showed declining trends for BDE-47 and BDE-99 at the master stations on Lakes Ontario and Huron. A faster decline was observed at the Lake Ontario station of Point Petre (halving times of 3-6 years) which is closer to urban development, probably reflecting the replacement of these substances in cities (UNEP 2015). A passive air and water sampling study in Lake Superior in 2011 showed that atmospheric (gaseous) and dissolved PBDEs, in particular BDE-47, were greatest near urban and populated sites (Ruge et al. 2015). Net gaseous deposition of BDE-47 was observed at coastal sites, while the central open lake and at Lake Superior's master station of Eagle Harbor generally displayed volatilization of PBDEs into the atmosphere, mainly of BDE-47.

The concentrations of PBEB were decreasing at almost all sites except for Eagle Harbor, where the highest PBEB levels were observed. HBB concentrations were decreasing at all sites except for Sturgeon Point, where HBB levels were highest. The reason for the relatively high levels of PBEB and HBB at Eagle Harbor and Sturgeon Point are not clear. DP concentrations were increasing with doubling times of 3-9 years at all sites except Cleveland and Sturgeon Point, where the concentrations were largely unchanged (Figure 7).

EHTBB and BEHTBP are the two main components of FireMaster 550, which is a replacement for the penta-BDE commercial mixture. IADN began to include EHTBB and BEHTBP in the analyses of samples collected starting in 2008. Because EHTBB and BEHTBP together are the major components of FireMaster 550, their concentrations were summed (notated here as EHTBB+BEHTBP), and this sum was regressed as a function of time. The atmospheric EHTBB+BEHTBP concentrations were also significantly and rapidly increasing at all the five sites, with doubling times of 2–5 years (Figure 7).

At the Canadian station of Point Petre, ally-2,4,6-tribromophenyl ether (ATE) and HBB air concentrations peaked in the summer months similar to the PBDEs. However, this seasonal pattern was not apparent at the more remote site of Burnt Island in most years. Statistically significant correlation between the natural logarithm of the air concentrations (ln C) of ATE and inverse temperatures [1/T(K)] was observed at Point Petre ($p<0.01$) but not at Burnt Island. For HBB, the correlation of ln C vs. 1/T were statistically significant at both sites ($p<0.01$) but the slope was much steeper at Point Petre than at Burnt Island. These observations imply significant volatilization of these compounds in the vicinity of Point Petre, which is close to urban centres, while atmospheric transport to Burnt Island, which is more remote, is of importance (Hung et al. 2016). DPs, which were found mostly in the particle phase, showed no temperature dependence at either site. No apparent change in air concentrations were observed for anti- and syn-DP at both Burnt Island and Point Petre between 2008 and 2013. Slight declining tendency was observed for ATE and HBB at Point Petre, but not at Burnt Island.

Polycyclic Aromatic Hydrocarbons (PAH)

IADN data for total PAH concentrations in air (see Figure 8) show some significant decreases over time, with halving times ranging from 7 to 24 years (Salamova et al. 2015). PAH levels at Chicago and Cleveland are 10 times higher than the concentrations at the other IADN sites. However, the concentrations are also decreasing most rapidly at these stations. These declines can probably be attributed to emission reductions from the implementation of the Clean Air Act. PAH concentrations are also decreasing at Eagle Harbor, the most remote IADN site in the U.S.

Concentrations of phenanthrene are decreasing at about the same rate as total PAH except at Sleeping Bear Dunes and Point Petre, where no significant decreases were observed (Salamova et al. 2015). Significant decreasing rates for benzo[*a*]pyrene were detected only at Chicago and Sturgeon Point, and the halving time at Chicago was about half that at Sturgeon Point (Salamova et al. 2015).

A passive air and water sampling study in Lake Superior in 2011 showed that surface water and atmospheric PAH concentrations were greatest at urban sites (Ruge et al. 2015). Net air-to-water deposition of PAHs was observed near populated areas, but deposition is near equilibrium off shore (Ruge et al. 2015). A similar study conducted in the lower Great Lakes using polyethylene passive samplers in air and water demonstrated that gaseous PAH concentrations were strongly correlated with population within 40 km of the sampling locations (McDonough et al. 2014). Source profiles differed for atmospheric and aqueous PAHs indicating that in addition to atmospheric deposition, runoff and sediment-water exchange contributed to dissolved concentrations.

Loadings calculations for the five lakes showed that the atmosphere is a source of PAHs to the lakes. Wet and dry deposition fluxes were dominant for higher molecular weight PAH, especially wet deposition, whereas absorbance fluxes were dominant for phenanthrene and pyrene. Greater deposition fluxes were observed in the winter, consistent with increased combustion during colder months for space heating purposes (GLB, unpublished). Lake Erie consistently showed the highest fluxes for PAHs; however, absorbance fluxes for phenanthrene and pyrene have declined by more than a factor of 3 from 1992 to 2010.

Dioxins and Furans (PCDD/Fs)

Areas with higher population generally showed higher annual mean air concentrations of PCDD/Fs in North America (CEC 2014; Venier et al. 2009; Cleverly et al. 2007). Air concentration measurements under Canada's National Air Pollution Surveillance (NAPS) reported high toxic equivalency (TEQs) in air at the Walpole Island site (in Lake St. Clair) and the Windsor/University Ave. sites (Windsor, ON), where profiles were characterized by a lower contribution of octachlorodibenzo-*p*-dioxin and an increased contribution of dibenzofurans. This profile might indicate the impact of a local emission source (CEC 2014). PCDD/F levels at rural, suburban, and urban NAPS sites (including sites in the Great Lakes Basin) declined after the early 1990s and in the early 2000s. This decline can be attributed to control measures taken in Canada with respect to PCDD/F emission sources. After the year 2005, a clear trend is not evident (CEC 2014).

Trace Metals

Wet and particle deposition of arsenic, cadmium, lead, and selenium were estimated at the Lake Huron and Ontario GLB master stations up to 2010 (GLB, unpublished). No apparent upward or downward trends for the fluxes of these metals aside from selenium and lead. Wet deposition is more important than particle deposition of selenium to the lakes. However, particle deposition fluxes have increased over time for both Lake Huron and Ontario (see Figure 9). Wet deposition also dominates atmospheric fluxes of lead to the lakes, but fluxes have apparently declined over the years reflecting results of risk management measures to reduce the emission of lead.

Mercury

Atmospheric mercury concentrations (Hg^0) and mercury wet deposition (Hg^{II}) fluxes have generally declined since the 1990s (Zhang et al. 2016). Atmospheric Hg^0 concentrations have decreased about 2% per year since 2005 as measured in Canada's Experimental Lakes Area (west of Lake Superior). Wet deposition measurements from the North American Mercury Deposition Network follow these trends with fluxes decreasing about 1.6% per year since 1996. Zhang et al. (2016) suggest that reduced emissions from utilities over the past few decades and the phase-out of mercury in many commercial products has led to lower global anthropogenic emissions and associated deposition to ecosystems.

Lepak et al. (2015) used stable isotope signatures to determine sources of mercury in Great Lakes sediment and predatory fish. They found that atmospheric sources dominate in Lakes Huron, Superior, and Michigan sediments while watershed-derived and industrial sources dominate in Lakes Erie and Ontario sediments. However, isotope signatures in predatory fish, such as Δ^{200}Hg, which is conserved during biogeochemical processing in Lakes Ontario, Superior and Michigan, showed that bioaccumulated mercury is more isotopically similar to atmospherically derived mercury than a lake's sediment. This finding suggests that atmospherically derived Hg may be a more important source of methyl mercury, which is a more toxic form that is biomagnified in aquatic food webs, to higher trophic levels than sediments in the Great Lakes.

Linkages

Atmospheric deposition is a significant route by which persistent, bioaccumulative and toxic (PBT) chemicals, such as PCBs, currently enter the Great Lakes. Increases in the concentration and loadings of atmospheric chemicals of concern, including PBTs, may result in increased contamination in sediment, toxic chemicals in offshore waters, and contaminants in whole fish and waterbirds. Bioaccumulation of these PBTs in fish may result in fish consumption advisories.

Comments from the Author(s)

Many remaining sources of PCBs are located in urban areas, which is reflected by the higher levels of PCBs measured in Chicago and Cleveland by IADN, and by other researchers in other areas (Wethington and Hornbuckle 2005; Totten et al. 2001). Research to investigate the significance of these remaining sources is underway (Shanahan et al. 2015). This is important because fish consumption advisories for PCBs exist for all five Great Lakes.

The agricultural chemical lindane was recently phased out in the U.S. and Canada, and endosulfans are scheduled to be phased out in the U.S. and Canada by 2016 (Federal Register, 2010; Health Canada Pest Management Regulatory Agency, 2011).

Residential garbage burning (burn barrels) is now the largest current source of dioxins and furans (Environment Canada and U.S. Environmental Protection Agency 2006). Basin and nationwide efforts are underway to eliminate emissions from burn barrels.

World-wide, the largest remaining source of mercury emissions to the atmosphere is coal-fired power plants. Regionally, many sources are reducing emissions. For instance, all coal-fired power plants in Ontario have ceased operation as of April 2014, being the first jurisdiction in North America to fully eliminate coal for producing electricity (Ontario Ministry of Energy, 2014).

Continued long-term monitoring of the atmosphere is necessary in order to measure progress brought about by toxic reduction efforts. Environment and Climate Change Canada and U.S. EPA recently added routine monitoring of PBDEs and some non-PBDE flame retardants to the IADN and GLB programs. Screening and method development for additional non-PBDE flame retardants and per- and polyfluoroalkyl substances (PFASs) is currently under way. Results from these monitoring efforts on emerging chemicals of concern will contribute to the scientific information needed for the risk assessment and identification of additional Chemicals of Mutual Concern (CMC).

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				

5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				

Acknowledgments

Authors: This report was prepared on behalf of the IADN Steering Committee by Todd Nettesheim, IADN Program Manager, U.S. Environmental Protection Agency, Great Lakes National Program Office; Hayley Hung, Air Monitoring in the Great Lakes Basin (GLB) Principal Investigator under the Chemicals Management Plan, Air Quality Processes Research Section, Environment and Climate Change Canada; and Ron Hites, Marta Venier, and Amina Salamova, Indiana University.

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IADN and GLB Data: http://data.gc.ca/data/en/dataset/531d6054-4179-4883-8022-1175cdfb6911, or contact Helena Dryfhout-Clark, IADN/GLB Data Manager, Air Quality Processes Research Section, Environment and Climate Change Canada, 6248 Eighth Line, Egbert (Ontario) L0L 1N0, Helena.Dryfhout-Clark@canada.ca, 705 458-3316

Link to IADN websites: http://www.ec.gc.ca/rs-mn/, and http://epa.gov/greatlakes/monitoring/air2/index.html

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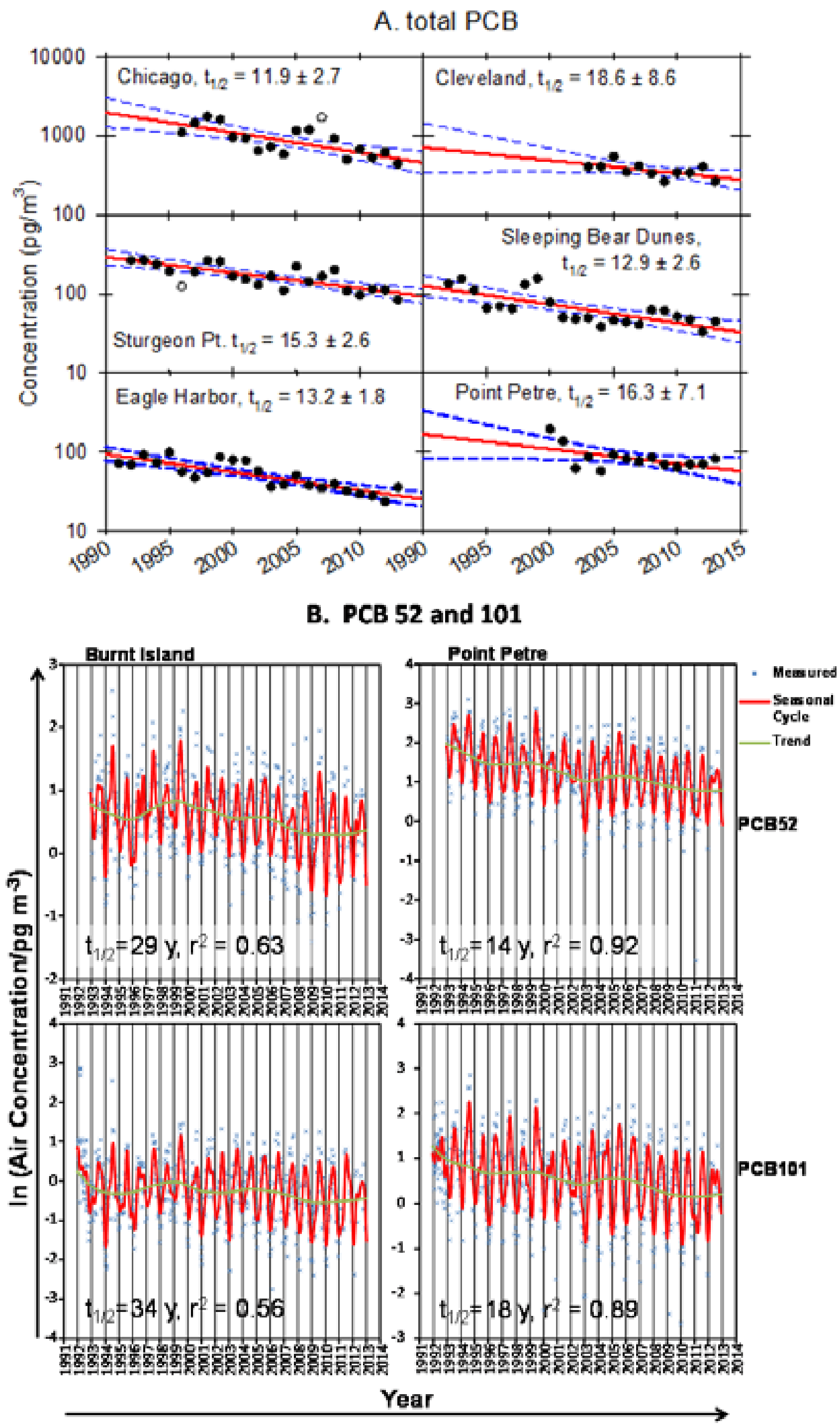

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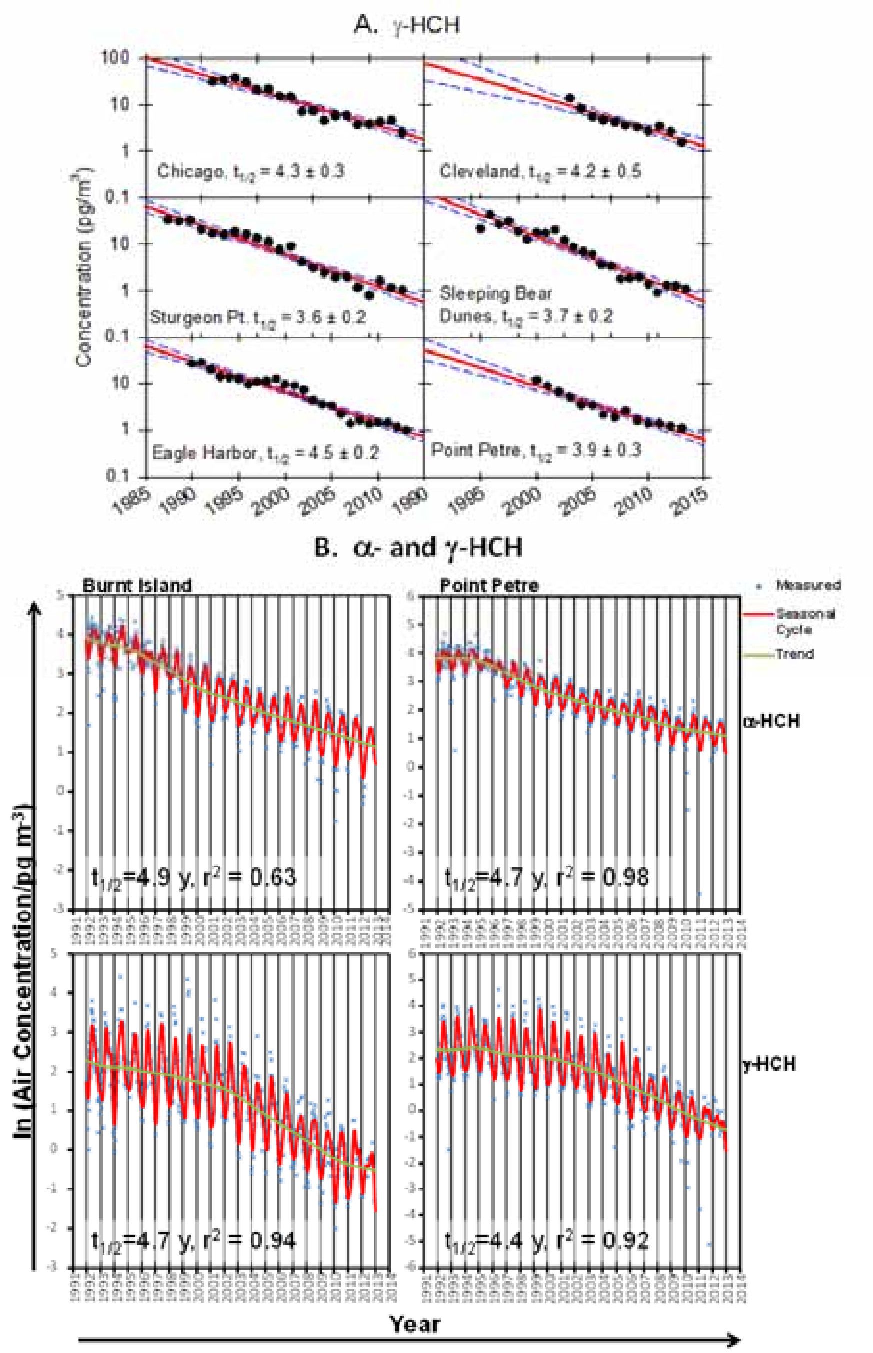

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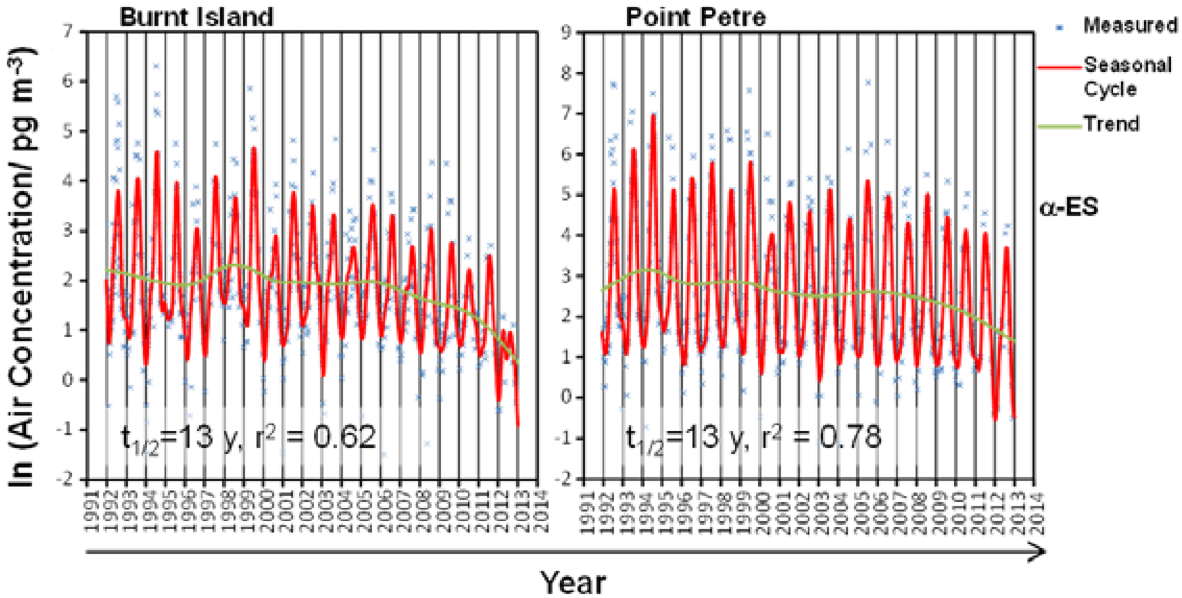

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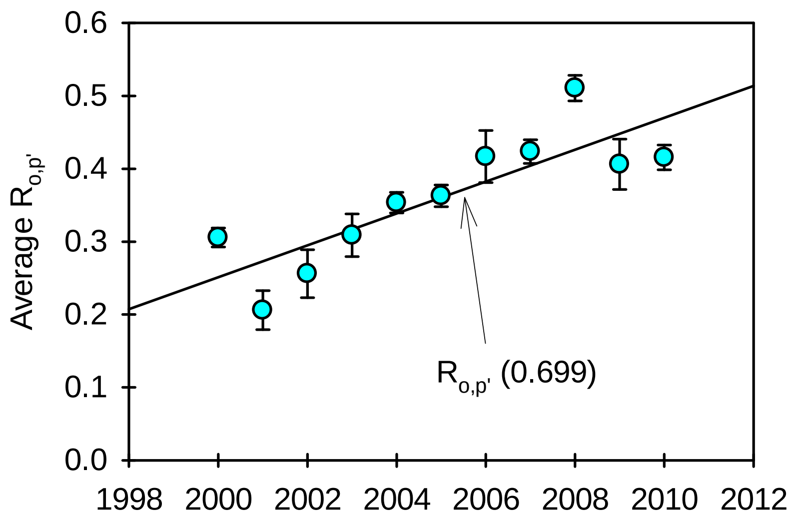

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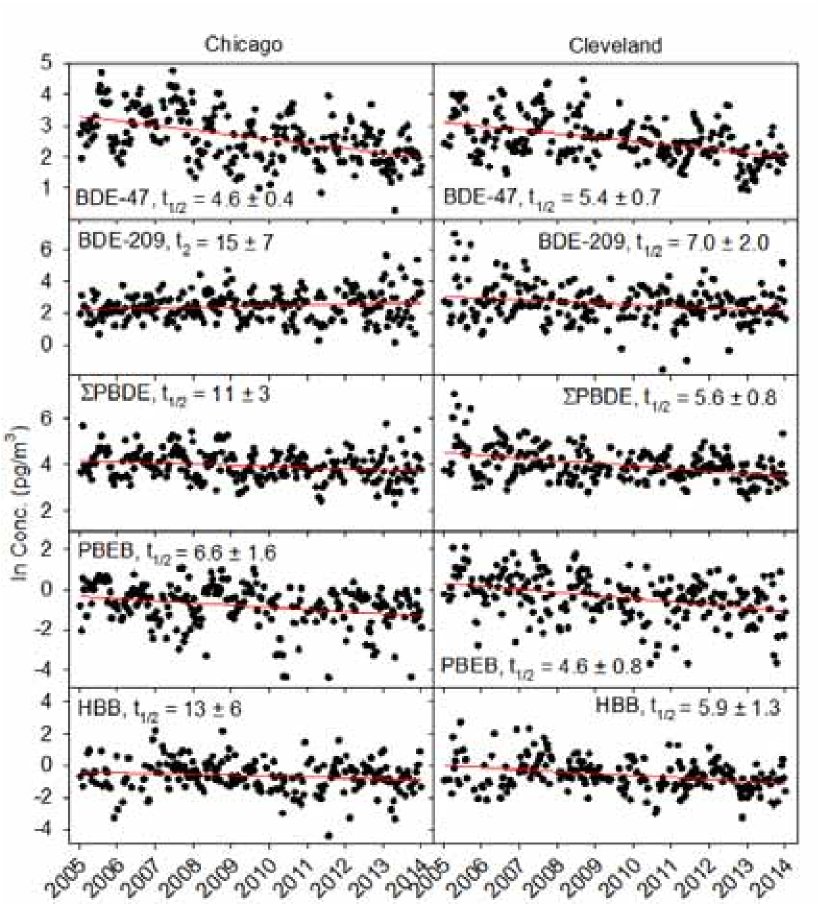

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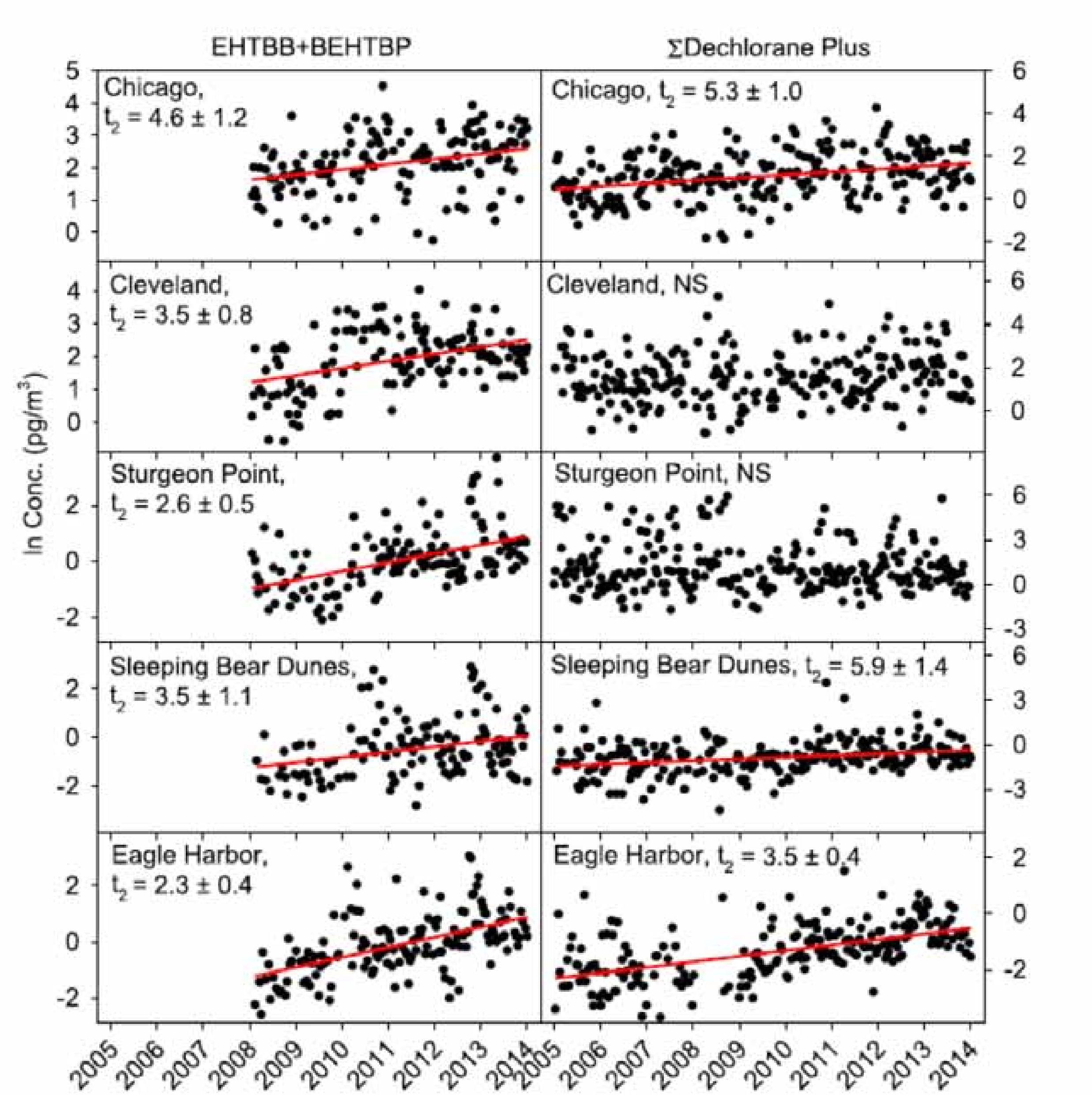
Source: Liu et al. submitted



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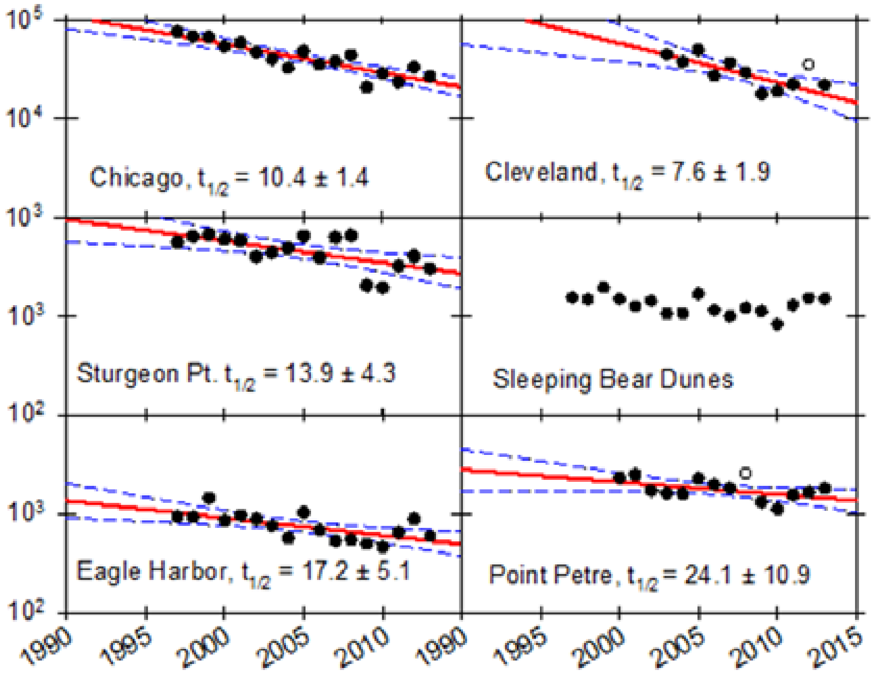

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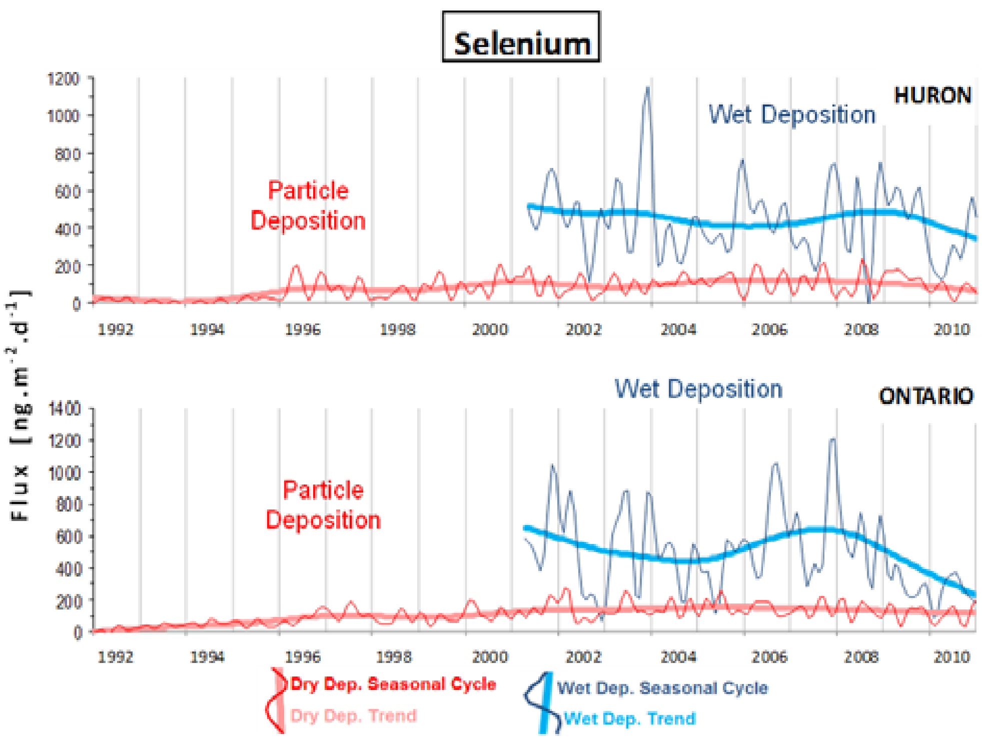

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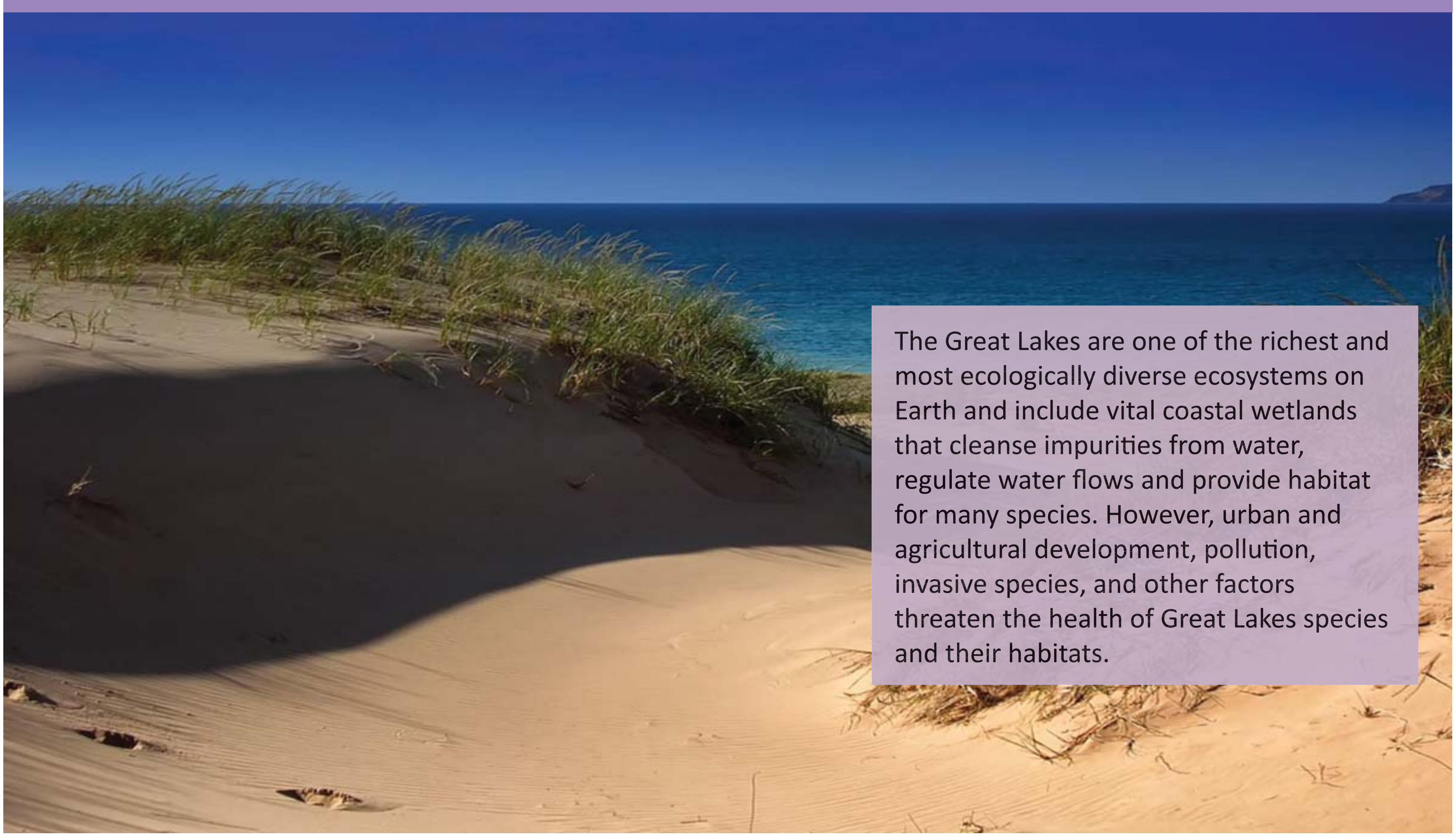
Habitat and Species

Status: Fair   Trend: Unchanging

The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should support healthy and productive wetlands and other habitats to sustain resilient populations of native species"*



The Great Lakes are one of the richest and most ecologically diverse ecosystems on Earth and include vital coastal wetlands that cleanse impurities from water, regulate water flows and provide habitat for many species. However, urban and agricultural development, pollution, invasive species, and other factors threaten the health of Great Lakes species and their habitats.

Habitat and Species

Assessment Highlights

The Habitat and Species indicator is used to assess habitats, such as wetlands, along with the species that reside in these areas. The Habitat and Species indicator shows that across the basin, the status is quite variable, ranging from good to poor and improving to deteriorating, depending on the lake basin and habitat or species of interest. The health of various species in the Great Lakes is also reflective of the availability and condition of the habitat that they dwell in and need. Overall, the Habitat and Species indicator is assessed as **Fair** and **Unchanging**.

Coastal Wetlands

Despite the fact that coastal wetland restoration and protection efforts have improved specific areas, wetlands continue to be lost and degraded. Efforts to better track and determine the extent and rate of this loss are currently underway. In the southern lakes region, almost all coastal wetlands are degraded by nutrient enrichment, sedimentation, or a combination of both. In Lake Ontario, water-level regulation also limits natural variation in wetlands, though work is underway to address this situation. A more recent concern in the southern lakes region and Lake Huron is the expansion of the invasive Frog-bit, a floating plant that forms dense mats capable of eliminating native submergent plants in coastal wetlands. Of similar concern, the invasive Water Chestnut is expanding rapidly in Lake Ontario.

Coastal wetland habitats in some regions of the Great Lakes, in particular in the northern parts, are intact and show fewer signs of impairment. Across the basin, improvements have also been seen in the diversity of coastal wetland fish species with recent data showing an average of 10 to 13 species per coastal wetland, with some wetlands having as many as 28. Although many invertebrates, birds and plants have experienced long-term declines, some birds and amphibians are showing a more recent unchanging trend. These stable populations may be preliminary indications of some progress in the rehabilitation and restoration of coastal wetlands.




Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Coastal Wetland Amphibians	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging
Coastal Wetland Birds	Unchanging	Unchanging	Unchanging	Deteriorating	Improving
Coastal Wetland Fish	No lake was assessed separately Great Lakes Basin assessment is **Fair** and **Improving**				
Coastal Wetland Invertebrates	No lake was assessed separately Great Lakes Basin assessment is **Fair** and **Deteriorating**				
Coastal Wetland Plants	Undetermined	Undetermined	Deteriorating	Deteriorating	Unchanging
Coastal Wetlands: Extent and Composition	No lake was assessed separately Great Lakes Basin assessment is **Undetermined**				
Aquatic Habitat Connectivity	Improving	Improving	Improving	Improving	Improving

Status:	GOOD	FAIR	POOR	UNDETERMINED

Habitat and Species

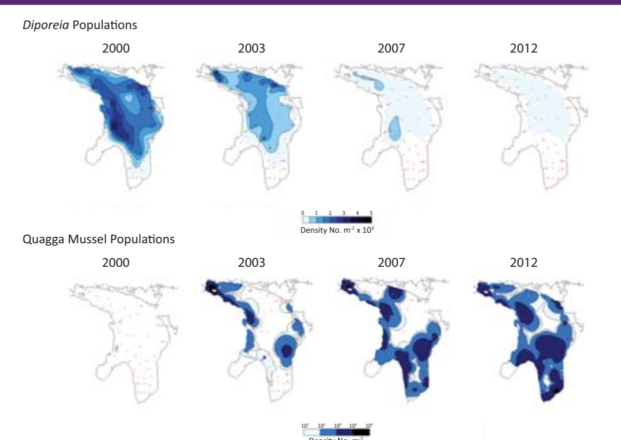
Aquatic Food Web

The Great Lakes aquatic food web is made of many important species, ranging from tiny plants and animals (phytoplankton and zooplankton) to top predator fish. Zooplankton communities in all lakes except Lake Huron are generally in good condition, although changes in quantity, density and type are occurring in Lakes Michigan and Ontario. Changes that are occurring in zooplankton communities are consistent with decreasing nutrient concentrations in offshore waters. Low nutrients levels result in a loss of algae for zooplankton to feed on. Also, *Diporeia*, a small bottom-dwelling shrimp-like species and an important source of food for fish, has severely declined in all the lakes except Lake Superior. The invasive dreissenid mussels (specifically Zebra and Quagga Mussels) have likely compounded this problem. Dreissenid mussels graze on phytoplankton and small zooplankton as well as filter and store nutrients which can prevent the movement of nutrients into the open waters of the lake. The situation is complex and the exact mechanisms causing these changes in *Diporeia* and zooplankton have yet to be fully determined.

Zooplankton and phytoplankton communities are the main source of food for prey fish and are essential to sustaining a healthy food web. Prey fish communities across the Great Lakes continue to change, although the direction and magnitude of those changes vary. The prey fish community is considered fair overall based on the diversity and the proportion of native prey fish species in the Great Lakes despite fluctuations in population levels. The abundance of prey fish is influenced by food availability and the abundance of predator fish, such as Lake Trout and Walleye, which eat prey fish to survive. A balance between the numbers of top predator fish and the available prey fish in the lakes is important.

The status of populations of native predator fish, such as Walleye and Lake Trout, is variable; however, populations of these fish are improving in some cases. Lake Trout populations, for example, are improving in some areas of the Great Lakes with support from stocking and rehabilitation efforts. In fact, natural reproducing populations of Lake Trout are now routinely detected in southwestern Lake Michigan, and wild Lake Trout make up over 50% of the population in Lake Huron. While changes in Lake Sturgeon status will take a long time to manifest, activities such as habitat improvements, dam removals, and stocking efforts indicate an improving trend for this species.

***Diporeia* Are Declining - Quagga Mussels are Increasing**



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Phytoplankton	Unchanging	Deteriorating	Deteriorating	Deteriorating	Unchanging
Zooplankton	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging
Benthos	Unchanging	Unchanging	Unchanging	Deteriorating	Unchanging
Diporeia	Unchanging	Deteriorating	Deteriorating	Deteriorating	Deteriorating
Prey fish	Unchanging	Deteriorating	Undetermined	Improving	Deteriorating
Lake Sturgeon	Improving	Improving	Improving	Improving	Improving
Walleye	Unchanging	Unchanging	Unchanging	Improving	Unchanging
Lake Trout	Unchanging	Improving	Improving	Improving	Improving
Fish Eating and Colonial Nesting Waterbirds	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Coastal Wetland Amphibians

Overall Assessment
Status: Poor
Trend: Unchanging
Rationale: Mean index of ecological condition (IEC), an objective biotic indicator summarizing standardized observations of breeding frogs (i.e., frogs and toads, Order Anura) in coastal wetlands was 5.6 (out of 10) in 2014 and did not significantly increase or decrease from 1995-2014 or from 2011-2014.

Lake-by-Lake Assessment
Lake Superior
Status: Fair
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 5.9 in 2014 and did not significantly increase or decrease from 2002-2014 or from 2011-2014.

Lake Michigan
Status: Poor
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 5.4 in 2014 and did not significantly increase or decrease from 2002-2014 or from 2011-2014.

Lake Huron
Status: Fair
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 5.9 in 2014 and did not significantly increase or decrease from 2002-2014 or from 2011-2014.

Lake Erie
Status: Poor
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 5.4 in 2014 and did not significantly increase or decrease from 1995-2014 or from 2011-2014.

Lake Ontario
Status: Poor
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 5.6 in 2014 and did not significantly increase or decrease from 1995-2014 or from 2011-2014.

Other Spatial Scales
Inland
Status and trend based on IECs were also calculated for inland wetlands for comparison with coastal wetlands. Results were similar to those for coastal wetlands.

Separate assessments for the connecting channels of the Great Lakes were not completed. Information for the channels is included with the adjacent down-stream lake, as shown on the maps of sample points.

Sub-Indicator Purpose
- To directly measure the species composition, diversity, and relative abundance of frogs over time, and to indirectly measure the condition of coastal wetland habitat as it relates to the health of this ecologically important component of wetland communities. To restore/maintain the overall biological integrity of Great Lakes coastal wetlands, various ecological components including coastal wetland amphibian communities need to be addressed.

Ecosystem Objective

Coastal wetlands provide critical habitat for various life stages of many wildlife species including amphibians. Conservation of remaining coastal wetlands and restoration of previously degraded or destroyed wetlands are vital components of restoring the Great Lakes ecosystem, and this sub-indicator can be used to report progress toward such an objective.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition

Background

Wetland breeding frogs are influenced by the physical, chemical, and biological components of wetlands and surrounding landscapes. For example, the occurrence and/or reproductive success of multiple species in the Great Lakes Basin declines as (1) wetland size decreases; (2) wetland habitat and natural cover in the surrounding landscape decreases or degrades in quality; and (3) pollution from pesticide, herbicide, and sediment runoff increases (Hecnar 1995; Hecnar and M'Closkey 1996, 1998; Bishop et al. 1999; Crosbie and Chow Fraser 1999; Kolozsvary and Swihart 1999; Houlahan and Findlay 2003; Price et al. 2004; Brazner et al. 2007a, 2007b; Gagné and Fahrig 2007; Eigenbrod et al. 2008a, 2008b). Thus, the occurrence or abundance of sensitive wetland breeding frogs can be a valuable indicator of the health of wetlands and the surrounding landscape.

Measures

Study design—Several initiatives monitor Great Lakes wetland breeding frogs. One of the longest running is Bird Studies Canada's Great Lakes Marsh Monitoring Program (GLMMP), which started in 1995 and has operated every year since then at coastal and inland wetlands throughout much of the Great Lakes Basin (Tozer 2013). Previous reports for this sub-indicator are based solely on data from this ongoing broad scale program (e.g., Tozer 2014). From 2001-2005, the University of Minnesota Duluth's Natural Resource Research Institute (NRRI) led an ambitious multi-institutional Great Lakes Environmental Indicator project (GLEI) aimed at assessing the overall biotic health of coastal wetlands in the U.S. portion of the Great Lakes (Howe et al. 2007a, 2007b; Hanowski et al. 2007a, 2007b). More recently, the Great Lakes Coastal Wetland Monitoring Program (CWMP) led by Central Michigan University was initiated in 2011 and currently is scheduled to operate until at least 2020 throughout both the U.S. and Canadian Great Lakes coastal zones (Cooper et al. 2014). These projects have somewhat different study designs but rely on standardized, fixed duration point counts that can be adjusted to maximize cross-project compatibility. To garner large numbers of trained volunteer participants to achieve large sample sizes at relatively low cost, the GLMMP allows participants to select sample points—a justifiable approach if one assumes that the sample points are approximately representative of wetlands across a region of interest. By contrast, the GLEI and CWMP projects select sample points via stratified random sampling of coastal wetlands and survey wetlands via paid professional staff. Nonetheless, all of the projects target wetlands dominated by non-woody emergent plants such as cattails (*Typha* spp.) and sedges (e.g., *Carex* spp.) with sample points located within wetlands. In this report datasets listed above were brought together for the first time to generate the most comprehensive analysis of the status and trend of Great Lakes coastal wetland breeding frogs and associated wetland health.

Frog surveys—Breeding frogs were sampled to an unlimited distance from a point located near the upland / wetland interface (shoreline) of a wetland (hereafter "sample point"). Each sample point was surveyed for 3 minutes on three visits separated by at least 10 or 15 days during the main frog breeding season, typically between late March and early July. Surveys occurred at night starting at least 0.5 hr after local sunset and only under weather conditions that were favourable for detecting all species present (no persistent or heavy precipitation; wind: Beaufort 0-3, 0-19 km/hr). The first survey in the season was conducted when night-time air temperature had reached > ~5°C, the second when > ~10°C had been reached, and the third when > ~17°C had been reached. With few exceptions, only shoreline locations were sampled due to night-time over-water safety issues. The survey protocols of each of the projects were similar to the North American Amphibian Monitoring Program protocol (Weir et al. 2009, 2014).

Analyses—Numerous methods are available for analyzing Great Lakes coastal wetland breeding frog data. Previous analyses for this report were based on the separate status and trend of the occupancy of eight wetland breeding frog species (e.g., Tozer 2014). Alternative approaches include various indices of wetland health, which combine data from suites of species (e.g., Chin et al. 2014). The latter approach is likely more objective and more practical for the purposes of State of the Great Lakes (previously known as SOLEC) because it provides a single comprehensive metric that represents the collective responses of breeding frog species to wetland condition. Multi-species metrics, like the widely used index of biotic integrity for fishes (Karr and Chu 1999) and mean coefficient of conservatism for plants (Taft et al. 1997), tend to be robust because informative values are produced even when some species are absent due to factors outside the system of interest. For example, a wide-ranging species might go undetected because, by chance, all individuals of that species happen to be located beyond survey plots during the sampling period, even though these individuals are resident within the wetland. Similarly, a high quality wetland might be missing a species because of a regional epidemic that affects individuals regardless of wetland condition.

In this report, a new approach is introduced to assessing frog community health based on multi-species data from wetland frogs across the Great Lakes Basin (Howe et al. 2007a, 2007b; Hanowski et al. 2007a, 2007b; Tozer 2013). Quantitative data were used for breeding frogs at approximately 6,000 sample points throughout the Great Lakes in both the U.S. and Canada. At many of these sample points, information is available on three potential environmental stressors: 1) agricultural intensity in the contributing watershed (i.e., the landscape draining into the wetland), 2) non-agricultural landscape development such as roads, buildings, and human population density in the contributing watershed, and 3) wetland area and fragmentation, measured by the total wetland area within 1 km of the sampled wetland's centroid. For convenience, these gradients are referred to in this report as agriculture, development, and wetland area, respectively. Clearly, many other stressors affect frog communities in coastal wetlands, but agricultural intensity, non-agricultural landscape development, and wetland area provide tractable quantitative yardsticks from which one can identify sensitive species and community variables (Brazner et al. 2007a, 2007b).

For frogs, it was assumed that poor wetland condition was associated with high agriculture, high development, and small wetland area. As such, values for the agriculture and development stressors were highly skewed in favour of degraded or unhealthy wetlands, but values for the wetland area stressor suffered from the opposite issue. To alleviate bias that these skewed distributions might cause in later analyses, i.e., to downplay the influence of the small but highly influential number of sites with extreme values, the Yeo-Johnson transformation was applied (Yeo and Johnson 2000) in R (version 3.1.3, R Core Team 2015) with package "car" (Fox and Weisberg 2011). This normalizing transformation resembles the general Box-Cox power transformation but allows for zero values in the data. To avoid power transformations involving decimal values, values of the environmental gradient were first multiplied by a large constant (e.g., 100). After transformation each stressor was converted to a standard scale with extreme values representing the most impacted (0) and least impacted (10) sample points with respect to that stressor. Distributions of the transformed and standardized variables for agriculture, development, and wetland area stressors resembled normality and could be evaluated alone or in combination. To develop a comprehensive measure of ecosystem health based on breeding frogs, principal components analysis (PCA) was used to combine the agriculture, development, and wetland area stressors into a single multi-variate "human footprint" (Gnass Giese et al. 2015), which was used throughout the analysis described below. Scores from two of the three PCA axes could be ordered and scaled from most stressed (condition = 0) to least stressed (condition = 10) based on correlations with the original stressor variables. (The magnitude of scores on one axis was opposite in direction to that of the other axis, so values were simply inverted to align with the 0-10 scale.) Scores from the two axes were weighted according to the percent variance explained (total = 61%), summed, and re-scaled from 0-10 to yield the multi-variate "human footprint" stressor gradient.

The health of coastal wetlands was evaluated using the *index of ecological condition* (IEC), an objective biotic indicator introduced by Howe et al. (2007a, 2007b), improved by Gnass Giese et al. (2015), and compared to other similar indices (using bird data) by Chin et al. (2015). Existing data on breeding frogs of Great Lakes coastal wetlands described in more detail below were used for the first step in IEC development. The quantitative response of a species or multi-species variable to a given stressor gradient can be modeled from presence/absence or abundance of the species at wetlands where accompanying stressor data were available. Parameters of the best-fit mathematical function were estimated by computer iteration in R (R Core Team 2015) with package "iec" (https://github.com/ngwalton/iec). Results of this analysis yielded three parameters (mean, standard deviation, and height) describing a bell-shaped or truncated Gaussian function within the range of 0-10. These biotic response (BR) functions provide the basis for estimating the health of coastal wetlands based on frog observations (Figure 1). By recording the species present at a wetland, one can essentially work backward to calculate an IEC. Species (or related biotic variables) that have been shown previously to favor minimally-stressed wetlands will indicate ecologically healthy conditions and high IEC scores. By contrast, species (or related biotic variables) that favour highly-stressed wetlands will indicate ecologically unhealthy or degraded conditions and low IEC scores. This method resembles other approaches to environmental indicator development, but the IEC framework establishes an explicit connection between stressors and biotic variables, providing a clear picture about what our indicator truly "indicates." A more detailed description of IEC methodology is available in a separate document (Howe et al. *in prep*.) and at http://www.uwgb.edu/BIODIVERSITY/forest-index/iec.asp.

CWMP data were used (2011-2014) to build BR functions because these samples could be associated with site-specific stressor data. Samples (n = 848) consisted of presence of each frog species detected during three night-time field surveys at a point within a single year (the first when night-time temperatures had reached > 5°C, the second when > 10°C had been reached, and the third when > 17°C had been reached). Although the distribution of some species varies across the region, all of the species used in this analysis occur in each of the Great Lakes, so BR functions were generated using data from the entire Great Lakes Basin. Several alternative approaches were considered for identifying the most informative frog-based indicator. For example, models were compared using BR functions of all potentially occurring species versus models using only BR functions of species that were present at the sample point. The latter is desirable because it avoids quantitative "penalties" for the absence of species that were present but not detected or species that do not have suitable microhabitat conditions at the sample point. To avoid excessive zeros in the response variable, the data were grouped into "bins" of 10 samples with similar stressor values. The response variable was then the frequency of occurrence in the 10 samples, which provides an estimate of probability of occurrence. In addition to single species metrics, a number of multi-species metrics was also calculated, including variables such as total species richness, total Hylidae species richness, and total Ranidae species richness. For these variables, "binned" data consisted of the average values for each group of 10 samples. Data from the CWMP were used to derive a final suite of BR functions, which in turn were used to derive IEC scores for wetlands from the GLMMP, GLEI, and CWMP projects. The results presented in this report are based on presence/absence data using only BR functions of individual species that were present at each sample point. Based on this examination of results from the many alternative approaches described above, this was the most informative and cost-effective approach for determining coastal wetland health based on wetland breeding frogs.

The final suite of species was identified for calculating BR functions and IECs via the following steps. The process started with all species in the dataset, and then eliminated all species present at fewer than five of the sample points. Species were then eliminated for which the BR functions were uninformative (lowest 10% range between minimum and maximum predicted response) or highly variable (10% poorest goodness-of-fit). The resulting seven species used to generate BR functions for calculating IECs are shown in Table 1.

IECs for each sample point were calculated in each year based on species observed across all field visits. Next the point-level IECs across all sample points were averaged within each wetland or wetland complex in each year, which adjusted for wetlands containing differing numbers of sample points. Means of these wetland-level IECs for coastal wetlands in each basin and throughout the entire Great Lakes Basin were reported (hereafter "overall") in each year. These means form the basis for the status and trend assessments, but comparable IEC metrics for inland wetlands are also reported. In addition, distributions of IECs for coastal and inland wetlands in each basin and overall for recent years from 2011-2014 were reported to illustrate variation in the health of wetlands. In these calculations frog-based IEC values were averaged across years for wetlands that were sampled in multiple years. Note that data from 2011-2014 were used in these calculations to increase sample sizes for illustrating the distribution of IECs of inland wetlands, but assessments of current coastal wetland status are based on 2014 data only.

Status— Definitions of good, fair, and poor condition were assigned based on wetland-level IECs from all years and all wetlands across all basins (n = 4,804). IEC values greater than the 66th percentile were good, values between and including the 33rd and 66th percentiles were fair, and values less than the 33rd percentile were poor. This translated into the following definitions:

- ***Good***: IEC > 6.1
- ***Fair***: 5.7 ≤ IEC ≤ 6.1
- ***Poor***: IEC < 5.7

Trend— The terms improving, unchanging, and deteriorating were applied based on geometric mean rates of change (% change / yr) using equation 4 in Smith et al. (2014). The statistical significance of trends was assessed via parametric bootstrapping in R (R Core Team 2015) with package "boot" (Canty and Ripley 2013). Bootstrapping in this manner was necessary to account for the varying precision of the beginning annual estimate and the ending annual estimate used to calculate each trend. Trend estimates with 95% confidence intervals that did not overlap zero were considered statistically significant. The short- and long-term trends were calculated but the trend assessments for the Great Lakes Basin and each individual basin are based on short-term changes in frog assemblages. Short term was defined as the period 2011-2014, whereas long term was 1995-2014 or 2002-2014 in cases where < 10 wetlands were sampled in 1995. The following definitions were used to describe the status of frog assemblages at Great Lakes coastal wetlands:

- ***Improving***: statistically significant short-term increase in IEC
- ***Unchanging***: no statistically significant short-term increase or decrease in IEC
- ***Deteriorating***: statistically significant short-term decrease in IEC

Endpoint— The endpoint of this sub-indicator was defined as the level when mean IECs were confidently above the lower cutoff for good condition. In other words, the endpoint was reached when the lower 95% confidence limit for mean IEC was > 6.1.

Status and trend of coastal wetland frogs
Data coverage—The dataset available for scoring sites consisted of mean annual wetland-level IECs based on 40,123 point counts conducted at 6,013 sample points in 1,545 wetlands over 20 years from 1995-2014 throughout the Great Lakes Basin (Figure 2). The number of years that each wetland was surveyed varied from 1 to 20, with a mean of 3.1 ± 3.4 (SD). Spatial patterns among locations of sampled points were due mainly to natural variation in the distribution of Great Lakes coastal wetlands and differences in observer participation in the long running, broad scale GLMMP (Figure 2). The majority of the surveyed wetlands were coastal (*n* = 1,043; 67%) rather than inland (*n* = 511; 33%) because both the GLEI and CWMP projects focus entirely on coastal wetlands, whereas the GLMMP surveys both (Figure 2).

The number of wetlands surveyed per year (240 ± 113 [mean ± SD]) ranged from 106 to 439, with substantially more wetlands surveyed from 2002-2003 and from 2011-2014 due to the GLEI and CWMP projects operating in those years (Figure 3). Annual coverage was also higher in Lake Erie and Lake Ontario compared to the upper Great Lakes mostly because GLMMP coverage is more extensive in the lower lakes, and annual coverage was higher at coastal compared to inland wetlands (Figure 3).

Overall—Mean IEC in coastal wetlands ranged from 5.5 to 5.9 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 5.6 in 2014 (Figure 4). The majority of coastal IECs from 2011-2014 were 5-7, with much lower frequency of scores from 0-5 and 7-9 (Figure 5). Based on these patterns, the status of coastal wetland health in the Great Lakes overall is poor and the trend is unchanging. Similar patterns occurred at inland wetlands (Figures 4, 5).

Lake Superior—Mean IEC in coastal wetlands ranged from 3.9 to 7.1 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 5.9 in 2014 (Figure 4). The majority of coastal IECs from 2011-2014 were 5-7, with much lower frequency of scores from 7-9, and very low frequency of scores from 0-5 (Figure 5). Similar patterns occurred at inland wetlands (Figures 4, 5).

Lake Michigan—Mean IEC in coastal wetlands ranged from 2.8 to 7.6 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 5.4 in 2014 (Figure 4). The majority of coastal IECs from 2011-2014 were 5-7, with much lower frequency of scores from 0-5 and 7-9 (Figure 5). Similar patterns occurred at inland wetlands (Figures 4, 5).

Lake Huron— Mean IEC in coastal wetlands ranged from 5.6 to 6.4 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 5.9 in 2014 (Figure 4). The majority of coastal IECs from 2011-2014 were 5-7, with much lower frequency of scores from 7-8, and very low frequency of scores from 3-5 (Figure. 5). Similar patterns occurred at inland wetlands (Figures 4, 5).

Lake Erie—Mean IEC in coastal wetlands ranged from 5.0 to 6.4 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 5.4 in 2014 (Figure 4). The majority of coastal IECs from 2011-2014 were 5-6, with much lower frequency of scores from 2-5 and 6-9 (Figure. 5). Similar patterns occurred at inland wetlands (Figures 4, 5).
Lake Ontario—Mean IEC in coastal wetlands ranged from 5.1 to 6.2 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 5.6 in 2014 (Figure 4). The majority of coastal IECs from 2011-2014 were 5-7, with much lower frequency of scores from 2-5 and 7-9 (Figure. 5). Similar patterns occurred at inland wetlands (Figures 4, 5).

Species Richness—Spring peeper showed by far the strongest response to our combined stressor gradient and therefore is the best indicator of wetland health among the seven species of frogs that are widespread enough to be monitored by our methods (Figure 1; see also Price et al. 2007). In general, frog species in the Great Lakes are relatively weak indicators of the stressor gradients evaluated in this report, although total number of frog species in the three combined seasonal counts was positively correlated with the combined condition gradient (Figure 6). High quality wetlands supported as many as five frog species, while poor quality wetlands typically supported only one to three species. Composition of the frog assemblage, however, provides more information than simply the number of species; for example an assemblage of four species that includes spring peeper would indicate higher quality condition than an assemblage of four species that does not include spring peepers.

Discussion—Throughout the Great Lakes Basin, the current status of coastal wetland health based on wetland breeding frogs is poor, with current status of Lake Superior and Lake Huron being fair and Lake Michigan, Lake Ontario, and Lake Erie being poor. Correspondingly, coastal IECs located towards the degraded end of the degraded-pristine gradient are more common in Lake Michigan, Lake Erie, and Lake Ontario compared to Lake Superior and Lake Huron. For instance, the proportion of coastal wetlands from 2011-2014 with IECs < 5 was 13-31% in Lake Michigan, Lake Erie, and Lake Ontario, with degraded wetlands especially prevalent in Lake Erie. By contrast, the proportion was 1-3% in Lake Superior and Lake Huron (Figure 5). These patterns are probably due to greater anthropogenic stress from agriculture, development, and perhaps wetland loss in Lake Michigan south of the Canadian Shield, and in all of Lake Erie and Lake Ontario compared to Lake Superior and most parts of Lake Huron (Allan et al. 2013, Bourgeau-Chavez et al. 2015, Danz et al. 2007, Niemi et al. 2009). Nonetheless, some high quality coastal wetlands are still present in all of the Great Lakes (Figure 5). By illustrating and documenting differences in wetland health in these ways, the analysis provides a unique baseline for assessing long-term changes in wetland quality and for quantifying the success of restoration efforts in individual wetlands, regions, and the entire Great Lakes Basin. A more detailed analysis of species' responses to individual stressors is available, but these results are beyond the scope of this report. The condition of sites based on a multi-variate "human footprint" stressor that incorporates measures of all three stressor variables (agriculture, development, and wetland area) was reported.

In addition to assessing status and trend of the health of coastal wetlands, status and trend of inland wetlands were examined for comparison (Figures 4, 5). The ability to compare coastal and inland wetlands due to differences in sample sizes was best for Lake Erie and Lake Ontario, whereas it was limited for the other lake basins. Similar patterns were found across coastal and inland wetlands, with the following exceptions. In Lake Erie and Lake Ontario, the status of coastal wetlands was poor, whereas the status of inland wetlands was fair (Figure 5). Thus, wetland health as represented by wetland frogs may be responding to different intensities of stressors in coastal versus inland wetlands within the Lake Erie and Lake Ontario watersheds. Similarly, a previous study using only the GLMMP dataset observed that occupancy of certain wetland-breeding frog species was lower at coastal marshes compared to inland marshes (Tozer 2013). Thus, continued sampling of both coastal and inland wetlands throughout the Great Lakes Basin is needed to completely monitor and assess the health of wetlands based on frogs throughout the entire region.

The overall poor status and unchanging trend reported for coastal wetlands throughout the Great Lakes Basin is the same as the status and trend noted in previous reports for this sub-indicator based on the prevalence of significant trends in occupancy among eight wetland breeding frog species using the GLMMP dataset alone (e.g., Tozer 2014). Previous reports, however, were based predominantly on data summarizing the status and trend of the southern portion of the Great Lakes Basin due to reliance on the mostly southern GLMMP dataset; the current report provides a more balanced assessment throughout the entire Great Lakes Basin by bringing GLMMP data together with data from the southern and northern GLEI and CWMP projects. As such, the current results more robustly corroborate the previous status and trend assessments. Nevertheless, it is important to note that the patterns summarized in this report are based on a comprehensive IEC metric, which represents the collective responses of multiple breeding frog species to wetland condition. Therefore, one should not lose sight of the fact that there are particular species, such as the western chorus frog (*Pseudacris triseriata*), which has experienced long-term declines at various scales in the Great Lakes (e.g., Tozer 2013) that may be responding in species-specific ways to environmental stressors that warrant unique management actions or present unique opportunities for improving wetland health. The results show no significant relationship between Chorus Frog occurrence and the combined stressor gradient (Figure 1), so it appears that across the Great Lakes Chorus Frogs are responding to factors other than the stressors that were measured in this report or that local or regional decreases are offset by local or regional increases elsewhere.

Linkages
Coastal wetland breeding frogs are influenced by numerous local and landscape-level characteristics, some of which are monitored by other State of the Great Lakes (previously known as SOLEC) indicators. For instance, coastal wetland breeding frogs are known to be influenced by various water pollutants, particularly nitrates (e.g., Rouse et al. 1999). Thus, the Coastal Wetland Amphibians sub-indicator can be expected to co-vary with the Inland Water Quality Index, Nutrients in Lakes, and Toxic Chemicals in Offshore Waters sub-indicators. Similarly, the Coastal Wetland Amphibians sub-indicator can be expected to co-vary with sub-indicators that track the extent and spatial arrangement of wetland breeding frog habitat (e.g., Coastal Wetland Landscape Extent and Composition) and prey (Coastal Wetland Invertebrate Communities; Coastal Wetland Fish Community Health).

Comments from the Author(s)
This approach has been completed using the GLEI component of the larger dataset analyzed in this report. Using step-wise logistic regression models and data from 279 GLEI point counts conducted at 93 sample points, Price et al. (2004) determined important local, wetland, and landscape-scale factors influencing occupancy of five wetland breeding frog species in coastal wetlands throughout U.S. portion of Lake Michigan and Lake Huron.

IECs for the Coastal Wetland Amphibians sub-indicator yielded relatively low variation among wetlands, individual lake basins, and over time (Figures 4, 5). By contrast, IECs for the Coastal Wetland Birds sub-indicator in this volume were much more variable. For instance, based on all years and all wetlands across all basins the interquartile range of IECs based on frogs was 0.7, whereas the interquartile range of IECs based on birds was 1.8. The difference in variation between frog-based and bird-based IECs is challenging to interpret. One explanation is that frog-based IECs are less variable than bird-based IECs because frog-based IECs are calculated using data from far fewer species than bird-based IECs (7 frog species or species groups versus 52 bird species). Thus, it may be that IECs based on larger numbers of species like the Coastal Wetland Birds sub-indicator are inherently capable of capturing more variation in wetland health compared to IECs based on fewer species like the Coastal Wetland Amphibians sub-indicator (Howe et al. 2007a).

Also, IECs from the Coastal Wetland Amphibians sub-indicator were moderately correlated with IECs from the Coastal Wetland Birds sub-indicator ($r = 0.3$, $p < 0.001$). Although the relationship includes much unexplained variation, this correlation suggests that information captured by frogs is reflected by information captured by birds. Indeed, basin-level status assessments based on frogs were similar to those based on birds: in both cases Lake Superior and Lake Huron were assessed as the most healthy compared to the other lakes, and Lake Erie was assessed as the least healthy. Thus, it may be that Great Lakes coastal frog data are best analyzed in combination with Great Lakes coastal bird data (Price et al. 2007), perhaps as a combined bird and frog sub-indicator based on IEC; however, justification for this awaits more extensive evidence and analysis. Because collection of frog data requires three separate nocturnal surveys and is often constrained by weather conditions (especially during early spring), the conclusion is that monitoring of Great Lakes coastal wetlands for frogs is less cost effective than monitoring for birds.

The assessment of the status and trend of coastal wetland health based on wetland breeding frogs is based on BR functions developed using CWMP data only. The BR functions were also developed based on information from three stressor gradients: agriculture, development, and wetland area. The ability of the IEC to capture the health of coastal wetlands based on frog data might be improved by expanding the development of the BR functions to include all of the marsh frog data that are available from the GLMMP, GLEI, and CWMP projects. The performance of the IEC might also be improved by incorporating other known wetland frog stressors in the development of BR functions, particularly within-wetland attributes like relative dominance of invasive plant species. These ideas are fruitful areas for future expansion.

For the first time, three large marsh frog datasets were brought together, specifically the GLMMP, GLEI, and CWMP project datasets to perform the analyses summarized in this report. This provided a tremendous improvement in analytical power at many different scales compared to using only one of the datasets on its own. However, it was evident that the combined dataset is lacking information from healthy wetlands. Future collection of marsh frog data from wetlands located close to the pristine end of the degraded-pristine gradient might improve the performance of the IEC.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

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No.	Common name	Scientific name
1	American Toad	*Anaxyrus americanus*
2	Bullfrog	*Rana catesbeiana*
3	Boreal Chorus Frog / Western Chorus Frog	*Pseudacris maculata / Pseudacris triseriata*
4	Gray Treefrog / Cope's Gray Treefrog	*Hyla versicolor / Hyla chrysoscelis*
5	Green Frog	*Rana clamitans*
6	Northern Leopard Frog	*Rana pipiens*
7	Spring Peeper	*Pseudacris crucifer*

Table 1. Wetland breeding frog species or groups of species (n = 7) used to generate biotic response functions for calculating indices of wetland health for Great Lakes coastal wetlands.
Source: Great Lakes Coastal Wetland Monitoring Program

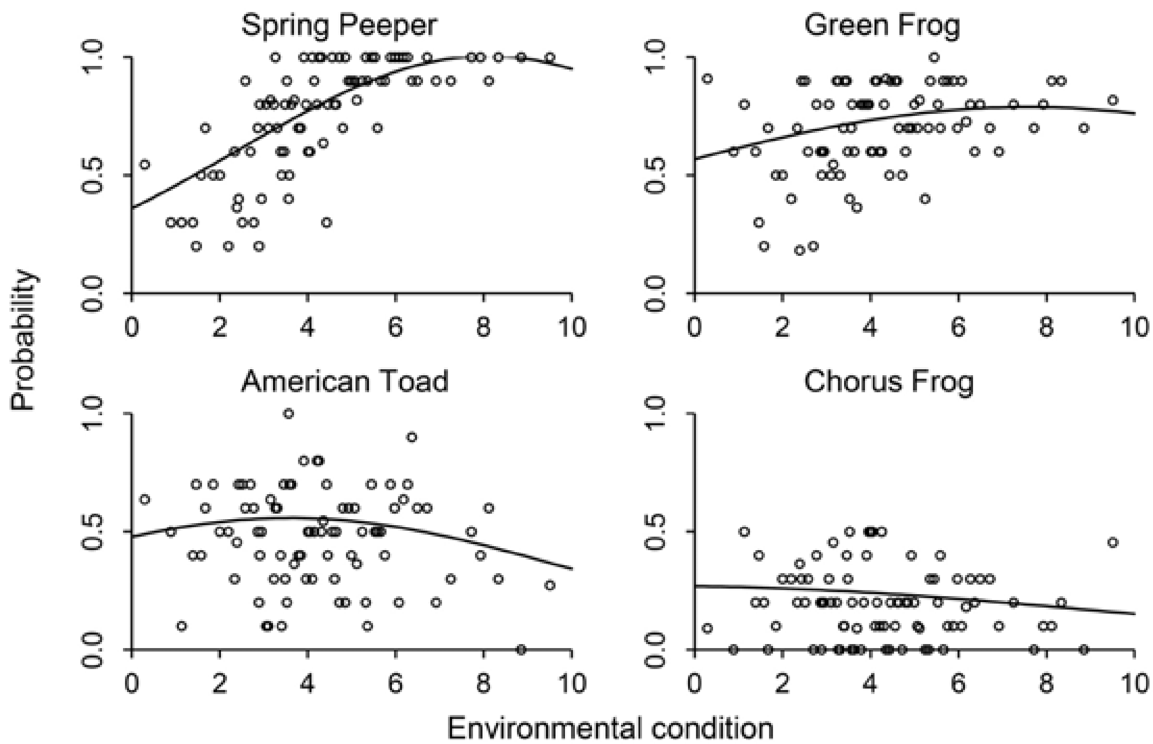

Figure 1. Biotic response functions (solid lines) for selected frog species from coastal wetlands throughout the Great Lakes Basin. Shown is the probability of occurrence as a function of a combined "human footprint" variable incorporating environmental condition due to agriculture, development, and wetland area (0 = poor condition, 10 = good condition). Open circles represent binned data at 10 observations per bin. See Table 1 for scientific names; note that Chorus Frog refers to Boreal Chorus Frog / Western Chorus Frog.
Source: Great Lakes Coastal Wetland Monitoring Program

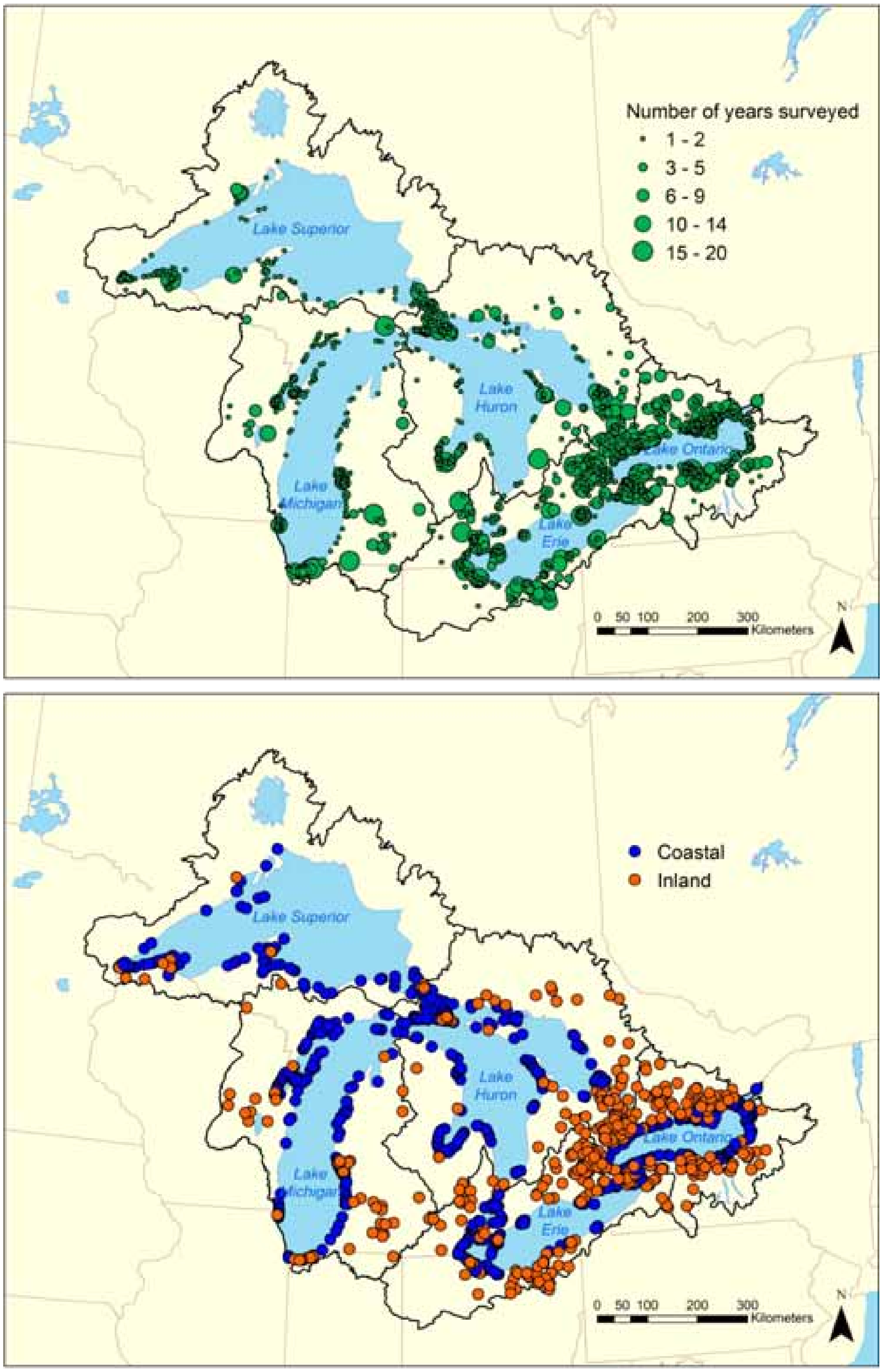

Figure 2. Wetlands surveyed for frogs from 1995-2014 throughout the Great Lakes Basin for the purpose of estimating indices of wetland health. Shown are wetlands as a function of the number of years that each wetland was surveyed (upper map), and as a function of coastal versus inland (lower map). Note that coastal wetlands far outnumber inland wetlands, although this does not appear to be the case due to tightly overlapping symbols. Source: Great Lakes Coastal Wetland Monitoring Program

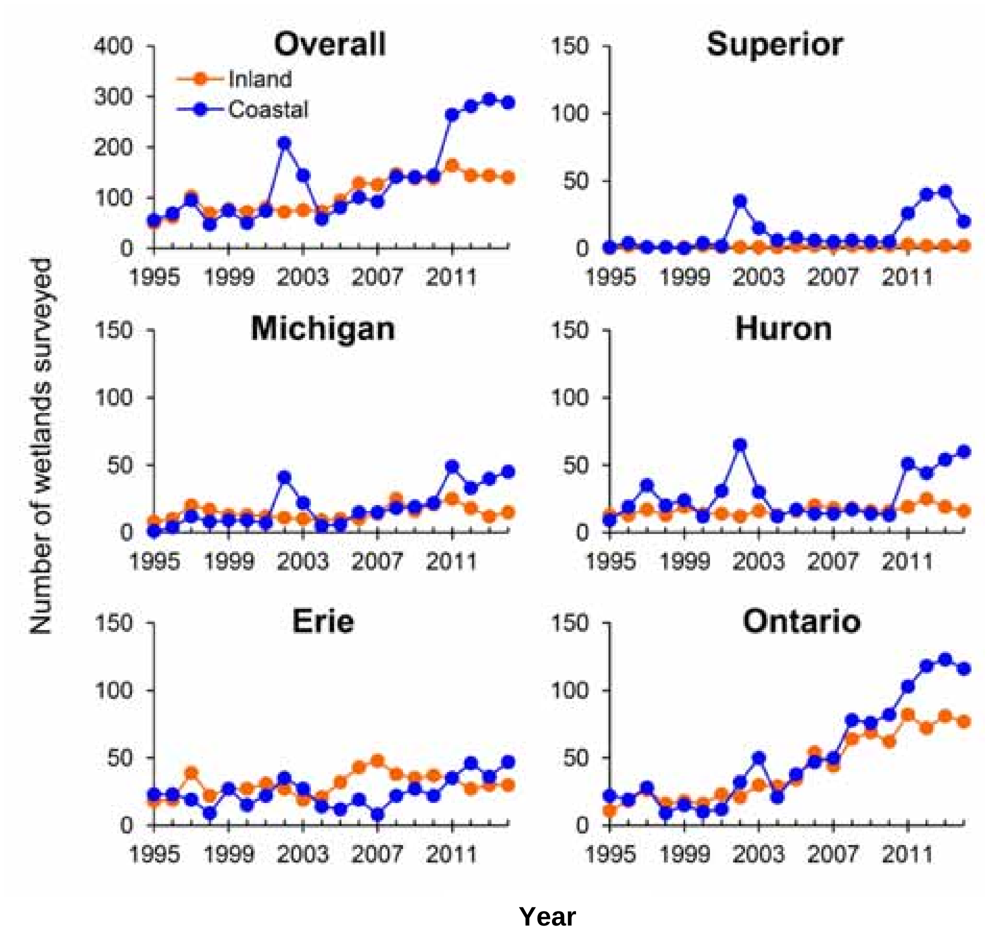

Figure 3. Number of wetlands surveyed for frogs per year from 1995-2014 throughout the Great Lakes Basin for the purpose of estimating indices of wetland health. Shown are wetlands surveyed as a function of the entire Great Lakes Basin (overall) and each individual lake basin for coastal and inland wetlands.
Source: Great Lakes Coastal Wetland Monitoring Program

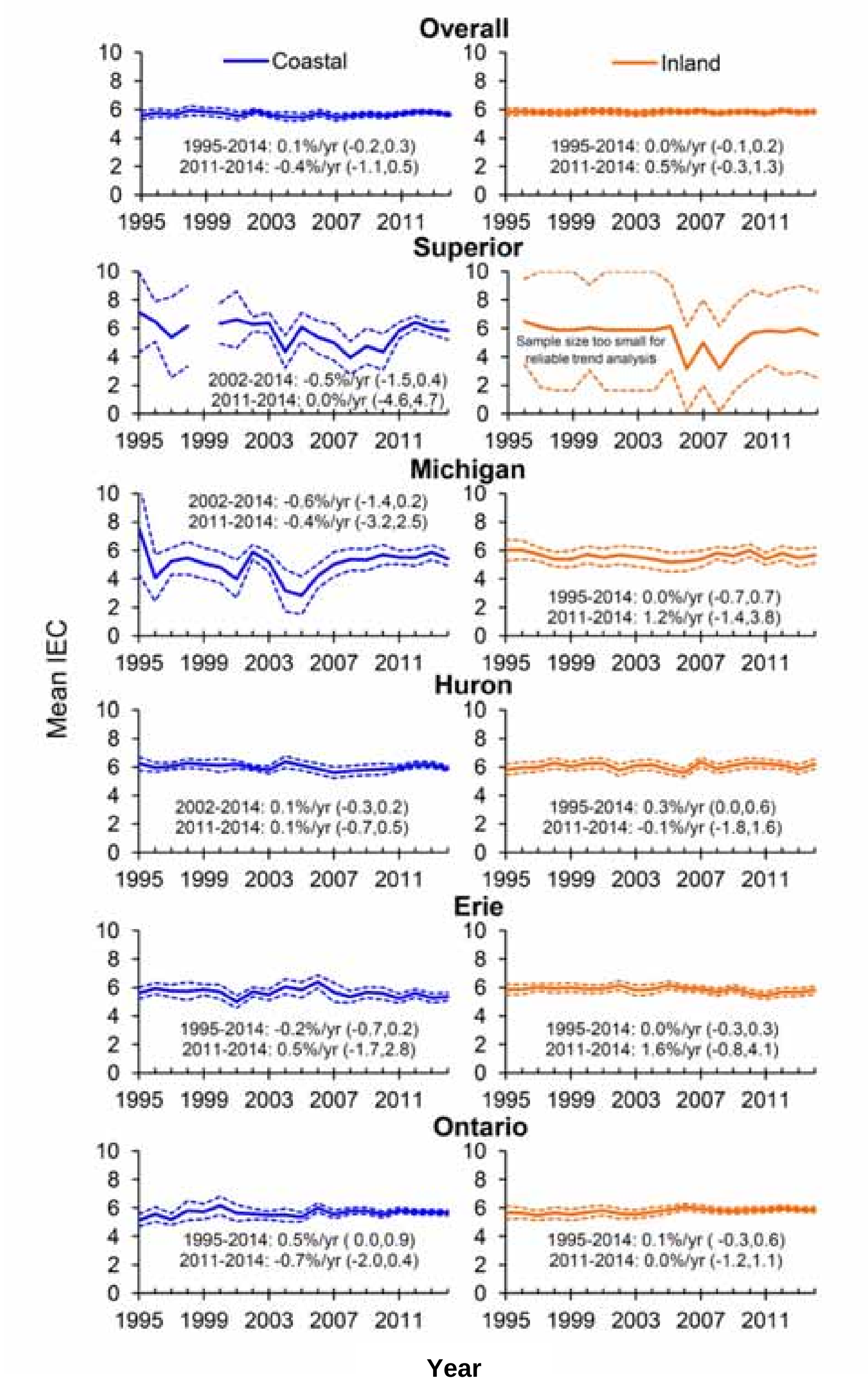

Figure 4. Temporal trends in mean index of ecological condition (IEC) based on frog data from 1995-2014 throughout the Great Lakes Basin (solid lines). Shown are means across all surveyed wetlands in each year as a function of the entire Great Lakes Basin (overall) and each individual lake basin for coastal and inland wetlands. Dashed lines are 95% confidence limits. Also shown are geometric mean rates of change (%/yr) over the long or short term. Short term was 2011-2014, whereas long term was 1995-2014 or 2002-2014 in cases where < 10 wetlands were sampled in 1995. Note that for Superior there were no coastal data for 1999 or inland data for 1995. Source: Great Lakes Coastal Wetland Monitoring Program

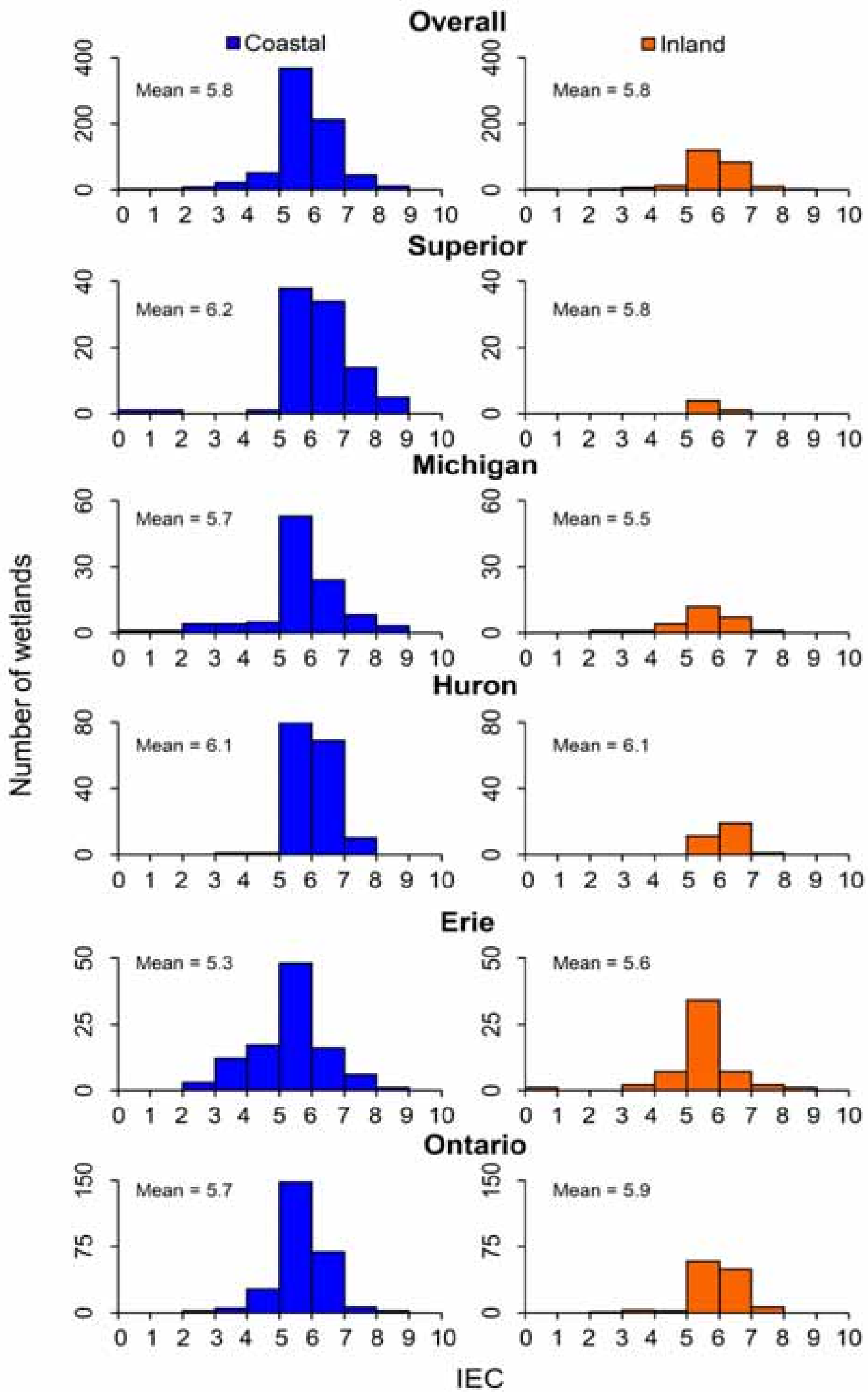

Figure 5. Distribution of index of ecological condition (IEC) based on frog data from 2011-2014 throughout the Great Lakes Basin. Shown are IECs for all surveyed wetlands as a function of the entire Great Lakes Basin (overall) and each individual lake basin for coastal and inland wetlands. Note that prior to these calculations we averaged across years for wetlands that were sampled in multiple years.
Source: Great Lakes Coastal Wetland Monitoring Program

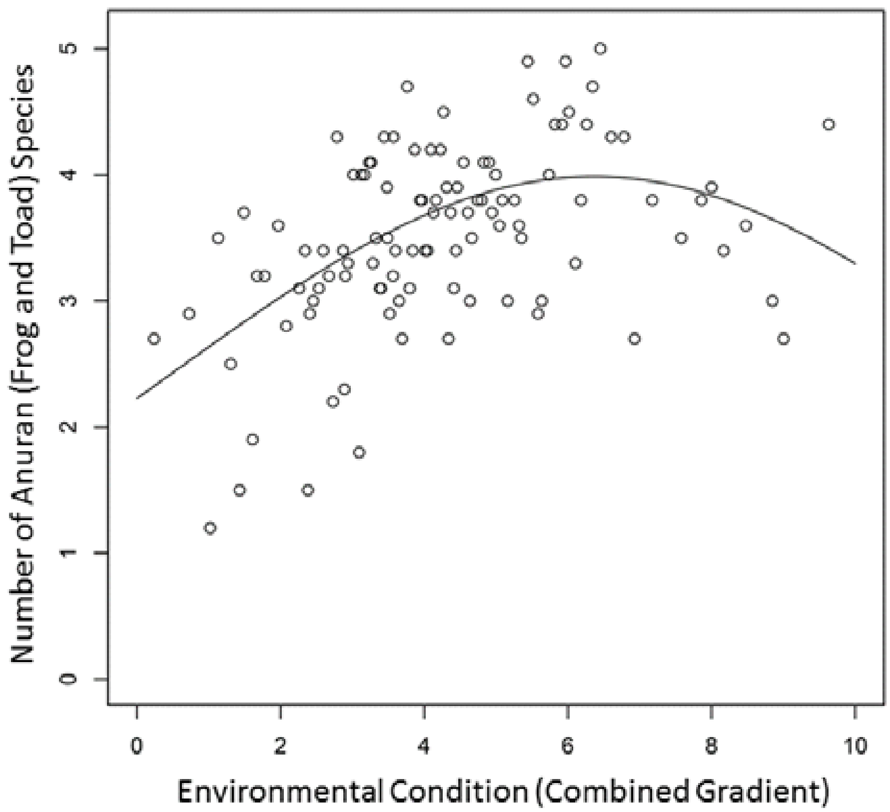

Figure 6. Biotic response function (solid line) for total number of frog species in three seasonal surveys of coastal wetlands throughout the Great Lakes Basin. Shown is the total number of species detected as a function of a combined "human footprint" variable incorporating environmental condition due to agriculture, development, and wetland area (0 = poor condition, 10 = good condition). Open circles represent binned data at 10 observations per bin.
Source: Great Lakes Coastal Wetland Monitoring Program

Sub-Indicator: Coastal Wetland Birds

Overall Assessment
Status: Fair
Trend: Unchanging
Rationale: Mean index of ecological condition (IEC), an objective biotic indicator summarizing standardized observations of breeding birds in coastal wetlands was 3.9 (out of 10) in 2014 and did not significantly increase or decrease from 1995-2014 or from 2011-2014.

Lake-by-Lake Assessment
Lake Superior
Status: Good
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 4.7 in 2014 and did not significantly increase or decrease from 2002-2014 or from 2011-2014.

Lake Michigan
Status: Fair
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 3.9 in 2014 and did not significantly increase or decrease from 2002-2014 or from 2011-2014.

Lake Huron
Status: Good
Trend: Unchanging
Rationale: Mean IEC in coastal wetlands was 4.6 in 2014 and did not significantly increase or decrease from 2002-2014 or from 2011-2014.

Lake Erie
Status: Poor
Trend: Deteriorating
Rationale: Mean IEC in coastal wetlands was 3.0 in 2014 and significantly decreased by -1.6%/yr (-2.1, -0.9) [lower, upper 95% confidence limits] from 1995-2014 and by -3.9%/yr (-6.4, -0.9) from 2011-2014.

Lake Ontario
Status: Fair
Trend: Improving
Rationale: Mean IEC in coastal wetlands was 3.8 in 2014 and significantly increased by 1.1%/yr (0.2, 2.0) [lower, upper 95% confidence limits] from 1995-2014 and by 2.9%/yr (0.5, 5.2) from 2011-2014.

Other Spatial Scales
Inland
Status and trend based on IECs were also calculated for inland wetlands for comparison with coastal wetlands. Results were similar to those described above for coastal wetlands, except that the status for Lake Superior and Lake Huron was fair instead of good, and there were no significant increases or decreases at any scale over time.

Separate assessments for the connecting channels of the Great Lakes were not completed. Information for the channels is included with the adjacent down-stream lake, as shown on the maps of sample points.

Sub-Indicator Purpose
- To assess the status and trends of Great Lakes coastal wetland ecosystem health by directly measuring the composition and relative abundance of wetland breeding birds, and thereby inferring the condition of coastal wetland habitat as it relates to the health of this ecologically and culturally important component of

wetland communities. To restore/maintain the overall biological integrity of Great Lakes coastal wetlands, various ecological components including coastal wetland bird communities need to be addressed.

Ecosystem Objective
Coastal wetlands provide critical breeding and migratory habitat for wildlife such as birds. Conservation of remaining coastal wetlands and restoration of previously degraded or destroyed wetlands are vital components of restoring the Great Lakes ecosystem. Birds are effective ecological indicators and can be used to report progress toward such an objective.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition
Background
Wetland breeding birds are influenced by the physical, chemical, and biological components of wetlands and surrounding landscapes. For example, the occurrence, abundance, and/or reproductive success of multiple bird species in the Great Lakes Basin declines as (1) wetland size decreases; (2) wetland habitat and natural cover in the surrounding landscape decreases or degrades in quality; (3) pollution from pesticides, herbicides, and sediment runoff increases; and (4) generalist predators (e.g., northern raccoon [*Procyon lotor*]) associated with anthropogenic habitats in the surrounding landscape increase (Brazner et al. 2007a, 2007b; Crosbie and Chow-Fraser 1999; Howe et al. 2007a; Grandmaison and Niemi 2007; Naugle et al. 2000; Smith and Chow-Fraser 2010 a, 2010b; Tozer et al. 2010). Thus, the occurrence or abundance of sensitive wetland breeding birds can be a valuable indicator of the health of wetlands and the surrounding landscape.

Measures
Study design—Several initiatives monitor Great Lakes wetland breeding birds. One of the longest running is Bird Studies Canada's Great Lakes Marsh Monitoring Program (GLMMP), which started in 1995 and has operated every year since then at coastal and inland wetlands throughout much of the Great Lakes Basin (Tozer 2013, 2016). Previous reports for this sub-indicator are based solely on data from this ongoing broad scale program (e.g., Tozer 2014). From 2001-2005, the University of Minnesota Duluth's Natural Resource Research Institute (NRRI) led an ambitious multi-institutional Great Lakes Environmental Indicator project (GLEI) aimed at assessing the overall biotic health of coastal wetlands in the U.S. portion of the Great Lakes (Howe et al. 2007a, 2007b; Hanowski et al. 2007a, 2007b). More recently, the Great Lakes Coastal Wetland Monitoring Program (CWMP) led by Central Michigan University was initiated in 2011 and currently is scheduled to operate until at least 2020 throughout both the U.S. and Canadian Great Lakes coastal zones (Cooper et al. 2014). These projects have somewhat different study designs, but rely on standardized, fixed duration point counts that can be adjusted to maximize cross-project compatibility. To garner large numbers of trained volunteer participants to achieve large sample sizes at relatively low cost, the GLMMP allows participants to select sample points—a justifiable approach if one assumes that the sample points are approximately representative of wetlands across a region of interest. By contrast, the GLEI and CWMP projects select sample points via stratified random sampling of coastal wetlands and survey wetlands via paid professional staff. Nonetheless, all of the projects target wetlands dominated by non-woody emergent plants such as cattails (*Typha* spp.) and sedges (e.g., *Carex* spp.) with sample points located within wetlands. In this report the datasets listed above were brought together for the first time to generate the most comprehensive analysis of the status and trend of Great Lakes coastal wetland breeding birds and associated wetland health.

Bird surveys—Breeding birds were sampled to an unlimited distance from a point located at the edge or within a wetland (hereafter "sample point"). In most large wetlands points were sampled both near the upland / wetland interface (shoreline) and in the interior of the wetland, while in most small wetlands only shoreline points were sampled. Each sample point was surveyed for 10 or 15 minutes on 1-3 visits separated by at least 10 or 15 days during the main avian breeding season, typically between late May and early July. Surveys occurred in either the morning (30 minutes before local sunrise to 10:00 h local time) or evening (4 hours before local sunset to dark) or both and only under weather conditions that were favourable for detecting all species and individuals present (little to no precipitation; wind: Beaufort 0-3, 0-19 km/hr). Observers broadcasted calls during surveys to entice vocal response by individuals of especially secretive species. The broadcast calls occurred during a 5-minute portion of each 10- or 15-minute survey and consisted of 30 seconds of vocalizations followed by 30 seconds of silence for each of the following species: Least Bittern (Ixobrychus exilis), Sora (Porzana carolina), Virginia Rail (Rallus limicola), a mixture of

American Coot (Fulica americana) and Common Gallinule (Gallinula galeata), and Pied-billed Grebe (Podilymbus podiceps), in that order. The survey protocols of each of the projects closely followed the Standardized North American Marsh Bird Monitoring Program protocol (Conway 2011).

Analyses—Numerous methods are available for analyzing Great Lakes coastal wetland breeding bird data. Previous analyses for this report were based on the separate status and trend of the relative abundance of approximately 20 wetland dependent breeding bird species (e.g., Tozer 2014). Alternative approaches include various indices of wetland health, which combine data from suites of species (e.g., Chin et al. 2014). The latter approach is likely more objective and more practical for the purposes of State of the Great Lakes (previously known as SOLEC) because it provides a single comprehensive metric that represents the collective responses of breeding bird species to wetland condition. Multi-species metrics, like the widely used index of biotic integrity for fishes (Karr and Chu 1999) and mean coefficient of conservatism for plants (Taft et al. 1997), tend to be robust because informative values are produced even when some species are absent due to factors outside the system of interest. For example, a wide-ranging species might go undetected because, by chance, all individuals of that species happen to be located beyond survey plots during the sampling period, even though these individuals are resident within the wetland. Similarly, a high quality wetland might be missing a species because of a regional epidemic that affects individuals regardless of wetland condition.

In this report a new approach is introduced for assessing bird community health based on multi-species data from wetland birds across the Great Lakes Basin (Howe et al. 2007a, 2007b; Hanowski et al. 2007a, 2007b; Tozer 2013, 2016). Quantitative data were used for breeding birds at approximately 4,000 sample points throughout the Great Lakes in both the U.S. and Canada. At many of these sample points, information is available on three potential environmental stressors: 1) agricultural intensity in the contributing watershed (i.e., the landscape draining into the wetland), 2) non-agricultural landscape development such as roads, buildings, and human population density in the contributing watershed, and 3) wetland area and fragmentation, measured by the total wetland area within 1 km of the sampled wetland's centroid. For convenience, these gradients are referred to in this report as agriculture, development, and wetland area, respectively. Clearly, many other stressors affect bird communities in coastal wetlands, but agricultural intensity, non-agricultural landscape development, and wetland area provide tractable quantitative yardsticks from which one can identify sensitive species and community variables (Brazner et al. 2007a, 2007b).

For birds, it was assumed that poor wetland condition was associated with high agriculture, high development, and small wetland area. As such, values for the agriculture and development stressors were highly skewed in favour of degraded or unhealthy wetlands, but values for the wetland area stressor suffered from the opposite issue. To alleviate bias that these skewed distributions might cause in later analyses, i.e., to downplay the influence of the small but highly influential number of sites with extreme values, the Yeo-Johnson transformation was applied (Yeo and Johnson 2000) in R (version 3.1.3, R Core Team 2015) with package "car" (Fox and Weisberg 2011). This normalizing transformation resembles the general Box-Cox power transformation but allows for zero values in the data. To avoid power transformations involving decimal values, values of the environmental gradient were first multiplied by a large constant (e.g., 100). After transformation each stressor was converted to a standard scale with extreme values representing the most impacted (0) and least impacted (10) sample points with respect to that stressor. Distributions of the transformed and standardized variables for agriculture, development, and wetland area stressors resembled normality and could be evaluated alone or in combination. To develop a comprehensive measure of ecosystem health based on breeding birds, principal components analysis (PCA) was used to combine the agriculture, development, and wetland area stressors into a single multi-variate "human footprint" (Gnass Giese et al. 2015), which was used throughout the analysis described below. Scores from two of the three PCA axes could be ordered and scaled from most stressed (condition = 0) to least stressed (condition = 10) based on correlations with the original stressor variables. (The magnitude of scores on one axis was opposite in direction to that of the other axis, so values were simply inverted to align with the 0-10 scale.) Scores from the two axes were weighted according to the percent variance explained (total = 61%), summed, and re-scaled from 0-10 to yield the multi-variate "human footprint" stressor gradient.

The health of coastal wetlands was evaluated using the *index of ecological condition* (IEC), an objective biotic indicator introduced by Howe et al. (2007a, 2007b), improved by Gnass Giese et al. (2015), and compared to other similar indices for wetland breeding birds by Chin et al. (2015). Existing data on breeding birds of Great Lakes coastal wetlands described in more detail below were used for the first step in IEC development. The quantitative response of a species or multi-species variable to a given stressor gradient can be modeled from presence/absence or abundance of the species at wetlands where accompanying stressor data were available. Parameters of the best-fit mathematical function were estimated by computer iteration in R (R Core Team 2015) with package "iec" (https://github.com/ngwalton/iec). Results of this analysis yielded three parameters (mean, standard deviation, and height) describing a bell-shaped or truncated Gaussian function within the range of 0-10. These biotic response (BR) functions provide the basis for estimating the health of coastal wetlands based on bird observations (Figure 1). By recording the species present at a wetland, one can essentially work backward to calculate an IEC. Species (or related biotic variables) that have been shown previously to favour minimally-stressed wetlands will indicate ecologically healthy conditions and high IEC scores. By contrast, species (or related biotic variables) that favour highly-stressed wetlands will indicate ecologically unhealthy or degraded conditions and low IEC scores. This method resembles other approaches to environmental indicator development, but the IEC framework establishes an explicit connection between stressors and biotic variables, providing a clear picture about what our indicator truly "indicates." A more detailed description of IEC methodology is available in a separate document (Howe et al. *in prep*.) and at http://www.uwgb.edu/BIODIVERSITY/forest-index/iec.asp.

CWMP data were used (2011-2014) to build BR functions because these samples could be associated with site-specific stressor data. Samples (*n* = 1,117) consisted of the maximum abundance of each bird species detected during two field surveys at a single observation point within a single year (one morning sample and one evening sample). Although the distribution of some species varies across the region, all of the species used in this analysis occur in each of the Great Lakes, so BR functions were generated using data from the entire Great Lakes Basin. Several alternative approaches were considered for identifying the most informative bird-based indicator. For example, the use of abundance data versus presence/absence data were compared, which are much less vulnerable to observer variation or bias. Models using BR functions were also compared of all potentially occurring species versus models using only BR functions of species that were present at the sample point. The latter is desirable because it avoids quantitative "penalties" for the absence of species that were present but not detected or species that do not have suitable microhabitat conditions at the sample point. To avoid excessive zeros in the response variable, the data were grouped into "bins" of 10 samples with similar stressor values. The response variable was then the average abundance among the 10 samples or, in the case of presence/absence data, the frequency of occurrence in the 10 samples. In addition to single species metrics, a number of multi-species metrics was also calculated, including variables such as total number of individuals of wading birds and number of marsh-obligate bird species. For these variables, "binned" data consisted of average values for each group of 10 samples. Data from the CWMP were used to derive a final suite of BR functions, which in turn were used to derive IEC scores for wetlands from the GLMMP, GLEI, and CWMP projects. The results presented in this report are based on presence/absence data using only BR functions of individual species that were present at each sample point. Based on this examination of results from the many alternative approaches described above, this was the most informative and cost-effective approach for determining coastal wetland health based on wetland breeding birds.

The final suite of species was identified for calculating BR functions and IECs via the following steps. The process started with all species in the dataset, and then eliminated all non-wetland affiliated species (e.g., forest birds), migrants, wintering species, unidentified species, and species present at fewer than five of the sample points. This left a suite of candidate species that were associated at least partly with open wetlands during the spring and early summer, i.e., "wetland breeding birds". This definition includes "marsh obligates" (species that live and breed exclusively or almost exclusively in open marshes) and "marsh users" (species that forage, rest or roost, use, or occasionally breed in an open marsh, but are more typical of other habitats, e.g., upland grasslands or woodlands). Species were then eliminated for which the BR functions were uninformative (lowest 10% range between minimum and maximum predicted response) or highly variable (10% poorest goodness-of-fit). Non-native species were also excluded that favoured minimally-stressed wetlands (e.g., Mute Swan [*Cygnus olor*]) or species of conservation concern (e.g., Common Tern [*Sterna hirundo*]) that favoured stressed sites where features like artificial nesting structures were present. While these species are predictive of the gradient, they are likely to be present due to factors other than wetland health. The resulting 52 species used to generate BR functions for calculating IECs are shown in Table 1.

IECs for each sample point were calculated in each year based on species observed across either two field visits (for CWMP and GLMMP) or a single visit (GLEI). Next the point-level IECs were averaged across all sample points within each wetland or wetland complex in each year, which adjusted for wetlands containing differing numbers of sample points. Means of these wetland-level IECs for coastal wetlands in each basin and throughout the entire Great Lakes Basin were reported (hereafter "overall") in each year. These means form the basis for the status and trend assessments, but comparable IEC metrics for inland wetlands are also reported. In addition, distributions of IECs for coastal and inland wetlands in each basin and overall for recent years from 2011-2014 were reported to illustrate variation in the health of wetlands. In these calculations bird-based IEC values were averaged across years for wetlands that were sampled in multiple years. Note that data from 2011-2014 were used in these calculations to increase sample sizes for illustrating the distribution of IECs of inland wetlands, but assessments of current coastal wetland status are based on 2014 data only.

Status—Dentitions of good, fair, and poor condition were assigned based on wetland-level IECs from all years and all wetlands across all basins (*n* = 4,938). IEC values greater than the 66th percentile were good, values between and including the 33rd and 66th percentiles were fair, and values less than the 33rd percentile were poor. This translated into the following definitions:

- ***Good***: IEC > 4.2
- ***Fair***: 3.1 ≤ IEC ≤ 4.2
- ***Poor***: IEC < 3.1

Trend—The terms improving, unchanging, and deteriorating were applied based on geometric mean rates of change (%/ yr) using equation 4 in Smith et al. (2014). The statistical significance of trends was assessed via parametric bootstrapping in R (R Core Team 2015) with package "boot" (Canty and Ripley 2013). Bootstrapping in this manner was necessary to account for the varying precision of the beginning annual estimate and the ending annual estimate used to calculate each trend. Trend estimates with 95% confidence intervals that did not overlap zero were considered statistically significant. The short- and long-term trends were calculated but the trend assessments for the Great Lakes Basin and each individual basin are based on short-term changes in bird assemblages. Short term was defined as the period 2011-2014, whereas long term was 1995-2014 or 2002-2014 in cases where < 10 wetlands were sampled in 1995. The following definitions were used to describe the status of bird assemblages at Great Lakes coastal wetlands:

- ***Improving***: statistically significant short-term increase in IEC
- ***Unchanging***: no statistically significant short-term increase or decrease in IEC
- ***Deteriorating***: statistically significant short-term decrease in IEC

Endpoint— The endpoint of this sub-indicator was defined as the level when mean IECs were confidently above the lower cutoff for good condition. In other words, the endpoint was reached when the lower 95% confidence limit for mean IEC was > 4.2.

<u>Status and trend of coastal wetland birds</u>
Data coverage—The dataset available for scoring sites consisted of mean annual wetland-level IECs based on 30,252 point counts conducted at 3,932 sample points in 1,511 wetlands over 20 years from 1995-2014 throughout the Great Lakes Basin (Figure 2). The number of years that each wetland was surveyed varied from 1 to 20, with a mean of 3.3 ± 3.7 (SD), due mostly to large differences in observer participation in the long running, broad scale GLMMP (Figure 2). The majority of the surveyed wetlands were coastal (*n* = 1,078; 71%) rather than inland (*n* = 433; 29%) because both the GLEI and CWMP projects focused entirely on coastal wetlands, whereas the GLMMP surveyed both (Figure 2).

The number of wetlands surveyed per year (296 ± 127 [mean ± SD]) ranged from 123 to 513 with substantially more wetlands surveyed from 2002-2003 and from 2011-2014 due to the GLEI and CWMP projects operating during those years (Figure 3). Annual coverage was also higher in Lake Erie and Lake Ontario compared to the upper Great Lakes mostly because GLMMP coverage is more extensive in the lower lakes. Annual coverage also was higher at coastal compared to inland wetlands (Figure 2).

Overall—Mean IEC in coastal wetlands ranged from 3.3 to 4.0 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 3.9 in 2014 (Figure 4). The distribution of coastal IECs across the degraded-pristine gradient from 2011-2014 approximated a normal distribution (Figure 5). Based on these patterns, the status of coastal wetland health in the Great Lakes overall is fair and the trend is unchanging. Similar patterns occurred at inland wetlands (Figures 4, 5).

Lake Superior—Mean IEC in coastal wetlands ranged from 1.8 to 5.3 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period above the endpoint at 4.7 in 2014 (Figure 4). The distribution of coastal IECs across the degraded-pristine gradient from 2011-2014 approximated a normal distribution, notably with no wetlands scoring less than 2.0 (Figure 5). Based on these patterns, the status of coastal wetland health in Lake Superior is good and the trend is unchanging. Similar patterns occurred at inland wetlands in the Lake Superior watershed, although the status of inland wetlands was fair rather than good and low sample sizes precluded trend estimates, or clear determination of the distribution of inland IECs from 2011-2014 (Figures 4, 5). Although landscapes in the coastal zone of Lake Superior are generally non-agricultural and minimally developed compared with wetlands in the more southern lakes (Bourgeau-Chavez et al. 2015), it was calculated that coastal wetlands of Lake Superior (with a few notable exceptions) are relatively small in area, accounting at least partially for the modest scores in comparison with those from other lakes.

Lake Michigan—Mean IEC in coastal wetlands ranged from 2.8 to 4.3 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period below the endpoint at 3.9 in 2014 (Figure 4). The distribution of coastal IECs across the degraded-pristine gradient from 2011-2014 approximated a normal distribution (Figure 5). Based on these patterns, the status of coastal wetland health in Lake Michigan is fair and the trend is unchanging. Similar patterns occurred at inland wetlands in the Lake Michigan watershed, although low sample sizes precluded trend estimates, or clear determination of the distribution of inland IECs from 2011-2014 (Figures 4, 5). Some of the highest quality wetlands with respect to birds occur in Lake Michigan, even though development and agricultural stressors are fairly strong in parts of the coastal zones of this lake (Bourgeau-Chavez et al. 2015).

Lake Huron—Mean IEC in coastal wetlands ranged from 3.8 to 5.0 from 1995-2014, with no significant increase or decrease from 1995-2014, or more recently from 2011-2014, ending the period above the endpoint at 4.6 in 2014 (Figure 4). The distribution of coastal IECs across the degraded-pristine gradient from 2011-2014 deviated from a normal distribution, with more wetlands located towards the degraded end of the gradient (Figure 5). Based on these patterns, the status for coastal wetland health in Lake Huron is good and the trend is unchanging. Similar patterns occurred at inland wetlands in the Lake Huron watershed, although the status of inland wetlands was fair rather than good and low sample sizes precluded clear determination of the distribution of inland IECs from 2011-2014 (Figures 4, 5). Some of the highest quality wetlands with respect to birds occur in Lake Huron, even though development and agricultural stressors are fairly strong in parts of the coastal zones of this lake (Bourgeau-Chavez et al. 2015).

Lake Erie—Mean IEC in coastal wetlands ranged from 2.8 to 4.1 from 1995-2014, with a significant decrease from 1995-2014, as well as more recently from 2011-2014, ending the period below the endpoint at 3.0 in 2014 (Figure 4). The distribution of coastal IECs across the degraded-pristine gradient from 2011-2014 deviated from a normal distribution, with more wetlands located towards the pristine end of the gradient (Figure 5). Based on these patterns, the status of coastal wetland health in Lake Erie is poor and the trend is deteriorating. Similar patterns occurred at inland wetlands in the Lake Erie watershed in terms of the distribution of IECs across the degraded-pristine gradient from 2011-2014 (Figure 5). By contrast, there were no significant trends over time at inland wetlands, partly because mean IEC at inland wetlands started out relatively low in 1995, unlike the comparatively high scores at coastal wetlands (Figure 4).

Lake Ontario—Mean IEC in coastal wetlands ranged from 3.1 to 3.9 from 1995-2014, with a significant increase from 1995-2014, as well as more recently from 2011-2014, ending the period below the endpoint at 3.8 in 2014 (Figure 4). The distribution of coastal IECs across the degraded-pristine gradient from 2011-2014 approximated a normal distribution (Figure 5). Based on these patterns, the status of coastal wetland health in Lake Ontario is fair and the trend is improving. Similar patterns occurred at inland wetlands in the Lake Ontario watershed in terms of the distribution of IECs across the degraded-pristine gradient from 2011-2014 (Figure 5). By contrast, there were no significant trends over time at inland wetlands (Figure 4).

Discussion—Throughout the Great Lakes Basin, the current status of coastal wetland health based on wetland breeding birds is fair, with current status of Lake Superior and Lake Huron being good, Lake Michigan and Lake Ontario being fair, and Lake Erie being poor. In addition, we found that coastal IECs located towards the degraded end of the degraded-pristine gradient are more common in Lake Michigan, Lake Erie, and Lake Ontario compared to Lake Superior and Lake Huron. For instance, the proportion of coastal wetlands from 2011-2014 with IECs < 5 was 73-94% in Lake Michigan, Lake Erie, and Lake Ontario, with degraded wetlands especially prevalent in Lake Erie and Lake Ontario. By contrast, the proportion was 46-52% in Lake Superior and Lake Huron (Figure 5). These patterns are probably due to greater anthropogenic stress from agriculture, development, and perhaps wetland loss in Lake Michigan south of the Canadian Shield, and in all of Lake Erie and Lake Ontario compared to Lake Superior and most parts of Lake Huron (Allan et al. 2013, Bourgeau-Chavez et al. 2015, Danz et al. 2007, Niemi et al. 2009). Nonetheless, some high quality coastal wetlands are still present in all of the Great Lakes (Figure 5). By illustrating and documenting differences in wetland health in these ways, the analysis provides a unique baseline for assessing long-term changes in wetland quality and for quantifying the success of restoration efforts in individual wetlands, regions, and the entire Great Lakes basin. A more detailed analysis of species' responses to individual stressors is available, but these results are beyond the scope of this report. The condition of sites based on a multi-variate "human footprint" stressor that incorporates measures of all three stressor variables (agriculture, development, and wetland area) was reported.

Throughout the Great Lakes Basin, coastal wetland health based on wetland breeding birds did not significantly increase or decrease over the short term from 2011-2014, or over the long term from 1995-2014, with trends in most individual lake basins showing no significant increase or decrease over the short or long term. Exceptions were in Lake Ontario, where IECs significantly increased both over the short term from 2011-2014 and over the long term from 1995-2014, and in Lake Erie, where IECs significantly decreased both over the short term from 2011-2014 and over the long term from 1995-2014 (Figure 4). The cause of Lake Ontario's recent increase in IECs is unclear, whereas the short- and long-term decreases in IECs in Lake Erie may be associated with increasing amounts of anthropogenic stress from agriculture, development, and perhaps wetland loss (e.g., Danz et al. 2007, Wolter et al. 2006). Thus, given that Lake Erie was the only lake basin where coastal IECs significantly decreased over time may suggest that the health of Lake Erie's coastal wetlands are particularly compromised compared to coastal wetlands in the remaining lake basins. The declining trends may also indicate that Lake Erie is experiencing unique stressors or relatively high intensities of stressors compared with stressors in the other lake basins.

In addition to assessing status and trend of the health of coastal wetlands, status and trend of inland wetlands were examined for comparison (Figures 4, 5). The ability to compare coastal and inland wetlands due to differences in sample sizes was best for Lake Erie and Lake Ontario, whereas it was limited for the other lake basins. Similar patterns across coastal and inland wetlands were found, with the following exceptions. In Lake Erie, coastal IECs significantly decreased over the short term from 2011-2014, and over the long term from 1995-2014, but inland IECs showed no significant corresponding short- or long-term decreases (Figure 4). In Lake Ontario, coastal IECs significantly increased over the short-term from 2011-2014, but inland IECs exhibited no significant corresponding increase (Figure 4). Thus, wetland health as represented by wetland birds may be responding to different intensities of stressors in coastal versus inland wetlands within the Lake Erie and Lake Ontario watersheds. Similarly, a previous study using only the GLMMP dataset observed that mean abundance of certain wetland-dependent bird species was lower at coastal marshes compared to inland marshes (Tozer 2013). Thus, continued sampling of both coastal and inland wetlands throughout the Great Lakes Basin is needed to completely monitor and assess the health of wetlands based on birds throughout the entire region.

The overall fair status and unchanging trend reported for coastal wetlands throughout the Great Lakes Basin contrasts with previous reports for this sub-indicator, which noted overall poor status and deteriorating trends based on the prevalence of significant negative trends in abundance among approximately 20 wetland-dependent breeding bird species using the GLMMP dataset alone (e.g., Tozer 2014). The apparent discrepancy in overall status and trend between this report and previous reports is likely at least partially due to differences in sampling coverage, with previous reports summarizing the status and trend of predominantly the southern portion of the Great Lakes basin due to reliance on the mostly southern GLMMP dataset; the current report provides a more balanced assessment throughout the entire Great Lakes Basin by bringing GLMMP data together with data from the southern and northern GLEI and CWMP projects. Thus, the overall poor status and deteriorating trend reported previously may have only been most representative, for instance, of the current poor status and deteriorating trend reported for Lake Erie. Nevertheless, it is important to note that the patterns summarized in this report are based on a comprehensive IEC metric, which represents the collective responses of dozens of breeding bird species to wetland condition. Therefore, one should not lose sight of the fact that there are particular species, including bitterns (e.g., *Botaurus*), shallow- (e.g., *Porzana*) and deep-water rails (e.g., *Gallinula*), and marsh-nesting terns (e.g., *Chlidonias*), which have experienced long-term declines at various scales in the Great Lakes (e.g., Tozer 2013, 2016) that may be responding in species-specific ways to environmental stressors that warrant unique management actions or present unique opportunities for improving wetland health.

Linkages

Coastal wetland breeding birds are influenced by numerous local and landscape-level characteristics, some of which are monitored by other Great Lakes (previously known as SOLEC) indicators. For instance, coastal wetland breeding birds are known to be influenced by changing water levels at local and individual Great Lakes Basin scales (e.g., Timmermans et al. 2008, Jobin et al. 2009). Thus, the Coastal Wetland Birds sub-indicator can be expected to co-vary with the Water Levels sub-indicator (e.g., Chin et al. 2014). Similarly, the Coastal Wetland Birds sub-indicator can be expected to co-vary with sub-indicators that track the extent and spatial arrangement of wetland breeding bird habitat (e.g., Coastal Wetland Landscape Extent and Composition) and prey (Coastal Wetland Invertebrate Communities; Coastal Wetland Fish Community Health). It can also be expected to co-vary with invasive plant species (e.g., *Phragmites australis*) that encroach upon preferred native vegetation (e.g., Aquatic and Terrestrial Non-Native Species) and pollution that may reduce prey abundance and/or availability (e.g., Contaminants in Sediments and Fish).

Comments from the Author(s)
This approach has been completed using the GLMMP component of the larger dataset analyzed in this report. Using multi-season site occupancy models and data from 21,546 GLMMP point counts conducted at 2,149 sample points, Tozer (2016) determined important local, wetland, and landscape-scale factors influencing occupancy of 15 wetland breeding marsh bird species in wetlands throughout the southern portion of the Great Lakes Basin.

The status and trend assessment of coastal wetland health based on wetland breeding birds is based on BR functions developed using CWMP data only. The BR functions were also developed based on information from three stressor gradients: agriculture, development, and wetland area. The ability of the IEC to capture the health of coastal wetlands based on bird data might be improved by expanding the development of the BR functions to include all of the marsh bird data that are available from the GLMMP, GLEI, and CWMP projects. The performance of the IEC might also be improved by incorporating other known wetland bird stressors in the development of BR functions, particularly within-wetland attributes like relative dominance of invasive plant species. These ideas are fruitful areas for future expansion.

For the first time, three large marsh bird datasets were brought together, specifically the GLMMP, GLEI, and CWMP project datasets to perform the analyses summarized in this report. This provided a tremendous improvement in analytical power at many different scales compared to using only one of the datasets. However, it was evident that the combined dataset is lacking information from healthy wetlands. Future collection of bird data from wetlands located towards the pristine end of the degraded-pristine gradient might improve the performance of the IEC.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

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List of Tables

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No.	Common name	Scientific name
1	American Bittern	*Botaurus lentiginosus*
2	American Crow	*Corvus brachyrhynchos*
3	American Goldfinch	*Spinus tristis*
4	American Robin	*Turdus migratorius*
5	Bald Eagle	*Haliaeetus leucocephalus*
6	Barn Swallow	*Hirundo rustica*
7	Belted Kingfisher	*Megaceryle alcyon*
8	Black Tern	*Chlidonias niger*
9	Black-crowned Night-Heron	*Nycticorax nycticorax*
10	Blue-winged Teal	*Anas discors*
11	Bobolink	*Dolichonyx oryzivorus*
12	Brown-headed Cowbird	*Molothrus ater*
13	Canada Goose	*Branta canadensis*
14	Caspian Tern	*Hydroprogne caspia*
15	Cliff Swallow	*Petrochelidon pyrrhonota*
16	Common Gallinule	*Gallinula galeata*
17	Common Goldeneye	*Bucephala clangula*
18	Common Grackle	*Quiscalus quiscula*
19	Common Loon	*Gavia immer*
20	Common Merganser	*Mergus merganser*
21	Common Yellowthroat	*Geothlypis trichas*
22	Double-crested Cormorant	*Phalacrocorax auritus*
23	Eastern Kingbird	*Tyrannus tyrannus*
24	European Starling	*Sturnus vulgaris*
25	Forster's Tern	*Sterna forsteri*
26	Green Heron	*Butorides virescens*
27	Herring Gull	*Larus argentatus*
28	Hooded Merganser	*Lophodytes cucullatus*
29	House Sparrow	*Passer domesticus*
30	Killdeer	*Charadrius vociferus*
31	Least Bittern	*Ixobrychus exilis*
32	Mallard	*Anas platyrhynchos*
33	Northern Harrier	*Circus cyaneus*
34	Norhtern Rough-winged Swallow	*Stelgidopteryx serripennis*
35	Osprey	*Pandion haliaetus*
36	Purple Martin	*Progne subis*
37	Red-breasted Merganser	*Mergus serrator*
38	Red-winged Blackbird	*Agelaius phoeniceus*
39	Ring-billed Gull	*Larus delawarensis*
40	Sandhill Crane	*Grus canadensis*
41	Sedge Wren	*Cistothorus platensis*
42	Song Sparrow	*Melospiza melodia*
43	Sora	*Porzana carolina*
44	Spotted Sandpiper	*Actitis macularius*
45	Swamp Sparrow	*Melospiza georgiana*
46	Traill's Flycatcher	*Empidonax alnorum/traillii*
47	Tree Swallow	*Tachycineta bicolor*
48	Trumpeter Swan	*Cygnus buccinator*
49	Virginia Rail	*Rallus limicola*
50	Wilson's Snipe	*Gallinago delicata*
51	Wood Duck	*Aix sponsa*
52	Yellow Warbler	*Setophaga petechia*

Table 1. Wetland breeding bird species (n = 52) used to generate biotic response functions for calculating indices of wetland health for Great Lakes coastal wetlands.
Source: Great Lakes Coastal Wetland Monitoring Program

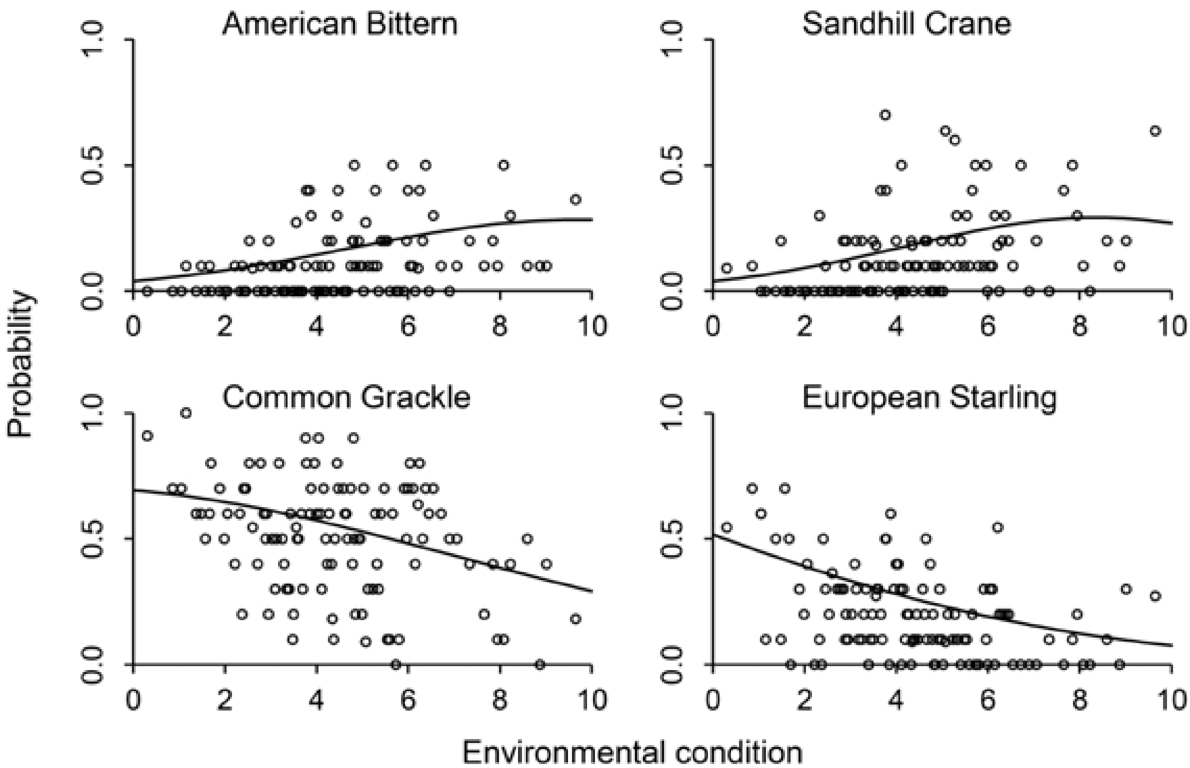
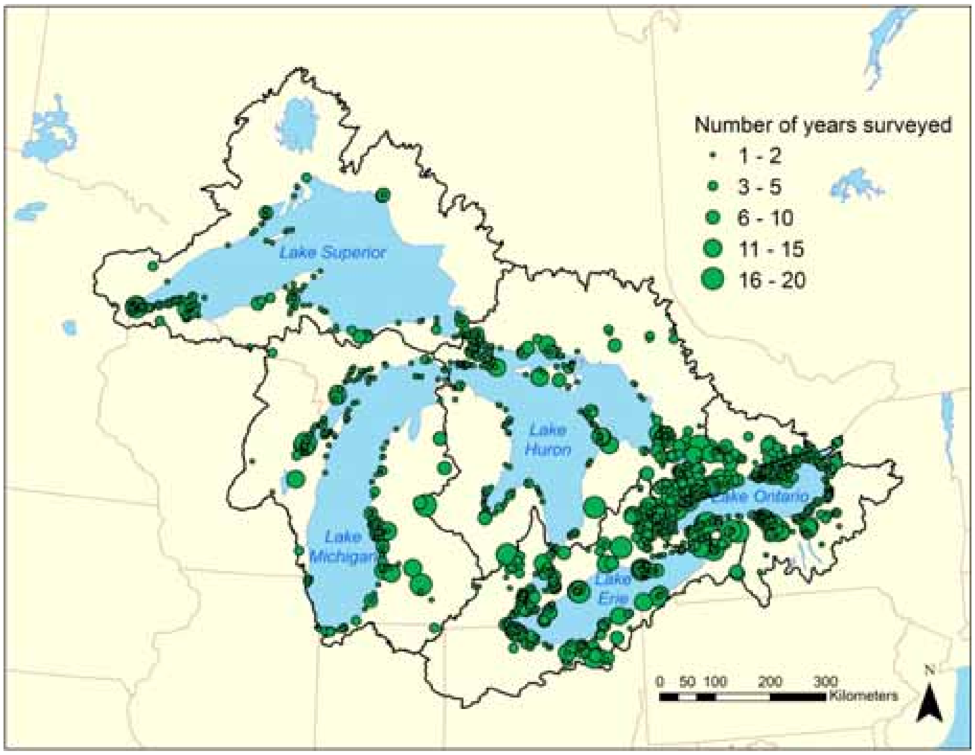


Figure 1. Biotic response functions (solid lines) for selected bird species from coastal wetlands throughout the Great Lakes Basin. Shown is the probability of occurrence as a function of a combined "human footprint" variable incorporating environmental condition due to agriculture, development, and wetland area (0 = poor condition, 10 = good condition). Open circles represent binned data at 10 observations per bin. See Table 1 for scientific names.
Source: Great Lakes Coastal Wetland Monitoring Program



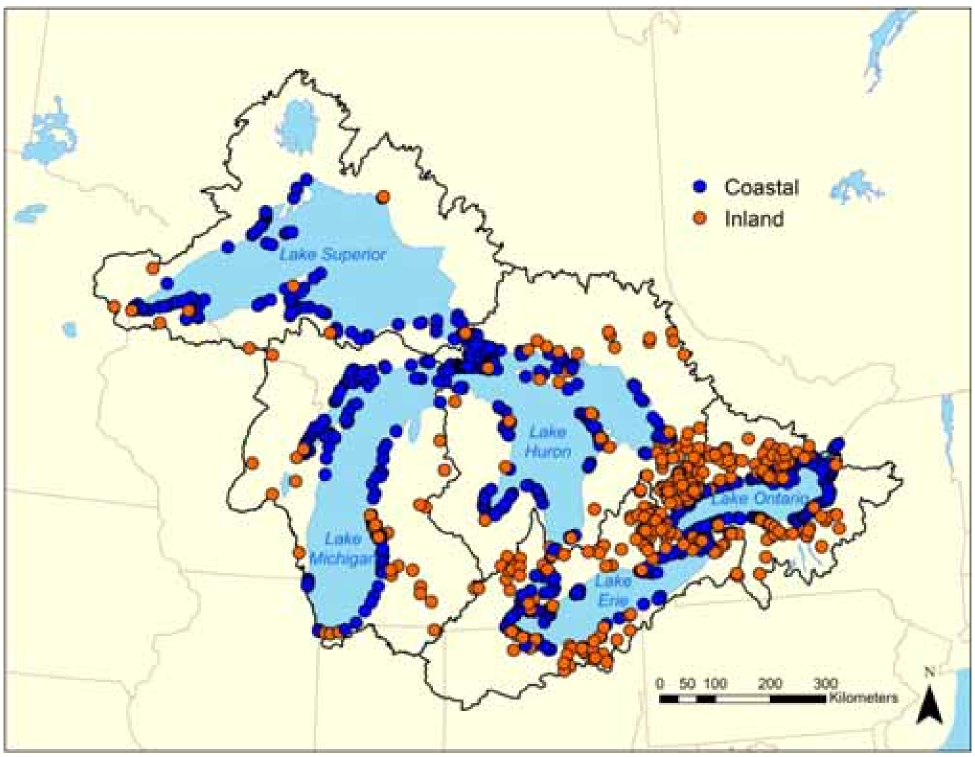


Figure 2. Wetlands surveyed for birds from 1995-2014 throughout the Great Lakes Basin for the purpose of estimating indices of wetland health. Shown are wetlands as a function of the number of years that each wetland was surveyed (upper map) and as a function of coastal versus inland (lower map). Note that coastal wetlands (*n* = 1,078) far outnumber inland wetlands (*n* = 433), although this does not appear to be the case due to tightly overlapping symbols.
Source: Great Lakes Coastal Wetland Monitoring Program

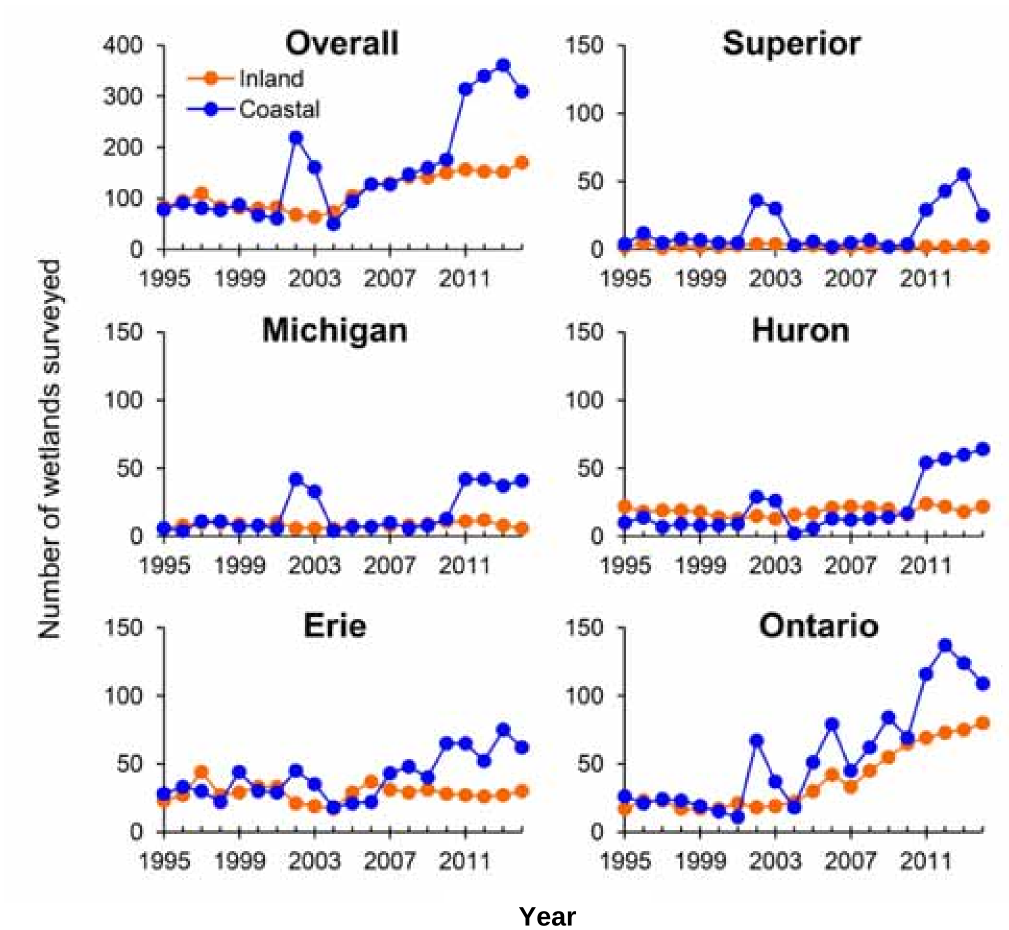


Figure 3. Number of wetlands surveyed for birds per year from 1995-2014 throughout the Great Lakes Basin for the purpose of estimating indices of wetland health. Shown are wetlands surveyed as a function of the entire Great Lakes Basin (overall) and each individual lake basin for coastal and inland wetlands.
Source: Great Lakes Coastal Wetland Monitoring Program

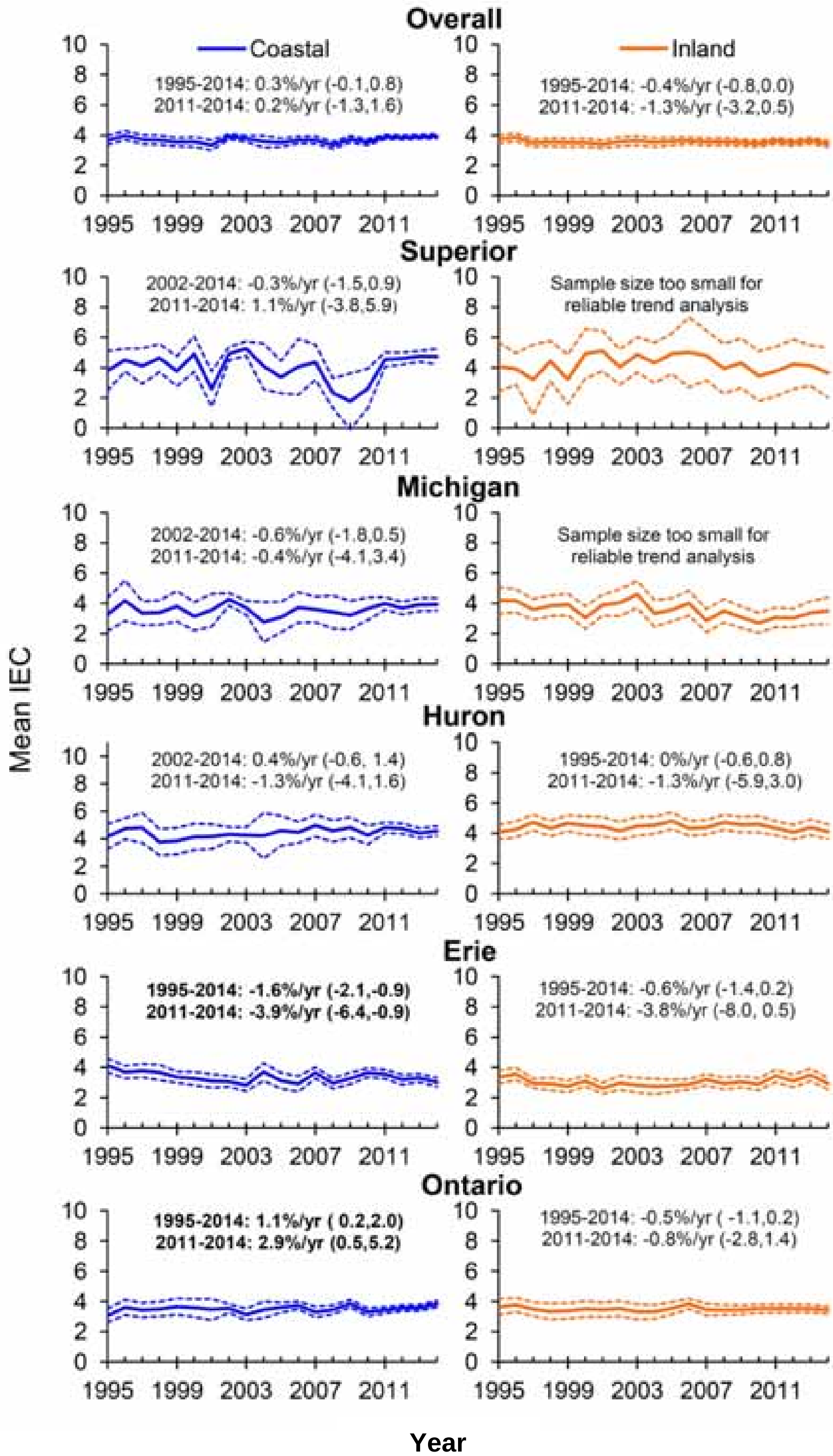


Figure 4. Temporal trends in mean index of ecological condition (IEC) based on bird data from 1995-2014 throughout the Great Lakes Basin (solid lines). Shown are means across all surveyed wetlands in each year as a function of the entire Great Lakes Basin (overall) and each individual lake basin for coastal and inland wetlands. Dashed lines are 95% confidence limits. Also shown are geometric mean rates of change (%/yr) over the long or short term. Short term was 2011-2014, whereas long term was 1995-2014 or 2002-2014 in cases where < 10 wetlands were sampled in 1995.
Source: Great Lakes Coastal Wetland Monitoring Program

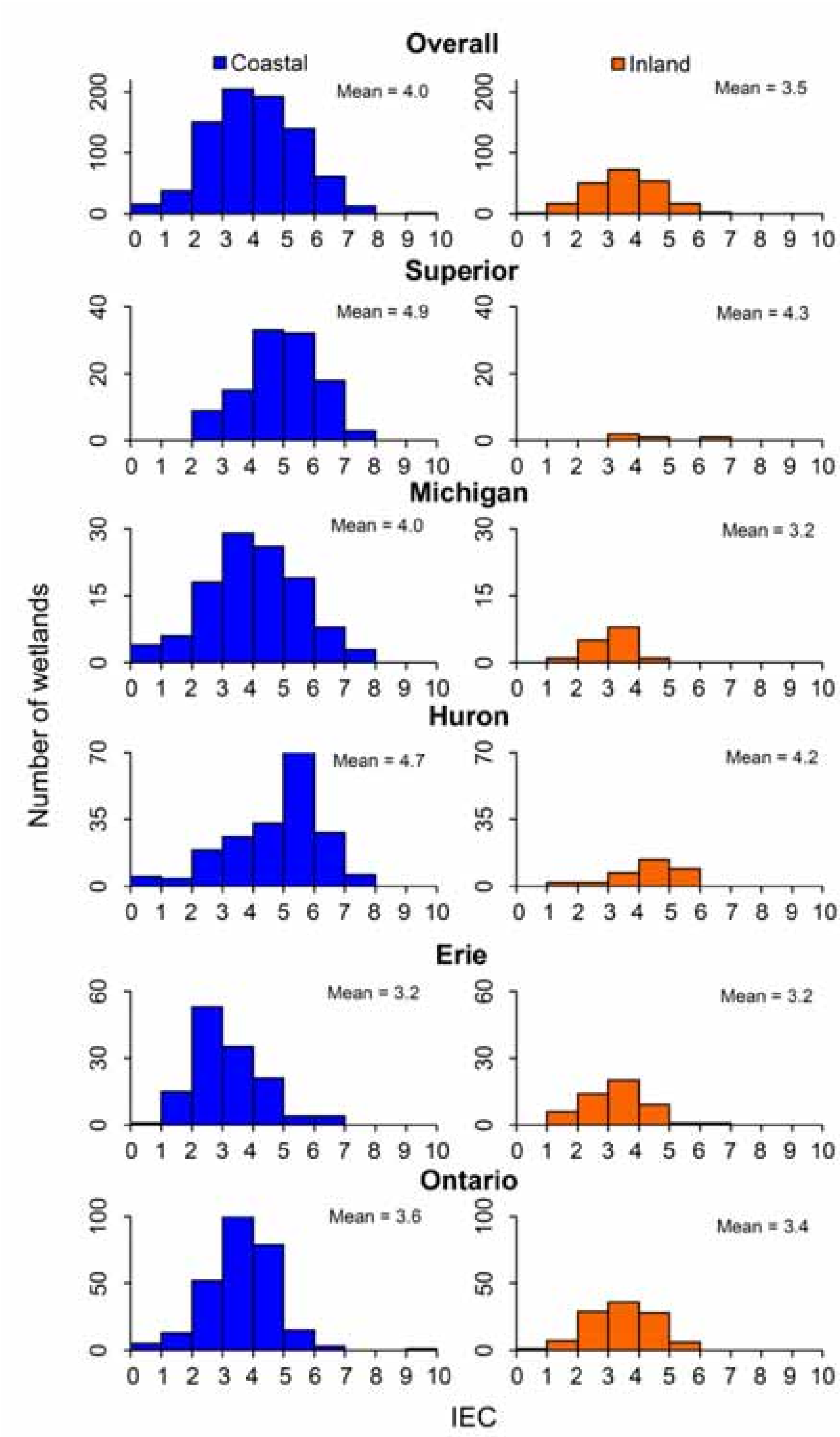


Figure 5. Distribution of index of ecological condition (IEC) scores based on bird data from 2011-2014 throughout the Great Lakes Basin. Shown are IECs for all surveyed wetlands as a function of the entire Great Lakes Basin (overall) and each individual lake basin for coastal and inland wetlands. Note that prior to these calculations we averaged across years for wetlands that were sampled in multiple years. We also note that the vertical axes differ among overall and each lake for clarity of small sample sizes, but are the same within overall and each lake to facilitate comparisons between coastal and inland.
Source: Great Lakes Coastal Wetland Monitoring Program

Sub-Indicator: Coastal Wetland Fish

Overall Assessment

Status: Fair

Trend: Improving

Rationale: As of 2015, the majority of wetland sites were in the moderately degraded category based on the health of coastal wetland fish communities. The trend is determined by comparing the current status of coastal wetland fish to that of three years prior and whether the metric increased, decreased, or showed no substantial change in score. Data are not currently available for long-term trend analysis. In 2012, 17% of wetland sites were in the degraded score category. In 2015, only 8% of wetlands were in the degraded score category. Fair is defined as "the vast majority of the wetlands are not in the degraded category".

Lake-by-Lake Assessment

In an effort funded by the Great Lakes Restoration Initiative (GLRI) through 2020 (about $2 million per year), approximately 200 wetlands were sampled annually since 2011. A total of 176 wetlands were sampled in 2011, 206 sampled in 2012, 201 in 2013, 216 in 2014, and 211 in 2015 for a total of 1010 Great Lakes coastal wetland sampling events. As of 2015, nearly 100% of the medium and large (> 4 hectares), hydrologically-connected coastal wetlands on the Great Lakes have been sampled. With respect to the entire Great Lakes, about 80% of coastal wetlands by count and area have been sampled (Figure 1).

Individual lake basin assessments were not prepared for this report.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to track the trends of Great Lakes coastal wetland ecosystem health by measuring the composition and density of fish communities, and to infer suitability of habitat and water quality for Great Lakes coastal wetland fish communities.

Ecosystem Objective

Coastal Wetland habitats are critical spawning and nursery areas for many fish species of ecological and economic importance. Conservation of remaining coastal wetlands and restoration of previously destroyed wetlands are vital components of restoring the Great Lakes ecosystem and this sub-indicator can be used to report progress toward such an objective.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Restore and maintain the diversity of the fish community of Great Lakes coastal wetlands while indicating overall ecosystem health (Annex 7 GLWQA). Significant wetland areas in the Great Lakes system that are threatened by urban and agricultural development and waste disposal activities should be identified, preserved and, where necessary, rehabilitated. This sub-indicator supports the restoration and maintenance of the chemical, physical and biological integrity of the Great Lakes basin and beneficial uses dependent on healthy wetlands (Annex1 GLWQA).

Ecological Condition

Coastal wetlands trap, process, and remove nutrients and sediment from Great Lakes nearshore waters and recharge groundwater supplies. However, over half of all Great Lakes coastal wetlands have been destroyed by human activities, and many remaining coastal wetlands suffer from anthropogenic stressors such as nutrient and sediment loading, fragmentation, invasive species, shoreline alteration, and water level control, as documented by a binational Great Lakes-wide mapping and attribution project (Albert and Simonson 2004; Ingram and Potter 2004).

In order to properly manage the Great Lakes coastal wetland fish community health there must be consistent sampling methods. Sampling was conducted no earlier than mid-June and no later than August due to migration patterns of the fish communities. Fish should be sampled using three replicate fyke nets of 4.8 mm mesh in each major plant zone in each wetland for one net-night. Dominant vegetation zones were identified because different zones support different fishes (Uzarski et al. 2005). There are two sizes of fyke nets that can be used: 0.5-m x 1-m opening and 1-m x 1-m opening. The smaller nets are placed in water that is 0.25-0.5 m deep and the larger fyke nets are placed in water that is greater than 0.50 m deep. The leads are 7.3 m long with 1.8 m long wings. Nets were haphazardly placed a minimum of 20 m apart in each vegetation zone. The fyke nets are placed perpendicular to the vegetation zone, therefore, fish swimming along the edge of the vegetation zone are captured. This sub-indicator can only be used where there is sufficient water depth to use fyke nets and a minimum of 10 fish must be captured or the sites must be fished another net-night.

Any fish collected that is greater than 25 mm were identified down to species. The number of the fish caught per fyke net were recorded. Fish abundance by taxon is used to calculate the Great Lakes Coastal Wetland Monitoring Program (GLCWMP) IBI scores (Uzarski et al. 2016). The GLCWC developed indices of biological integrity (IBIs) in 2002 and protocols were finalized in 2008 (GLCWC 2008). These were further developed by the GLCWMP. The Index of Biotic Integrity (IBI) was developed based on measures of richness and abundance, percent exotic species, functional feeding groups, and other species-level parameters. Several different fish metrics are being utilized. See GreatLakeswetlands.org ‘Documents’ for details on indicator metrics.

The IBI provides a rigorous approach to quantify the biological condition of fish communities within the Great Lakes. It is based on reference conditions and is developed from a composite of specific measures used to describe fish community, structure, function, individual health, and abundance. Specific parameters, termed "metrics," are scored based on how similar they are to the reference condition. Individual IBIs are derived for each of the measures and can be used independently as a measure of coastal wetland health, based on a percentage of points possible reflected as ‘reference conditions’ to ‘extremely degraded’. The IBI also provides a narrative characterization that provides a measure of the environmental condition and will be calibrated for regional use.

From 2011 to 2015, an average of 10 to about 13 fish species were collected in Canadian and U.S. Great Lakes coastal wetlands, respectively (Table 1). These data include sites in need of restoration, and some had very few species. However, wetlands with the highest richness had as many as 23 (CA) or 28 (US) fish species. The average number of non-native fish species per wetland was approximately one, though some wetlands had as many as 5 (U.S.). There are wetlands in which no non-native fish species were caught in fyke nets, although some non-native fish are adept at net avoidance (e.g. common carp).

From 2011-2015, total fish species did not differ greatly by lake, averaging 12-14 species per wetland (Table 2). Lake Ontario wetlands had the lowest maximum number of species, with the other lakes all having similar maximums of 27-28 species. Lake Huron wetlands averaged the lowest mean number of non-native fish taxa. All other lakes had a similar average number of non-native fish species per wetland, about 1.

When the fish communities of reference wetlands are compared across the entire Great Lakes, the most similar sites come from the same ecological province rather than from any single Great Lake or specific wetland types. Data from several studies indicate that the characteristic groups of fish species in reference wetlands from each ecological province tend to have similar water temperature and aquatic productivity preferences.

There are a number of carp introductions that have the potential for substantial impact on Great Lakes fish communities, including coastal wetlands. Goldfish (*Carassius auratus*) are common in some shallow habitats, and they occurred along with common carp young-of-the-year in many of the wetlands sampled along Green Bay. In addition, there are several other carp species, e.g., grass carp (*Ctenopharyngodon idella),* bighead carp (*Hypophthalmichthys nobilis)* and silver carp (*Hypophthalmichthys molitrix)* that escaped aquaculture operations and are now in the Illinois River and migrating toward the Great Lakes through the Chicago Sanitary and Ship Canal. Most of these species attain large sizes. Some are planktivorous, but also eat phytoplankton, snails, and mussels, while the grass carp eats vegetation. These species represent yet another substantial threat to food webs in wetlands and nearshore habitats with macrophytes (U.S. Fish and Wildlife Service (USFWS) 2002).

Linkages

Pressures

Agriculture

Agriculture degrades wetlands in several ways, including nutrient enrichment from fertilizers, increased sediments from erosion, increased rapid runoff from drainage ditches, introduction of agricultural non-native species (reed canary grass), destruction of inland wet meadow zone by plowing and diking, and addition of herbicides. In the southern lakes, Saginaw Bay, and Green Bay, agricultural sediments have resulted in highly turbid waters which support few or no submergent plants.

Urban development

Physical modifications to the shoreline have disrupted coastal and nearshore processes, flow and littoral circulatory patterns, altered or eliminated connectivity to coastal wetlands/dunes, and have altered nearshore and coastal habitat structure. Urban development degrades wetlands by hardening shoreline, filling wetland, adding a broad diversity of chemical pollutants, increasing stream runoff, adding sediments, and increased nutrient loading from sewage treatment plants. In most urban settings, almost complete wetland loss has occurred along the shoreline. Thoma (1999) and Johnson et al. (2006) were unable to find coastal wetlands on the U.S. side of Lake Erie that experienced minimal anthropogenic disturbances. According to Seilheimer and Chow-Fraser (2006; 2007), there has been accelerated loss of wetland fish habitat in Lake Ontario, Lake Erie and Lake Michigan near urban areas and agriculture.

Residential shoreline development

Along many coastal wetlands, residential development has altered wetlands by nutrient enrichment from fertilizers and septic systems, shoreline alterations for docks and boat slips, filling, and shoreline hardening. Agriculture and urban development are usually less intense than local physical alteration which often results in the introduction of non-native species. Shoreline hardening can completely eliminate wetland vegetation, which results in degradation of fish habitat. It appears that when a wetland becomes affected by human development, the fish community changes to that typical of a warmer, richer, more southerly wetland. This finding may help researchers anticipate the likely effects of regional climate change on the fish communities of Great Lakes coastal wetlands.

Mechanical alteration of shoreline

Mechanical alteration takes a diversity of forms, including diking, ditching, dredging, filling, and shoreline hardening. With all of these alterations, non-native species are introduced by construction equipment or in introduced sediments. Changes in shoreline gradients and sediment conditions are often adequate to allow non-native species to become established.

Introduction of non-native species

Non-native species are introduced in many ways. Some were purposefully introduced as agricultural crops or ornamentals, later colonizing in native landscapes. Others came in as weeds in agricultural seed. Increased sediment and nutrient enrichment allow many of the worst aquatic weeds to out-compete native species. Most of the worst non-native species are either prolific seed producers or reproduce from fragments of root or rhizome. Non-native animals have also been responsible for increased degradation of coastal wetlands. Common and grass carp reproductive and feeding behaviour results in loss of submergent vegetation in shallow marsh waters.

Precipitation Amounts– change in atmospheric temperature will potentially affect the number of extreme storms in the Great Lakes region which will, in turn, affect coastal wetlands

Water Levels – water level change has strong influences on Great Lakes habitat and biological communities associated with Coastal Wetlands. Lake levels have a major influence on undiked coastal wetlands and are basic to any analysis of wetland change trends

Pressures were also described in the Coastal Wetland Plants sub-indicator.

Comments from the Authors(s)

Individual IBIs can be used independently as a measure of coastal wetland health, based on a percentage of points possible reflected as ‘reference conditions’ to ‘extremely degraded’. The sub-indicator has been used basin wide (U.S. and Canada) over the past four years and much longer in some regions. This sub-indicator can also be evaluated as part of an overall analysis of biological communities of Great Lakes coastal wetlands and nearshore aquatic systems. This can be done by by considering the coastal wetland sub-indicators in combination, because they function and indicate anthropogenic disturbance at different spatial and temporal scales and have varying resolution of detection. For example, fish tend to detect disturbance somewhere between the local and regional scale.

The sites sampled in 2015 are shown in Figure 2 and are colour coded by which taxonomic groups were sampled at the sites. Many sites were sampled for all taxonomic groups. Sites not sampled for birds and amphibians typically were sites that were impossible to access safely without a boat, and often related to private property access issues. Most bird and amphibian crews do not operate from boats since they need to arrive at sites in the dark or stay until well after dark. There are also a number of sites sampled only by bird and amphibian crews because these crews can complete their site sampling more quickly and thus have the capacity to sample more sites than do the fish, macroinvertebrate, and vegetation crews.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada	X					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

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Last Updated

State of the Great Lakes 2017 Technical Report

Country	*Sites*	*Mean*	*Max*	*Min*	*St. Dev.*
Overall					
Canada	156	10.0	23	2	3.9
U.S.	365	13.3	28	2	5.2
Non-natives					
Canada	156	0.7	3	0	0.7
U.S.	365	0.7	5	0	0.9

Table 1. Total fish species in wetlands, and non-native species; summary statistics by country for sites sampled from 2011 through 2015.
Source: Great Lakes Coastal Wetland Monitoring Program (CWMP), Uzarski et al. 2016

		Total Fish			Non-native Fish		
Lake	*Sites*	*Mean*	*Max*	*Min*	*Mean*	*Max*	*Min*
Erie	66	12.2	27	2	1.1	4	0
Huron	180	11.5	27	2	0.4	2	0
Michigan	75	13.1	28	5	0.8	4	0
Ontario	135	12.3	23	4	0.8	3	0
Superior	65	14.1	28	3	0.9	5	0

Table 2. Fish total species and non-native species found in Great Lakes coastal wetlands by lake. Mean, minimum, and minimum number of species per wetland. Data from 2011 through 2015.
Source: Great Lakes Coastal Wetland Monitoring Program (CWMP), Uzarski et al. 2016

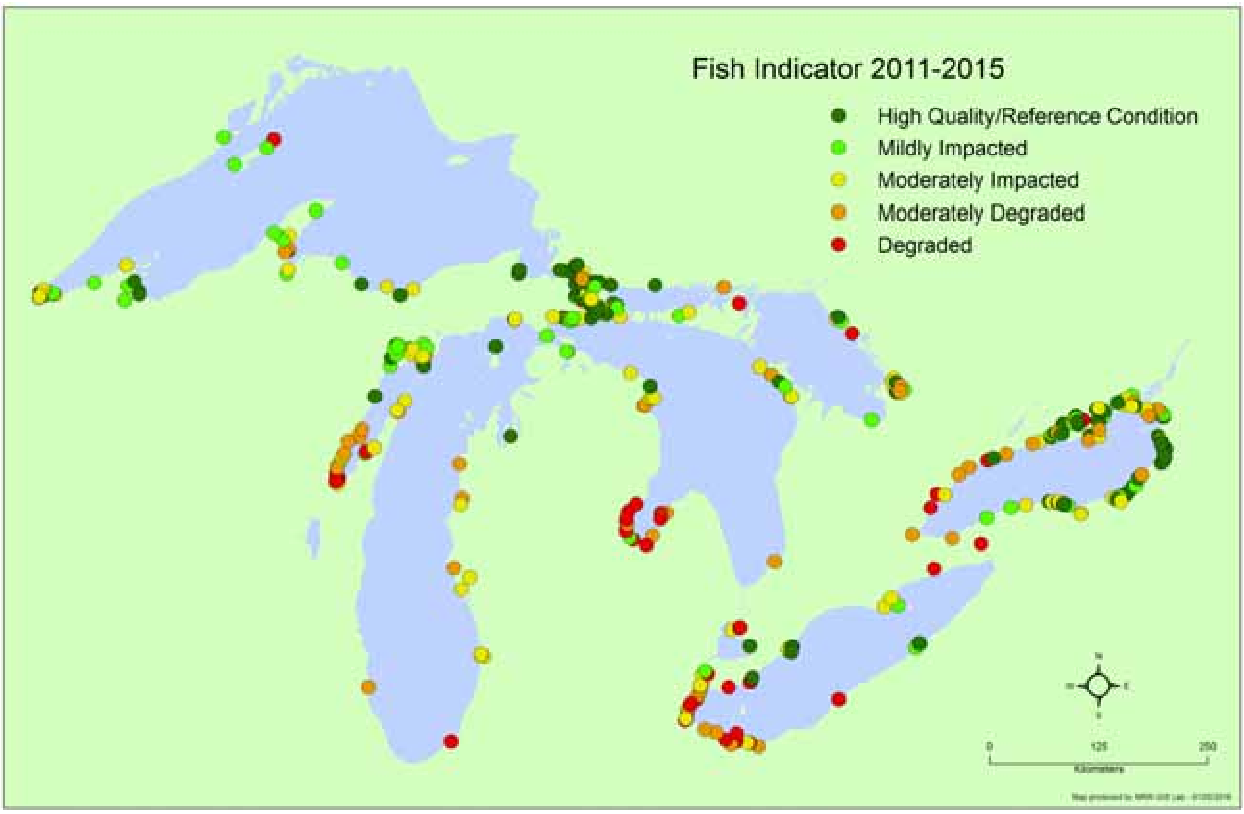

Figure 1. Condition of coastal wetland fish communities based upon data from all sites sampled from 2011 through 2015.
Source: Great Lakes Coastal Wetland Monitoring Program (CWMP), Uzarski et al. 2016

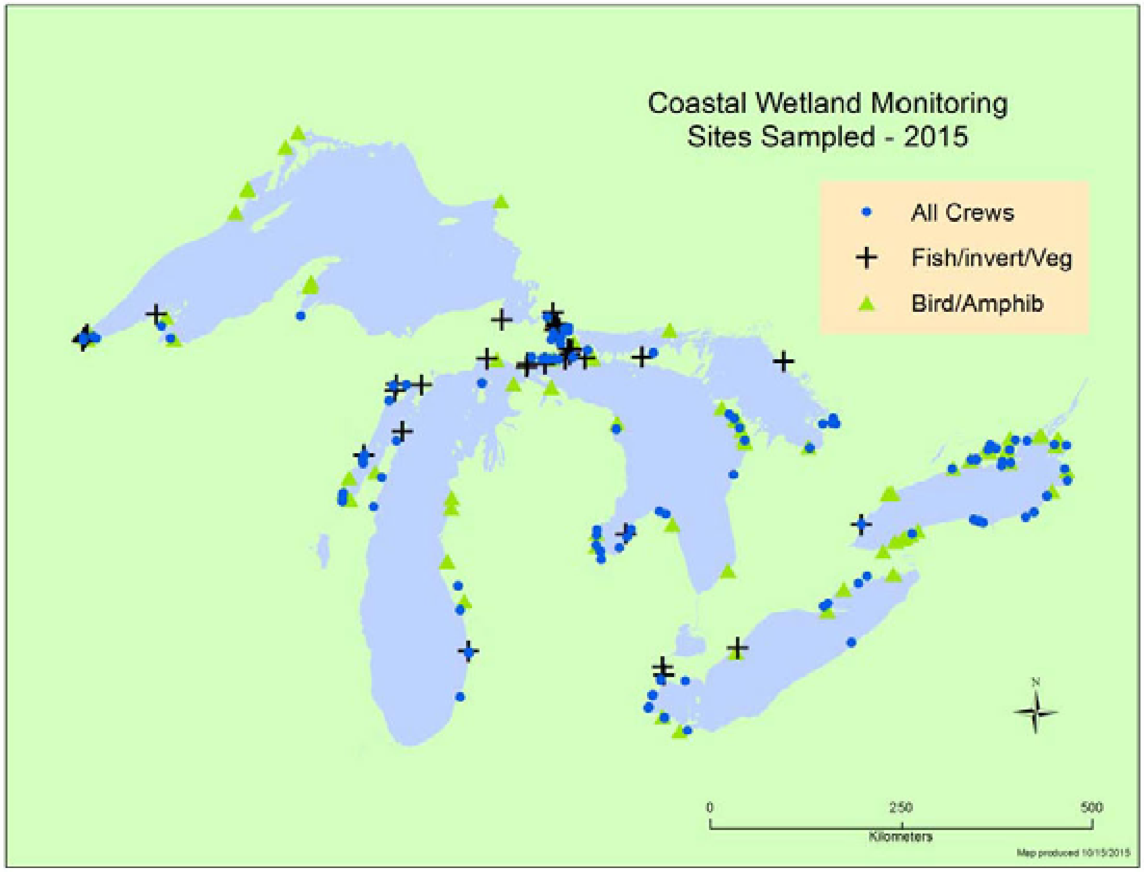

Figure 2. The sites sampled in 2015 are color coded by which taxonomic groups were sampled at the sites. Source: Great Lakes Coastal Wetland Monitoring Program (CWMP), Uzarski et al. 2016

Sub-Indicator: Coastal Wetland Invertebrates

Overall Assessment
Status: Fair
Trend: Deteriorating
Rationale: As of 2015, the vast majority of wetland sites are not in the degraded category based on the health of coastal wetland invertebrate communities. However, in the southern portion of the basin most sites fall within the moderately impacted category or worse. In the norther region, most fall within the moderately impacted category or better. The trend is determined by comparing the current status of invertebrate communities in coastal wetlands to that of three years prior and whether the metric increased, decreased, or showed no substantial change in score. Data are not currently available for long-term trend analysis. In 2012, 17% of wetland sites were in the degraded score category. In 2012, 15% of wetland sites were in the degraded score category. In 2015, 19% of wetlands were in the degraded score category. Fair is defined as "the vast majority of the wetlands are not in the degraded category".

Lake-by-Lake Assessment

In an effort funded by the Great Lakes Restoration Initiative (GLRI) through 2020 (about $2 million per year), approximately 200 wetlands were sampled annually since 2011. A total of 176 wetlands were sampled in 2011, 206 sampled in 2012, 201 in 2013, 216 in 2014, and 211 in 2015 for a total of 1010 Great Lakes coastal wetland sampling events. As of 2015, nearly 100% of the medium and large (> 4 hectares), hydrologically-connected coastal wetlands on the Great Lakes have been sampled. With respect to the entire Great Lakes, about 80% of coastal wetlands by count and area have been sampled, however the most recent sub-indicator map includes data from years 2011 through 2014 as data from 2015 are still being processed into map configuration (Table 1).

Individual lake basin assessments were not prepared for this report.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess the diversity of the invertebrate community, especially aquatic insects; to track the trends of Great Lakes coastal wetland ecosystem health by measuring the composition and density of macroinvertebrates; and to infer water quality, habitat suitability, and biological integrity of Great Lakes coastal wetlands.

Ecosystem Objective

Coastal Wetland habitats are critical spawning and nursery areas for many invertebrate species of ecological and economic importance. Conservation of remaining coastal wetlands and restoration of previously destroyed wetlands are vital components of restoring the Great Lakes ecosystem and this sub-indicator can be used to report progress toward such an objective.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Significant wetland areas in the Great Lakes system that are threatened by urban and agricultural development and waste disposal activities should be identified preserved and, where necessary, rehabilitated. Conducting monitoring and surveillance activities will gather definitive information on the location, severity, aerial or volume extent, and frequency of the monitoring of Great Lakes coastal wetlands. This sub-indicator supports the restoration and maintenance of the chemical, physical and biological integrity of the Great Lakes Basin and beneficial uses dependent on healthy wetlands (Annex 1 GLWQA).

Ecological Condition

Coastal wetlands trap, process, and remove nutrients and sediment from Great Lakes nearshore waters; and recharge groundwater supplies. However, over half of all Great Lakes coastal wetlands have been destroyed by human activities and many remaining coastal wetlands suffer from anthropogenic stressors such as nutrient and sediment loading, fragmentation, invasive species, shoreline alteration, and water level control, as documented by a binational Great Lakes-wide mapping and attribution project (Albert and Simonson 2004; Ingram and Potter 2004).

To restore/maintain the overall biological integrity of Great Lakes coastal wetlands, the various ecological components need to be adequately represented. The Great Lakes Coastal Wetland Consortium (GLCWC)-adopted Index of Biotic Integrity (IBI, Uzarski *et al.* 2004) and further developed by the Great Lakes Coastal Wetland Monitoring Program (GLCWMP) offers information on overall diversity of the invertebrate community and trends over time (Uzarski et al. 2016). The presence, diversity and abundance of invertebrates tend to correlate with factors such as water depth, vegetation, and sediment type. Such localized conditions influence the invertebrate community present in each wetland. Therefore, a sufficient number of representative wetlands were needed to characterize each lake basin adequately. The SOLEC 98 Biodiversity Investment Areas paper on Coastal Wetland Ecosystems identified the eco-reaches from which representative wetlands were selected.

Macroinvertebrate samples should be collected annually from the dominant plant zones in each wetland using dip nets in accordance with standard protocols initially developed by the GLCWC and further developed by the GLCWMP. Plant zones are defined as patches of vegetation in which a particular plant type or growth form dominates the plant community based on visual coverage estimates. Numerous replicate samples are collected from each plant zone within each wetland. Samples should be collected annually and depending on latitude and wetland type during either June, July, or August when vegetation has developed. Southern drowned river mouths should be sampled during June while lacustrine sites should be sampled during July in the south latitudes and during August in the northern latitudes.

The invertebrate IBI has been applied to coastal wetlands basin-wide by a syndicate of universities from 2011 to 2015. IBI scores were primarily based on richness and relative abundance of Odonata; richness and relative abundance of Crustacea plus Mollusca taxa; total genera richness; relative abundance of Gastropoda; relative abundance of Sphaeriidae; richness of Ephemeroptera plus Trichoptera taxa; relative abundance Isopoda; relative abundance of Amphipoda; Evenness; Shannon Diversity Index; and Simpson Index. See GreatLakeswetlands.org ‘Documents’ for details on indicator metrics.

As of 2014, the average number of macroinvertebrate taxa (taxa richness) per site was about 40, but some wetlands had more than twice this number (Table 1). Sites scheduled for restoration and other taxonomically poor wetlands had fewer taxa, as little as 10 at a Canadian site and as little as zero at restoration sites in the US. However, the average number of non-native invertebrate taxa in coastal wetlands was less than 1, with a maximum of no more than 5. It is important to note that the one-time sampling method used at coastal wetland sites may not be capturing all of the non-native taxa and it is not necessarily intended to. Furthermore, some non-native macroinvertebrates are very cryptic, may resemble native taxa, and may not yet be recognized as invaders to the Great Lakes.

There is some variability among lakes in the mean number of macroinvertebrate taxa per wetland. Lake Ontario and Erie wetlands averaged 32 and 35 taxa, respectively (Table 2), while Lakes Huron and, Superior, and Michigan about 42-47 taxa. The maximum number of invertebrate taxa was higher in lakes Huron and Michigan wetlands (>80) than for the most invertebrate-rich wetlands in other lakes, which have a maximum of 60-70 taxa. Wetlands with the fewest taxa are sites in need of restoration and have as few as no taxa found at all (in both Erie and Ontario). Patterns are likely driven by differences in habitat complexity, which may in part be due to the loss of wetland habitats on lakes Erie and Ontario from diking and water level control, respectively. There is little variability among lakes in non-native taxa occurrence, although Erie and Huron had wetlands with 4-5 non-native taxa. In each lake, a portion of wetlands had zero non-native taxa; however, as noted above, this does not necessarily mean that these sites do not harbor non-native macroinvertebrates.

Linkages

Pressures

Physical alteration and eutrophication of wetland ecosystems continue to be a threat to invertebrates of Great Lakes coastal wetlands. Both can promote establishment of non-native vegetation, and physical alteration can destroy plant communities altogether while changing the natural hydrology to the system. Invertebrate community composition is directly related to vegetation type and densities; changing either of these components will negatively impact the invertebrate communities.

Agriculture
Agriculture degrades wetlands in several ways, including nutrient enrichment from fertilizers, increased sediments from erosion, increased rapid runoff from drainage ditches, introduction of agricultural non-native species (reed canary grass), destruction of inland wet meadow zone by plowing and diking, and addition of herbicides.

Urban development
Physical modifications to the shoreline have disrupted coastal and nearshore processes, flow and littoral circulatory patterns, altered or eliminated connectivity to coastal wetlands/dunes, and have altered nearshore and coastal habitat structure. Urban development degrades wetlands by hardening shoreline, filling wetland, adding a broad diversity of chemical pollutants, increasing stream runoff, adding sediments, and increased nutrient loading from sewage treatment plants. In most urban settings, almost complete wetland loss has occurred along the shoreline.

Residential shoreline development
Along many coastal wetlands, residential development has altered wetlands by nutrient enrichment from fertilizers and septic systems, shoreline alterations for docks and boat slips, filling, and shoreline hardening. Agriculture and urban development are usually less intense than local physical alteration which often results in the introduction of non-native species.

Mechanical alteration of shoreline
Mechanical alteration takes a diversity of forms, including diking, ditching, dredging, filling, and shoreline hardening. With all of these alterations, non-native species are introduced by construction equipment or in introduced sediments.

Introduction of non-native species
Non-native species are introduced in many ways. Some were purposefully introduced as agricultural crops or ornamentals, later colonizing in native landscapes. Others came in as weeds in agricultural seed. Increased sediment and nutrient enrichment allow many of the worst aquatic weeds to out-compete native species. Most of the worst non-native species are either prolific seed producers or reproduce from fragments of root or rhizome. Non-native animals have also been responsible for increased degradation of coastal wetlands. The faucet snail (Bithynia tentaculata) is an example of a prolific macroinvertebrate invader of particular interest to USFWS and others because it carries parasites that can cause disease and die-offs of waterfowl.

Pressures were also described in the Coastal Wetland Plants sub-indicator.

Precipitation Amounts – change in atmospheric temperature will potentially affect the number of extreme storms in the Great Lakes region which will, in turn, affect coastal wetlands

Water Levels – water level change has strong influences on Great Lakes habitat and biological communities associated with Coastal Wetlands. Lake levels have a major influence on undiked coastal wetlands and are basic to any analysis of wetland change trends

Comments from the Author(s)

The invertebrate IBI is a multi-indicator, developed from a composite of specific parameters, termed "metrics," used to describe the invertebrate community, structure, function, and abundance. The IBI provides a rigorous approach that quantifies the biological condition of the invertebrate community of Great Lakes coastal wetlands based on data from least-impacted sites that are representative of Great Lakes coastal wetlands, referred to as a reference condition. These are then compared to sites experiencing a gradient of the amount and type of anthropogenic disturbance and stratified by region and wetland type. It is important to note that the invertebrate IBI has been developed for coastal wetlands that are directly connected to the Great Lakes, not for those wetlands that are only connected hydrologically via groundwater.

This sub-indicator can also be evaluated as part of an overall analysis of biological communities of Great Lakes coastal wetlands and nearshore aquatic systems. This can be done by considering the coastal wetland sub-indicators in combination, because they function and indicate anthropogenic disturbance at different spatial and temporal scales and have varying resolution of detection. For example, invertebrates detect much more local disturbance of the lakeward portion of the wetland within regions.

The sites sampled in 2015 are shown in Figure 2 and is colour coded by which taxonomic groups were sampled at the sites. Many sites were sampled for all taxonomic groups. Sites not sampled for birds and amphibians typically were sites that were impossible to access safely, and often related to private property access issues. Most bird and amphibian crews do not operate from boats since they need to arrive at sites in the dark or stay until well after dark. There are also a number of sites sampled only by bird and amphibian crews because these crews can complete their site sampling more quickly and thus have the capacity to sample more sites than do the fish, macroinvertebrate, and vegetation crews.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada	X					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

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Figure 1. Condition of coastal wetland macroinvertebrate communities based upon data from all sites sampled from 2011 through 2014.
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Last Updated

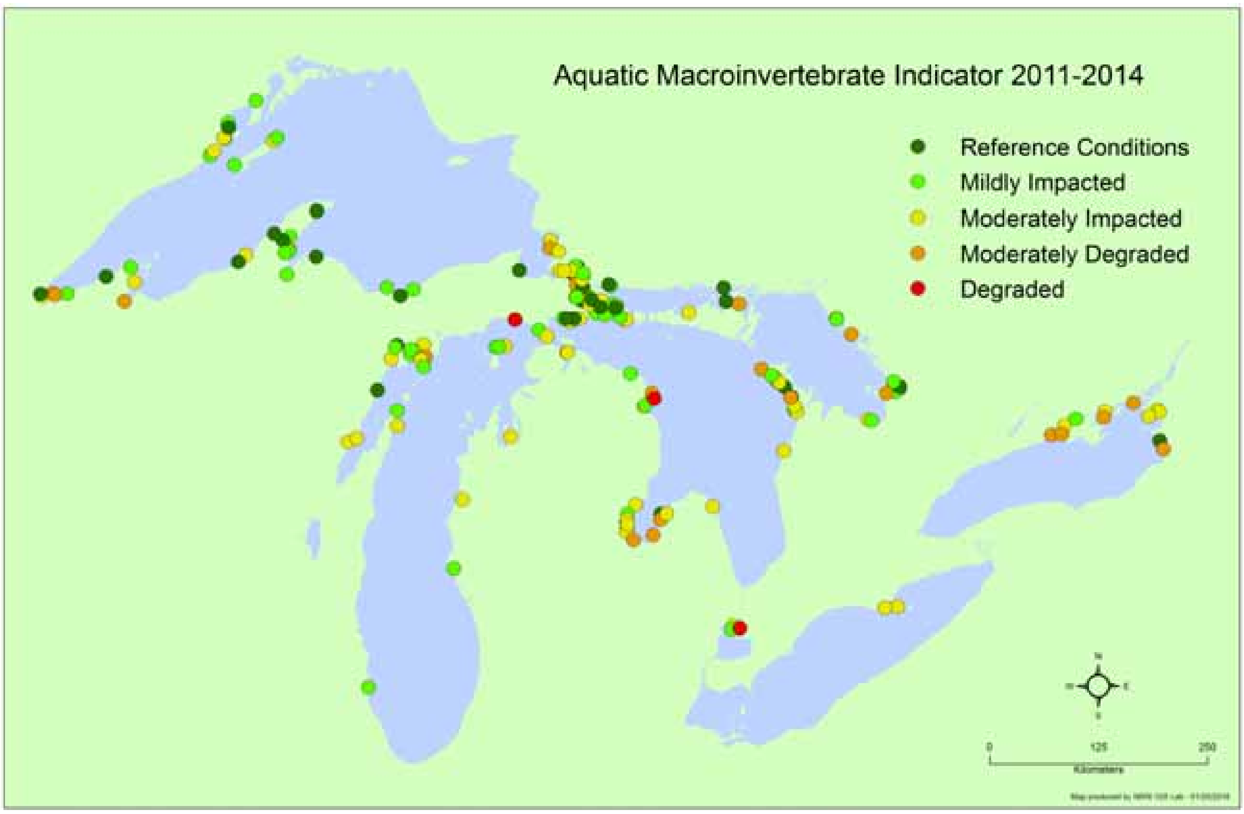
State of the Great Lakes 2017 Technical Report

Country	*Sites*	*Mean*	*Max*	*Min*	*St. Dev.*
Overall					
Canada	149	39.8	76	10	13.5
U.S.	326	40.7	85	0	5.2
Non-natives					
Canada	149	0.8	3	0	0.9
U.S.	326	0.7	5	0	1.0

Table 1. Total macroinvertebrate taxa in Great Lakes coastal wetlands, and non-native species; summary statistics by country. Data from 2011 through 2014.
Source: Uzarski, D.G., V.J. Brady, M.J. Cooper, D.A. Wilcox, D.A. Albert, R. Axler, P. Bostwick, T.N. Brown, J.J.H. Ciborowski, N.P. Danz, J. Gathman, T. Gehring, G. Grabas, A. Garwood, R. Howe, L.B. Johnson, G.A. Lamberti, A. Moerke, B. Murry, G. Niemi, C.J. Norment, C.R. Ruetz III, A.D. Steinman, D. Tozer, R. Wheeler, T.K. O'Donnell, and J.P. Schneider. 2016. Standardized measures of coastal wetland condition: implementation at the Laurentian Great Lakes basin-wide scale. Wetlands doi:10.1007/s13157-016-0835-7.

		Total Macroinvertebrates			*Non-native Macroinvertebrates*		
Lake	*Sites*	*Mean*	*Max*	*Min*	*Mean*	*Max*	*Min*
Erie	58	34.9	70	0	1.1	4	0
Huron	168	44.7	81	13	0.7	5	0
Michigan	66	42.1	85	19	0.7	3	0
Ontario	114	32.3	63	0	0.8	3	0
Superior	67	46.7	69	15	0.1	2	0

Table 2. Macroinvertebrate total taxa and non-native species found in Great Lakes coastal wetlands by lake. Mean, maximum, and minimum number of taxa per wetland. Data from wetlands sampled in 2011 through 2014.
Source: Uzarski, D.G., V.J. Brady, M.J. Cooper, D.A. Wilcox, D.A. Albert, R. Axler, P. Bostwick, T.N. Brown, J.J.H. Ciborowski, N.P. Danz, J. Gathman, T. Gehring, G. Grabas, A. Garwood, R. Howe, L.B. Johnson, G.A. Lamberti, A. Moerke, B. Murry, G. Niemi, C.J. Norment, C.R. Ruetz III, A.D. Steinman, D. Tozer, R. Wheeler, T.K. O'Donnell, and J.P. Schneider. 2016. Standardized measures of coastal wetland condition: implementation at the Laurentian Great Lakes basin-wide scale. Wetlands doi:10.1007/s13157-016-0835-7.



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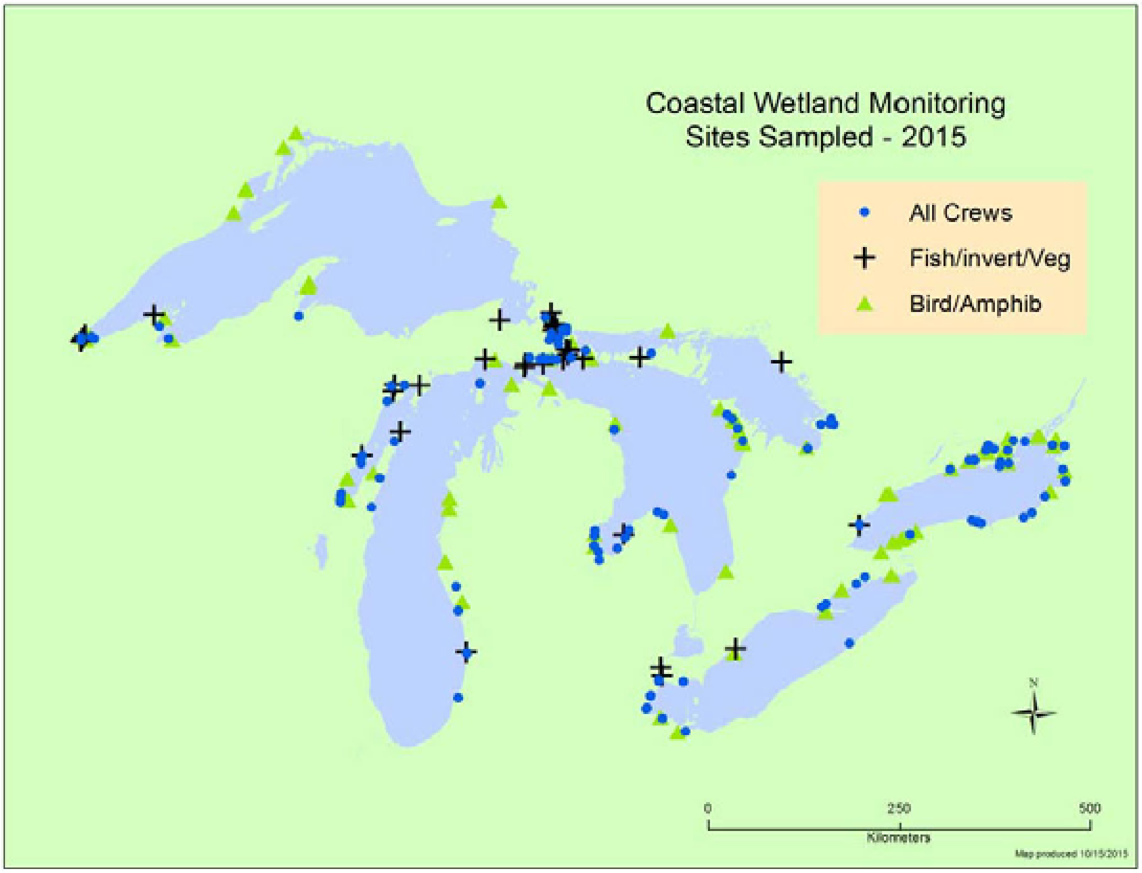

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Sub-Indicator: Coastal Wetland Plants

Overall Assessment
Status: Fair
Trend: Undetermined
Rationale: Based on scores of three plant community measures from the Coastal Wetland Monitoring* inventory between 2011 and 2014 (Tables 1 and 2, Figures 1 and 2), status of the coastal wetland plant community in the Great Lakes is fair. The three measures tell a similar story, although IBI scores (Albert 2008) are consistently higher than Mean C (Herman et al. 2001) and weighted Mean C (wC) (Bourdaghs et al. 2006) scores. On average, wetlands in Lakes Huron, Michigan, and Superior generally harbour fair or good wetland plant communities with some very high quality sites and lower numbers of poor sites. Wetlands in Lakes Erie and Ontario tend to be of more uniformly low quality, with only scattered high quality sites.

Lake-by-Lake Assessment

Lake Superior
Status: Good
Trend: Undetermined
Rationale: Lakewide average values for the three plant community measures all fall in the 'good' category. Over half the surveyed wetland sites in Lake Superior have overall site scores categorized as good. While there are low-quality sites adjacent to urban centers and in other scattered locations, most wetlands in Lake Superior have good quality plant communities. The highest quality wetlands in Lake Superior tend to be barrier-protected poor fens (average mean C and wC >5), since many species in these wetlands are habitat specialists with high conservatism values. Trends cannot be determined because of the lack of comparable pre-existing data of the measures. Benchmark and lake-wide data for all of the Great Lakes will limit the use of the undetermined category in the future.

Lake Michigan
Status: Fair
Trend: Undetermined
Rationale: Among all Great Lakes, Lake Michigan has the widest distribution of sites across the gradients. On average, most wetland plant communities are considered having fair condition, with the higher quality wetlands generally occurring in the northern part of the lake. Riverine wetlands have lower average scores, especially those in the south with extreme urban and agricultural nutrient enrichment, while open lacustrine and barrier wetlands farther north have higher scores associated with surrounding forest cover. Many wetlands in the Green Bay, WI region have experienced severe wetland degradation resulting from long-term agricultural and urban nutrient enrichment and more recent low water levels and associated invasion by reed (*Phragmites australis*). Restoration efforts in this region are improving wetland plant condition. Trends cannot be determined because of the lack of comparable pre-existing data of the measures. Benchmark and lake-wide data for all of the Great Lakes will limit the use of the undetermined category in the future.

Lake Huron
Status: Fair
Trend: Deteriorating
Rationale: The overall status of Lake Huron wetlands is fair based on Mean C and wC scores, and good based on IBI scores. Wetlands in Lake Huron occur across a wide gradient in plant community condition, with some very poor and high quality sites and many good sites. Sites in the northern and eastern portion of Lake Huron tend to be of higher quality for barrier (protected), lacustrine, and riverine wetlands that reflect surrounding forest cover and management. Extensive plowing, raking, and mowing during recent low water periods has led to vast areas of native wetland vegetation in open lacustrine wetlands being replaced by *Phragmites australis* and *Typha x glauca*, particularly in the Saginaw Bay region. This long-term change was documented by observed changes between surveys conducted in the mid-1990s and those conducted between 2011-2015. During the recent extended low-water conditions, *Phragmites australis* has expanded lakeward beyond native emergent vegetation on Ontario's Bruce Peninsula and eastern shoreline of Lake Huron, although perhaps recent high water conditions will erode these extensive *Phragmites* beds. Loss of emergent vegetation has also occurred in wetlands bordering the St. Marys River,

the connecting river between Lakes Superior and Huron during the 1999 to 2013 low-water conditions, probably the result of both winter ice and ship wakes on exposed sediments and vegetation beds. This long-term change is based on surveys conducted in the late 1980s, mid 1990s (summarized in Minc 1997), and between 2011 and 2015. Wetlands in eastern Georgian Bay are susceptible to nutrient enrichment from runoff through shallow soils or on exposed bedrock; in this area, increasing pressures from development and changing water levels are expected to have the greatest impacts in the near future. Overall, wetland quality in this lake is considered deteriorating.

Lake Erie

Status: Poor
Trend: Deteriorating
Rationale: Wetlands of Lake Erie have plant communities of generally poor status. Some high quality sites exist at Presque Isle, Pennsylvania and at several large Ontario sites along the north shore, including Long Point, Turkey Point, Rondeau, and Point Pelee, while restoration activities have recently improved Metzger Marsh, Ohio. Overall, the coastal wetland plant communities of Lake Erie are also classified as deteriorating based on historical data from 1975 in Lake Erie (Stuckey 1989). In Lake Erie, riverine wetlands have slightly lower average quality than barrier or lacustrine wetlands. Mean C scores are consistently higher than Weighted Mean C, indicating widespread dominance by species with low Conservatism values, including cattails and invasive species.

Lake Ontario

Status: Fair
Trend: Unchanging
Rationale: The overall status of Lake Ontario's coastal wetlands is fair. There are very few high quality coastal wetlands in Lake Ontario, whereas there are many wetlands of moderately low quality. Riverine wetlands have lower average quality than barrier or lacustrine wetlands. Substantially lower scores for Weighted Mean C compared to Mean C indicate Lake Ontario wetlands tend to be dominated by species with low Conservatism scores, including cattails and invasive species. There is a strong east to west gradient in condition, due largely from high levels of urbanization in the western portion of the basin.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess the quality of the vegetation as an integral component of the condition of coastal wetlands.

Ecosystem Objective

Coastal wetlands throughout the Great Lakes basin are influenced by coastal manipulations and the input of sediments, nutrients, and pollutants. About half of coastal wetlands have been lost basinwide. Remaining wetlands should be dominated by native vegetation with low numbers of invasive plant species at low levels of coverage. Conservation of these wetlands and restoration of previously destroyed wetlands are vital components of restoring the Great Lakes ecosystem and this sub-indicator can be used to report progress toward such objectives.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement that states the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition

Across the entire Great Lakes basin, the state of the wetland plant community is quite variable, ranging from good to poor depending primarily on local land use history, nearshore management, and the prevalence of invasive plant species. Plant communities in some wetlands have deteriorated rapidly in recent years due to extremely low water levels that have allowed invasion and dominance by exotic species. With water levels rebounding in 2014-2015, it will be critical to evaluate how these wetlands respond. In other wetlands, there have been recent improvements to plant community condition. For example, the turbidity of the southern Great Lakes has reduced with expansion of zebra mussels, resulting in improved submergent plant diversity in many wetlands. Moreover, wetland restoration activities have been undertaken throughout the basin over the past 5 years, especially targeting wetlands dominated by invasive plants.

Short- and long-term trends in wetland condition based on plants have not been well-established in the Great Lakes. In the southern lakes (Lake Erie, Lake Ontario, and the Upper St. Lawrence River), almost all wetlands are degraded by water-level control, nutrient enrichment, sedimentation, or a combination of these factors. Probably the strongest demonstration of this is the prevalence of broad zones of cattails, reduced submergent diversity and coverage, and prevalence of non-native plants, including reed (*Phragmites australis*), reed canary grass (*Phalaris arundinacea*), purple loosestrife (*Lythrum salicaria*), curly pondweed (*Potamogeton crispus*), Eurasian milfoil (*Myriophyllum spicatum*), frog bit (*Hydrocharis morsus-ranae*), and water chestnut (*Trapa natans*).

In the remaining Great Lakes (Lake St. Clair, Lake Huron, Lake Michigan, Georgian Bay, Lake Superior, and their connecting rivers), intact, diverse wetlands can be found for most geomorphic wetland types. However, low water conditions have resulted in the explosive expansion of reed in many wetlands, especially in Lake St. Clair and southern Lake Huron, including Saginaw Bay (Albert and Brown 2008) as well as Green Bay in Lake Michigan. As water levels rise, the response of reed should be monitored.

One of the disturbing trends is the expansion of frog bit, a floating plant that forms dense mats capable of eliminating submergent plants, from the St. Lawrence River and Lake Ontario into Lake Erie, Lake St. Clair, Lake Huron, and the St. Mary's River. This expansion will probably continue into all of the remaining Great Lakes. In addition, our sampling has shown water chestnut to be expanding rapidly in Lake Ontario—increasing in both distribution and density.

Studies in the northern Great Lakes have demonstrated that non-native invasive species like reed, reed canary grass, and purple loosestrife have become established throughout the Great Lakes but that the abundance of these species is low, often restricted to only local disturbances such as docks and boat channels. It appears that undisturbed marshes are not easily colonized by these species. However, as these species become locally established, seeds or fragments of plants may be able to establish themselves when water-level changes create appropriate sediment conditions. Hybrid cattail (*Typha x glauca*) expansion has also been recently documented in northern Lakes Michigan and Huron and the St. Marys River (Lishawa et al. 2010).

Regional Wetland Types
The conditions of the plant community in coastal wetlands naturally differ across the Great Lakes basin, due to differences in geomorphic and climatic conditions. The characteristic size and plant diversity of coastal wetlands vary by wetland type, lake, and latitude; in this document these differences will be described broadly as "regional wetland types."

Coastal wetlands are divided into three main categories based on the hydrology of the area. Lacustrine wetlands are connected to the Great Lakes, and they are largely impacted by fluctuations in lake levels. Riverine wetlands occur in the lower reaches of rivers that flow into the Great Lakes basin. Typically, the quality of riverine wetlands is influenced by the river drainage system; however, coastal processes cause lakes to flood back into these wetlands, which control water levels. The last type of coastal wetlands is barrier protected. Barrier protected wetlands are derived from coastal processes that deposit sediment to create barrier beaches that separate wetlands from the Great Lakes. Coastal wetlands contain different vegetation zones (treed or shrub swamp, meadow, emergent, submergent and floating), some of which may be absent in certain types of wetlands and under different water-level conditions. Great Lakes wetlands were classified and mapped in 2004 (see http://glc.org/wetlands/inventory.html) with coastal wetland inventory maps developed for the United States (see http://glc.org/wetlands/us_mapping.html) and Canada (see http://glc.org/wetlands/can_mapping.html).

Lake Variations
Physical properties such as the type of shoreline, substrate, bedrock, and chemical and physical water quality parameters vary between Great Lakes. Variation in nutrient levels creates both a north to south gradient, and an increase in nutrient levels from Lake Erie in the west to Lake Ontario and the upper St. Lawrence River in the east. Lake Superior is the most distinct Great Lake due to its low alkalinity and prevalence of bedrock shoreline.

Differences in Latitude
Latitudinal variations result in different climatic conditions based on the location of the coastal wetlands. Temperature differences between the north and south lead to differences in the species of plants found in coastal wetlands. Watersheds in the southern portion of the Great Lakes also have increased agricultural activity, resulting in increased nutrient loads, sedimentation, and non-native species introductions.

Linkages
There are characteristics of coastal wetlands that make use of plants as indicators difficult in certain conditions.

Among these are:

Water-level fluctuation
Great Lakes water levels fluctuate greatly from year to year. Either an increase or decrease in water level can result in changes in numbers of species or overall species composition in the entire wetland or in specific zones with change in level of human disturbance. Such changes make it difficult to monitor change over time. Changes are great in two zones: the wet meadow, where grasses and sedges may disappear in high water or new annuals may appear in low water, and in shallow emergent or submergent zones, where submergent and floating plants may disappear when water levels drop rapidly. Recent studies indicate that prolonged periods of low water favor rapid expansion of invasive species like *Phragmites australis* (Albert and Brown 2008, Lishawa etal. 2010, Wilcox 2012). In addition, water levels of Lakes Superior and Ontario are regulated, which has altered plant community dynamics. This is most obvious in Lake Ontario, where cattails have displaced sedge/grass meadow (Wilcox et al. 2008).
Pressures
Lake-wide alterations
For the southern lakes, most wetlands have been dramatically altered by both intensive agriculture and urban development of the shoreline. Alterations of coastal wetland especially in the wet meadow and upper emergent zone will lead to drier conditions which may allow invasive species to establish.

Agriculture
Agriculture degrades wetlands in several ways, including nutrient enrichment from fertilizers, increased sediments from erosion, increased rapid runoff from drainage ditches, introduction of agricultural non-native species (reed canary grass), destruction of inland wet meadow zone by plowing and diking, and addition of herbicides. In the southern lakes, Saginaw Bay, and Green Bay, agricultural sediments have resulted in highly turbid waters that support few or no submergent plants.

Lake-level regulation
Regulation of Lake Ontario water levels since 1960 has reduced the range of fluctuations. The most evident effect has been the elimination of low lake-level periods, even when water supplies are low. The competitive advantage of sedges and grasses at higher elevations due to their tolerance of low water levels and low soil moisture has been lost, and they have been displaced by larger cattails that are no longer limited by their need for more water.

Urban development
Urban development degrades wetlands by hardening shoreline, filling wetland, adding a broad diversity of chemical pollutants, increasing stream runoff, adding sediments, and increased nutrient loading from sewage treatment plants. In most urban settings, almost complete wetland loss has occurred along the shoreline.

Residential shoreline development
Along many coastal wetlands, residential development has altered wetlands by nutrient enrichment from fertilizers and septic systems, shoreline alterations for docks and boat slips, filling, and shoreline hardening. Agriculture and urban development are usually less intense than local physical alteration, which often results in the introduction of non-native species. Shoreline hardening can completely eliminate wetland vegetation.
Mechanical alteration of shoreline
Mechanical alteration takes a diversity of forms, including diking, ditching, dredging, filling, shoreline hardening, and disking and plowing of coastal vegetation by private landowners. With all of these alterations, non-native species are introduced by construction equipment or in introduced sediments. Changes in shoreline gradients and sediment conditions are often adequate to allow non-native species to become established. Disking and plowing of coastal wetlands continued through 2011 in exposed coastal marshes along Saginaw Bay, Grand Traverse Bay, and on islands within the St. Clair River delta.

Introduction of non-native species
Non-native species are introduced in many ways. Some were purposefully introduced as agricultural crops or ornamentals, later colonizing in native landscapes. Others came in as weeds in agricultural seed. Increased sediment and nutrient enrichment allow many of the worst aquatic weeds to out-compete native species. Most of the worst non-native species are either prolific seed producers or reproduce from fragments of root or rhizome. Non-native animals have also been responsible for increased degradation of coastal wetlands. One of the worst invasive species has been common carp, whose mating and feeding habits result in loss of submergent vegetation in shallow marsh waters. The most prevalent non-native plants including common reed (*Phragmites australis),* reed canary grass (*Phalaris arundinacea*), purple loosestrife (*Lythrum salicaria*), curly pondweed (*Potamogeton crispus*), and Eurasian milfoil

(*Myriophyllum spicatum*). Low water conditions have resulted in the almost explosive expansion of common reed in many wetlands, especially in Lake St. Clair and southern Lake Huron, including Saginaw Bay (Albert and Brown 2008). One of the disturbing recent trends is the expansion of frog bit, a free floating plant that forms dense mats along the emergent margin capable of eliminating submergent and emergent plants, from the St. Lawrence River and Lake Ontario into Lake Erie, Lake St. Clair, Lake Huron, and the St. Mary's River. This expansion will likely continue to all of the remaining Great Lakes. In addition, our sampling has shown water chestnut to be expanding rapidly in Lake Ontario—increasing in both distribution and density. The recent rediscovery of a non-native macroalgae, starry stonewort (*Nitellopsis obtusa*), is of conservation concern because of its long-term establishment since the 1970s and its current distribution within better quality wetlands in northeastern Lake Ontario as well as wetlands in Saginaw Bay, Lake St. Clair, and the Detroit River.

Comments from the Authors

*The Coastal Wetland Monitoring program was funded by the Great Lakes Restoration Initiative 2011-2015 to implement statistically sound basin-wide monitoring of select physical and biotic components (Uzarski et al.). This binational program involved a consortium of universities and agencies with the goal of producing scientifically-defensible information on status and trends of Great Lakes coastal wetlands. As of 2015, the majority of coastal wetlands ≥4 ha with a surface water connection to the lakes have been surveyed at least once since 2011. Data from 2011-2014 were included in the analysis reported here. In each wetland, data from up to three wetland zones (wet meadow, emergent, submergent) are included if all zones are present.

The tables in this document summarize data collected between 2011 and 2014 on three broad hydrogeomorphic wetland types: barrier, lacustrine, and coastal wetlands that were characterized for each separate Great Lake. In subsequent analyses these types will be further divided into recognized subtypes (Albert et al. 2006) that are subject to different environmental and human stresses, and thus characterized by different status and potential for restoration.

This sub-indicator incorporates information on the presence, abundance, and diversity of aquatic macrophytes within Great Lakes coastal wetlands. Plant abundance data are used to calculate three measures of wetland plant quality including: 1.Mean Coefficient of Conservatism (C); 2.Weighted Mean Coefficient of Conservatism (wC); and 3. Vegetation Index of Biological Integrity (IBI). The Mean C approach is preferred by many, because it provides a nice, neat, easily computed number however, it provides little understanding of the overall diversity of the wetlands within the lake. In both Lake Michigan and Lake Huron there is an extreme environmental gradient [climate and hydro-geomorphology] that are reflected in land use and vegetation response, and a single FAIR designation ignores that gradient. One number or condition cannot reflect these lakes. The IBI better demonstrates the breadth of types and conditions. However, for the purposes of this sub-indicator report, if calculation results fall into different assessment categories than the conservative score is used. More information on these calculations can be found in the Coastal Wetlands Plant sub-indicator description.

It has been estimated that approximately half of the coastal wetlands have been lost basinwide, but this estimate does not include degraded wetlands, but just those that have been lost by shoreline hardening or complete erosion of vegetation from an area. There is no agreed on approach to providing a more accurate estimate for several reasons, the most important of which are 1) The original land surveys, the basis of many original plant community area estimates, did not consistently reference herbaceous wetland vegetation along the shoreline, 2) Emergent wetland vegetation is not easily seen in aerial photos limiting the use of 1930s and 1940s early aerial photos to estimate original wetland sites, and 3) the earliest Great Lakes-wide surveys of coastal wetlands were conducted in the late 1970s and early 1980s, well after most of the coastal wetland destruction had occurred due to a combination of shoreline hardening, dredging, agricultural planting, and destruction by invasive fish [carp].

While no Great Lake-wide surveys of coastal wetland vegetation were conducted before the 1980s, cluster analyses of physical and vegetation data from field surveys conducted in the 1980s and 1990s identify several distinct native plant communities, as well as some plant communities dominated by invasive plants, that show strong relationships to regional climatic, sediment, and hydro-geomorphic conditions (Minc 1997, Albert and Minc 2001, Albert et al. 2006) that can justifiably be used as the basis for assuming there are predictable regional wetland vegetation types or communities.

Cattails have been noted as a major source of degradation because the expansion of cattails into wetlands following nutrient enrichment and water-level manipulation had been documented in numerous studies (Prince and D"Itri 1985, Stuckey 1989, Wilcox 1993, Minc 1997, Wilcox et al. 2008, Lishawa et al. 2010, and Robert Humphreys (refuge manager for MI DNR), personal communications). The native cattail in Great Lakes coastal wetlands was

Typha latifolia (common or wide-leaved cattail) a species that was limited in distribution by characteristic fluctuations in Great Lakes water levels. *Typha angustifolia* (narrow-leaved cattail) has expanded into Great Lakes wetlands, where it tolerates deeper water levels than common cattail, expanding its range rapidly through the eastern U.S. and the Midwest along roadside ditches. Common and narrow-leaved cattails hybridized, forming *Typha* x *glauca* (hybrid cattail), a larger and more aggressive plant that along with narrow-leaved cattail created broad, dense monocultures that did not meet the habitat needs of many native waterbirds and waterfowl. Their dense mats were also able to float in drown river mouth wetlands, eliminating important fish habitat as well.

Damage to Great Lakes wetlands by exotic invasive plants during the most recent low-water event (1999-2013 in Lakes Michigan and Huron) is considered to be linked to anthropogenic degradation because all of the invasive plants that have expanded dramatically into Great Lakes coastal wetlands were introduced into the Great Lakes by humans and respond aggressively to agricultural and urban nutrient enrichment and/or sedimentation. Earlier surveys of Great Lakes wetlands in low-water conditions in the 1980s and 1990s documented existing large-scale or localized expansions of these invasive plants in Lakes Ontario, Erie, and Lake St. Clair, but the expansion of these same plants was much greater than the extended low-water conditions in Lakes Huron and Michigan between 1999 and 2013. Prior to the 1970s, our most aggressive invasive plants (*Phragmites australis*, *Typha angustifolia*, *Typha* x *glauca*, *Lythrum salicaria*, *Hydrocharis morsus-ranae*, etc.) that respond to low-water conditions were not widespread along the Great Lakes shoreline, but since then and into the future prolonged periods of low-water can be expected to result in at least localized expansions of invasive wetland plants.

Baseline condition in biological or restoration studies has typically been based on characteristic native flora and fauna in an ecosystem. Several examples of wetlands with no extensive populations of invasive plants were inventoried during the 2011-2015 of invasive plants and animals (Uzarski et al. 2016) is the definition of baseline condition and the goal of restoration. These high quality wetlands will remain the basis for monitoring wetland condition and guiding restoration efforts, even if it is determined in the future that returning degraded wetlands to these conditions is impossible.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report			x			

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Source: GLRI Coastal Wetland Monitoring Program, analysis by Nicholas Danz

Table 2. Condition class categories based on sub-indicator definitions for three measures of coastal wetland plant communities.

Source: GLRI Coastal Wetland Monitoring Program, analysis by Nicholas Danz

Table 3. Lakewide and wetland-type means and 95% confidence intervals for three measures of Great Lakes coastal wetland plant community condition observed 2011-2014. Some sites with missing vegetation zones were not used in calculations for the vegetation IBI, resulting in slightly lower sample size. Mean C and wC have a maximum score of 10, while Vegetation IBI has a maximum score of 5 and must be doubled to be the equivalent of Mean C and wC.

Source: GLRI Coastal Wetland Monitoring Program, analysis by Nicholas Danz

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Figure 1. Frequency histogram of overall site Mean C (blue) and Weighted Mean C (red) values for 451 Great Lakes coastal wetland sites surveyed between 2011 and 2014.

Source: GLRI Coastal Wetland Monitoring Program, analysis by Nicholas Danz

Figure 2. Frequency histogram of overall site Vegetation IBI values for 415 Great Lakes coastal wetland sites surveyed between 2011 and 2014.

Source: GLRI Coastal Wetland Monitoring Program, analysis by Nicholas Danz

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		Mean C and wC					Veg IBI		Veg IBI x2
Lake	*n*	Mean C	95% CI	wC	95% CI	n	Veg IBI	95% CI	
Lake Erie	52	2.53	0.19	2.22	0.25	50	1.6	0.15	3.2
Lake Huron	162	4.33	0.17	4.21	0.19	140	3.0	0.15	6.0
Lake Michigan	65	3.57	0.26	3.46	0.30	61	2.9	0.20	5.8
Lake Ontario	107	3.02	0.13	2.53	0.16	104	1.9	0.10	3.8
Lake Superior	65	5.18	0.30	5.19	0.34	60	3.7	0.23	7.4

Table 1. Lakewide means and 95% confidence intervals for three measures of Great Lakes coastal wetland plant community condition observed 2011-2014. Some sites with missing vegetation zones were not used in calculations for the vegetation IBI, resulting in slightly lower sample size. Mean C and wC scores are based on a maximum score of 10, while Veg IBI scores are based on a maximum score of 5. Vegetation IBI scores must be doubled to be equivalent of Mean C and wC scores.

Source: Great Lakes Coastal Wetlands Consortium

	Measures			
Lake	Mean C	Weighted Mean C	Veg IBI	Overall
Lake Erie	Poor	Poor	Fair	Poor
Lake Huron	Fair	Fair	Good	Fair
Lake Michigan	Fair	Fair	Good	Fair
Lake Ontario	Fair	Poor	Fair	Fair
Lake Superior	Good	Good	Good	Good

Table 2. Condition class categories based on sub-indicator definitions for three measures of coastal wetland plant communities.

Source: Great Lakes Coastal Wetlands Consortium

		Mean C and wC					Veg IBI		
Lake	Hydrogeomorphic Type	*n*	Mean C	95% CI	wC	95% CI	*n*	IBI	95% CI
Erie	Barrier (protected)	10	2.61	0.25	2.34	0.44	5	1.78	0.49
	Lacustrine (coastal)	22	2.66	0.33	2.40	0.41	17	1.61	0.22
	Riverine	31	2.40	0.30	2.06	0.39	28	1.45	0.21
Huron	Barrier (protected)	16	4.60	0.70	4.58	0.76	12	3.46	0.57
	Lacustrine (coastal)	113	4.23	0.23	4.07	0.26	82	2.95	0.18
	Riverine	62	4.46	0.25	4.36	0.30	46	3.03	0.27
Michigan	Barrier (protected)	11	3.75	0.65	3.69	0.80	10	3.32	0.68
	Lacustrine (coastal)	37	3.74	0.39	3.67	0.42	30	2.88	0.27
	Riverine	26	3.25	0.39	3.07	0.47	21	2.67	0.28
Ontario	Barrier (protected)	27	3.39	0.41	2.95	0.48	23	1.99	0.27
	Lacustrine (coastal)	28	3.04	0.20	2.49	0.24	24	1.88	0.18
	Riverine	68	2.87	0.15	2.38	0.20	57	1.81	0.13
Superior	Barrier (protected)	17	6.29	0.55	6.48	0.55	15	4.35	0.29
	Lacustrine (coastal)	9	5.12	0.51	4.99	0.78	7	3.63	0.56
	Riverine	42	4.75	0.33	4.71	0.39	38	3.48	0.29

Table 3. Lakewide and wetland-type means and 95% confidence intervals for three measures of Great Lakes coastal wetland plant community condition observed 2011-2014. Some sites with missing vegetation zones were not used in calculations for the vegetation IBI, resulting in slightly lower sample size. Mean C and wC have a maximum score of 10, while Vegetation IBI has a maximum score of 5 and the value noted above must be doubled to be the equivalent of Mean C and wC.
Source: Great Lakes Coastal Wetlands Consortium

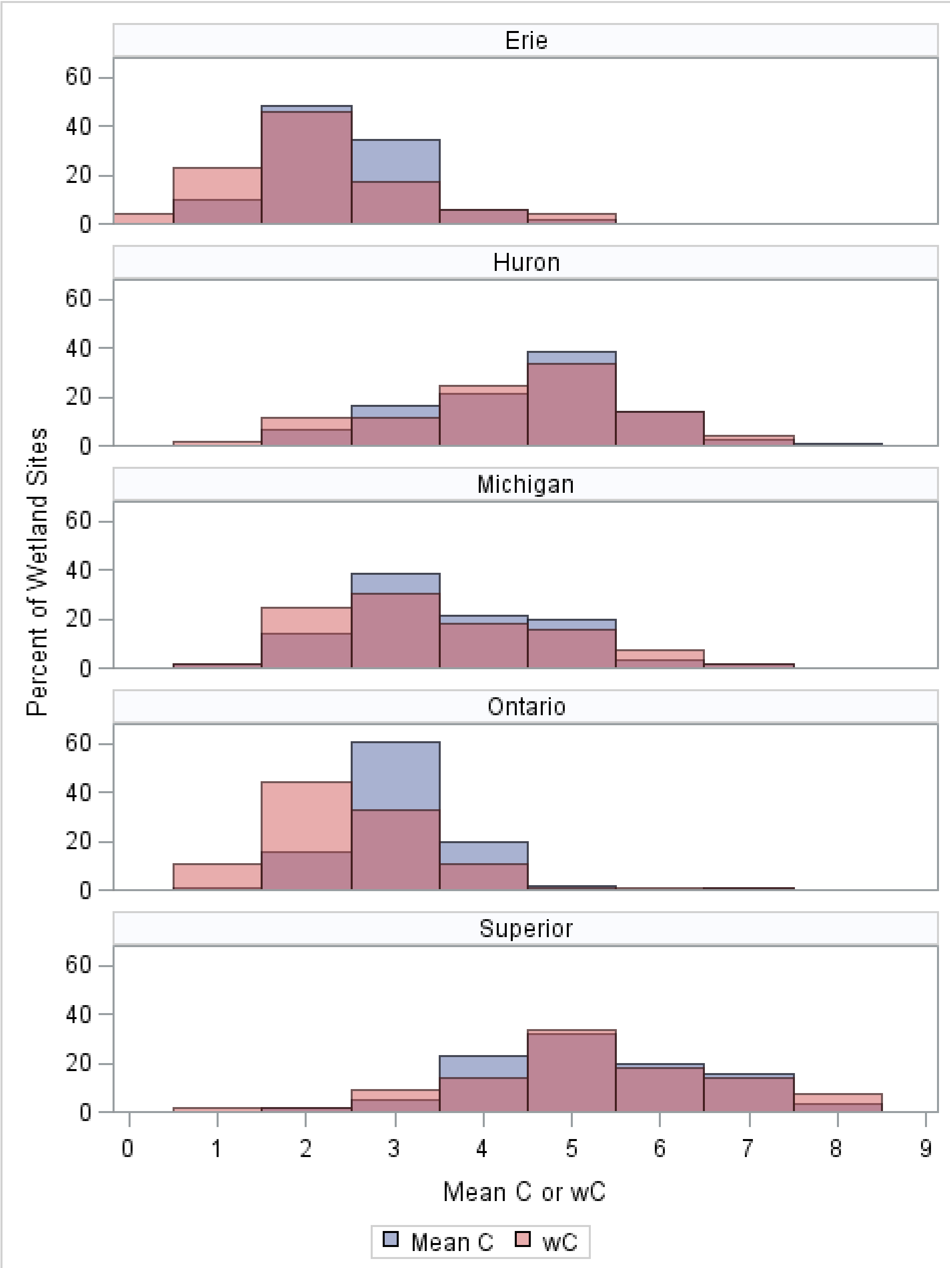

Figure 1. Frequency histogram of overall site Mean C (blue) and Weighted Mean C (red) values for 451 Great Lakes coastal wetland sites surveyed between 2011 and 2014. Lake Assessment Scale for Mean C and wC are Good: 5.0 and above; Fair: 3.0 - 4.9 and Poor: 0.0 - 2.9. Please note the difference in scale between Figure 1 and 2 on the x-axis.

Source: Great Lakes Coastal Wetlands Consortium

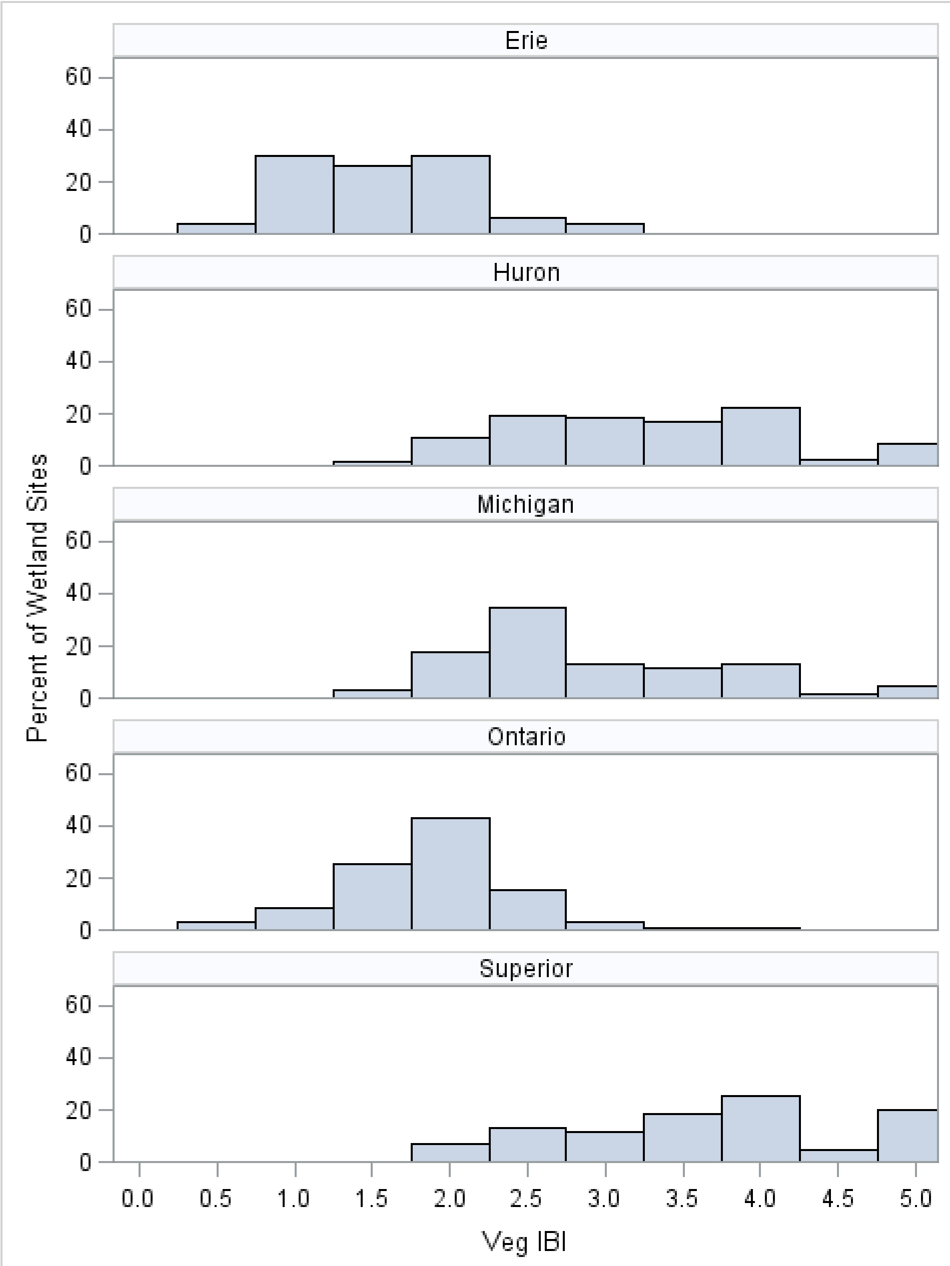

Figure 2. Frequency histogram of overall site Vegetation IBI values for 415 Great Lakes coastal wetland sites surveyed between 2011 and 2014. Lake Assessment Scale for IBI are Good: 5.0 and above; Fair: 3.0 - 4.9; and Poor: 0.0 - 2.9. Please note the difference in scale between Figure 1 and 2 on the x-axis.
Source: Great Lakes Coastal Wetlands Consortium

Sub-Indicator: Coastal Wetlands: Extent and Composition

Overall Assessment

Status: Undetermined
Trend: Undetermined
Rationale: Mapping and estimation of the areal coverage of Great Lakes coastal wetlands was done in 2004. An update is underway but has not yet been completed. Because there has not been an update to the estimation of areal extent in over 10 years, the status and trend are undetermined.

Lake-by-Lake Assessment

Lake-by-lake assessments are not available for the same reason the basin-wide assessments are not available.

Sub-Indicator Purpose

- To assess the periodic changes in area (particularly losses) of coastal wetland types, taking into account natural lake level variations. Coastal wetlands provide critical breeding and migratory habitat for wildlife such as birds, mammals, reptiles, and amphibians. These habitats are also critical spawning and nursery areas for many fish species of ecologic and economic importance.

Ecosystem Objective

Maintain total areal extent of Great Lakes coastal wetlands, ensuring adequate representation of coastal wetland types across their historical range. Conservation of remaining coastal wetlands and restoration of previously destroyed wetlands are vital components of restoring the Great Lakes ecosystem and this sub-indicator can be used to report progress toward such an objective.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition

This sub-indicator will measure areal extent of coastal wetlands by hydro geomorphic type for a specific time period based on data sources/imagery available. Coastal wetlands trap, process, and remove nutrients and sediment from Great Lakes nearshore waters, and recharge groundwater supplies. However, over half of all Great Lakes coastal wetlands have been destroyed by human activities and many remaining coastal wetlands suffer from anthropogenic stressors such as nutrient and sediment loading, fragmentation, invasive species, shoreline alteration, and water level control (Albert and Simonson, 2004; Ingram and Potter, 2004).

An existing baseline map circa 2004 of the binational coastal wetland occurrence and general boundaries was produced from available data sources on wetland occurrence including the USFWS National Wetland Inventory, Michigan National Wetland Inventory, Ohio Wetlands inventory, Wisconsin DNR Wetlands Inventory, and best professional judgement (Figures 1, 2, and 3). There has not yet been a complete update to this map, so current areal extent and composition of coastal wetlands across the entire Great Lakes basin cannot be reported.

New data sets have been produced that allow the circa 2004 data set to be reexamined and refined, which will ultimately allow determination of a more current status and trend over time. For example, a multi-season (spring, summer and fall) satellite optical and L-band radar data with a minimum mapping unit of 0.2 ha (Bourgeau-Chavez *et al*. 2015) for wetland plant communities and other landuse classes was produced (Figure 4). This map delineates ecosystem type (i.e. emergent, shrub and forested wetland) as well wetland monocultures (*Typha, Phragmites, Schoenoplectus*) and peatland types (fens and bogs). In addition, upland and landuse classes, potential wetland stressors, are mapped. An overall accuracy of 94% was documented by this effort when the map was compared to vegetation types identified in field studies between 2008 and 2011. The bands found most important for wetland mapping were the thermal, NIR and L-band SAR and should be integrated into any map update to maintain the integrity and level of accuracy. Optical data alone may be used but woody wetlands in particular are not mapped as accurately with optical data alone (e.g. forested wetlands, scrub shrub, bogs, fens). This map could be updated on an incremental basis, such as a five year cycle, using change detection methods.

Updating maps in a standardized way across the whole Great Lakes Basin is now planned, and there are efforts underway to use the 2008-2011 field study data set and update the circa 2004 coastal wetland data set in select geographic areas (e.g., Saginaw Bay to Western Lake Erie Basin – US side only, state of Michigan.)

It should be noted that the assessment in the State of the Great Lakes 2011, 2009, 2007 and 2005 reports was Fair (Mixed) and Deteriorating for this sub-indicator, based on historical data, 1981-1997.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Hardened Shorelines – physical modifications to the shoreline have disrupted coastal and nearshore processes, flow and littoral circulatory patterns, altered or eliminated connectivity to coastal wetlands/dunes, and have altered nearshore and coastal habitat structure
- Precipitation Events – change in atmospheric temperature will potentially affect the number of extreme storms in the Great Lakes region which will, in turn, affect coastal wetlands
- Terrestrial Invasive Species – many terrestrial invaders are found in Great Lakes coastal wetlands and can displace native vegetation as they spread
- Water Levels – water level change has strong influences on Great Lakes habitat and biological communities associated with Coastal Wetlands. Water levels have a major influence on un-diked coastal wetlands and are basic to any analysis of wetland change trends

This sub-indicator links directly to the other sub-indicators in the Habitats and Species indicator, particularly the other coastal wetlands-related sub-indicators.

Comments from the Author(s)

This sub-indicator needs to be evaluated in terms of both wetland quality and extent. While some wetlands may decrease in both area and quality due to the lack of water level fluctuation, as on Lake Ontario, the area of other wetlands could remain within the range determined by natural water level fluctuations, but be degraded by other factors, such as sedimentation, excessive nutrients, invasive species or land use pressures. When interpreting the data, the other coastal wetland sub-indicators that evaluate wetland quality need to be considered. Measurement should be based upon total area of inventoried coastal wetlands where known. Where areal extent is not known, efforts should be focused on collecting that baseline data. Total change can be roughly determined on a lake basin basis and for scientifically-based sampling, priority sites should be established where regular ground-truthing facilitates a statistical analysis.

An overall view of wetland health can be derived by considering the 6 Coastal Wetland sub-indicators in combination, because they function and indicate anthropogenic disturbance at different spatial and temporal scales and have varying resolution of detection. For example, landscape measures are used to determine loss, transformation and restoration of wetland types experiencing varying degrees of anthropogenic disturbance. However, landscape measures have been challenging due to data gaps and because coastal wetlands are extremely dynamic systems; they migrate, disappear, and appear with changing water levels not necessarily related to anthropogenic disturbance.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					

4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada					X	
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					
Clarifying Notes: The Data Quality assessment given here is copied from the State of the Great Lakes (previously known as SOLEC) 2009 data quality assessment, which was based on the State of the Great Lakes (SOLEC) 2005 report. This is done because the majority of this report still refers to the SOGL 2005 report.						

Acknowledgments

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Krista Holmes, Canadian Wildlife Service, Environment Canada
Dennis Albert, Michigan Natural Features Inventory, Michigan State University Extension

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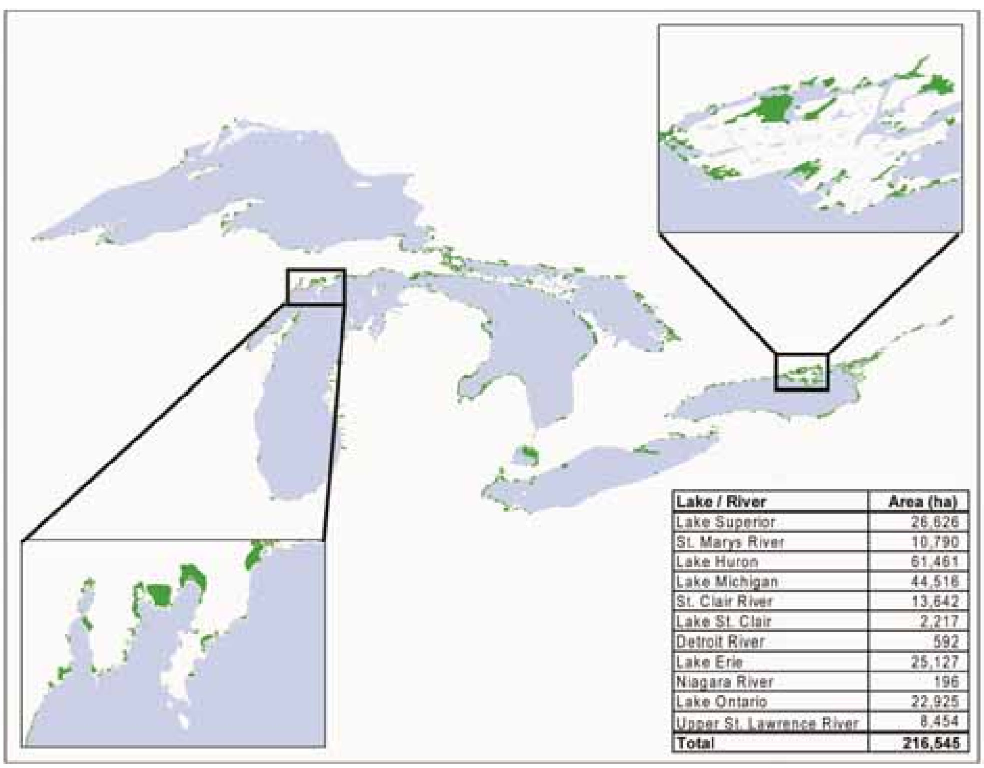

Lake / River	Area (ha)
Lake Superior	26,626
St. Marys River	10,790
Lake Huron	61,461
Lake Michigan	44,516
St. Clair River	13,642
Lake St. Clair	2,217
Detroit River	592
Lake Erie	25,127
Niagara River	196
Lake Ontario	22,925
Upper St. Lawrence River	8,454
Total	216,545

Figure 1. Great Lakes coastal wetland distribution and total area by lake and river.
Source: Great Lakes Coastal Wetlands Consortium, from SOGL 2007 report

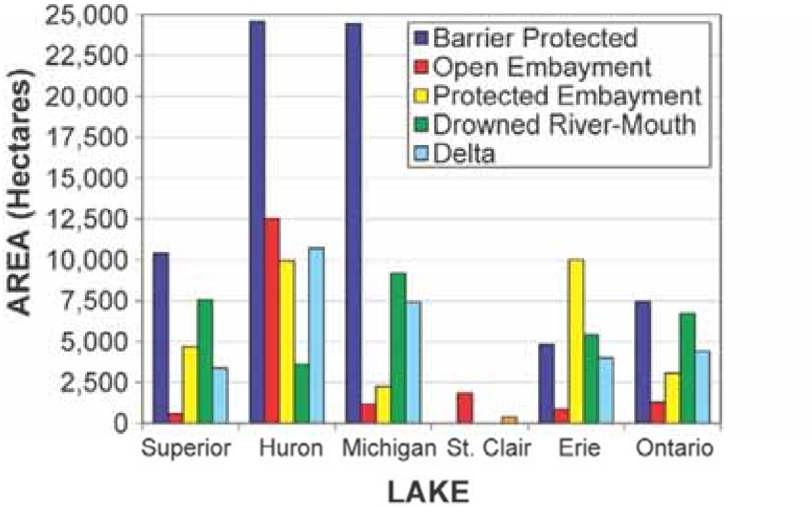

Figure 2. Coastal wetland area by geomorphic type within lakes of the Great Lakes system.
Source: Great Lakes Coastal Wetlands Consortium, from SOGL 2007 report

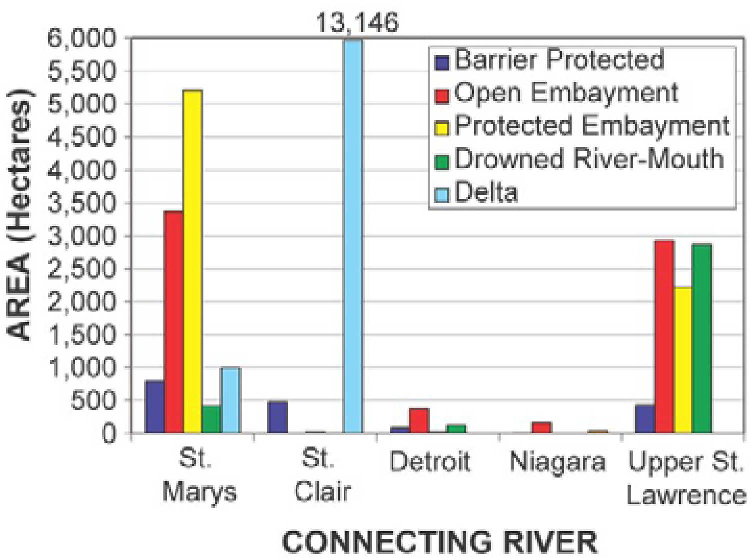

Figure 3. Coastal wetland area by geomorphic type within connecting rivers of the Great Lakes system.
Source: Great Lakes Coastal Wetlands Consortium, from SOGL 2007 report

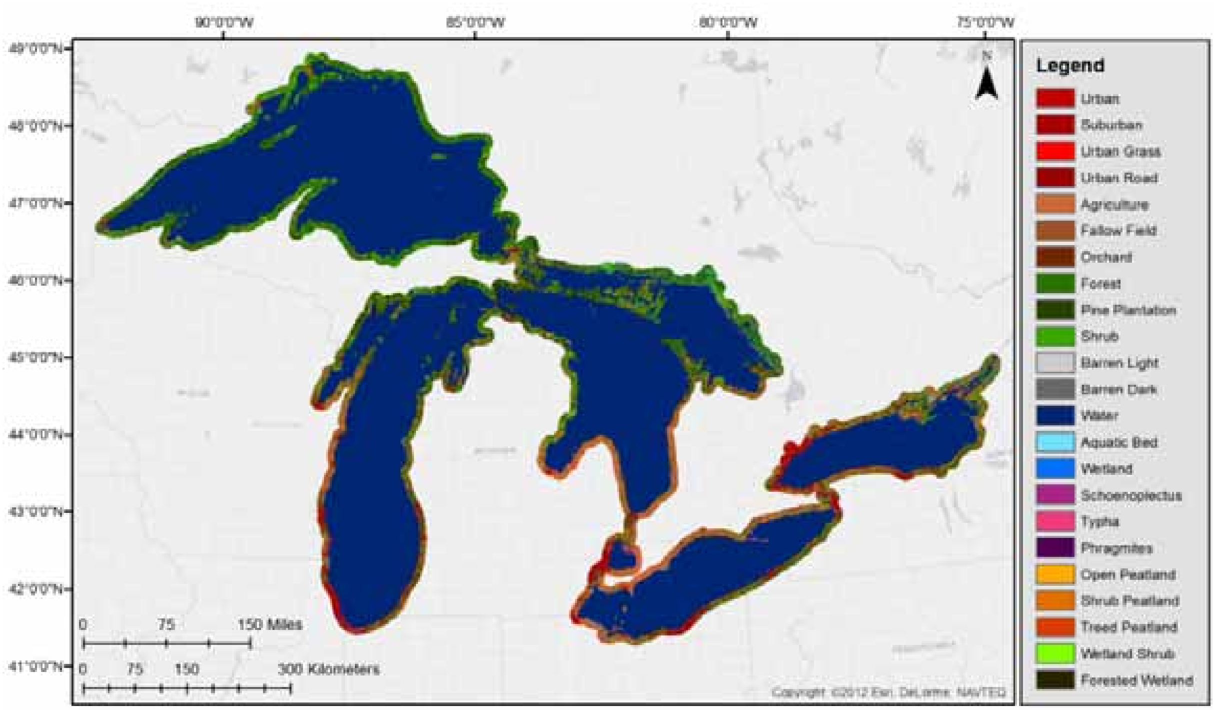

Figure 4: Wetlands and land use land cover (LULC) classes within a 10 km buffer of the Great Lakes coastline in both the United States and Canada.
Source: Bourgeau-Chavez, Laura. 2015

Sub-Indicator: Aquatic Habitat Connectivity

Overall Assessment
Status: Fair
Trend: Improving
Rationale: Dams and barriers have been impacting the health of aquatic ecosystems in the Great Lakes Basin for over a century and are limiting the recovery of some fish populations. In addition to limiting access of fishes to spawning and nursery habitats, loss of aquatic connectivity impacts nutrient flows, and riparian and coastal processes. The construction of new dams and barriers on Great Lakes tributaries peaked over a century ago when water power was primary energy source in the basin. Many of the larger dams were built in the 20th century for hydro-electric power generation. Over the last few decades very few new dams have been built, and there has been a recent trend to remove old dams. The potential impacts of road-stream crossings are now better understood, and there have been several regional initiatives to identify and mitigate culverts that act as barriers. The assessments are based on expert opinion and data review, and are largely based on Biodiversity Conservation Strategies developed for each lake.

Lake-by-Lake Assessment

Lake Superior
Status: Fair
Trend: Improving
Rationale: Dams and barriers are identified as a high threat to migratory fishes (Lake Superior LAMP 2013) and are considered an impediment to the recovery of some fishes, such as Lake Sturgeon, Brook Trout and Walleye (Horns et al. 2003). There are several projects that have been completed or are exploring options to improve connectivity (http://greatlakes.fishhabitat.org/projects) such as the Camp 43 dam on the Black Sturgeon River. A collaborative geo-database of inventoried connectivity barriers within the South Central Superior Basin will be used to prioritize restoration for approximately 1,800 inventoried road-stream crossings and is an example of the efforts to address connectivity (https://www.fws.gov/glri/documents/GLRIBook2014.pdf).

Lake Michigan
Status: Poor
Trend: Improving
Rationale: Approximately 83% of tributary stream habitat is unavailable to migratory fish due to fragmentation caused by dams and dams are ranked as a high threat to migratory fishes (Pearsall et. al 2012a). Several dam removal and mitigation projects have been initiated through the Great Lakes Restoration Initiative (e.g. Boardman River dam removal projects will connect over 250 km of stream habitat back to Lake Michigan - the dam closest to the river mouth will be modified to allow for fish passage while blocking access for sea lamprey.)

Lake Huron
Status: Poor
Trend: Improving
Rationale: Approximately 86% of major tributaries are no longer connected to the Lake Huron basin (Gebhardt et al. 2005) and dams are ranked as a high threat to migratory fishes (Franks Taylor et al. 2010). Aquatic habitat connectivity varies in the basin. Franks Taylor et al. (2010) identified that Eastern Georgian Bay has sufficient access to spawning habitat to maintain fish population while in Saginaw Bay access to spawning habitat is severely limiting fish populations.

Lake Erie
Status: Fair
Trend: Improving
Rationale: Approximately 64% of tributary stream habitat is unavailable to migratory fish due to fragmentation caused by dams, and dams are ranked as a medium threat to migratory fishes (Pearsall et. al 2012b) Several dam removal and mitigation projects have been initiated in the last few years through the Great Lakes Restoration Initiative (e.g. Ballville Dam on the Sandusky River will open up 35 km of river habitat for walleye).

Lake Ontario

Status: Fair

Trend: Improving

Rationale: The Lake Ontario Biodiversity Conservation Strategy identified dams and barriers as critical threat to the health of the lake (Lake Ontario Biodiversity Conservation Strategy Working Group, 2009). In addition to dams on Lake Ontario tributaries, the Moses-Saunders Power Dam on the St. Lawrence River impacts habitat connectivity, particularly for the migration of the American Eel (MacGregor et. al 2013). The Eel Passage Research Center was established in 2013 to address this issue. Several dam mitigation projects have been initiated including dam removal in the Duffins Creek watershed by the Toronto Region Conservation Authority to improve access for Atlantic Salmon and removal of the Hogansburg dam to restore connectivity in the St. Regis River.

Other Spatial Scales

To assist in targeting these investments to reconnect habitats and barrier removal, spatial data on the location and attributes of barriers (dams and road-stream crossings) throughout the Great Lakes Basin is being synthesized and used to analyze the optimal strategy for enhancing connectivity to restore fish migrations by the University of Wisconsin. The project will provide the basis for a decision-support tool to guide restoration at scales from individual watersheds to the entire basin, and provide a systematic framework for comparing costs (direct economic costs, species invasions) and benefits (connectivity, focal fish species) of barrier removal (Januchowski-Hartley et al. 2013).

Sub-Indicator Purpose

- To determine the amount of accessible tributary habitat for migratory Great Lakes fishes;
- To summarize key initiatives to improve the connectivity of aquatic habitat; and
- To highlight some of the issues related to barrier mitigation.

Ecosystem Objective

Maintaining or increasing the aquatic habitat/connectivity to native fish would be considered desirable. Conversely, decreases in aquatic habitat connectivity would be considered undesirable.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should “support healthy and productive wetlands and other habitats to sustain resilient populations of native species.”

Ecological Condition

The installation and management of dams threatens the diversity of native Great Lakes fishes by restricting or eliminating connectivity between the lake and critical spawning, nursery, and overwintering habitats (Januchowski-Hartley et al. 2013). For example, in Lake Huron before the 1800’s, over 10,000 km (more than 6,000 miles) of tributary habitats were accessible to Lake Huron fish (Liskauskas et al. 2004, LHBP 2008). In 2005, 86% of major tributaries were no longer connected to the Lake Huron basin (Gebhardt et al. 2003). This loss of tributary habitat has resulted in significant declines in native fish populations in the lake, such as Lake Herring, Yellow Perch, Walleye, Lake Sturgeon, River Redhorse, Black Redhorse, Eastern Sand Darter, and Channel Darter (Great Lakes Fishery Commission. 2007, Bredin 2002).

Linkages

Linkages to other sub-indicators in the indicator suite include:

- **Aquatic Invasive Species –** There are examples in all of the Great Lakes where dams and barriers, in some instances, are protecting the native stream assemblages from competition and physical disturbance of substrates from non-native salmonids (Bredin 2002). Hence, decisions about removal of dams and barriers in Lake Huron must balance competing interests and goals, which may not always be explicit. Some dams and barriers may also play a role in limiting the spread. of other invasive species such as Round Gobies, Tubenose Gobies, and Viral Hemorrhagic Septicemia
- **Lake Sturgeon –** Loss of aquatic connectivity has contributed to the decline of the species
- **Lake Trout –** Removed barriers that result in more parasitic Sea Lampreys would likely cause declines in numbers of lake trout and slow progress towards restoration.
- **Sea Lamprey –** Barrier removal is not straightforward as there are also potential ecological benefits to some dams and barriers. For example, dams and barriers currently limit the spread of some Great Lakes in-

vaders. Lake Huron supports the largest population of sea lamprey in the Great Lakes (Liskauskas et al. 2007), and dams and low-head barriers are a major control mechanism used by managers
- **Walleye** – Loss of aquatic connectivity has contributed to the decline of the species
- **Water Quality in Tributaries** – Barrier removal could improve water quality as natural flow patterns are restored and stream temperatures are reduced.

This sub-indicator also links directly to the other sub-indicators in the Habitats and Species indicator.

Comments from the Author(s)

Aquatic habitat connectivity is defined for the purposes of this report as the direct connection between the Great Lakes and waterways that are used by migratory fishes.

Aquatic connectivity provides chemically and physically unobstructed routes to fulfill life history requirements of aquatic species, including access to intact refugia and opportunities for genetic exchange. Certain migratory fish species (e.g. Atlantic Salmon and Walleye) depend on unimpeded access to spawning habitats in streams. In many cases dams and other obstructions (e.g. perched culverts) prevent mature fish from reaching spawning habitat and thus compromise stock and species diversity, losses in annual recruitment and reduced production and harvests. For some fishes (e.g. Walleye, Lake Sturgeon) passage facilities will mitigate these effects, because these species cannot jump. In addition to impacting the fishes that migrate from the Great Lakes into tributaries, many stream-dwelling species of fish (e.g. suckers and minnows) suffer discontinuity in their ranges because of barriers.

Although there have been significant improvements in the cataloging of dams and barriers across the basin in the last few years, some dams are undocumented. Spatial analysis of connectivity can be challenging if dams coordinates do not intersect with the hydrology layer. Road stream crossing can highlight potential barriers, but these need to be ground-truthed to assess their impact. Recent efforts to relicense hydropower dams in the United States have led to a reconsideration of the habitat losses associated with these dams and a useful picture is emerging which allows an assessment of the adverse impacts of habitat fragmentation on migratory and resident stream-fish communities. Data for tributary habitat are being developed in connection with Federal Energy Regulatory Commission (FERC) dam relicensing procedures in the United States. Data are presently available for Michigan, New York State, and Wisconsin. The identification of new projects will require research and contact with agencies.

The Upper Midwest and Great Lakes Landscape Conservation Cooperative has established an Aquatic Connectivity Collaborative to provide tools for strategic planning and optimization of efforts to connect habitats. The Collaborative will develop, prioritize, review, recommend and fund research that supports connectivity in the Great Lakes. This effort should increase the amount of habitat connected in each of the Great Lakes in the future. (https://lccnetwork.org/group/great-lakes-aquatic-connectivity-collaborative)

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization						
2. Data are traceable to original sources						
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada		x				

6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				

Acknowledgments
Authors: Dan Kraus, Nature Conservancy of Canada
Contributors: Joseph Sheahan, U.S Fish and Wildlife Service

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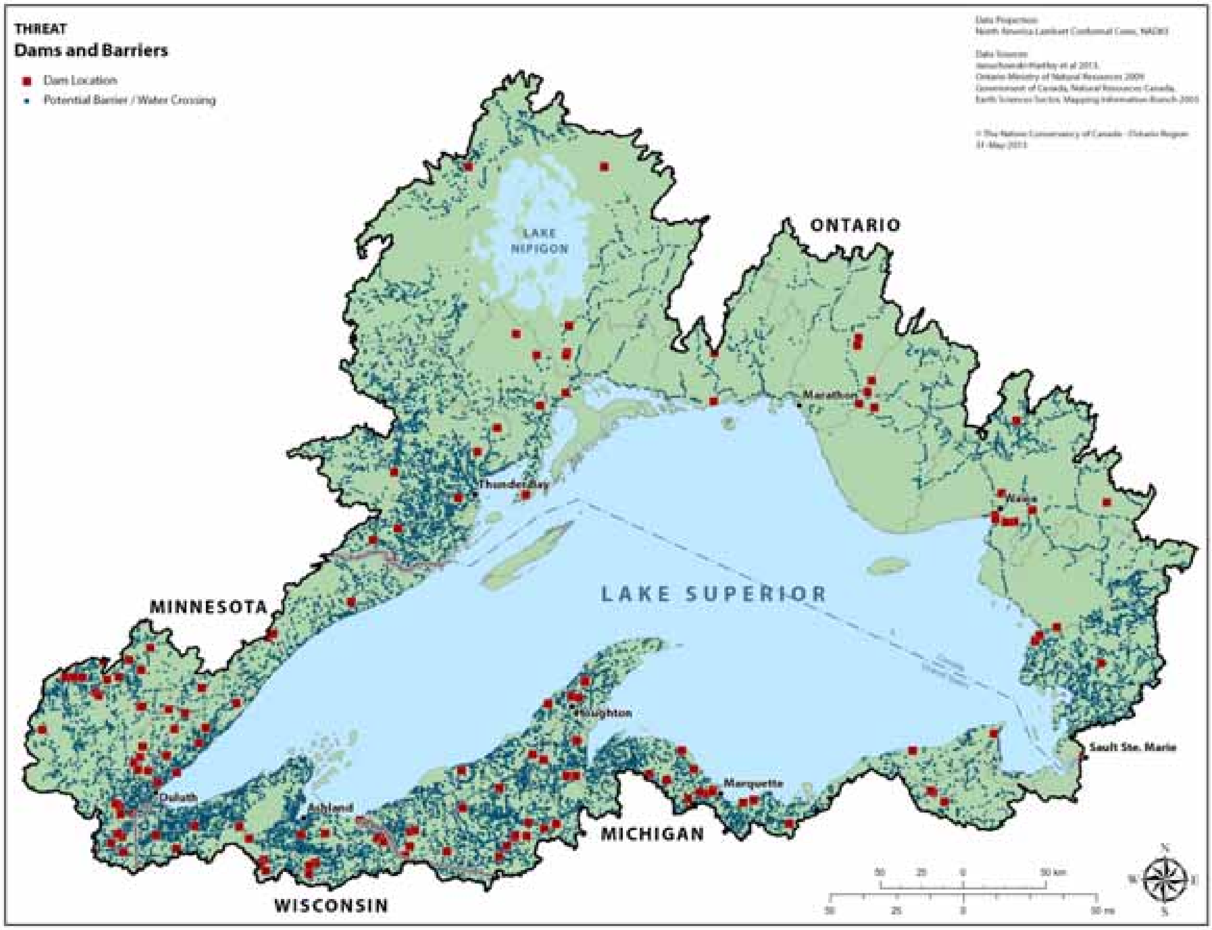

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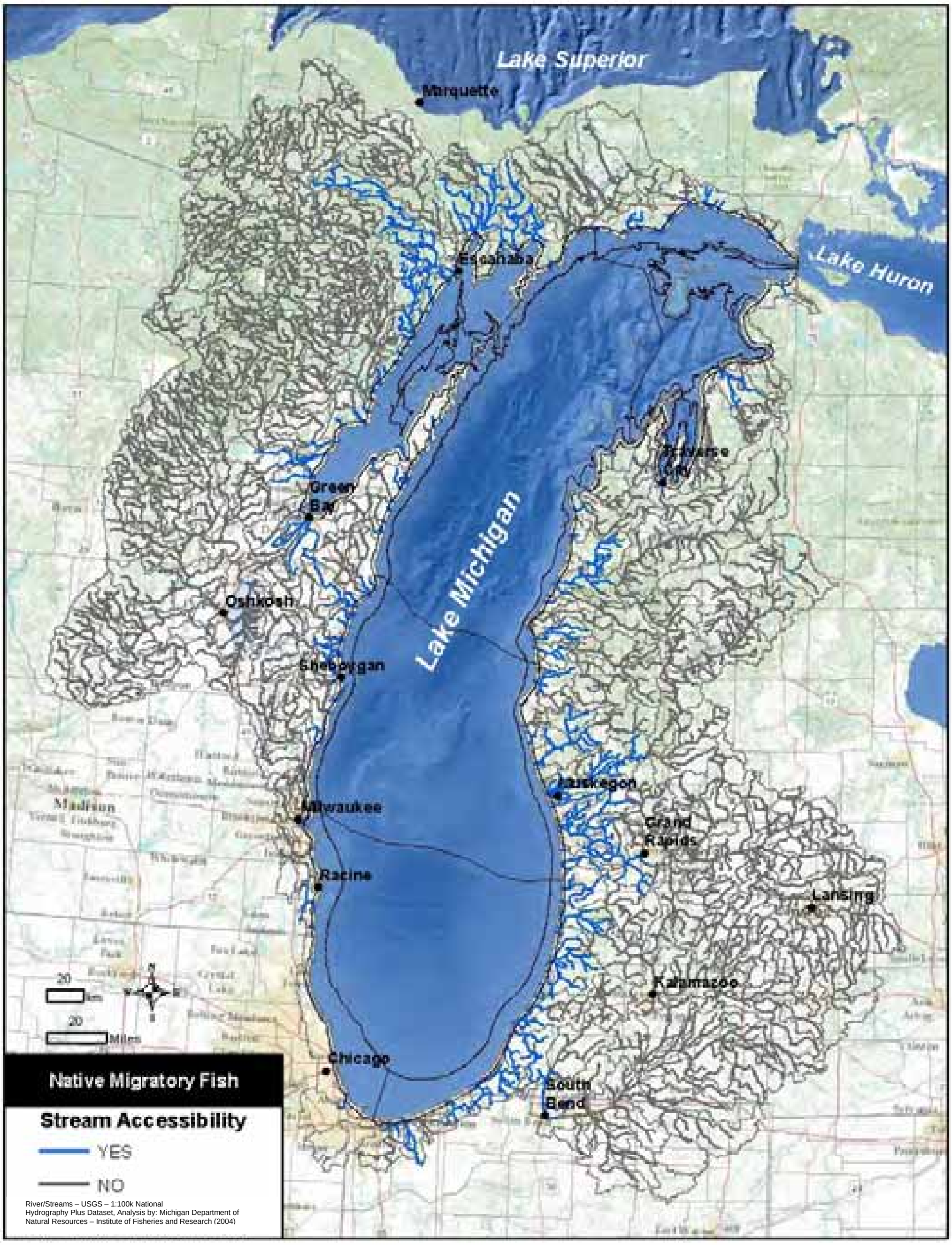

Figure 2. Lake Michigan Aquatic Habitat Connectivity – Stream Accessibility
Source: Pearsall et al. (2012a)

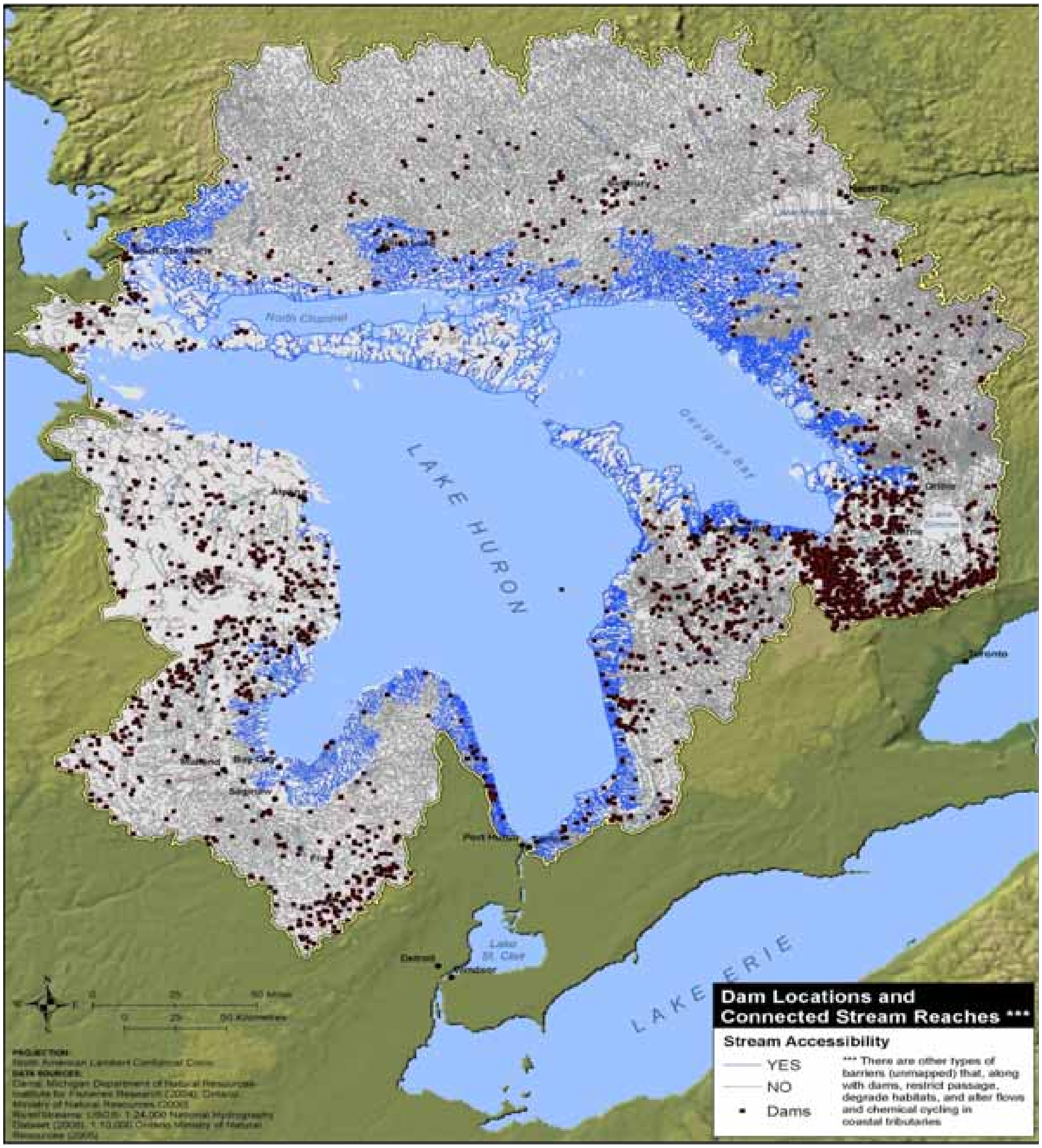

Figure 3. Lake Huron Aquatic Habitat Connectivity – Stream Accessibility
Source: Franks Taylor et. al (2010)

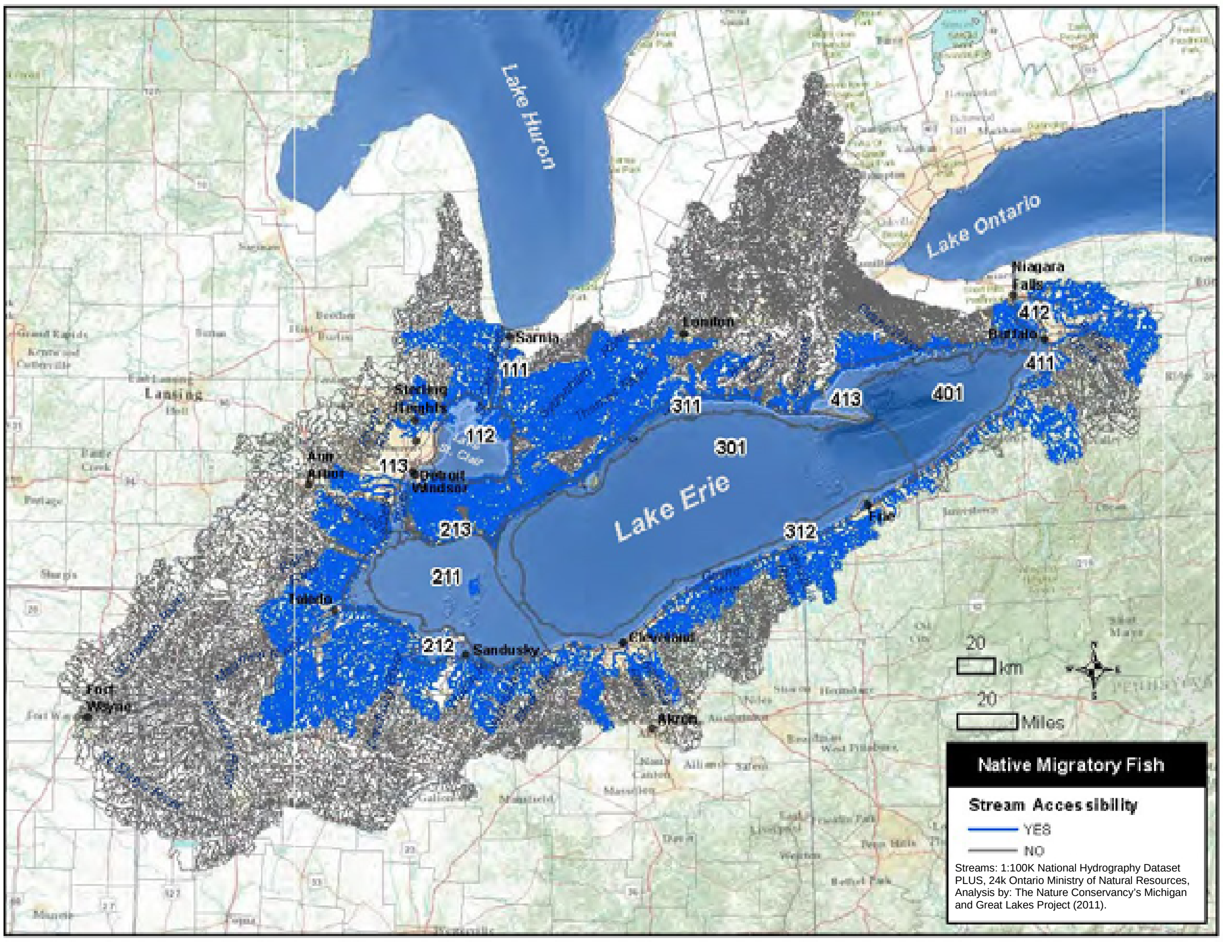

Figure 4. Lake Erie Aquatic Habitat Connectivity – Stream Accessibility
Source: Pearsall et al. (2012b)

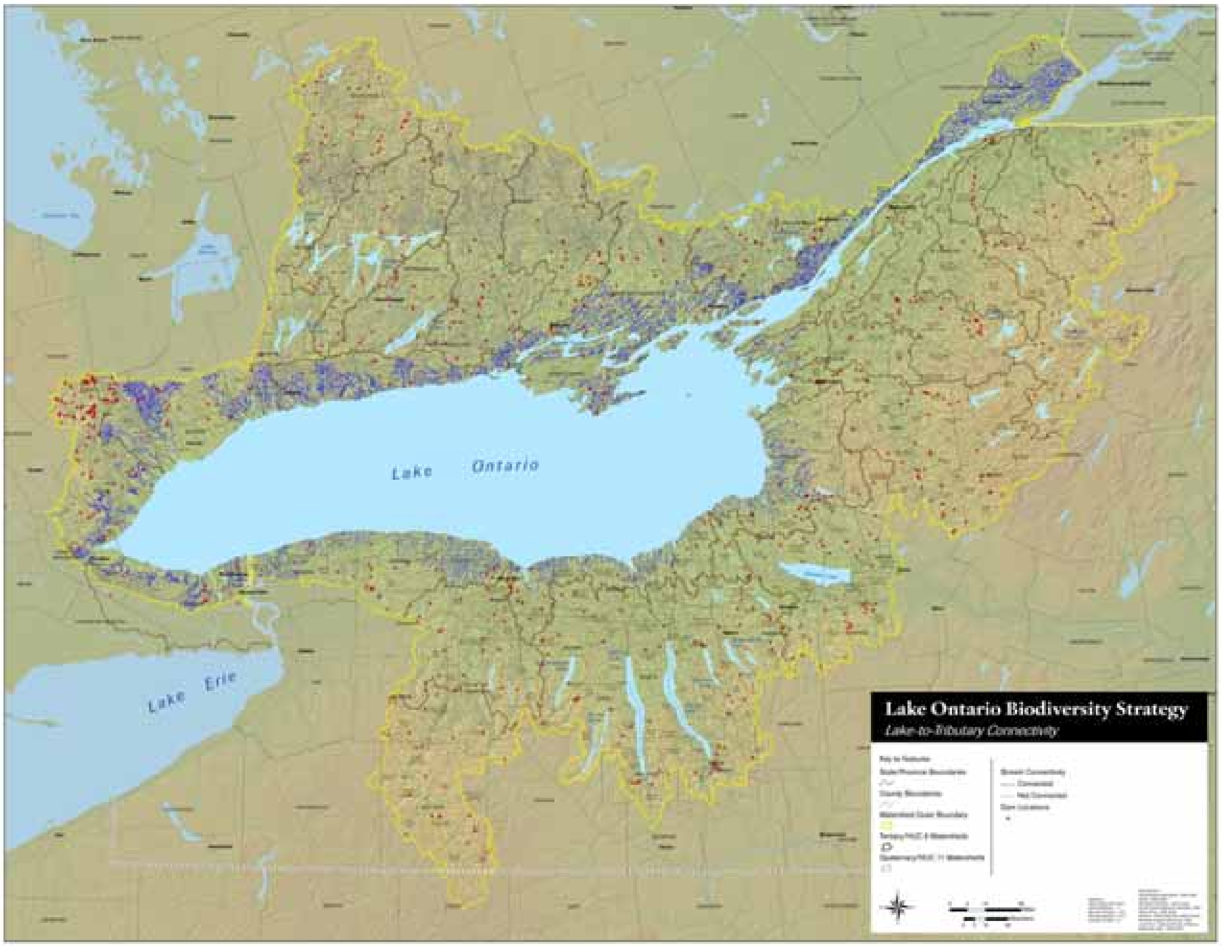

Figure 5. Lake Ontario Aquatic Habitat Connectivity – Tributary Connectivity
Source: Lake Ontario Biodiversity Conservation Strategy Working Group (2009)

Sub-Indicator: Phytoplankton

Open water

Overall Assessment
Status: Fair
Trend: Deteriorating
Rationale: Phytoplankton are a critical food resource for zooplankton and small fish. Invasive mussels have caused algal reductions in Lake Michigan and Lake Huron, negatively impacting food webs of those lakes. Re-eutrophication has occurred in Lake Erie. Changes in Lake Superior and Lake Ontario are more subtle.

Lake-by-Lake Assessment

Lake Superior
Status: Good
Trend: Unchanging
Rationale: The lake has maintained a phytoplankton assemblage reflecting oligotrophic conditions. Invasive species are not notably affecting phytoplankton, but there is evidence from paleolimnological data of gradual assemblage reorganization due to recent climate changes.

Lake Michigan
Status: Fair
Trend: Deteriorating
Rationale: The lake has a phytoplankton assemblage reflecting oligotrophic conditions. A reduction in phytoplankton and consequent diminution in seasonality has occurred. Lower levels of primary production could be reducing resources for higher trophic levels.

Lake Huron
Status: Fair
Trend: Deteriorating
Rationale: The lake has a phytoplankton assemblage reflecting oligotrophic conditions, more so due to the recent invasion by mussels that have reduced pelagic primary producers (negatively affecting invertebrate grazers).

Lake Erie
Status: Poor
Trend: Deteriorating
Rationale: Re-eutrophication and proliferation of undesirable cyanobacteria is an increasing problem, particularly in the western basin. The central basin exhibits substantial spring diatom blooms indicating periodic eutrophic or mesotrophic conditions.

Lake Ontario
Status: Good
Trend: Unchanging
Rationale: The lake has a phytoplankton assemblage reflecting mesotrophic to oligotrophic conditions. There is some evidence of assemblage changes due to invasive dreissenids.

Sub-Indicator Purpose

The purpose of this indicator is to directly assess phytoplankton species composition, biomass, and primary productivity in the Great Lakes, and to indirectly assess the impact of stressors on Great Lakes lower food webs. This includes inferring impacts from water quality changes, invasive non-native species and climate change.

Ecosystem Objective

(1) Maintain trophic states with phytoplankton biomass and composition consistent with a healthy aquatic

ecosystem in open waters of the Great Lakes. Desired objectives are phytoplankton biomass and community structure indicative of oligotrophic conditions (i.e. a state of low biological productivity, as is generally found in the cold open waters of large lakes) for Lakes Superior, Huron and Michigan; and of mesotrophic (or better) conditions for Lakes Erie and Ontario.

(2) Qualitatively and quantitatively detect and predict changes in phytoplankton biomass and composition and apply those changes to stressor impacts or recovery. Desired outcomes are maintenance of good condition over several years or a detectable transition to better conditions.

(3) This indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species." Also, as an indicator at the bottom of the food chain phytoplankton are capable of detecting subtler ecosystem changes, so Article 2(1)(b) of the GLWQA ("develop programs, practices and technology necessary for a better understanding of the Great Lakes Basin Ecosystem") applies.

Ecological Condition

The amount and taxonomic structure of phytoplankton populations can be related to anthropogenic stressors, thereby permitting inferences to be made about lake condition and change (Stoermer 1978). Recently, the most important, comprehensive data sources for phytoplankton-based assessments have been time series data on phytoplankton community size and composition (e.g. Reavie et al. 2014a; Figure 1), satellite-based measurements of chlorophyll (e.g. Barbiero et al. 2012) and recent paleolimnological studies of fossil phytoplankton (e.g. Chraïbi et al. 2014). Additional phytoplankton data have been collected by Canadian agencies, such as that for Lake Erie winter conditions (Twiss et al. 2012; Environment and Climate Change Canada 2015).

Status of the Great Lakes ecosystem as whole is characterized as *fair* although condition and trends vary significantly among lakes. Invasive mussels have caused reductions in algae in Lake Michigan and Lake Huron, negatively impacting food webs of those lakes. Re-eutrophication has occurred in Lake Erie in the last decade, mainly indicated by cyanobacterial blooms that are occurring with greater frequency in the western basin of Lake Erie. Slower, long-term changes are occurring in Lake Superior and Lake Ontario, but these changes are not yet well understood. However, with the exception of Lake Erie, trophic status across the basin would generally be considered good. For the most part, trends herein reflect compiled datasets from 2001 through 2014 ("long-term"), as well as some long-term inferences from previous collections.

Assigning firm condition assessments was also complicated in individual lakes. Consider Lake Michigan and Lake Huron, for instance: if trophic status was the only factor considered their low phytoplankton abundance would superficially reflect *good* conditions. However, the periodic, mussel-driven depletion of phytoplankton in these lakes represents food web stress. From an ecological perspective that simultaneously considers multiple parameters *fair* is a more appropriate assessment.

The 2011 State of the Great Lakes report noted the rapid changes that occurred in the phytoplankton community of several Great Lakes in the decade prior. In general, these changes are continuing, or the lakes remain in the "changed" state reported in 2011. In association with the dreissenid advance, the spring phytoplankton bloom in Lake Huron, which practically disappeared in 2003 (Barbiero et al. 2011), remains absent. Declines in the spring bloom were also seen in Lake Michigan (Reavie et al. 2014a). Such trends of oligotrophication can be viewed positively, but it likely also represents an overall reduction in the carrying capacity of the two lakes, as evidenced by coinciding losses of invertebrates and reductions in fish energy content (Pothoven and Fahnenstiel 2014).

Lake Superior will always be oligotrophic, so in that context it will remain in *good* condition. But, it is noteworthy that the lake's phytoplankton assemblage continues to change over decadal timescales, likely associated with atmospheric warming that is changing the physical properties of the lake (Chraïbi et al. 2014). Such a shift has now been recognized across all of the Great Lakes and their sub-basins (Reavie, unpublished data), so such longer-term changes in primary producers should continue to be observed to determine future impacts.

In the western basin of Lake Erie, blooms of the nuisance algae *Microcystis* (among other cyanobacteria) have continued to occur (Michalak et al. 2013). The spring algal bloom in the central basin, largely attributed to filamentous diatoms (Reavie et al. 2014a, Twiss et al. 2012) is likely contributing substantial biomass to the hypolimnion and exacerbating hypoxia.

Over the last decade in Lake Ontario spring chlorophyll levels have remained stable, but there is evidence of a slight summer chlorophyll increase (USEPA, unpublished data) since declines seen in the 1980s (Johengen et al. 1994). This corresponds with recent changes in Lake Erie, albeit at a smaller scale. Future conditions in Lake Ontario should be observed carefully.

Linkages

Linkages to other indicators include:
(1) Nutrients and Dreissenid Mussels – it is well known that the phytoplankton population and its productivity changes with anthropogenic pollution. The ecosystem changes are reflected by the change of phytoplankton composition and productivity. For example, Lake Superior represents an oligotrophic ecosystem and is widely considered to be in the best condition of the Great Lakes. Similarly, Lake Erie's phytoplankton composition, which was once eutrophic, dramatically changed to meso-oligotrophic status due to phosphorous abatement and the invasion of zebra mussels, a trophic trend that has since reversed to indicate re-eutrophication. A great deal of recent data are available for phytoplankton biomass, composition and primary productivity which will reflect the overall ecosystem health including grazing pressures of non-native filter-feeders and bottom-up influences from nutrients.
(2) This sub-indicator also links directly to the other sub-indicators in the Habitat and Species indicator, such as invertebrate grazers that rely on phytoplankton as a primary food resource. The cycling of phosphorus is being driven by catchment inputs and sedimentary processes, impacting the food web and having implications on many forms of aquatic life, especially benthos, zooplankton and phytoplankton. Effects on fish communities are less direct, but must also be considered.

Comments from the Author(s)

Objective, quantitative mechanisms for evaluating ecosystem health from phytoplankton are gradually being developed. For instance, nutrient optima and tolerances for indicator species are now available for the Great Lakes (Reavie et al. 2014b), thereby allowing quantitative reconstructions of water quality variables from assemblage data. Several qualitative indicators also exist: the abundance of cyanobacteria is a clear indicator for nutrient stress; reductions in algal abundance signal dreissenid-driven oligotrophication; and phytoplankton assemblage changes reflect changes in pelagic ecology due to climate change and other factors. The U.S. Environmental Protection Agency has an active program for phytoplankton collection and analysis in the pelagic regions of all Great Lakes in spring and summer, and other, more localized programs are ongoing (e.g. Fahnenstiel et al. 2010). Satellite imagery has also enabled the detection of chlorophyll trends in the surface waters of the Great Lakes (e.g., Kerfoot et al., 2010), and these data can provide a broad overview of algal abundance.

To date the main purposes of this indicator have been to (1) measure biological responses of primary producers to changing water quality and invasive species abundance; (2) evaluate direct problems (e.g. blooms) associated with phytoplankton; (3) indirectly evaluate the trophic efficiency of the food web at transferring algal production to fish. As a sensitive indicator of changes in primary producers due to various drivers (invasive species effects, nutrients, climate, etc.), phytoplankton provide information on the effects of multiple stressors. As a newly-recognized driver of phytoplankton assemblages in Lake Superior (Chraïbi et al. 2014), climate change effects on phytoplankton and their potential impacts on food webs will be tracked.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				

4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada			X			
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				
Clarifying Notes: These data have been derived from many sources, including scientific literature, satellite data, and unpublished data.						

Acknowledgments
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Figure 1. Histograms of phytoplankton biovolume and community composition in the Great Lakes basins from 2001 through 2013. Spring and summer assemblages are provided from offshore, surface waters. Small numbers at the bottom of each bar indicate the number of samples averaged. Major noteworthy trends include: declines in phytoplankton abundance in Lake Huron and Lake Michigan (particularly in spring and attributed to diatom loss); and increases in spring and summer phytoplankton in central and western Lake Erie (mainly attributed to increases in spring diatoms and summer cyanophytes).
Source: U.S. Environmental Protection Agency, Great Lakes National Program Office. Modified from Reavie et al. (2014a).

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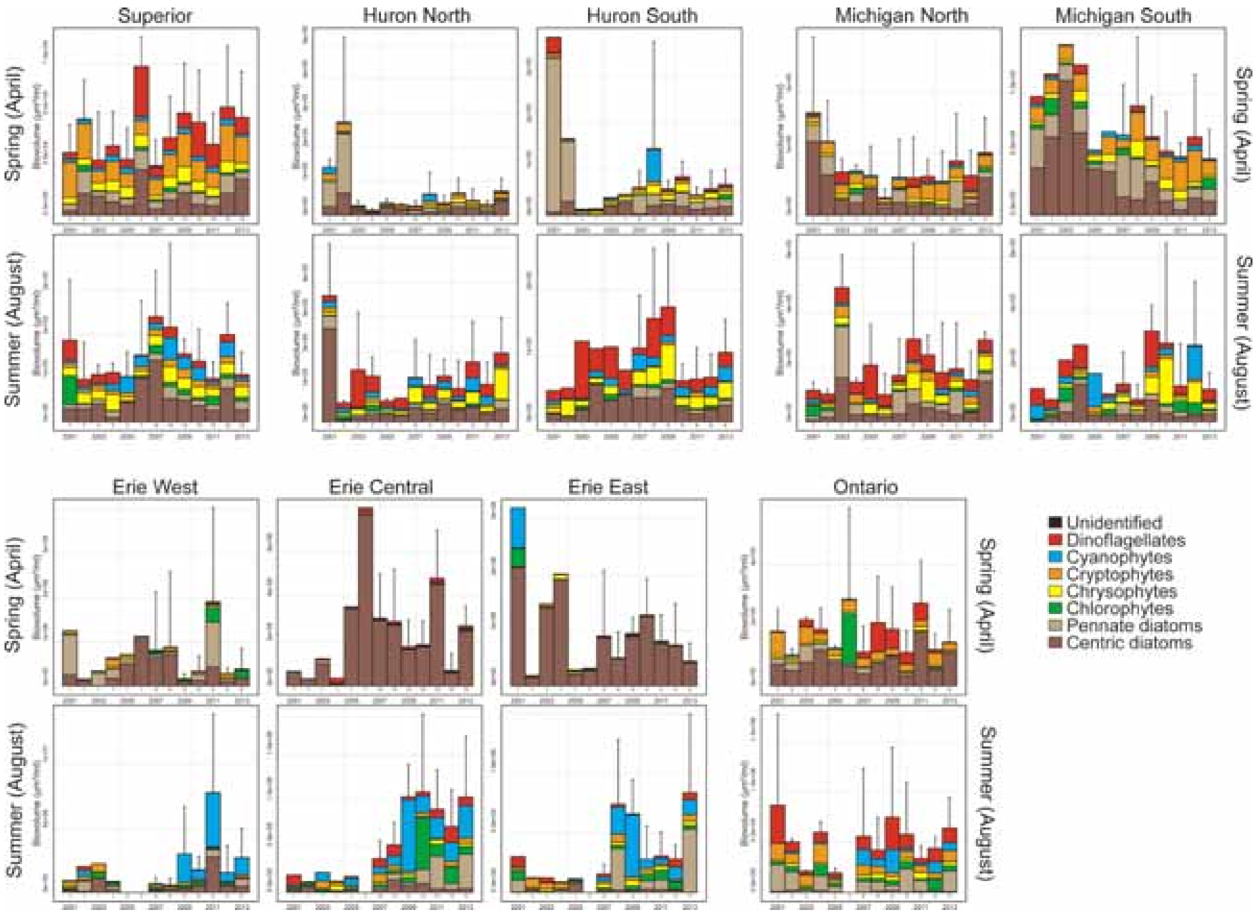

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Source: U.S. Environmental Protection Agency, Great Lakes National Program Office. Modified from Reavie et al. (2014a).

Sub-Indicator: Zooplankton

Open water

Overall Assessment
Status: Good
Trend: Unchanging
Rationale: Zooplankton biomass levels and community composition are consistent with the oligotrophic state of the four deepest Great Lakes. Lake Erie has more cladocerans which is typical of a shallow productive lake. The 14 year trends are declining in Lake Huron and perhaps Lake Ontario, unchanging in Lakes Superior and Michigan and perhaps increasing in Lake Erie. The proportion of calanoid copepods, an index of oligotrophication has increased in Lakes Michigan, Huron and Ontario. Shorter term trends are largely unchanging (2006-2011).

Lake-by-Lake Assessment

Lake Superior

Status: Good
Trend: Unchanging
Rationale: Zooplankton biomass stable and near 3 g m^{-2}. Community composition also stable with high prevalence of calanoid copepods including the large copepod *Limnocalanus*, an indicator of cold deep oligotrophic lakes.

Lake Michigan

Status: Good
Trend: Unchanging
Rationale: Zooplankton biomass higher than Lake Superior near 5-6 g m^{-2}. No overall decline in zooplankton despite observed declines in primary productivity. Shift in zooplankton community was apparent around 2001-2004 with reduction of daphnid cladoceran biomass by 50%, and increased prevalence of calanoid copepods particularly *Limnocalanus*. However since that time, there has been no change in community composition.

Lake Huron

Status: Fair (low)
Trend: Unchanging
Rationale: Zooplankton biomass has remained low in Lake Huron since 2003. In 2003, zooplankton biomass decreased from 4-8 g m^{-2} to 2 g m^{-2}, falling below Lake Superior biomass levels. Sharp declines in cladoceran biomass, particularly daphnids, yielded a community dominated by calanoid copepods. Zooplankton biomass decrease coincided with decline in primary productivity and fishery indicators (Riley et al. 2008, Barbiero et al. 2011). However, since that decline, there has been no further change in biomass or community composition. Although the current status is similar to Lake Superior, the abrupt change that the zooplankton community underwent in 2003 has had ecosystem implications.

Lake Erie

Status: Good
Trend: Unchanging
Rationale: Note: Areal biomass goals are lower for shallow Lake Erie relative to the deeper Great Lakes.
Lake Erie has three distinct basins- Western, Central, and Eastern. Biomass in shallow (10 m depth) Western Basin has increased from 0.5 g m^{-2} to 1.0 g m^{-2} with persistent cyclopoid copepods and cladocerans and a small but increasing calanoid copepod component. Deeper Central (20 m) and Eastern (50 m) Basins have similar overall zooplankton biomass at 2-4 g m^{-2}. Although areal (total water column) biomass levels are similar to oligotrophic Lake Superior, zooplankton are more concentrated (more individuals per unit volume) in the shallower basins of Lake Erie. Some evidence of increased overall biomass in later years, 2010-2011. Lake Erie has the highest zooplankton diversity rich in cladoceran species. Deep-dwelling *Limnocalanus*, increasingly important in other Great Lakes, is

rare in Lake Erie due to limited hypolimnetic habitat. *Limnocalanus* copepodites can be washed into Western Lake Erie from Lake Huron in the spring.

Lake Ontario
Status: Good
Trend: Unchanging
Rationale: Zooplankton biomass levels are intermediate between Lake Michigan and Lake Superior at levels around 4-5 g m^{-2}. Some recovery occurred after a biomass minimum during the time period 2004-2007, however, for the most part, the biomass in Lake Ontario has not changed significantly since 2000. Community shift away from cyclopoid copepods toward calanoid copepods suggests oligotrophication. Some signs of recovery in daphnid cladoceran biomass in 2010-2011. Predation by alewife is high relative to other Great Lakes.

Sub-Indicator Purpose

- The offshore zooplankton biomass sub-indicator assesses the standing stock and community composition of zooplankton in the Great Lakes over time and space.
- Changes in the offshore zooplankton biomass sub-indicator track forcing from both bottom-up (primary production) and top-down (vertebrate or invertebrate predation) mechanisms as well as energy transfer across trophic levels. The purpose of this sub-indicator is to measure the trophic efficiency of the food web at transferring algal production to fish.
- Zooplankton biomass has often been used to explain deviations in the relationship of nutrients (total phosphorus, TP) and phytoplankton biomass (chl *a*) (Taylor and Carter 1997).
- Mean body size and species composition of zooplankton are also sensitive indicators of predatory pressure by planktivorous fish and large invertebrates (*Mysis* and predatory cladocerans). Such indicators need further development.

Ecosystem Objective

Maintain and support a healthy and diverse fishery; maintain trophic states consistent with the lake-specific goals – oligotrophic Lake Superior, Huron, Michigan, and Ontario, and mesotrophic Lake Erie. Zooplankton represent an important trophic link from primary production to fish and abundant zooplankton tend to improve water quality and fish production capacity.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement that states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition

Lakes with lower target Total Phosphorus (TP) concentrations (e.g. Lake Superior and Huron at 5 µg P l^{-1} and Lake Michigan at 7 µg P l^{-1}) will have a lower target offshore zooplankton biomass of 3 g m^{-2} than lakes with higher target TP concentrations (e.g. Lake Ontario at 10 µg P l^{-1}) having a target offshore zooplankton biomass of 5 g m^{-2}. Although Lake Erie has a similar TP target as Lake Ontario, a shallower habitat suggests a lower zooplankton biomass goal of 3 g m^{-2} for the central (20 m) and eastern (40 m) basins and 1 g m^{-2} for the western basin (10 m). Summer biomass of crustacean zooplankton communities in the offshore waters of Lake Superior has remained at a relatively low but stable level near 3 g m^{-2} since at least 1998 (Figure 1). The plankton community is dominated by large calanoid copepods (*Leptodiaptomus sicilis* and *Limnocalanus macrurus*) that are characteristic of oligotrophic, coldwater ecosystems. In 2003, the biomass of cladocerans and cyclopoid copepods in Lake Huron declined dramatically, with total biomass falling below that of Lake Superior (Barbiero et al. 2011). Our updated time series shows that there has been little additional change since 2003 in Lake Huron. Similar declines of cladocerans occurred in Lake Michigan, although this decline has been offset by the increase in *L. macrurus* (Barbiero et al. 2009). Our time series suggest overall zooplankton biomass levels near 5-6 g m^{-2} have been maintained. Summer zooplankton communities in Lakes Huron and Michigan have become increasingly similar to that of Lake Superior, with composition characteristic of cold oligotrophic systems (Barbiero et al. 2012).

Overall zooplankton biomass of Lake Ontario (4-5 g m^{-2}) is between that of Lake Michigan and Lake Superior. Cyclopoid copepods comprised a large part of the zooplankton community before decreasing in 2004. Cladocerans biomass was also important but has varied over time. Decreases in cyclopoid and cladoceran biomass have been offset by increases in calanoid copepods including *L. macrurus*. Thus, changes in the zooplankton community of Lake Ontario mirror that of lakes Superior, Michigan, and Huron although cyclopoid copepods and cladocerans remain higher than in the other deep lakes (Barbiero et al. 2014, Rudstam et al. 2015).

Zooplankton biomass of shallow Western Lake Erie has slightly increased to levels near 1-2 g m^{-2}. Zooplankton biomass in the deeper central and eastern basins has maintained levels near 3 g m^{-2} and community composition has remained diverse and rich in native and non-native cladoceran species.

The proportion of biomass represented by calanoid copepods in Lake Superior has remained fairly stable at 85%, indicating oligotrophic conditions. Summer zooplankton communities in lakes Huron, Michigan, and Ontario have shown an increasing proportion of calanoid copepods in recent years, which suggests increased oligotrophication. It has been a result primarily of substantial declines in cladoceran and cyclopoid copepod populations. This had led to decreased overall zooplankton biomass in Lake Huron to levels that may be limiting to alewife, although other fish species have increased (Riley et al. 2008). In contrast, calanoid biomass has made up for the decrease in cladocerans in Lakes Michigan and Ontario. *Limnocalanus* is a large deep dwelling copepod so that, although overall biomass has been maintained, the zooplankton community has shifted toward less dense, larger organisms that live deep in colder water. Therefore, zooplankton production decreases following these species changes even though biomass does not change. Some fish species (e.g. native coregonids) may benefit from this change but others (e.g. alewife) may not. Primary production, and in particular the spring phytoplankton bloom, has indeed declined notably in lakes Huron and Michigan coincident with the shifts in the zooplankton communities. Lake Ontario has not experienced recent declines in primary production, suggesting that top-down control from alewife and predatory cladocerans (particularly *Bythotrephes*) may better explain observed zooplankton community shifts in this lake (Barbiero et al. 2014, Rudstam, et al. 2015). Maintenance of cladoceran fauna relative to calanoids in Lake Erie can be attributed to shallow habitat as well as a mesotrophic state.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Other Habitat and Species sub-indicators (phytoplankton and benthos).
- Nutrients in Lakes (open water) – phosphorus levels regulate primary productivity by phytoplankton and thus food levels for zooplankton.
- Dreissenid Mussels – filter feeding of phytoplankton by mussels competes with zooplankton grazers. Smaller zooplankton may be ingested by mussels. Increased water clarity shifts primary production to deeper depths in the form of deep chlorophyll layers (DCL).
- The connection of the zooplankton sub-indicator to other trophic levels provides a test of the principle developed in marine settings that pelagic communities, on average, have approximately equal biomass in exponentially widening size classes (Sheldon et al. 1972). Material and energy flow up this size spectrum from bacteria and phytoplankton via zooplankton to fish with varying efficiency (Borgmann 1987). Some of this production sinks from the surface euphotic zone to nourish the benthos. It may flow efficiently, with high productivity across the size-spectrum, or it may accumulate as algae, negatively affecting water quality while little energy reaches top predators.

Comments from the Author(s)

Changes in the zooplankton communities of Lake Huron and Lake Michigan, and to a lesser extent Lake Ontario, are consistent with reductions in nutrient levels, which have been seen in all three lakes, and could represent a consequence of nutrient reduction activities, perhaps compounded by effects of dreissenid mussels. The reductions in cladocerans in the former two lakes, along with continued declines in populations of the benthic amphipod *Diporeia*, could represent a decreasing food base for forage fish. However, exact mechanisms of these declines, and the relative strength of bottom-up versus top-down forcing, have yet to be fully determined.

An important threat to the zooplankton communities of the Great Lakes is posed by invasive species. The continued proliferation of dreissenid populations can be expected to impact zooplankton communities through the alteration of the structure and abundance of the phytoplankton community that many zooplankton depend on for food. Predation from the non-native cladocerans *Bythotrephes longimanus* and *Cercopagis pengoi* may also have an impact on zooplankton abundance and community composition. Invasive predatory cladocerans have been shown to have had a major impact on zooplankton community structure in the Great Lakes (Lehman 1991; Barbiero and Tuchman 2004; Warner et al. 2006).

Currently U.S. EPA monitoring data for crustaceans are available through 2011. Details on methods for zooplankton sampling and analysis can be found in Barbiero et al. (2001). Summer offshore crustacean zooplankton biomass is the main indicator reported this year.

Note that unlike previous indicator reports, we use areal biomass (g m^{-2}) rather than volumetric (mg m^{-3}) units to better evaluate the overall standing biomass of these lakes for connecting to fish production potential (Bunnell et al. 2014). Whole water column (in this case maximum of 100 m) tows in deep lakes include large strata of hypolimnion that have few zooplankton. Volumetric biomass estimates are thus “diluted” relative to shallower lakes that have less hypolimnion. Areal biomass is calculated by summing the zooplankton biomass found within one meter squared of lake water column. Note that for Lakes Superior, Michigan, and Ontario most offshore GLNPO sites are > 100 m but many of the sites for Lake Huron are < 100 m. In Lake Erie, depths range from 10 m in the Western to 20 m in the Central to 50 m in the Eastern basins.

The length-weight coefficients have been updated for calanoid copepods based on recent studies to better reflect their contribution (Watkins et al. 2011, Burgess et al. 2015). This update leads to an increase in estimated calanoid biomass by a factor of 2 compared to previous State of the Great Lakes (previously known as SOLEC) indicator reports and Bunnell et al. 2014.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		x				
2. Data are traceable to original sources		x				
3. The source of the data is a known, reliable and respected generator of data		x				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the U.S. are comparable to those from Canada						x
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				

Acknowledgments

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Richard P. Barbiero, CSC, Chicago, IL, gloeotri@sbcglobal.net

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List of Figures

Last Updated

State of the Great Lakes 2017 Technical Report

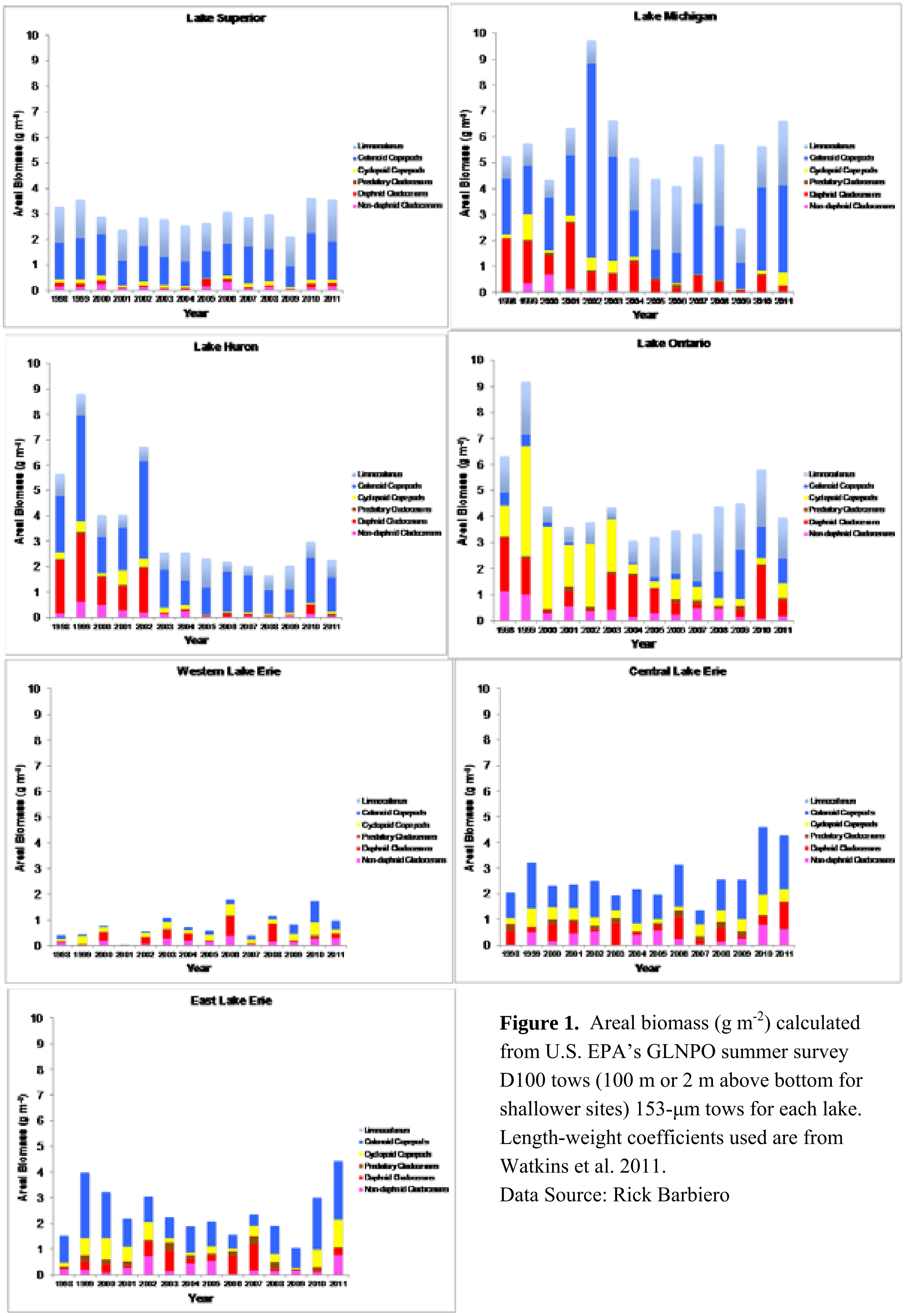

Figure 1. Areal biomass (g m^{-2}) calculated from U.S. EPA's GLNPO summer survey D100 tows (100 m or 2 m above bottom for shallower sites) 153-µm tows for each lake. Length-weight coefficients used are from Watkins et al. 2011.
Data Source: Rick Barbiero

Sub-Indicator: Benthos

Open water

Overall Assessment
Status: Good
Trend: Unchanging
Rationale: Based on the benthic community, both the long-term (1997 - 2012) and short-term (2010-2012) trends in the trophic condition of the lakes are generally considered to be good and unchanging, except for the Lake Erie where the long-term trends are indicative of increased eutrophication. Overall, an increasing Oligochaete Trophic Index (OTI) means increasing eutrophication or increasing trophic conditions.

Lake-by-Lake Assessment
Lake Superior
Status: Good
Trend: Unchanging
Rationale: All sites in Lake Superior were classified as oligotrophic based on the oligochaete community index both long-term (since 1997) and in the recent years. The endpoint for this sub-indicator is to maintain oligotrophic conditions in the open waters of Lake Superior.

Lake Michigan
Status: Good
Trend: Unchanging
Rationale: All sites in northern and central Lake Michigan, as well as deep sites in the southern part of the lake have a trophic index value below 0.6 indicating an oligotrophic condition. Overall, no significant negative trends were found in the trophic condition of the lake since 1997 and in the last few years. Poor OTI (> 1.0) scores were found in recent years at two nearshore sites (of 16 total) in the southeastern part of the lake, and significant trends of increasing eutrophication are evident at one of these two sites (near the Grand River outlet) since 2002. The endpoint for this sub-indicator is to maintain an oligotrophic state in the open waters of Lake Michigan.

Lake Huron
Status: Good
Trend: Unchanging
Rationale: Almost all sites in northern, southern and central Huron are oligotrophic, except for one mesotrophic site in the southern part and two eutrophic sites: on the eastern shore near the outlet of Saugeen River in Ontario, Canada, and in Saginaw Bay. The trophic state of the lake has not changed significantly in the last 16 years. The endpoint for this sub-indicator is to maintain an oligotrophic state in the open waters of Lake Huron.

Lake Erie
Status: Poor
Trend: Deteriorating
Rationale: All sites on Lake Erie are eutrophic, and several have a long-term trend of increasing OTI. The highest OTI values are found in the eastern basin. The endpoint for this sub-indicator is to maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

Lake Ontario
Status: Fair
Trend: Unchanging
Rationale: All deep-water sites (>80 m) in both basins of Lake Ontario are oligotrophic, and one shallow site is eutrophic. Most of the nearshore sites are mesotrophic and two sites in western basin showed trends toward eutrophication in the last decade. Overall, no significant negative trends were found in the trophic condition of the lake since 1997 and in the last few years.

There are no permanent stations on connecting channels, so they are not assessed as part of this sub-indicator report.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess trends in trophic conditions in the Great Lakes using oligochaete diversity, abundances, and the individual species responses to organic enrichment and to infer health of the benthic community.

Ecosystem Objective

The Ecosystem Objective is that the benthic community in the Great Lakes should remain relatively constant over time and be comparable to unimpaired waters with similar depth and substrate. One estimate is based on the Oligochaete Trophic Index which uses oligochaete diversity, trophic classifications and abundance to compute trophic status of a body of water.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

This sub-indicator will evaluate trophic conditions in the Great Lakes using oligochaete diversity, abundances, and the individual species responses to organic enrichment.

Calculation of the Oligochaete Trophic Index (OTI)

To evaluate trends in the benthic community of the Great Lakes, an Oligochaete Trophic Index (OTI) is used. The OTI was initially described by Mosley and Howmiller (1977) with subsequent modifications by Howmiller and Scott (1977), Milbrink (1983), and Lauritsen et al. (1985). This sub-indicator primarily follows Milbrink's formula (Riseng et al. 2014). Milbrink classifies Tubificids and Lumbriculids oligochaetes into four ecological classes relative to trophic status of the lake. The values range from 0 indicating intolerant of enrichment (oligotrophic conditions) to 3 indicating tolerant of enrichment (highly eutrophic conditions). The index is calculated as:

$$\mathrm{OTI} = c \times \frac{\frac{1}{2}\sum n_0 + \sum n_1 + 2\sum n_2 + 3\sum n_3}{\sum n_0 + \sum n_1 + \sum n_2 + \sum n_3}$$

where n_0, n_1, n_2, and n_3 indicate the abundances of organisms in each of the four trophic categories (Table 1) and c is a density coefficient that scales the index to absolute densities of Tubificids and Lumbriculids. The c coefficient is calculated as follows (Milbrink 1983):

$c = 1$ if $n > 3{,}600$

$c = 0.75$ if $1{,}200 < n < 3{,}600$

$c = 0.50$ if $400 < n < 1{,}200$

$c = 0.25$ if $130 < n < 400$

$c = 0$ if $n < 130$

In this modification of original Milbrink's OTI calculations (Riseng et al. 2014):

- only lumbriculids and tubificids were used to calculate the index;
- all immature lumbriculids were classified as *Stylodrilus heringianus* (Styheri);
- the c coefficient was estimated from abundances (n) of mature and immature lumbriculids and tubificids;

Milbrink (1983) assigned the tubificid *Tubifex tubifex* (Tubtubi) dual classifications depending on the dominance of *Stylodrilus heringianus* or *Limnodrilus hoffmeisteri* (Limhoff). Riseng et al (2014) formalized the dual classification as follows: if the ratio of abundances of n_0 oligochaetes to n_3 oligochaetes (Limhoff) < 1 then Tubtubi is classified as a 3; if the ratio is > 1 then Tubtubi is classified as a 0; however, if the ratio is close to one (0.75 to 1.25) then Tubtubi is a 3 if $c \geq 0.5$ and a 0 if $c < 0.5$;
if Limhoff density is zero and n_0 is relatively high and/or total density is low, then Tubtubi is 0, otherwise 3; and, finally, if the total density of oligochaetes is zero, then the index is zero.

Trophic classifications were obtained from literature for the Great Lakes and are shown in Table 1.

Ecological Condition

In the 2012 Great Lakes Water Quality Agreement (GLWQA), the Areas of Concern (AOC) Annex's purpose is to contribute to the achievement of the General and Objectives of the Agreement by restoring the beneficial uses that have become impaired due to location conditions. Beneficial Use Impairments are the measures of the environmental, human health or economic impact of poor water quality. The GLWQA defines 14 Beneficial Use Impairments that contribute to a location's designation as an AOC. Degradation of Benthos is one of the BUIs for the Great Lakes and further emphasizes the importance of the sub-indicator in the suite.

State of the Great Lakes reporting (previously knowns as SOLEC) uses the modified oligochaete-based trophic condition index (OTI, Milbrink 1983; Howmiller and Scott 1977) to assess trophic status of each site. The trophic condition index is calculated based on known organic enrichment tolerances and abundances of oligochaete taxa (see attached summary of calculation procedure). The index ranges from 0 – 3: scores less than 0.6 (the lower blue line in Figure 1) indicate oligotrophic conditions; scores above 1 (the top black line in Figure 1) indicate eutrophic conditions; and scores between 0.6 and 1.0 suggest mesotrophic conditions. Scores approaching 3 indicate high densities of oligochaetes dominated by the pollution tolerant tubificidae including *Limnodrilus hoffmeisteri*. Overall, an increasing OTI means increasing eutrophication or increasing trophic conditions.

A consistent difference in trophic conditions among and within Great Lakes was found during the study period (1997– 2012) (Figure 1). Trophic state was significantly inversely related to site depth ($r = -0.58$), with Lake Erie being the most eutrophic lake, followed in order of decreasing trophic state by lakes Ontario, Michigan, Huron and Superior. To assess the temporal trends in OTI at each site we used linear regression. The only significant lake-wide long-term trend of increasing trophic conditions or becoming more eutrophic ($P < 0.005$) was observed in Lake Erie, where significant trends were found in half of the sampled sites. Localized increases in OTI over time were found at nearshore sites in southeastern Lake Michigan, eastern Lake Huron, and western Lake Ontario (Figure 2).

The most eutrophic sites in Lake Erie were found in the eastern basin, where OTI at deep sites doubled since the early 2000s as a result of drastic decrease in pollution-intolerant species. Significant trends of OTI increase were found here at 4 of 5 sampled sites (Figure 3). One more site that showed a significant trend of increasing trophic conditions was a nearshore site in the central basin located between Ashtabula and Erie, PA (Figure 3). The average OTI for the eastern basin (1.96±0.45, mean ± standard deviation) exceeded those for both the western (1.41±0.51) and the central basins (1.39±0.36). The overall phytoplankton biomass in the lake has increased since the mid-1990s (Conroy et al. 2005b), potentially a result of the dramatic increase in dissolved reactive phosphorus loads from tributaries (Richards et al. 2010), in contrast to the relatively constant Total Phosphorus loads (Scavia et al. 2014). In addition, dreissenid populations declined in the central basin in early 2000s (Patterson et al. 2005; Karatayev et al. 2014) most likely due to hypoxia events. Considering that the eastern basin is the main region of sediment and organic matter deposition in Lake Erie, the increase in basin- and lake-wide OTI may be indicative of increasing trophic state of the lake.

Deepwater sites in Lake Ontario continue to be oligotrophic throughout the whole study period. In contrast, the nearshore sites, especially along the southern shore, are mesotrophic or eutrophic (Figure 2). Two nearshore sites in the western basin showed a trend toward increasing eutrophication since 2001 (Figure 3), likely being affected in the southern shore by the outlet of the Niagara River, and on the northern shore by the Toronto metropolitan area.

All sites in northern and central Lake Michigan, as well as deep sites in the southern part of the lake are oligotrophic (Figure 2). Two nearshore sites in southeastern Michigan (near the Grand and Kalamazoo River outlets) are eutrophic and one of them (at the mouth of Grand River) had a significant trend of increasing eutrophication ($P < 0.001$). One site in northern Michigan and one in Green Bay showed opposite trends of increasing oligotrophication (Figure 3).

Almost all sites in northern, southern and central Huron are oligotrophic; one site in the southern part is mesotrophic (Figure 2). Only two sites in Lake Huron are eutrophic: one on the central-eastern shore (near the outlet of Saugeen River in Ontario, Canada) where the total density of Oligochaeta increased 20-fold since the early 2000s, and eutrophication is significantly increased ($P = 0.004$), and the other in Saginaw Bay, which was highly eutrophic in late 1990s, improved to mesotrophic in 2002, but has trended towards eutrophic again starting in 2007.

All sites in Lake Superior were oligotrophic based on OTI values since 1997, and one easternmost site even showed trends of decreasing OTI in the last four years (Figure 3). There was an increase in OTI at one western site north of Duluth (Figure 3) but the change was minimal (from 0 to 0.125).

Linkages

Linkages to other sub-indicators in the indicator suite include:

• Dreissenid Mussels – the relative abundance of non-native benthos such as zebra and quagga mussels can change dramatically the structure of aquatic communities including the benthos, affect ecosystem functioning and lake trophic state. In addition to direct local effects, dreissenid mussels also interact indirectly with benthic community by affecting other sub-indicators such as Nutrients in Lakes, therefore decreasing the amount of available food. There are strong interactions between these sub-indicators although not well understood and require further investigation.

• Nutrients in Lakes (open water) – nutrients impact the food web and are important for many forms of aquatic life, especially benthos, zooplankton and phytoplankton. Addition of nutrients affects the structure and abundance of benthic community, changing the share of tolerant and intolerant species, but the magnitude of changes varies depending on the depth and lake trophic status. Since the OTI was designed to reflect community changes following organic enrichment, it can be expected to co-vary with increase in nutrients. Indeed, OTI positively correlates with the amount of Total Phosphorus and Total Soluble Phosphorus measured at the bottom (Burlakova et al. in preparation).

• *Diporeia* (open water) – *Diporeia* is a benthic macroinvertebrate in the cold, deep-water habitats of all the Great Lakes (except Lake Erie), an indicator of oligotrophic conditions, and an important fish food item. Historically *Diporeia* has been a dominant benthic macroinvertebrate in profundal regions of all five of the Great Lakes (Cook and Johnson, 1974). Proliferation of dreissenid mussels coincided with significant declines in *Diporeia* in Lakes Ontario, Michigan and Huron, but the nature of these interactions is not yet well understood. While the abundance of *Diporeia* is not considered by the current index (OTI), a significant increase in organic enrichment may negatively affect *Diporeia*.

This sub-indicator also links directly to the other sub-indicators in the Habitat and Species indicator.

Comments from the Author(s)

The oligochaete sub-indicator used for the State of the Great Lakes (previously known as SOLEC) assesses trophic status of the lakes and may suggest pressures due to organic enrichment. Most of the sites that showed increasing eutrophication are located near large river mouths, suggesting that pollution abatement mitigation in the upland watersheds could help to improve water quality and sediment conditions at these sites. Other pressures not accounted for in the oligochaete trophic index include invasive species, regional climate change, water level changes, toxic or other contaminants. The tendency of decreasing OTI with depth (due to the lack of pollution tolerant species at depths over 60m) may affect the lake-wide index depending on the ratio of deep to shallow sites sampled in each lake. The regular benthic monitoring program of U.S. EPA Great Lakes National Program Office (U.S. EPA GLNPO) has a relatively small number of stations, with poor representation of nearshore areas, and complementing these annual surveys with a wider range of sites during CSMI years will aid greatly in identifying trends in benthic community.

Invasive species that strongly affect freshwater ecosystems (e.g., *Dreissena* spp.) can alter the composition and abundance of benthic communities, affecting behavior of benthic indices, including OTI. Even though mussel biomass has been declining in the 30-90m depth zones in some of the lakes, dreissenids are still a dominant component of the benthos.

There is an emerging realization of the importance of benthic processes and pathways within whole-lake context (Vander Zanden and Vadeboncoeur 2002). Recent analysis of long-term dynamics of major trophic levels in Laurentian Great Lakes revealed a far greater prevalence of bottom-up regulation since 1998, emanated from long-term declines in TP inputs and the more recent proliferation of nonindigenous dreissenid mussels (Bunnell et al. 2013). Filter feeding Ponto-Caspian bivalves *Dreissena polymorpha* and *D. rostriformis bugensis* are powerful ecosystem engineers that affect both abiotic (e.g., enhance water clarity and alter nutrient cycling) and biotic (e.g., reduce abundance of phytoplankton and microzooplankton, enhance benthic algae and macrophytes, induce changes in benthic community) components of the ecosystem (Karatayev et al. 1997, 2002; Higgins and Vander Zanden 2010). Filter-feeding activity, sediment deposition and habitat provided by dreissenids directly affect benthic macroinvertebrate community abundance and composition by promoting epifaunal predators, scavengers and collectors while replacing native filter feeders (e.g., Karatayev et al. 1997; 2002; Burlakova et al. 2012; Ward and Ricciardi 2007; Higgins and Vander Zanden 2010). However, most of the changes in benthic community following dreissenid invasion are described for the littoral zone rich in epifaunal species while changes in profundal infaunal community are poorly understood (Burlakova et al. 2014; Karatayev et al. 2015). The abundance of non-dreissenid taxa (e.g., *Diporeia*, Sphaeriidae) declined in profundal habitats after *Dreissena* invasion (Higgins and Vander Zanden 2010;

Nalepa et al. 2007, 2009; reviewed in Karatayev et al. 2015) where quagga mussels compete for space and food resources with most of native invertebrates. This may be a result of system-wide (e.g. food interception effect, resulting in strong decline of spring phytoplankton blooms) *vs.* local *Dreissena* effects (e.g. enrichment of sediments with biodeposits). The resulting effect of *Dreissena* on oligochaete community may induce changes in the OTI that will not reflect the changes in the trophic status of the ecosystem. Therefore, more data on the effect of dreissenids on species composition and abundance of benthic invertebrates in profundal *vs.* nearshore zone are needed to fully understand their impact on benthic communities.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin			X*			
5. Data obtained from sources within the U.S. are comparable to those from Canada						X
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				
Clarifying Notes: *The regular benthic monitoring program of U.S. EPA GLNPO has a relatively small number of stations, with poor representation of nearshore areas and thus it provides limited information.						

Acknowledgments

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List of Tables

Table 1**.** Trophic classifications for select mature lumbriculids and tubificids taken from Howmiller and Scott (1977), Milbrink (1983) with additions from Kreiger (1984), Lauritsen et al. (1985). If Milbrink classifications differed from Howmiller and Scott, Howmiller and Scott was used.
Source: Riseng et al. 2014.

List of Figures

Figure 1. Scatterplot of the index values for Milbrink's (1983) Modified Environmental Index, applied to data from GLNPO's 1997 through 2012 summer surveys. Values ranging from 0 to less than 0.6 indicate oligotrophic conditions (blue line); values from 0.6 to 1.0 indicate mesotrophic conditions (black line); and values greater than 1.0 indicate eutrophic conditions. Data points represent the average of triplicate samples taken at each sampling site; immature specimens were included in the analysis for calculation of overall density used to establish the coefficient *c* but only mature specimens were used to calculate the number belonging to each ecological group of oligochaetes (see attached description of index calculation).
Source: 1997-2012 U.S. EPA GLNPO benthic data collected from permanent stations.

Figure 2. Map of the Great Lakes showing the mean trophic status at each sampling site calculated for 2010-2012. Trophic status was based on the modified trophic index for oligochaete worms from Milbrink (1983).
Source: 2010-2012 U.S. EPA GLNPO benthic data.

Figure 3. Maps of the Great Lakes showing sites with significant temporal trend in trophic status between 1997 and 2012. Sites without significant changes in oligochaete trophic index with time ("no change", $P > 0.10$, linear regression), with marginally significant trends ("eutrophication or oligotrophication", $0.05 < P < 0.10$) and with significant trends ("strong eutrophication or oligotrophication", $P < 0.05$) are indicated.
Source: 1997-2012 U.S. EPA GLNPO benthic data.

Last Updated

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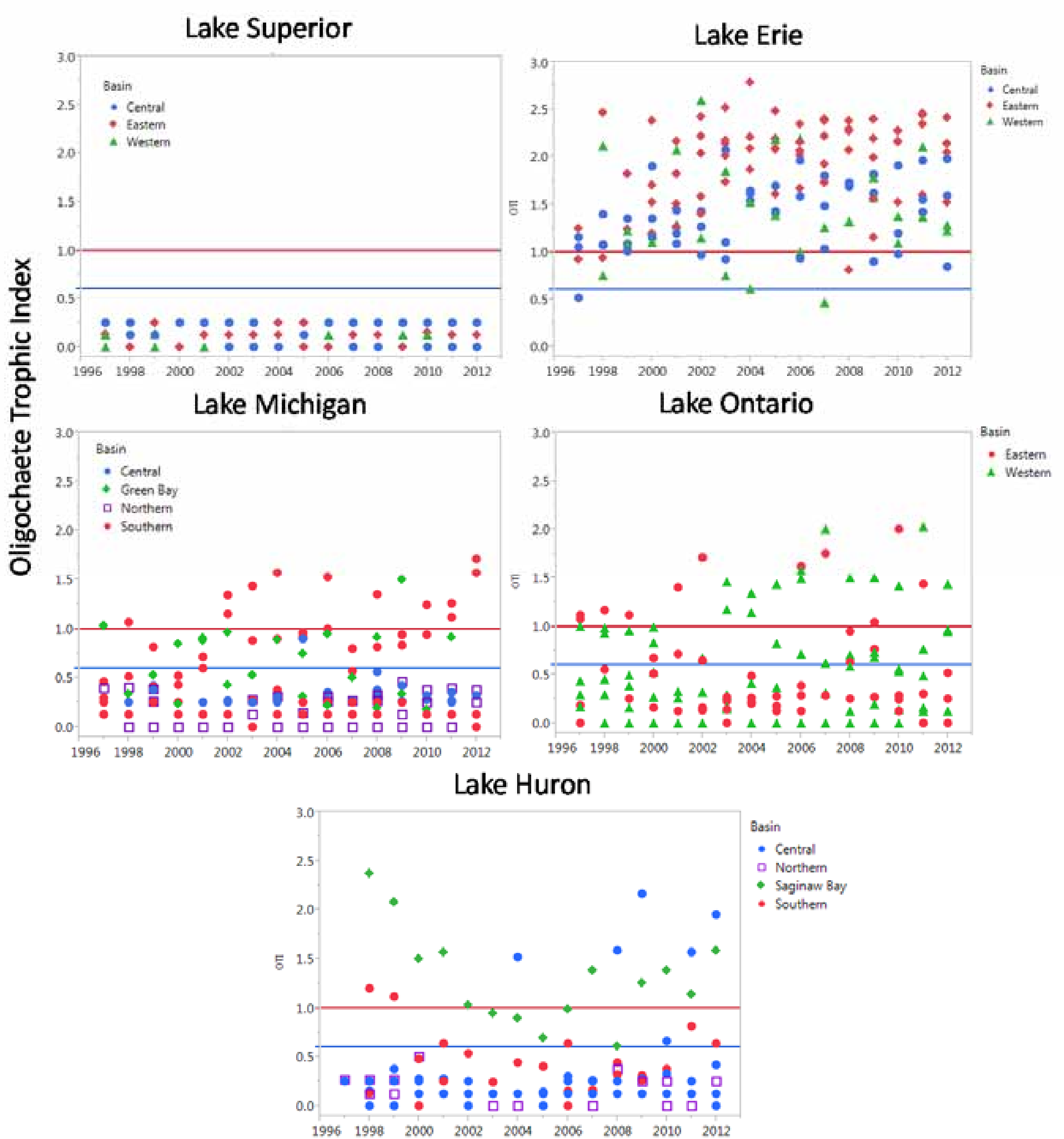
SPEC-CODE	GENUS	SPECIES	Trophic Class	Source	Comment
RHY-COCC	Rhyacodrillus	coccineus	0	Howmiller & Scott 1977	Same classification as Krieger 1984 & Lauritsen et al. 1985
TASA-MER	Tasserkidrilus	americanus	0	Howmiller & Scott 1977	Formerly *T. Kessler* i in both Lauritsen et al. 1985 and Krieger
LIM-PROF	Limnodrilus	profundicola	0	Howmiller & Scott 1977	Same classification as Krieger 1984 & Lauritsen et al. 1985
RHYMONT	Rhyacodrilus	montana	0	Krieger 1984	Same classification as Lauritsen et al. 1985
RHYSP	Rhyacodrilus	spp.	0	Krieger 1984	Same classification as Lauritsen et al. 1985
SPINIKO	Spirosperma	nikolskyi	0	Krieger 1984	Same classification as Lauritsen et al. 1985
STYHERI	Stylodrilus	heringianus	0	Howmiller & Scott 1977	General agreement from all sources for this taxon
TAS-SUPE	Tasserkidrilus	superiorensis	0	Krieger 1984	Same classification as Lauritsen et al. 1985
AU-LAMER	Aulodrilus	americanus	1	Howmiller & Scott 1977	Classification based on Aulodrilus sp.
AULL-IMN	Aulodrilus	limnobius	1	Milbrink 1983	
AULPIGU	Aulodrilus	pigueti	1	Milbrink 1983	
ILYTEMP	Ilyodrilus	templetoni	1	Krieger 1984	Same classification as Milbrink 1983 & Lauritsen et al. 1985
ISOFREY	Isochaetides	freyi	1	Krieger 1984	Same classification as Lauritsen et al. 1985
SPIFERO	Spirosperma	ferox	1	Howmiller & Scott 1977	Same classification as Krieger 1984 & Lauritsen et al. 1985
AULPLUR	Aulodrilus	pluriseta	2	Milbrink 1983	
LI-MANGU	Limnodrilus	angustipenis	2	Howmiller & Scott 1977	
LIMCERV	Limnodrilus	cervix	2	Howmiller & Scott 1977	Same as Milbrink 1983
LIMCECL	Limnodrilus	cervix/claparedeianus	2	Howmiller & Scott 1977	Same as Milbrink 1983
LIMCLAP	Limnodrilus	claparedeianus	2	Howmiller & Scott 1977	Same as Milbrink 1983
LIM-MAUM	Limnodrilus	maumeensis	2	Howmiller & Scott 1977	
LIMUDEK	Limnodrilus	udekemianus	2	Howmiller & Scott 1977	Same as Milbrink 1983
POT-BEDO	Potamothrix	betodi	2	Milbrink 1983	
POT-MOLD	Potamothrix	moldaviensis	2	Milbrink 1983	Same classification as Lauritsen et al. 1985
POT-VEJD	Potamothrix	vejdovskyi	2	Milbrink 1983	Same classification as Lauritsen et al. 1985
QUIM-ULT	Quistadrilus	multisetosus	2	Howmiller & Scott 1977	
LIM-HOFF	Limnodrilus	hoffmeisteri	2	Milbrink 1983	Differs from classification in Lauritsen et al. 1985
TUBTUBI	Tubifex	tubifex	0 OR 3	Milbrink 1983	Depends on densities of LIMHOFF and STYHERI and total oligochaete density

Table 1. Trophic classifications for select mature lumbriculids and tubificids taken from Howmiller and Scott (1977), Milbrink (1983) with additions from Kreiger (1984), Lauritsen et al. (1985). If Milbrink classifications differed from Howmiller and Scott, Howmiller and Scott was used.
Source: Riseng et al. 2014.



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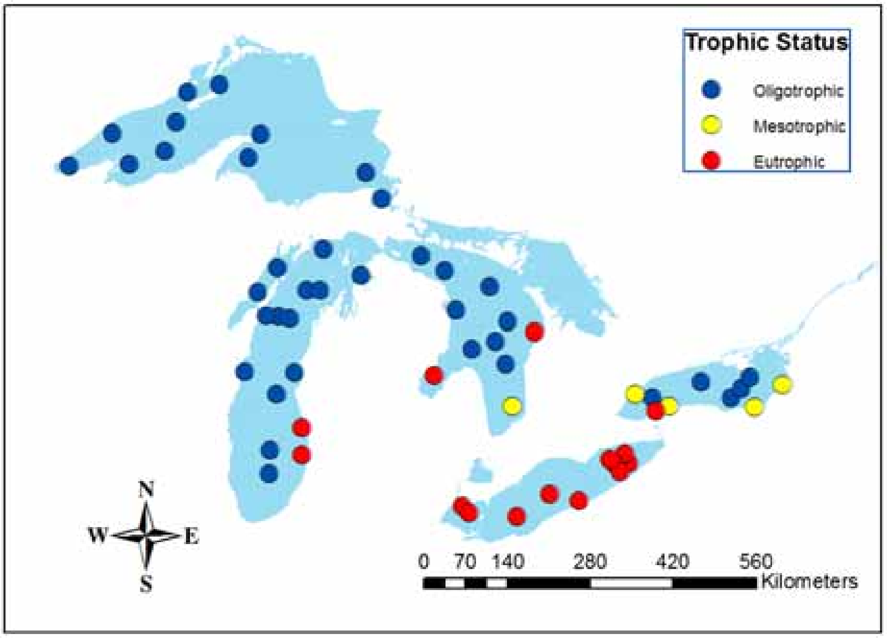

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Source: 2010-2012 U.S. EPA GLNPO benthic data.

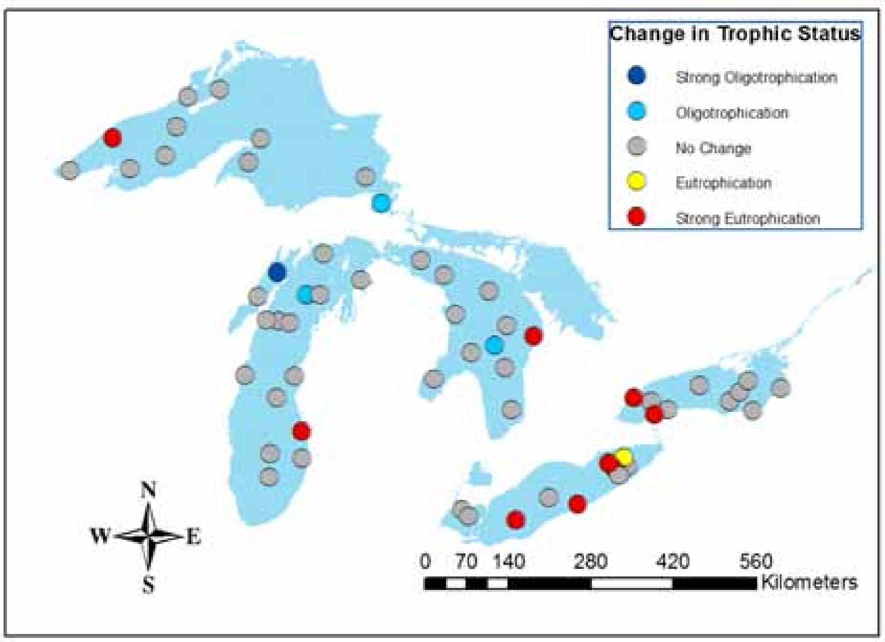

Figure 3. Map of the Great Lakes showing sites with significant temporal trend in trophic status between 1997 and 2012. Sites without significant changes in oligochaete trophic index with time ("no change", P > 0.10, linear regression), with marginally significant trends ("eutrophication or oligotrophication", 0.05 < P < 0.10) and with significant trends ("strong eutrophication or oligotrophication", P < 0.05) are indicated.
Source: 1997-2012 U.S. EPA GLNPO benthic data.

Sub-Indicator: *Diporeia*

Open Water

Overall Assessment
Status: Poor
Trend: Deteriorating
Rationale: Abundances of the benthic amphipod *Diporeia* spp. continue to decline in Lakes Michigan, Huron and Ontario. Abundances in Lake Superior are variable but overall trends are not apparent. *Diporeia* is currently extremely rare in Lake Erie and has likely been extirpated. In all the lakes where *Diporeia* has declined, lower abundances first became apparent a few years after dreissenid mussels became established. Because of high variability at depths < 30 m and a preference of *Diporeia* for offshore regions, trends in populations are best assessed at depths > 30 m. Assessments are restricted to the main basins of each of the lakes since *Diporeia*, being a cold –water stenotherm, is not found in the shallow-warm bays and basins, nor in the connecting channels. Since lake-wide assessments are mostly based on surveys every 5 years, temporal trends can be considered mainly at this level of detail. Some regional assessments are made on an annual basis, and these are included if data are available.

Lake-by-Lake Assessment

Lake Superior
Status: Good
Trend: Unchanging
Rationale: Long term monitoring and studies of distribution patterns indicate that, although substantial temporal variability can occur, there are no directional trends in abundances of *Diporeia* in the lake.

Lake Michigan
Status: Poor
Trend: Deteriorating
Rationale: *Diporeia* abundances continue to decline in Lake Michigan. A lakewide survey in 2010 indicated that *Diporeia* is now extremely rare at depths < 90 m (297 ft.) over the entire lake (Figure 1). At depths > 90 m, this taxa can still be found, but abundances were lower by 66 % compared to abundances found in 2005 (Figure 2). Recent annual surveys (2012-2014) conducted in just the southern basin of Lake Michigan reveal continued declines since 2010 (Figure 4). A lakewide survey of the population occurred again in 2015 but results are not yet available.

Lake Huron
Status: Poor
Trend: Deteriorating
Rationale: *Diporeia* abundances continue to decline in Lake Huron. The most recent lakewide survey occurred in 2012, and abundances were lower compared to a similar survey in 2007 (Figures 1, 2, 3). Abundances are now < 100 m^{-2} at depths 31-90 m and < 300 m^{-2} at depths > 90 m.

Lake Erie
Status: Poor
Trend: Deteriorating
Rationale: Because of shallow, warm waters, *Diporeia* are naturally not present in the western basin and most of the central basin. *Diporeia* declined in the eastern basin beginning in the early 1990s and have not been found in that basin since 1998.

Lake Ontario
Status: Poor
Trend: Deteriorating
Rationale: *Diporeia* abundances continue to decline in Lake Ontario (Figures 1 and 2). The last lake-wide survey in Lake Ontario occurred in 2013 and, of the 45 sites sampled, only a single individual was found. That individual occurred at a 140-m site. Based on these results, this organism is near extirpation in Lake Ontario.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to show the status and trends in *Diporeia* populations, and to infer the basic structure of cold-water benthic communities and the general health of the Great Lakes ecosystem.

Ecosystem Objective

The cold, deep-water regions of the Great Lakes should be maintained as a balanced, stable, and productive oligotrophic ecosystem with *Diporeia* as one of the key organisms in the food chain.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement (GLWQA) which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition

This glacial-marine relic was once the most abundant benthic organism in cold, offshore regions (greater than 30 m (98 ft) of each of the lakes. It was present, but less abundant in nearshore regions of the open lake basins, but naturally absent from shallow, warm bays, basins, and river mouths. *Diporeia* occurs in the upper few centimetres of bottom sediment and feeds on algal material that freshly settles to the bottom from the water column (i.e., mostly diatoms). In turn, it is fed upon by most species of Great Lakes fish; in particular by many forage fish species, which themselves serve as prey for the larger piscivores such as trout and salmon. For example, sculpin feed almost exclusively upon *Diporeia*, and sculpin are eaten by lake trout. Also, lake whitefish, an important commercial species, feeds heavily on *Diporeia*. Thus, *Diporeia* was an important pathway by which energy was cycled through the ecosystem, and a key component in the food web of offshore regions.

On a broad scale, abundances are directly related to the amount of food settling to the bottom, and population trends reflect the overall productivity of the ecosystem. Abundances can also vary somewhat relative to shifts in predation pressure from changing fish populations. In nearshore regions, this species is sensitive to local sources of pollution, but because of varying conditions such as temperature fluctuations, substrate heterogeneity, and wave-induced turbulence, it is difficult to assess population trends in this region.

Methods for estimating abundances of *Diporeia* are generally similar across the Great Lakes. Samples of bottom substrates are collected with a Ponar grab and contents are washed through a screen (or net mesh) of 0.5-mm openings. All *Diporeia* retained on the screen are immediately preserved, and later counted and identified. Densities are reported as numbers per square metre. Nalepa et al. (2009) provides additional details on sampling methods and abundances.

Diporeia populations are currently in a state of dramatic decline in all the lakes except Lake Superior (Figures 1 and 2). Based on the most recent surveys, *Diporeia* are present but continue to decline in lakes Michigan and Huron, while it has likely been extirpated from Lake Erie and is near extirpation in Lake Ontario. The population in Lake Superior, although highly variable, remains unchanged. Initial declines were first observed in all lake areas within two to three years after zebra mussels (*Dreissena polymorpha*) or quagga mussel (*Dreissena bugensis*) first became established. These two species were introduced into the Great Lakes in the late 1980s via the ballast water of ocean-going ships. Reasons for the negative response of *Diporeia* to these mussel species are not entirely clear. One hypothesis is that dreissenid mussels are out-competing *Diporeia* for available food. That is, large mussel populations filter food material before it reaches the bottom, thereby decreasing amounts available to *Diporeia*. However, evidence suggests that the reason for the decline is more complex than a simple decline in food because *Diporeia* have completely disappeared from areas where food is still settling to the bottom and where there are no local populations of mussels. Also, individual *Diporeia* show no signs of starvation before or during population declines. Further, *Diporeia* and *Dreissena* apparently coexist in some lakes outside of the Great Lakes (i.e., Finger Lakes in New York). Some studies suggest that the decline in *Diporeia* could be related to disease/parasites, but the findings are often inconclusive and further work is needed in this area. Given the decline and disappearance of *Diporeia* in nearshore regions, and very low abundances of *Diporeia* in offshore regions in each of the lakes except Lake Superior, it seems that these present monitoring programs are adequate to detect population changes.

Linkages

Linkages of this sub-indicator to other sub-indicators in the indicator suite include:

- Impacts of Aquatic Invasive Species

- Dreissenid Mussels
- Toxic Chemicals in Sediment

This sub-indicator also links directly to the other sub-indicators in the Habitat and Species indicator, particularly Lake Trout, as lake trout are among the fish species that are energetically linked to *Diporeia*. Young lake trout feed on *Diporeia* directly, while adult lake trout feed on sculpin, and sculpin feed heavily on *Diporeia*. Lake trout are a top predator in the deep-water habitat, and therefore assessments of both *Diporeia* and lake trout provide an evaluation of lower and upper trophic levels in the cold, deep-water habitat.

Comments from the Author(s)

The continuing decline of *Diporeia* has strong implications to the Great Lakes food web. As noted, many fish species rely on *Diporeia* as a major prey item, and the loss of *Diporeia* has impacted many of these species. Fish responses include changes in diet, movement to areas with more food, or a reduction in weight or energy content. Implications to fish populations include changes in distribution, abundance, growth, recruitment, and condition. Recent evidence suggests that fish are already being affected. Studies have shown that populations of lake whitefish, an important commercial species, have been affected, as well as fish species that serve as prey for salmon and trout such as alewife, sculpin, and bloater.

Because of the rapid rate at which *Diporeia* has declined in many areas, and its significance to the food web, agencies committed to documenting trends should report data in a timely manner. The population decline has a defined natural pattern, and studies of food web impacts should be spatially well coordinated. Also, studies to define the cause of the negative response of *Diporeia* to *Dreissena* should continue and build upon existing information. Potential areas of study are physiological and biochemical responses of *Diporeia* to *Dreissena*, and influence of potential pathogens, including bacteria and viruses. With an understanding of exactly why *Diporeia* populations are declining, one may better predict what additional areas of the lakes are at risk. Also, by better understanding the cause, one can better assess the potential for population recovery if dreissenid populations significantly decline.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada						X
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Acknowledgments

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Figure 1. Mean densities (number per square metre) of the amphipod *Diporeia* spp. from sites at 31-90 m in lakes Michigan, Huron, and Ontario, 1995 – 2014. Data are from lake-wide surveys conducted mostly at 5-year intervals. Lake Michigan = triangles, dashed line (blue); Lake Huron = squares, dot-dash line (red); Lake Ontario = circles, solid line (black).
Sources: Watkins et al. 2007; Birkett et al. 2015; Great Lakes Environmental Research Lab, NOAA

Figure 2. Mean densities (number per square metre) of the amphipod *Diporeia* spp. from sites at > 90 m in lakes Michigan, Huron, and Ontario, 1995 - 2014. Data are from lake-wide surveys conducted mostly at 5-year intervals. Lake Michigan = triangles, dashed line (blue); Lake Huron = squares, dot-dash line (red); Lake Ontario = circles, solid line (black).
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Source: Great Lakes Environmental Research Lab, NOAA

Figure 4. Mean densities (number per square metre) of the amphipod *Diporeia* spp. in southern Lake Michigan, reported by depth: < 30 m (squares, solid line); 31-90 m (triangles, long dashed line); and > 90 m (circles, short dashed line), 2010-2014. Note that the axis scale is greatly reduced compared to Figures 1 and 2.
Source: Great Lakes Environmental Research Lab, NOAA

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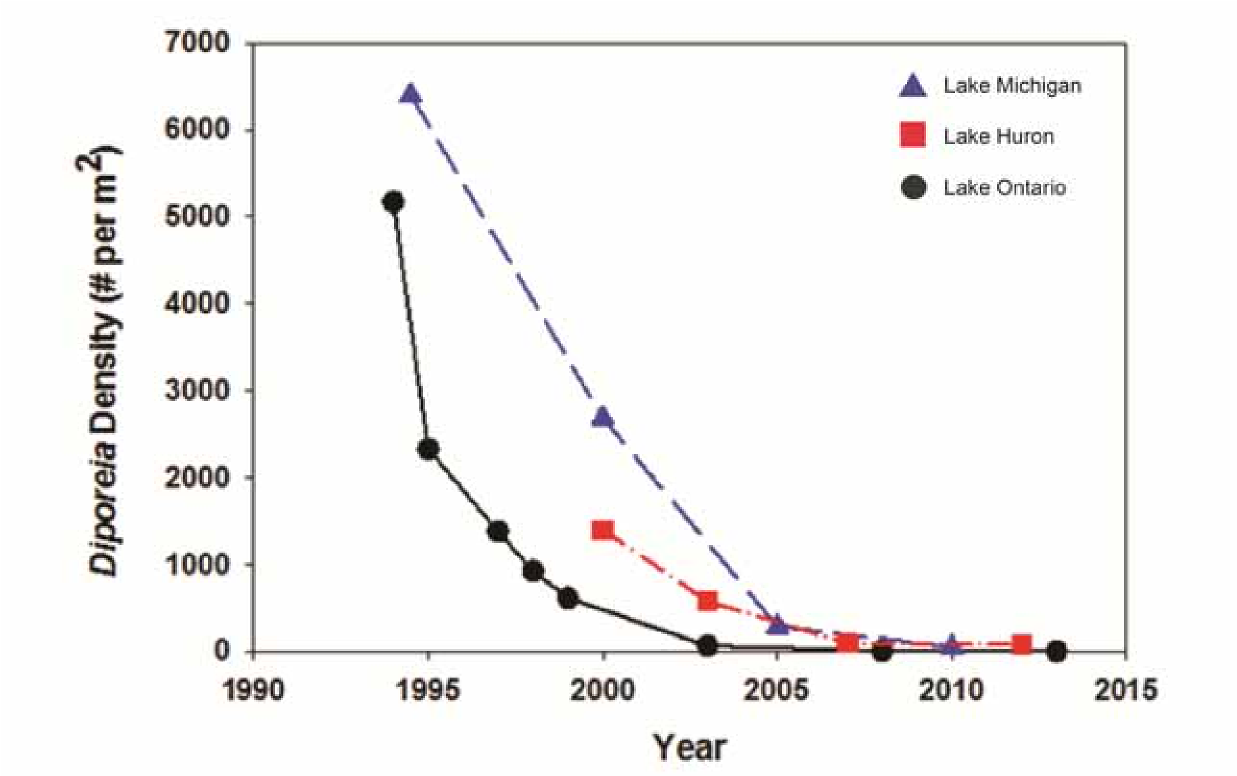

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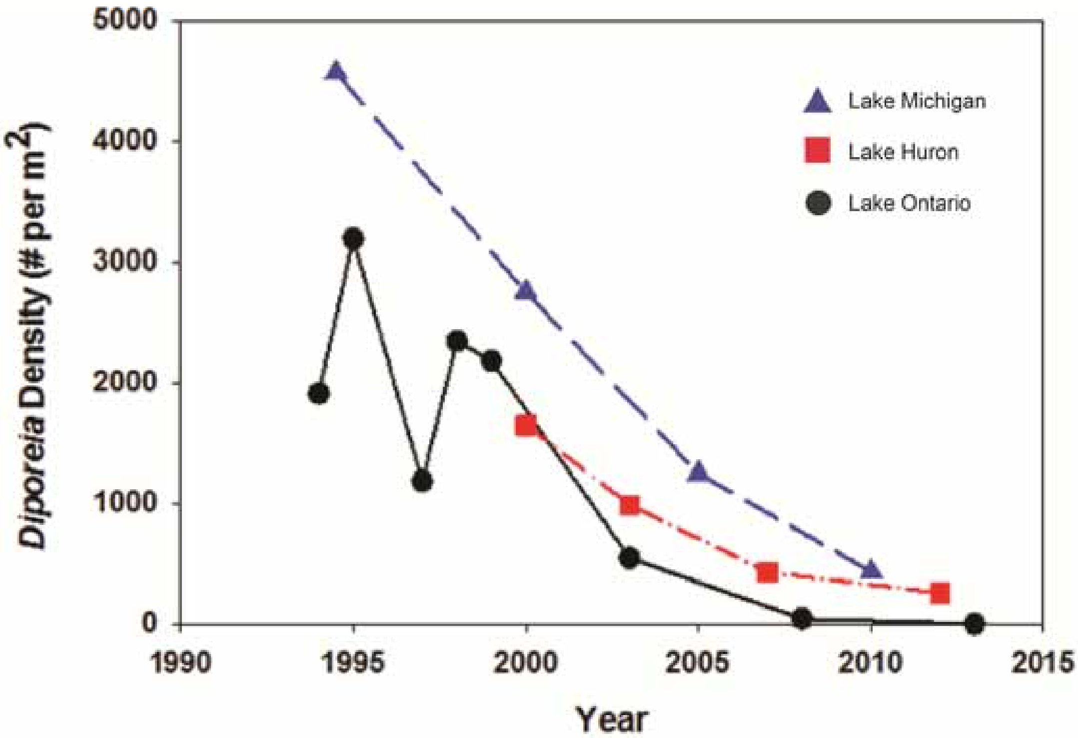

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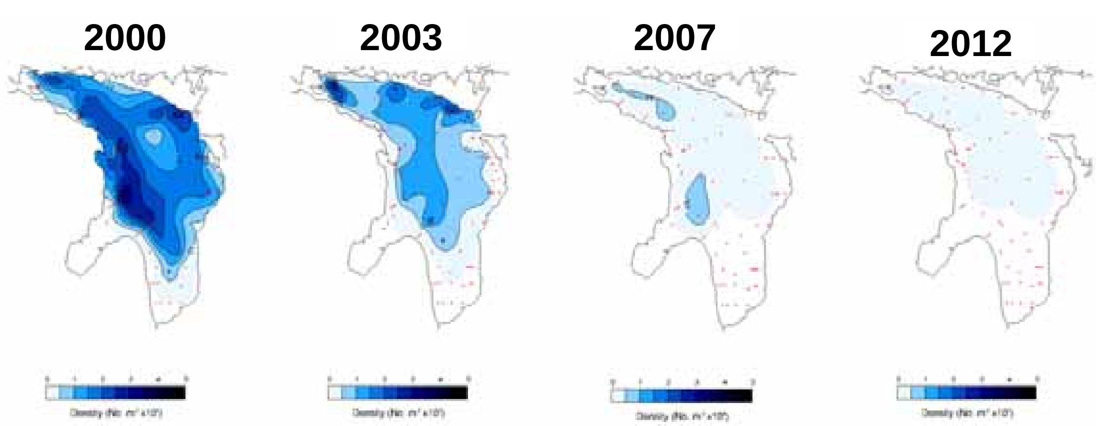

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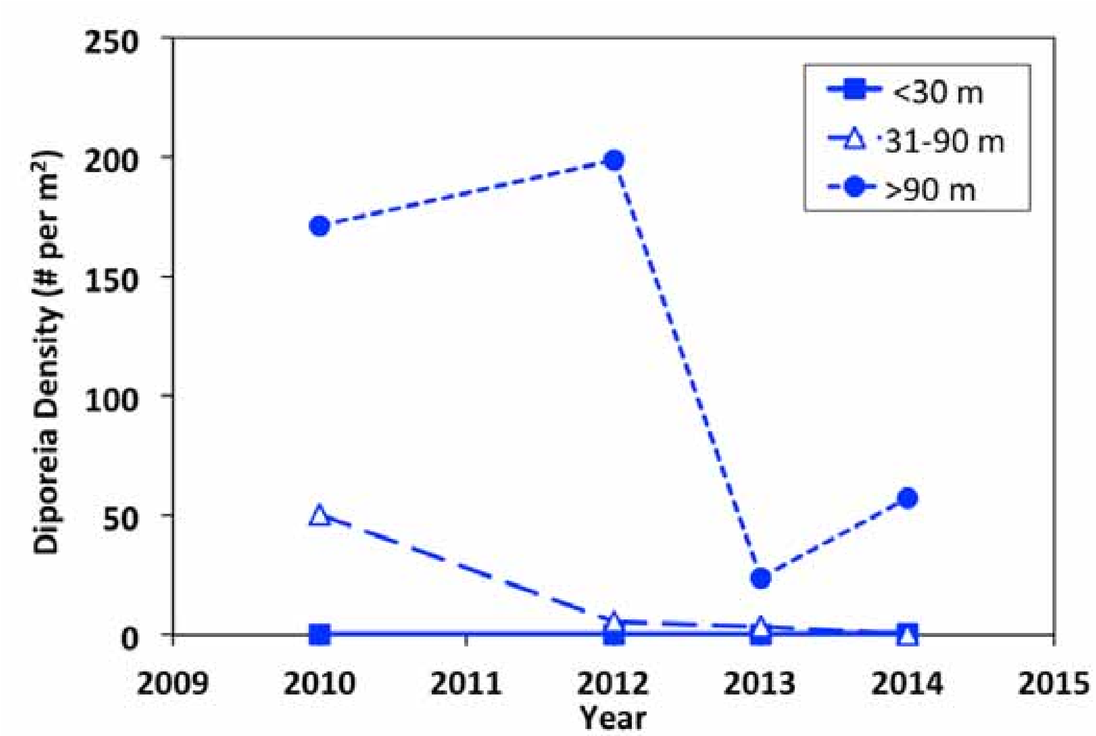

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Source: Great Lakes Environmental Research Lab, NOAA

Sub-Indicator: Prey fish
Open water

Overall Assessment:
Status: Fair
Trend: Undetermined
Rationale: Prey fish communities across the Great Lakes continue to change, although the direction and magnitude of those changes are not consistent across the lakes. The metrics used to categorize prey fish status in this and previous periods are based on elements that are common among each of the lake's Fish Community Objectives and include diversity and the relative role of native species in the prey fish communities. The diversity index categorized three of lakes as '*fair*', while Superior and Erie were '*good*' (Table 1). The short term trend, from the previous period (2008-2010) to the current period (2011-2014) found diversity in Erie and Superior to be unchanging, but the other three lakes to be '*deteriorating*', resulting in an overall trend categorization of '*undetermined*' (Table 1). The long term diversity trend suggested Lakes Superior and Erie have the most diverse prey communities although the index for those prey fish have been quite variable over time (Figure 1). In Lake Huron, where non-native alewife have substantially declined, the diversity index has also declined. The continued dominance of alewife in Lake Ontario (96% of the prey fish biomass) resulted in the lowest diversity index value (Figure 1). The proportion of native species within the community was judged as '*good*' in Lakes Superior and Huron, '*fair*' in Michigan and Erie and '*poor*' in Ontario (Table 2). The short term trend was improving in in all lakes except Michigan ('*deteriorating*') and Ontario ('*unchanging*'), resulting in an overall short term trend of '*undetermined*' (Table 2). Over the current period, Lake Superior consistently had the highest proportion native prey fish (87%) while Lake Ontario had the lowest (1%) (Figure 2). Lake Michigan's percent native has declined as round goby increase and comprises a greater proportion of the community. Native prey fish make up 51% of Lake Erie, although basin-specific values differed (Figure 2). Most notably, native species in Lake Huron comprised less than 10% of the community in 1970, but since alewife have declined, now represent nearly 80% of the community (Figure 2). Prey fish data are most consistent for in-lake populations, which are reported here; data from connecting channels was not consistently available across the basin. Abundance was not used to judge prey fish status since successful, basin-wide management actions, including mineral nutrient input reductions and piscivore restoration, both inherently reduce prey fish abundance. However, recent abundance trends as they relate to predator prey balance are referenced, such as in Lakes Michigan and Huron where piscivore stocking is being reduced to lower predation demand on prey fish populations and maintain sport fisheries.

Lake-by-Lake Assessment:
Lake Superior
Status: Good
Trend: Unchanging
Rationale: The average prey fish diversity index of the current reporting period (2011-2014) was 79% of the maximum value in the time series and the proportion of native species by biomass in the prey fish community was 87%. As these values are greater than 75%, the status of Lake Superior was categorized as '*good*'. There was little change in the metrics between the current reporting period and the previous period (2008-2010). Despite fluctuations and current lower overall density, the Lake Superior prey fish community is considered healthy due to the high number of different native species present, the high proportion of biomass of native versus non-native species, and the ability of the prey fish community to support a health sustaining predator fish population. More recently biologists have become concerned that Lake Superior prey fish abundance is declining and may potentially influence native, sport and commercial fisheries.

Lake Michigan
Status: Fair
Trend: Deteriorating
Rationale: The average prey fish diversity index of the current reporting period (2011-2014) was 72% of the maximum value in the time series and the proportion of native species by biomass in the prey fish community was

48%. As these values are between 75% and 25%, the status of Lake Michigan is categorized as *'fair'*. Both metrics were lower in the current reporting period relative to the previous reporting period (2008-2010) resulting a trend of '*deteriorating*'.

Lake Huron
Status: Fair
Trend: Undetermined
Rationale: The average prey fish diversity index of the current reporting period (2011-2014) was 47% of the maximum value in the time series and the proportion of native species by biomass in the prey fish community was 77%. These values are categorized as 'fair' and 'good', respectively, and the final status was conservatively based on the lowest status. The trend was '*undetermined'* since between the current and previous reporting periods the proportion of native species increased but the diversity index declined slightly.

Lake Erie
Status: Fair
Trend: Improving
Rationale: The average prey fish diversity index of the current reporting period (2011-2014) was 77% of the maximum value in the time series and the proportion of native species by biomass in the prey fish community was 49%. These values are both categorized as 'good' and 'fair', respectively, based on our sub-indicator description. The overall trend was judged to be '*improving'* since the variable diversity index was similar to the overall trend from the previous reporting period, but the proportion of native prey fish has continued to increase over the time series.

Lake Ontario
Status: Poor
Trend: Deteriorating
Rationale: The average prey fish diversity index of the current reporting period (2011-2014) was 25% of the maximum value in the time series, a value determined to be at the lowest end of the '*fair*' categorization, while the proportion of native species was judged as '*poor*' representing only 1% of the total. The overall status of Lake Ontario was categorized as *'poor'* while the unchanging trend in proportion native and declining diversity trend resulted in an overall trend assessment of '*deteriorating'*.

Sub-Indicator Purpose:
The purpose of this sub-indicator is to report on the status of the Great Lakes' prey fish communities as they relate to community diversity and proportion of native species.

Ecosystem Objective:
Ecosystem objectives are based on the lake-specific Fish Community Objectives (FCO) that pertain to prey fish. These FCOs are developed by each of the respective Lake Committees and the Great Lakes Fishery Commission (GLFC).

Lake Superior: Fish Community Goal – *"To rehabilitate and maintain a* ***diverse****, healthy, and self-regulating fish community, dominated by* ***indigenous species*** *and supporting sustainable fisheries"*. Additional principals note: "*Preservation of indigenous species is of the highest concern"* (Horns et al. 2003).

Lake Michigan: Planktivore Objective **–** "M*aintain a* ***diversity*** *of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lakewide planktivore biomass of 0.5 to 0.8 billion kg."* (Eshenroder et al. 1995).

Lake Huron: Prey Objective – "*Maintain a* ***diversity*** *of prey species at population levels matched to primary production and to predator demands. Emphasis is placed on species diversity and self-regulation of the fish community"* (DesJardine et al. 1995).

Lake Erie: Forage Fish Objective – *"Maintain a* ***diversity*** *of forage fishes to support terminal predators and to sustain human use"* (Ryan et al. 2003).

Lake Ontario: Offshore Pelagic Zone Objective- "*Increase prey-fish* ***diversity*** *– maintain and restore a* ***diverse*** *prey-fish community that includes Alewife, Lake Herring (Cisco), Rainbow Smelt, Emerald Shiner, and Threespine Stickleback. Status and trend indicators are 1) maintaining or increasing populations and increasing species* ***diversity*** *of the pelagic prey fish community including introduced species (Alewife, Rainbow Smelt) and selected* ***native*** *prey fish species (Threespine Stickleback, Emerald Shiner and Lake Herring (Cisco)); and 2) increasing spawning populations of* ***native*** *Lake Herring (Cisco) in the Bay of Quinte, Hamilton Harbor, and Chaumont Bay*" (Stewart et al. 2013).

Ecological Condition:

Lake Superior, Status: Good, Trend: Unchanging

Observations from Lake Superior suggest the prey fish community is both diverse and primarily composed of native species resulting in a status categorization of good and an unchanging trend. These metrics support the idea that the Lake Superior food web and fish community is the least-impacted of the five lakes. Unlike the other Great Lakes that have a variety of non-native prey fish, Rainbow Smelt are the only non-native prey that contributes to the Lake Superior community. Diversity changes illustrated across the time series are primarily driven by fluctuations in the coregonid populations which are known to exhibit variable year class strength.

Lake Michigan, Status: Fair, Trend: Deteriorating

Based on the two metrics of this sub-indicator, Lake Michigan prey fish status remains fair, however trends suggest the community is changing in ways that are inconsistent with the stated fish community objectives. The decline in proportion of native species was primarily driven by decreased proportions of bloater and increased proportions of non-native round goby. Diversity index declines were the result of round goby and alewife comprising proportionally more of the catch and proportional declines in bloater and slimy sculpin, although the current diversity index is similar to the long term average. Recently, declines in Lake Michigan prey fish abundance (primarily alewife) have caused resource management to reduce native and sport fish stocking levels in an effort to reduce predation on prey fish populations and maintain sport fisheries (Tsehaye et al., 2014).

Lake Huron *Status: Fair, Trend: Undetermined*

Across the entire period of observation the Lake Huron prey fish community has arguably seen the most change. The prey fish community was dominated by non-native alewife and rainbow smelt from the 1970s through the early 2000s then abruptly shifted to a community dominated by native bloater after alewife populations severely declined (Dunlop and Riley, 2013). This change has been attributed to physical factors, bottom-up influences of reduced mineral nutrients, proliferation of dreissenids mussels, as well as top-down forces by increasing populations of naturally reproduced piscivorous lake trout and Pacific Salmon (Dunlop and Riley, 2013; Kao et al., 2016). Interestingly, this shift towards a more native community has also resulted in an overall decline in prey fish diversity as measured by the index used in this analysis. The diversity decline is also partly driven by the decline of deepwater sculpin in bottom trawls. This species historically comprised approximately 5% of the community biomass but has declined to 1% of the total.

Lake Erie *Status: Fair, Trend: Improving*

Lake Erie status, as the warmest and most nutrient-rich Great Lake, likely explains the high prey fish diversity observed since 1990. Although variable, the proportion of native species observed in bottom trawls has generally increased over the period of observation although some specific native species are generally in decline such as Silver Chub (McKenna Jr and Castiglione, 2014). It is important to note that bottom trawl observations of prey fish from Lake Erie are based on basin-specific surveys by various agencies. Results are reported according to a lake-wide standardized numerical density as opposed to surveys from other lakes that are reported as biomass density.

Lake Ontario, Status: Poor, Trend: Unchanging

Over the period of observation, the Lake Ontario prey fish community has been dominated by a single, non-native species, alewife. This results in low and unchanging metrics for prey fish diversity and proportion of native species between this and the previous reporting periods. Across the time series the proportional importance of alewife increased from 50-65% of the community to more recently over 96% of the prey fish community. This change was primarily driven by a steady decrease in the proportional importance of non-native rainbow smelt. The benthic prey fish community, once dominated by native slimy sculpin, is now primarily composed of non-native round goby with lower abundances of slimy sculpin and the rebounding native deepwater sculpin. Alewife's dominance drives both reported metrics to low values but their high abundance supports abundant and fast-growing populations of stocked lake trout and Pacific Salmon. Active management efforts to improve Lake Ontario prey fish diversity and restore native species began in 2012. Efforts included reintroducing previously-extirpated bloater from Lake Michigan to Lake Ontario and enhancing the remnant native Cisco population by stocking historically-important spawning locations.

Linkages:
As an intermediate trophic level within Great Lakes food webs, prey fish are closely linked with many of the other sub-indicators including those addressing nutrients, physical properties, lower tropic levels and predators. Some examples of those linkages include:

- Nutrients in Lakes – fuels the food web supporting prey fish
- Zooplankton –primary food of most prey fish
- Benthos – benthic invertebrates are primary food of some prey fish
- *Diporeia* – important food of some prey fishes, generally declining
- Dreissenid mussels –provide food for round goby, alter lower trophic levels that support prey fish
- Surface Water Temperature – drives prey fish energetics and behavior
- Water Levels – regulator of habitat and spawning habitat
- Lake Trout – native predator of prey fish
- Walleye – native predator of prey fish

Comments from the Author(s)
This sub-indicator report is one of the first to provide readily-interpretable, consistent metrics that illustrate prey fish status across all five Great Lakes. Focusing on prey fish diversity and the proportion of native species across the basin, this report builds on our understanding of Great Lakes prey fish dynamics such as those illustrated in aggregate across lakes (Bunnell et al. 2014) or by individual species in each lake such as those illustrated in Gorman and Weidel (2015). Diversity in both prey fish communities and how they are surveyed across the basin make it difficult to compare their status along a common gradient. The metrics reported herein were selected based on the availability of similar data from each lake and common elements found in each of the Lake Committee-created Fish Community Objectives. For example, the terms *diverse* or *diversity* appear in each of the respective lake Fish Community Objectives. Similarly, the importance of native or indigenous prey fish species is directly referenced or mentioned in supporting principals of four of the five Fish Community Objectives. In contrast to previous prey fish indicator reports, prey fish abundance was not directly used as a specific judging metric. Prey fish abundance depends heavily on intentionally-implemented management actions, specifically nutrient load reductions and piscivore stocking. These actions improved Great Lakes ecosystems and their services however their success naturally resulted in reduced prey fish abundance, confounding the utility of abundance as an indicator.

A number of factors likely influence the data and results used to judge this sub-indicator including how the data were collected, the use of raw or model-based estimates, the metrics chosen, and the thresholds used to create categories. Data used to judge this sub-indicator came from bottom trawls, however these gears do not catch all species in equal proportion to their true abundance (catchability) and that catchability can be altered by the environment (Kocovsky and Stapanian, 2011). Most notably the proportional importance of pelagic species including alewife, rainbow smelt, bloater and cisco is likely under represented by these gear types. Warner et al. 2015 noted that yearly Lake Michigan alewife biomass estimates generated by acoustic surveys were 4.5 times greater than bottom trawl-based estimates across a 20+ year time series. In Lake Superior acoustic surveys yielded greater abundances and more precise estimates of Cisco as compared to bottom trawls (Stockwell et al., 2006). In addition, seasonal survey timing and methodologies likely influence interpretations. Weidel et al. (2015) illustrated the biomass density of round goby in Lake Ontario differed by an order of magnitude (10x) between a spring survey that used a trawl designed to avoid Dreissena mussels and a fall survey that employed the more traditional bottom trawl. Admittedly, the choice of metrics to illustrate prey fish community diversity is imperfect and intended serve as a starting point from which to improve. While the Shannon index is commonly applied to describe “diversity” it has both notable flaws and utility (Hurlbert, 1971; Jost, 2006). Finally, theoretical or widely-agreed upon thresholds for what constitutes a prey fish community as ‘good’, ‘fair’, or ‘poor’ do not exist. Future indicator-type reports would benefit from thoughtful discussion and thorough examination of how these potential sources of bias and threshold choices influence this sub-indicator and our understanding of prey fish in the Great Lakes.
An important component missing from this sub-indicator but conspicuous across the prey fish-related Fish

Community Objectives is the idea of managing prey fish in balance with their food supply or the number of predators. Potential metrics that could be used in future reports to 'judge' this balance include predator:prey biomass ratios or a simpler approach that uses the condition (fatness) or relative weights of prey fish and predators as integrated indicators of predator prey balance.

Assessing Data Quality:

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin			X			
5. Data obtained from sources within the U.S. are comparable to those from Canada				X		
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report			X			

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List of Tables:

Table 1. Diversity index status and trends for Great Lakes prey fish. Diversity is represented by the Shannon index and status categories are based on the average value of the current reporting period (2011-2014) relative to the maximum value observed in the time series for a given lake. To attain as status of 'Good' the current period average diversity index must be 75% or more of the maximum value observed in the time series; similarly, the 'Poor' status represents average values that are less than 25% of the maximum observed index value. Trend judgement is based on comparisons between the current and previous period (2008-2010) average.

Table 2. The proportion of native species in the bottom trawl prey fish samples describes the status and trends for Great Lakes prey fish. For this sub-indicator's categorization, status categories are 'Good' if the average proportion native for the current period (2011-2014) is equal to or greater than 75% and 'Poor' if that value is less than 25%, and 'Fair' otherwise.

Table 3. Overall assessment for prey fish communities of the Great Lakes as determined by the community diversity index and proportion native species.

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Lake	Percent of maximum	Current Avg. (2011-2014)	Previous Avg. (2008-2010)	Long term Avg.	Status	Trend
Superior	79%	1.33	1.27	1.26	Good	Unchanging
Michigan	72%	1.23	1.60	1.17	Fair	Deteriorating
Huron	47%	0.73	0.76	1.08	Fair	Deteriorating
Erie	77%	1.60	1.70	1.60	Good	Unchanging
Ontario	25%	0.25	0.31	0.57	Fair	Deteriorating

Table 1. Diversity index status and trends for Great Lakes prey fish. Diversity is represented by the Shannon index and status categories are based on the average value of the current reporting period (2011-2014) relative to the maximum value observed in the time series for a given lake. To attain as status of 'Good' the current period average diversity index must be 75% or more of the maximum value observed in the time series; similarly, the 'Poor' status represents average values that are less than 25% of the maximum observed index value. Trend judgement is based on comparisons between the current and previous period (2008-2010) average.

Lake	Current	Previous	Long term	Status	Trend
Superior	87%	83%	83%	Good	Improving
Michigan	48%	64%	64%	Fair	Deteriorating
Huron	77%	69%	36%	Good	Improving
Erie	49%	30%	35%	Fair	Improving
Ontario	1%	1%	5%	Poor	Unchanging

Table 2. The proportion of native species in the bottom trawl prey fish samples describes the status and trends for Great Lakes prey fish. For this sub-indicator's categorization, status categories are 'Good' if the average proportion native for the current period (2011-2014) is equal to or greater than 75% and 'Poor' if that value is less than 25%, and 'Fair' otherwise.

Lake	Status	Trend
Superior	Good	Unchanging
Michigan	Fair	Deteriorating
Huron	Fair	Undetermined
Erie	Fair	Improving
Ontario	Poor	Deteriorating

Table 3. Overall assessment for prey fish communities of the Great Lakes as determined by the community diversity index and proportion native species.

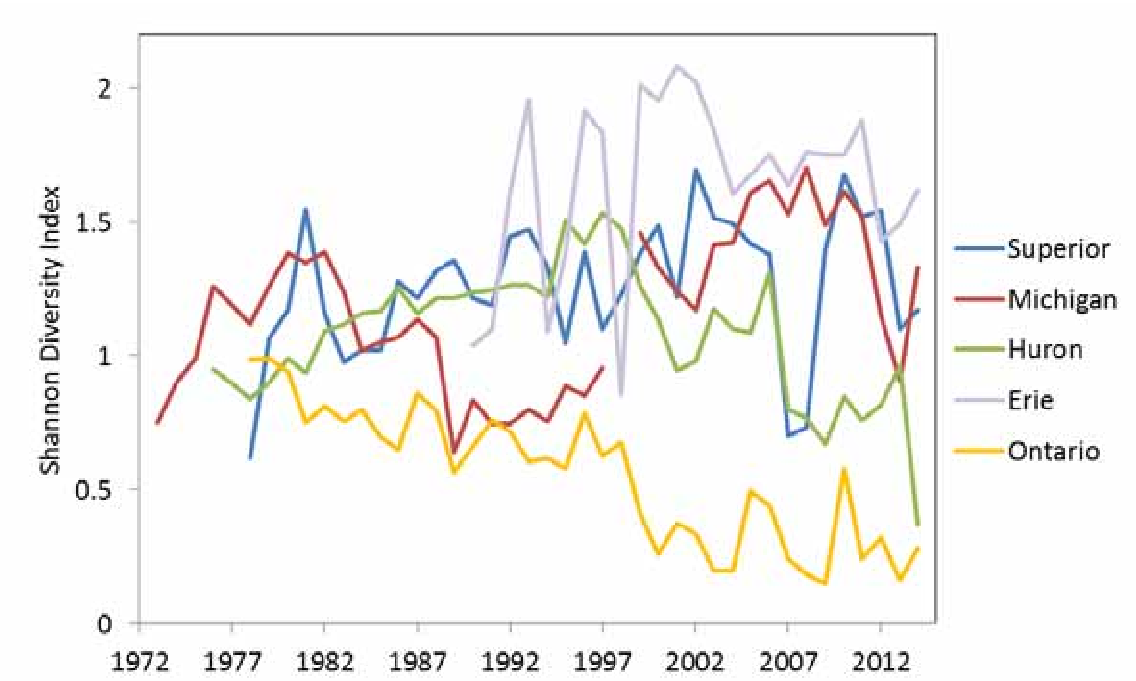

Figure 1. Shannon Diversity index values for Great Lakes prey fish communities.
Source: Data primarily derive from bottom trawl surveys conducted by US federal and state and Canadian provincial agencies.

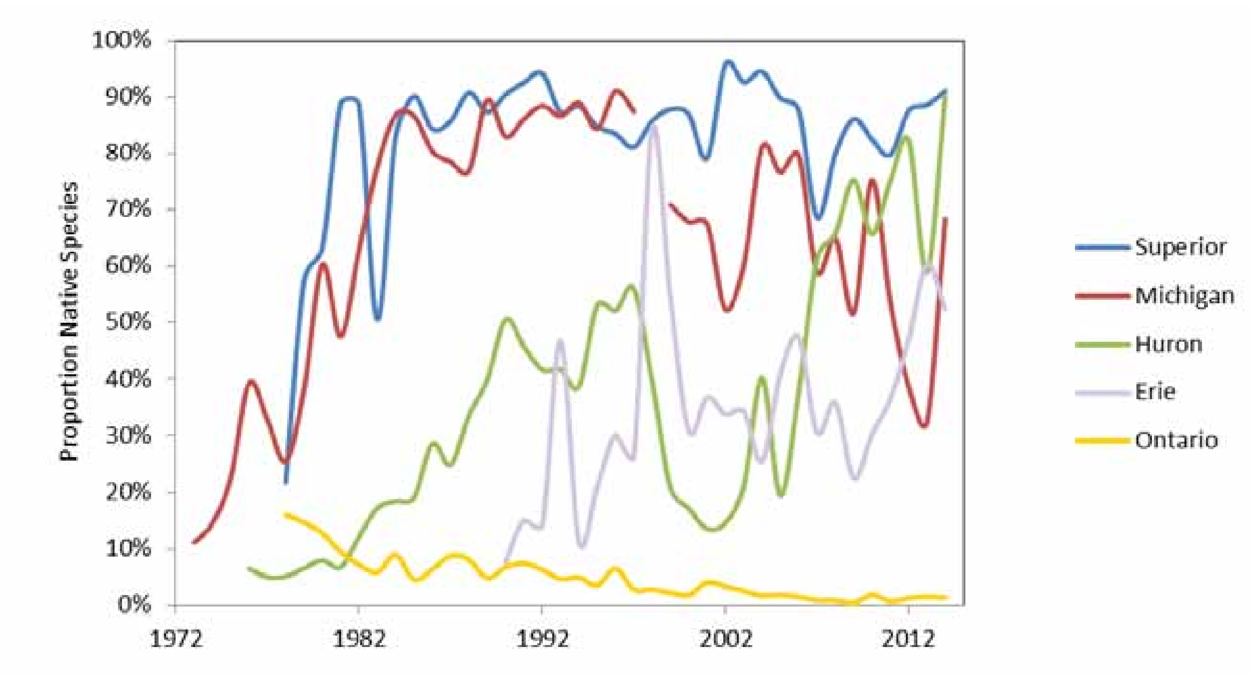

Figure 2. Proportion of native species in Great Lakes prey fish communities.
Source: Data primarily derive from bottom trawl surveys conducted by US federal and state and Canadian provincial agencies.

Sub-Indicator: Lake Sturgeon

Overall Assessment
Status: Poor
Trend: Improving
Rationale: There are remnant populations of Lake Sturgeon in each basin of the Great Lakes, but few of these populations are large. Progress continues as agencies learn more about population status in many tributaries and the Great Lakes proper. Confirmed observations and captures of Lake Sturgeon continue to increase in all lakes. Stocking is contributing to increased abundance in some areas. The trend for the overall and lake-by-lake assessments are improving over the last ten years based on increased observations, stocking, and habitat restoration efforts. There remains a need for information on some remnant spawning populations. In many areas habitat restoration is needed because spawning and rearing habitat has been destroyed or altered, or access to it has been blocked.

Lake-by-Lake Assessment

Lake Superior
Status: Poor
Trend: Improving
Rationale: Populations meet all rehabilitation criteria in two Lake Superior tributaries and most criteria in four other rivers. Reproduction occurs in at least 10 tributaries and Lake Nipigon. Abundance is increasing through natural reproduction and limited stocking.

Lake Michigan
Status: Poor
Trend: Improving
Rationale: Remnant populations persist in at least nine tributaries. Natural recruitment supports stable or growing populations in at least four of these. Streamside hatcheries are being used to rear and stock fingerlings to help rehabilitate two populations and reintroduce populations to four other rivers.

Lake Huron (including St. Mary's River)
Status: Poor
Trend: Improving
Rationale: Consistent Lake Sturgeon spawning occurs in five tributaries, the Garden, Mississaugi, Spanish, and Nottawasaga Rivers, as well as at the upper St. Clair River. Stocks of mixed sizes are consistently captured in the North Channel, Georgian Bay, southern Lake Huron and Saginaw Bay.

Lake Erie (including the St. Clair, Detroit, and Niagara rivers)
Status: Poor
Trend: Improving
Rationale: Lakewide incidental catches since 1992 indicate a possible improvement in their status in Lake Erie. Spawning occurs in the Detroit and St. Clair Rivers, connecting Lakes Huron and Erie and habitat restoration efforts in this system have created an additional five spawning locations over the last ten years. Spawning is suspected in Buffalo Harbor and the upper Niagara River, connecting Lakes Ontario and Erie. A restoration plan and stocking program are being developed for the Maumee River.

Lake Ontario (including the Niagara and St. Lawrence rivers)
Status: Poor
Trend: Improving
Rationale: Lakewide incidental catches since 1995 indicate a possible improvement in their status. Spawning occurs in the lower Niagara River, Trent River, and Black River. There are sizeable populations within the Ottawa and St. Lawrence River systems. Stocking for restoration began in 1995 in New York.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to measures status and trends in population abundance of key life stages, distribution, habitat utilization, and recruitment of Lake Sturgeon in the Great Lakes and their connecting waterways and tributaries. Lake Sturgeon are representative of healthy fish communities in major habitats of the Great Lakes and support valuable fisheries in the Great Lakes and that reflect ecosystem health through their roles in the aquatic food web.

Ecosystem Objective

Conserve, enhance, or rehabilitate self-sustaining populations of Lake Sturgeon where the species historically occurred and at a level that will permit all state, provincial and federal de-listings of classifications that derive from degraded or impaired populations (e.g. threatened, endangered or at risk species).

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should “support healthy and productive wetlands and other habitats to sustain resilient populations of native species.”

Ecological Condition

Background

Lake Sturgeon (*Acipenser fulvescens*) were historically abundant in the Great Lakes with spawning populations using many of the major tributaries, connecting waters, and shoal areas across the basin. Prior to European settlement of the region, they were a dominant component of the nearshore benthivore fish community, with populations estimated in the millions in each of the Great Lakes (Baldwin *et al*. 1979). In the mid- to late 1800s, they contributed significantly as a commercial species ranking among the five most abundant species in the commercial catch (Baldwin *et al*. 1979, Figure 1).

The decline of Lake Sturgeon populations in the Great Lakes was rapid and commensurate with habitat destruction, degraded water quality, and intensive fishing associated with settlement and development of the region. Sturgeon were initially considered a nuisance species of little value by European settlers, but by the mid-1800s, their value as a commercial species began to be recognized and a lucrative fishery developed. In less than 50 years, their abundance had declined sharply, and since 1900, they have remained a highly depleted species of little consequence to the commercial fishery. Sturgeon are now extirpated from many tributaries and waters where they once spawned and flourished (Figures 2-7). They are considered rare, endangered, threatened, or of watch or special concern status by the various Great Lakes fisheries management agencies. Their harvest is currently prohibited or highly regulated in waters of the Great Lakes.

Status of Lake Sturgeon

Efforts continue by many agencies and organizations to gather information on remnant spawning populations in the Great Lakes. Most sturgeon populations continue to sustain themselves at a small fraction of their historical abundance. In many systems, access to spawning habitat has been blocked and other habitats have been altered. However, there are remnant populations in each basin of the Great Lakes and some of these populations are large in number (tens of thousands of fish, Figures 3-7). Genetic analysis has shown that Great Lakes populations are regionally structured and show significant diversity within and among lakes (DeHaan *et al*. 2006, Welsh *et al*. 2008).

Lake Superior

The fish community of Lake Superior remains relatively intact in comparison to the other Great Lakes (Bronte et al. 2003). Historic and current information indicate that at least 21 Lake Superior tributaries supported spawning Lake Sturgeon populations (Holey et al 2000; Quinlan 2007). Successful reproduction was confirmed in the St. Louis River in spring 2011 through capture of larval sturgeon. In the White River, Ontario successful spawning was implied through the identification of a staging and spawning location (C. Avery, AOFRC, pers. comm.). Lake Sturgeons currently reproduce in 11 Lake Superior tributaries. The Lake Sturgeon Rehabilitation Plan for Lake Superior (Auer 2003) serves as the guiding document for agency activities. Populations in the Sturgeon River, Michigan, and Bad River, Wisconsin, meet rehabilitation plan criteria for self-sustaining populations (Auer 2003, Auer and Baker 2007, GLIFWC unpublished data, Quinlan 2007, Quinlan et al. 2010). Improvements in assessment techniques have provided better estimates of lakewide abundance (Auer and Baker 2007, Schram 2007, and GLIFWC unpublished data). The estimated combined annual spawning run population size in the Bad and White rivers, Wisconsin, was 844 individuals, 666 in the Bad River and 178 in the White River (Schloesser and Quinlan 2011). The estimated number of Lake Sturgeon in annual spawning runs in the Sturgeon River, Michigan range from 350 to 400 adults (Auer and Baker 2007). The abundance of juvenile Lake Sturgeon was estimated at 4,977 (95% CI 3,295-7,517) in Goulais Bay, eastern Lake Superior (Pratt et al. 2014). Lake Sturgeon abundance in Goulais Bay is the highest measured in Lake Superior (Schloesser 2014). Stocking in the St. Louis River, Minnesota and Ontonagon River, Michigan have resulted in increases in abundance in localized areas. Genetic analysis has shown that Lake Sturgeon populations in most areas of Lake Superior, except eastern waters, are distinct from one another and significantly different from those in the other Great Lakes (Welsh et al. 2008).

Studies and assessments continue in embayments and nearshore waters associated with each of the 21 historic spawning tributaries. A key study on the Kaministiquia River, Ontario, examined the effect of controlled flow regimes at Kakabeka Falls on the migratory behavior and reproductive response of Lake Sturgeon from 2002-2009 (Friday 2009). Habitat (substrate type and water depth) for adult and juvenile fish was geo-referenced and quantified using hydroacoustics in the Kaministiquia River, Ontario (Biberhofer and Prokopec 2005) and Bad River (Cholwek *et al*. 2005). Habitat preference of stocked sturgeon in the Ontonagon and St. Louis rivers was described using radio telemetry (Fillmore 2003, 1854 Treaty Authority unpublished data). Due to potential for overexploitation, sport fishing regulations in Ontario waters have been changed to eliminate harvest. There remains a prohibition of commercial harvest of Lake Sturgeon in Lake Superior. Regulation of recreational and subsistence/home use harvest in Lake Superior varies by agency.

In 2011 and 2016, fishery agencies conducted coordinated lakewide Lake Sturgeon index surveys to evaluate trends in abundance and biological characteristics associated with all known current and historic Lake Sturgeon populations. Despite progress, challenges remain. Spawning runs are absent in 1*0* of 21 historic spawning tributaries, and data gathered has provided evidence for only two populations to meet targets identified in the 2003 Rehabilitation Plan. Overall, Lake Sturgeon abundance remains a small fraction of historical abundance, estimated at 870,000 (Hay-Chmielewski and Whelan 1997).

Lake Michigan

Sturgeon populations in Lake Michigan continue to sustain themselves at a small fraction of their historical abundance. An optimistic estimate of the lakewide adult abundance is less than 10,000 fish, well below 1% of the most conservative estimates of historic abundance (Hay-Chmielewski and Whelan 1997). Remnant populations currently are known to spawn in waters of at least nine tributaries having unimpeded connections to Lake Michigan (Schneeberger *et al.* 2005, Elliott 2008, Clapp *et al.* 2012). Two rivers, the Menominee and Peshtigo, appear to support annual spawning runs of 200 or more adults. Six rivers, the Manistee, Muskegon, Grand, Kalamazoo, Fox and Oconto, appear to support annual spawning runs of between 20 and 100 adults, and smaller numbers of sturgeon in spawning condition have been captured or observed in the lower Mansitique and St. Joseph rivers (Baker 2006; Elliott and Gunderman 2008; K. Smith, unpublished data). Successful reproduction has been documented in eight of these rivers, and age 0 juveniles can be captured regularly in many of these rivers. Recent recruitment estimates have been made from research efforts in the Peshtigo River indicating that in some years, several hundred fall recruits are produced from that system (Caroffino *et al.* 2007), and research and assessment efforts in the Manistee and Muskegon rivers indicate significant recruitment from those systems as well (K. Smith, MDNR, personal communication). In addition, abundance of spawners in some rivers appears to have increased in the last decade, indicating that increased recruitment may have been occurring for several years in some rivers. Some Lake Sturgeon have been observed during spawning times in a few other Lake Michigan tributaries such as the Cedar, Millecoquins and Boardman rivers, and near some shoal areas where sturgeon are thought to have spawned historically, but it is not known if spawning occurs in these systems. A large self-sustaining population exists in the Lake Winnebago system upstream of the lower Fox River. This population spawns in the Wolf and Upper Fox rivers and supports an active winter recreational spear fishery. The upper Menominee River also supports two self-sustaining populations which are separated from each other and from the lower Menominee River population by several dams. These populations also support a limited hook and line fishery in the fall of each year.

Active management in the form of reintroduction and rearing assistance stocking has been implemented in seven Lake Michigan basin tributaries. To date, over 30,000 fingerling sturgeon have been stocked into these rivers using Streamside Rearing Facilities. Since 2005, Lake Sturgeon have been reared from eggs to fingerling size using streamside hatcheries and stocked into the Milwaukee, Kewaunee, Cedar and Whitefish rivers, all rivers where sturgeon were considered extirpated for some time. Streamside rearing facilities have also been used on the Manistee River (since 2003, Holtgren *et al* 2007) and the Kalamazoo River (since 2011) to rear fingerling sturgeon from wild fertilized eggs and larva collected from these rivers to help increase survival during early development and boost population growth. Over the next 20-25 years, these stocking efforts are intended to rebuild self-sustaining populations that use these rivers to spawn. Stocking has also occurred in the upper Menominee River for many years and in portions of the Winnebago system. Though limited recreational harvest is allowed in both the upper Menominee River and the Winnebago system, no harvest is allowed from other Lake Michigan tributaries or from Lake Michigan. Habitat evaluations have been conducted in many sturgeon tributaries within the Lake Michigan basin (Daugherty *et al.* 2008) and have guided habitat and flow restoration projects and fish passage via dam removal and installation of fish passage facilities. A fish elevator for upstream passage and downstream bypass facilities began operation on the lower Menominee River in 2015.

Lake Huron

Lake Sturgeon populations continue to be well below estimated historical levels. Spawning has been identified in the Garden, Mississaugi and Spanish rivers in the North Channel, and in the Moon, Musquash, and Nottawasaga rivers in Georgian Bay. Spawning also continues to occur at the mouth of the St. Clair River in southern Lake Huron. Spawning surveys in the Mississaugi and Nottawasaga Rivers have consistently captured hundreds of Lake Sturgeon while over 50 fish are commonly captured during surveys in the Spanish River. The spawning population at the mouth of the St. Clair River in southern Lake Huron contains one of the largest populations of Lake Sturgeon in the Great Lakes with an estimated population near 30,000 individuals (Chiotti *et al.* 2013). Research in the Saginaw River watershed in 2005 – 2007 indicated that Lake Sturgeon are no longer spawning in that watershed, although sufficient spawning habitat does exist below the Dow Dam (Midland, MI) on the Tittabawassee River, and below the Hamilton Dam (Flint, MI) on the Flint River (Boase 2007). Also, creation of rock ramps at the Chesaning Dam (Chesaning, MI) on the Shiawassee River and Frankenmuth Dam (Frankenmuth, MI) on the Cass River now allows Lake Sturgeon passage and access to approximately 40 miles (64 kilometres) and 73 miles (117 kilometres), respectively above each former dam site. Research since 2007 on the St. Marys River system has yet to determine a spawning stock of Lake Sturgeon, however anecdotal evidence of spawning behavior exists (A. Moerke, LSSU, personal communication) Spawning activity has been observed in a number of new locations including the Moon and Musquash rivers in eastern Georgian Bay and the Manitou River on Manitoulin Island. Barriers and habitat degradation in Michigan's and Ontario's tributaries to Lake Huron continue to be a major impediment to successful rehabilitation in Lake Huron.

Stocks of Lake Sturgeon in Lake Huron are monitored by various resource management agencies along with the volunteer efforts of commercial fishers. To date the combined efforts of researchers in U.S. and Canadian waters have resulted in over 7,000 sturgeon tagged in Saginaw Bay, southern Lake Huron, Georgian Bay and the North Channel, with relatively large stocks of mixed sizes being captured at each of these general locations. Tag recoveries, telemetry studies, and genetic collections indicate that Lake Sturgeon are moving within and between jurisdictional boundaries and between lake basins. There is currently no commercial or recreational harvest of Lake Sturgeon in Lake Huron. Regulation of subsistence harvest in Lake Huron varies by agency and is largely unknown.

In an effort to assess basin-wide juvenile abundance in Lake Huron, eleven tributaries were sampled in 2012 and 2013 using a protocol successful in capturing juvenile Lake Sturgeon in Lake Superior (Schloesser *et al.* 2014). Nine of tributaries were sampled in Ontario and two in Michigan. Juvenile Lake Sturgeon were captured at four of these tributaries including the Blind, Echo, Serpent, and Spanish rivers all located in the North Channel. The development of a juvenile index to assess the status of Lake Sturgeon in Lake Huron continues to be of interest to management agencies.

In an effort to understand the migration patterns of Lake Sturgeon in southern Lake Huron and the St. Clair River, 126 adult Lake Sturgeon have been implanted with acoustic transmitters. Utilizing the Great Lakes Acoustic Telemetry Observation System (GLATOS) over four million detections have been documented since 2011, providing valuable information regarding the movements of adult Lake Sturgeon in Lake Huron and the St. Clair River system (Hondorp *et al.* 2015).

Lake Erie

Lake Sturgeon populations continue to be well below historical levels with the exception of the stocks located in the St. Clair – Detroit River System. Spawning has been identified at seven locations in the connecting waters between lakes Huron and Erie (Caswell *et al.* 2004; Manny and Kennedy 2002; Roseman *et al.* 2011) and is likely occurring in Buffalo Harbor and the upper Niagara River (Legard 2015). Three new spawning sites have been identified in the St. Clair River resulting from artificial reef restoration projects aimed at removing the loss of fish and wildlife habitat beneficial use impairment (BUI) in this river (E. Roseman, USGS, personal communication). Tag recovery data and telemetry research indicate that a robust Lake Sturgeon stock of approximately 11,000 fish reside in the North Channel of the St. Clair River and Lake St. Clair (Thomas and Haas 2002; Chiotti *et al.* 2013). The spawning population in the upper St. Clair River near Port Huron, Michigan contains one of the largest populations of Lake Sturgeon in the Great Lakes with an estimated population near 30,000 individuals (Chiotti *et al.* 2013). The North Channel of the St. Clair River, Anchor Bay in Lake St. Clair, the Detroit River (East of Fighting Island), and the western basin of Lake Erie have been identified as nursery areas as indicated by consistent catches in commercial and survey fishing gears. The upper Niagara River is a suspected nursery area based on reports from anglers and divers (C. Legard NYSDEC, personal communication). However, a dedicated Lake Sturgeon survey has not been done in the upper Niagara River to confirm to these reports. In the central and eastern basins of Lake Erie, Lake Sturgeon are scarcer with only occasional catches of sub-adult or adult Lake Sturgeon in commercial and research fishing nets. Survey work conducted in 2005 and 2006 indicated that no Lake Sturgeon spawning is taking place in the Maumee River, Ohio (J. Boase, USFWS, personal communication). A habitat suitability model and restoration plan is currently being developed for the Maumee River to assess reintroduction efforts (Sherman *et al.* 2015). An observed concentration of sturgeon in the spring of 2009 and subsequent sampling through 2015 in Buffalo Harbor has yielded maturing and sexually mature adult and sub-adult Lake Sturgeon suggesting spawning is occurring in the area. Sidescan sonar imagery for a roughly seven square mile (18 square kilometres) section of Buffalo Harbor has been collected to develop a categorical habitat map intended to identify potential sturgeon spawning habitat.

In an effort to understand the migration patterns of Lake Sturgeon in the St. Clair – Detroit River System, nearly 300 adult Lake Sturgeon have been implanted with acoustic transmitters. Utilizing the Great Lakes Acoustic Telemetry Observation System (GLATOS) over four million detections have been documented since 2011, providing valuable information regarding the movements of adult Lake Sturgeon in this system as well as lakes Huron and Erie (Hondorp *et al.* 2015). In Buffalo Harbor, a total of 19 Lake Sturgeon were implanted with acoustic transmitters, nine of which were equipped with satellite transmitters, in the spring of 2015. To date GLATOS has provided nearly five million detections for sturgeon acoustically tagged in Buffalo Harbor.

In an effort to assess basin-wide juvenile abundance in Lake Erie, 14 tributaries were sampled in 2013 and 2014 using a protocol successful in capturing juvenile Lake Sturgeon in Lake Superior (Schloesser *et al*. 2014). A total of 176 nets were set and a total of 15 Lake Sturgeon were captured, all in the St. Clair – Detroit River System.

Research efforts will continue to focus on identifying rivers with suitable habitat for reintroduction efforts, identification of spawning locations, habitat requirements, and migration patterns.

Lake Ontario/ Upper St. Lawrence River
The numbers of mature sturgeon are not well quantified for most of the spawning areas surrounding Lake Ontario; however, some data is available to address the long term restoration indicator. Biesinger et al. (2013) reported a mark-recapture population estimate of 2,856 (95% confidence interval of 1,637 to 5,093) mature and immature fish for the lower Niagara River. Also, numbers of sturgeon counted at or near the two artificial spawning beds constructed in the vicinity of Iroquois Dam in the upper St. Lawrence River ranged between 122 and 395 at the peak of spawning activity during 2008-2012 (NYSDEC 2013). Spawning populations also exist at Black River, NY (Klindt and Gordon 2014), and the Trent River, ON (A. Mathers, OMNR, personal. communication); however, these populations are small – likely in the 10s to 100s of fish.

Several management actions have been taken to promote sturgeon recovery. Commercial harvest of sturgeon in Lake Ontario and upper St. Lawrence River was banned in 1976 in New York and in 1984 in Ontario. In addition, all recreational fishing has been closed since 1979. During the past decade artificial spawning shoals for sturgeon have been created in the upper St. Lawrence River and their success has been evaluated showing egg deposition and emergence of larvae (NYSDEC 2013).

Between 1993 and 2013, NYSDEC in collaboration with U.S. FWS, have stocked 85,814 (0 to 14,047 fish per year) sturgeon into the Lake Ontario system. Gametes for these efforts were collected in St. Lawrence River (below Moses-Saunders power dam since 1996). Stocking locations extend from the Genesee River east to Lake St. Francis tributaries. Research on sturgeon stocked in the lower Genesee River documented high level of survival and good growth suggesting these types of habitats are highly suitable for sturgeon and also that stocking has the potential to increase sturgeon abundance substantially (Dittman and Zollweg 2006). It is expected that spawning populations based on stocked fish will develop in the Genesee River, as well as the Oswego River, in the next few years (Chalupnicki *et al.* 2011).

Research will continue assessing the Lake Sturgeon spawning shoals for aggregations of adults, egg deposition, and fry emergence. Monitoring of sturgeon catches and population age structure via agency fish community assessment programs will provide an index of population status in, and recruitment to, eastern Lake Ontario. Targeted surveys of sturgeon in the lower Niagara River appears to be required to monitor this population. Efforts to stock sturgeon by agencies appear to be highly successful and monitoring of its effects should continue. Because sturgeon become sexual mature at an advanced age, a decade or more may be needed to observe responses to restoration efforts.

Linkages

- Aquatic Habitat Connectivity – loss of aquatic connectivity has contributed to the decline of Lake Sturgeon. Research and development are needed to determine ways for Lake Sturgeon to pass man-made barriers on rivers.
- Aquatic Invasive Species and Dreissenid Mussels – An additional concern for Lake Sturgeon in many of the Great Lakes is the ecosystem changes that have resulted from high densities of invasive species such as Dreissenid Mussels and round gobies and the presumed related exposure to Botulism Type E which has produced measurable die-offs of Lake Sturgeon in several years since 2001.

Comments from the Author(s)

Research and development is needed to determine ways for Lake Sturgeon to pass man-made barriers on rivers. In addition, there are significant, legal, logistical, and financial hurdles to overcome in order to restore degraded spawning habitats in connecting waterways and tributaries to the Great Lakes. More monitoring is needed to determine the current status of Great Lakes Lake Sturgeon populations, particularly the juvenile life stage.

As monitoring programs and techniques are refined, our ability to detect Lake Sturgeon has likely increased making it difficult to determine whether changes observed are a result of increasing populations or reflect more efficient monitoring. Long-term standardized monitoring programs need to be developed in order to effectively assess the status of Lake Sturgeon stocks in each lake.

It should also be noted that the overall assessment for each lake changed from fair and improving in 2011 to poor and improving in 2016, but this is not due to deteriorating populations. Based on the status assessment measures used in both the 2011 and 2016 reports, all of the lakes should have been assessed as poor and improving in 2011.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		x				
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data		x				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the U.S. are comparable to those from Canada		x				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				
Clarifying Notes: Since the status assessment is highly dependent upon the number of self-sustaining populations within each lake basin, the source of the data for the historical population status is currently being assessed for Lakes Huron and Erie. For some of the Great Lakes, the 4. "Geographic coverage and scale of data" may not be appropriate.						

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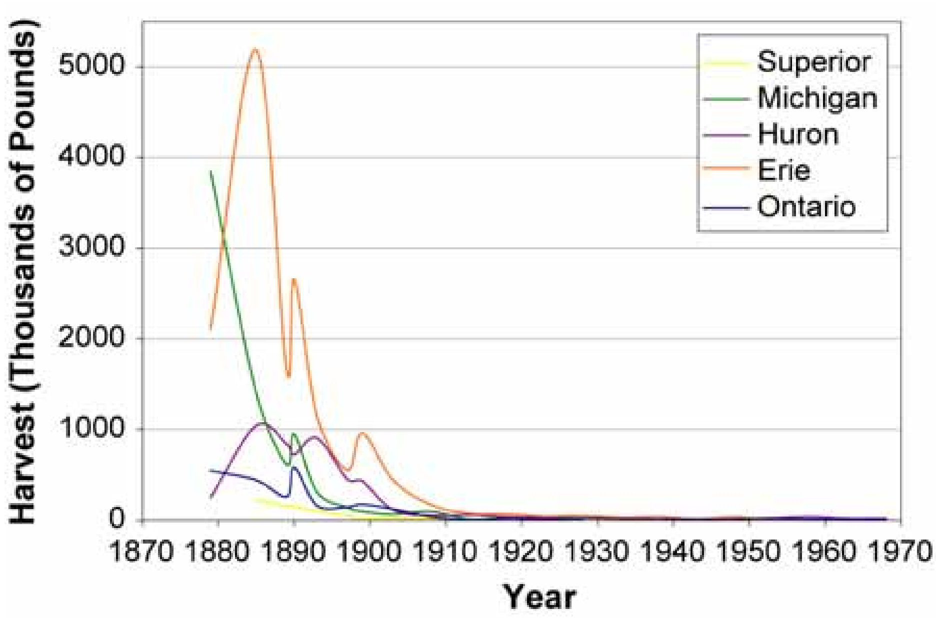

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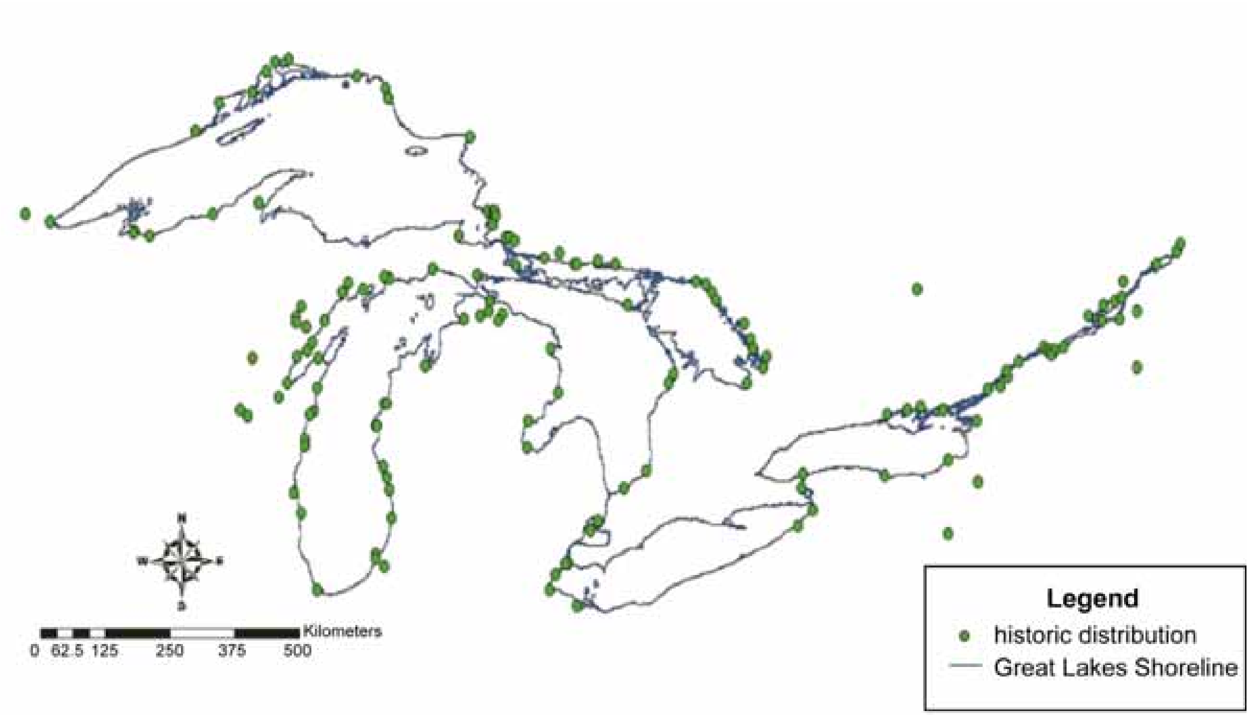

Figure 2. Historic distribution of Lake Sturgeon.
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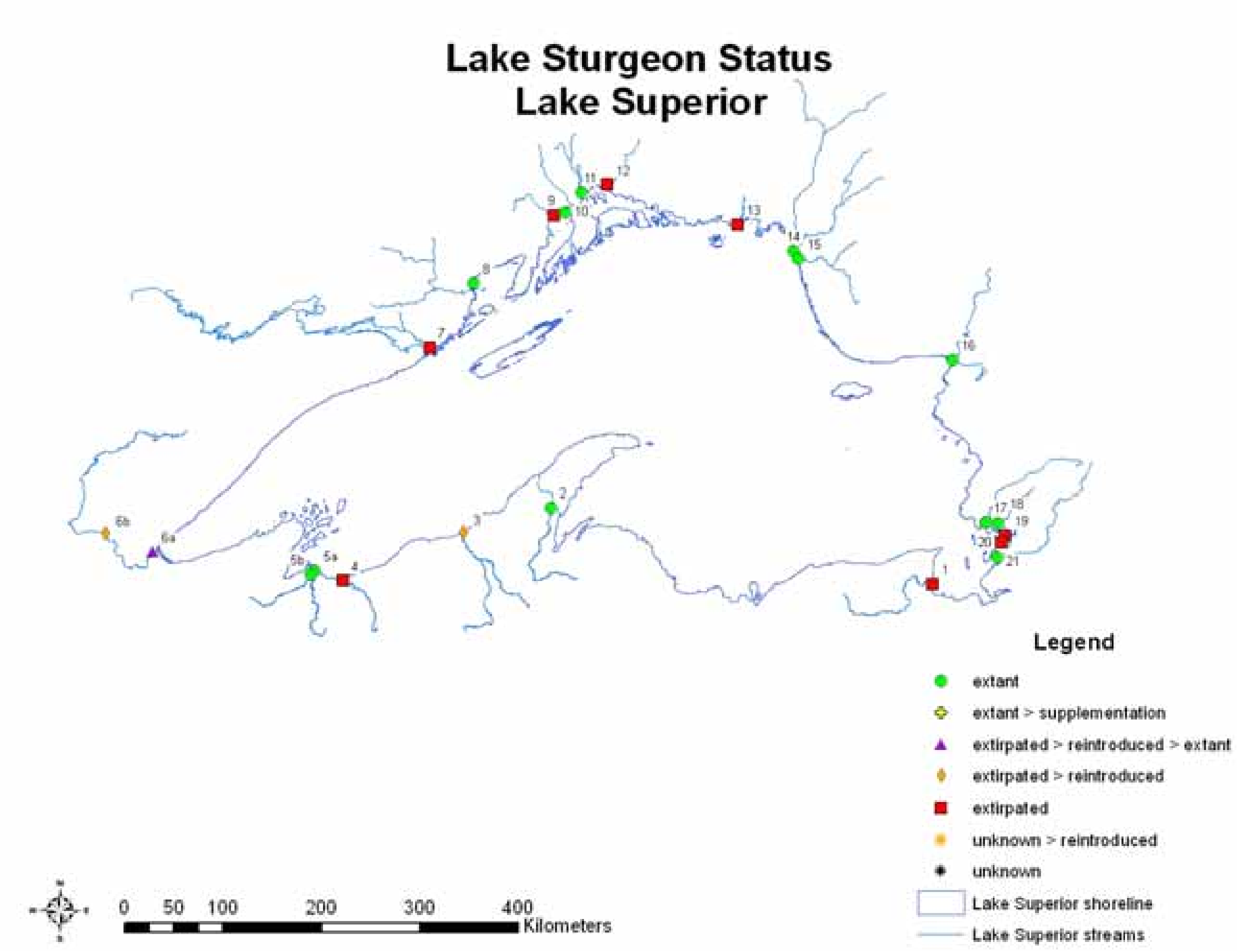

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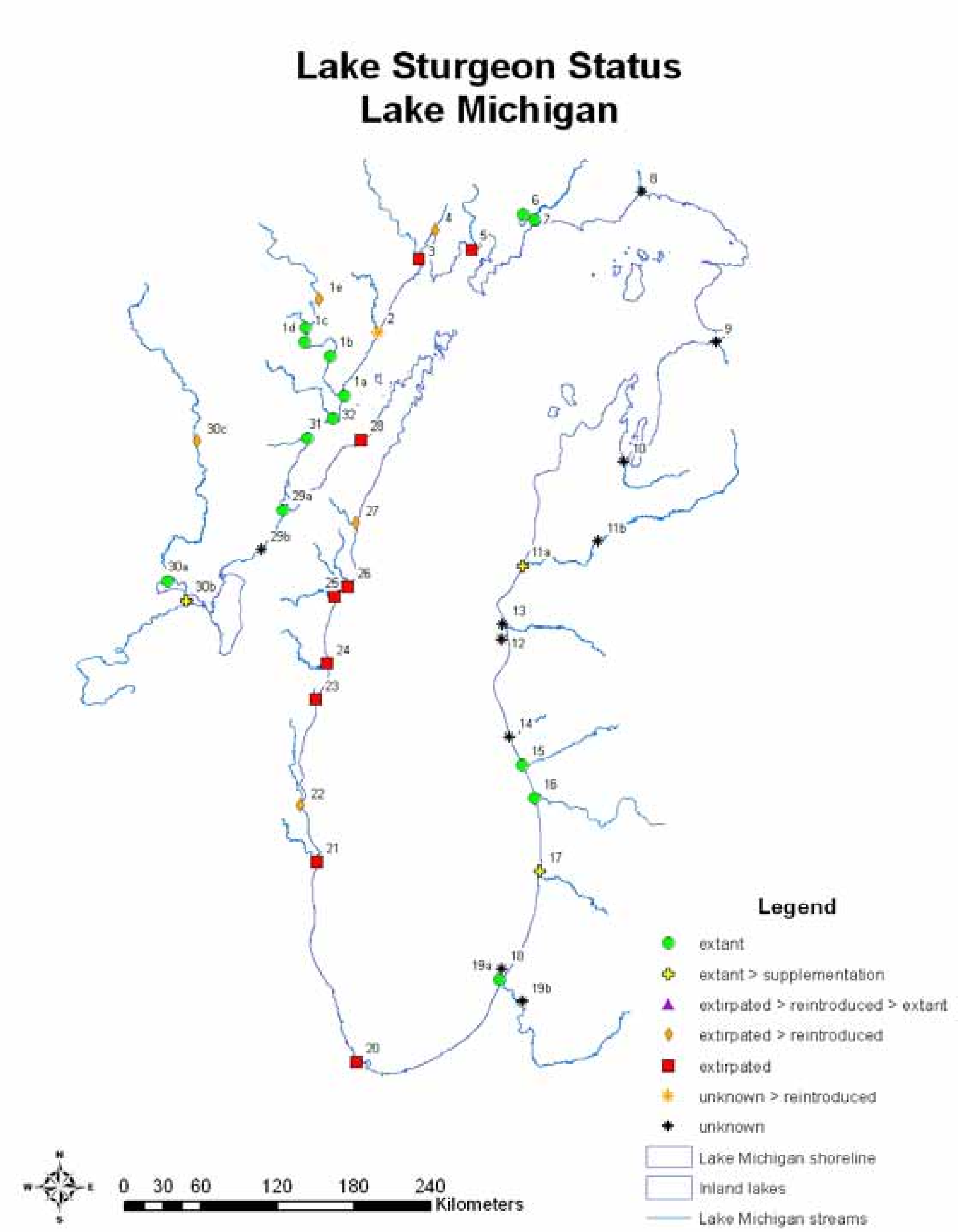

Figure 4. Lake Sturgeon population status in Lake Michigan, 2012.
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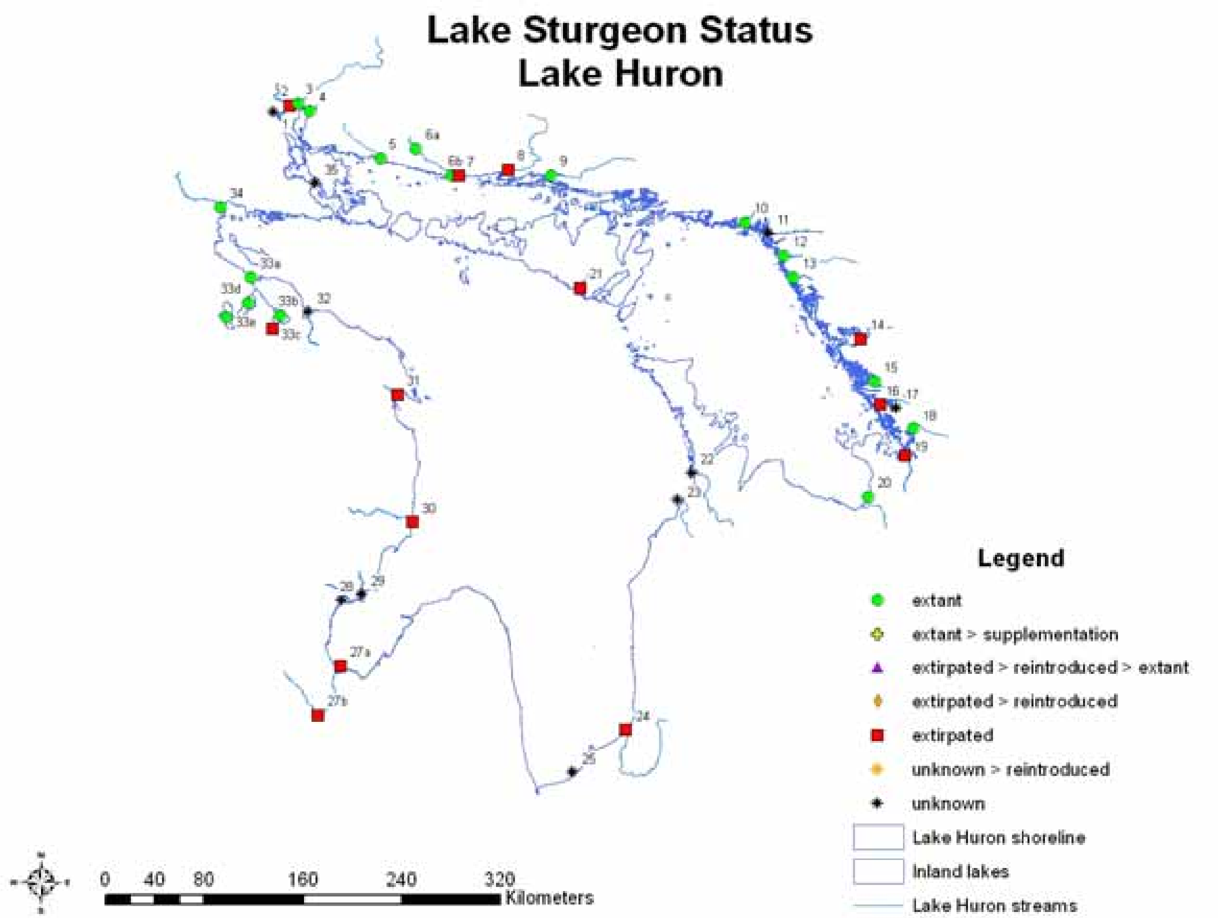

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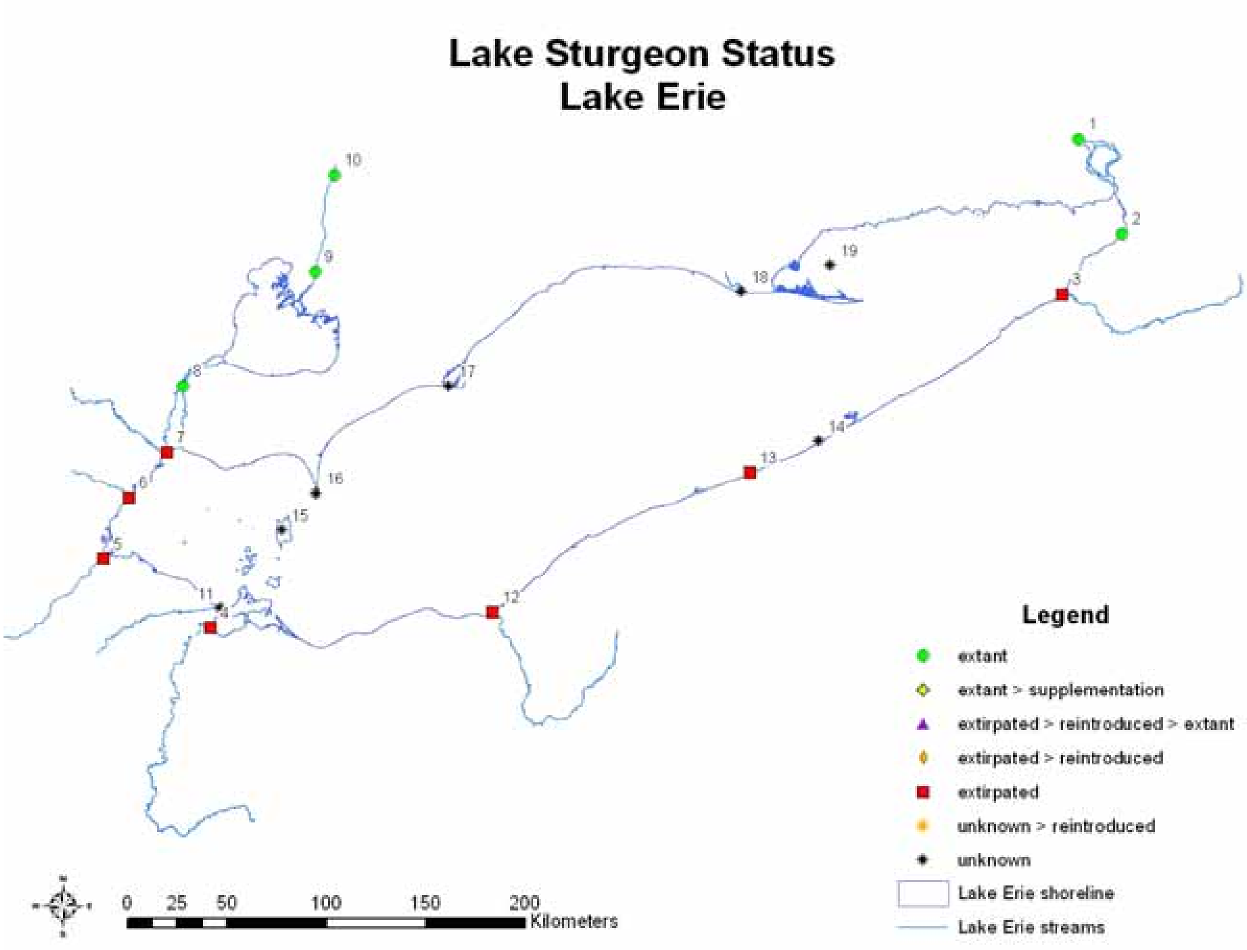

Figure 6. Lake Sturgeon population status in Lake Erie, 2012.
Source: Lake Erie Lake Sturgeon Working Group

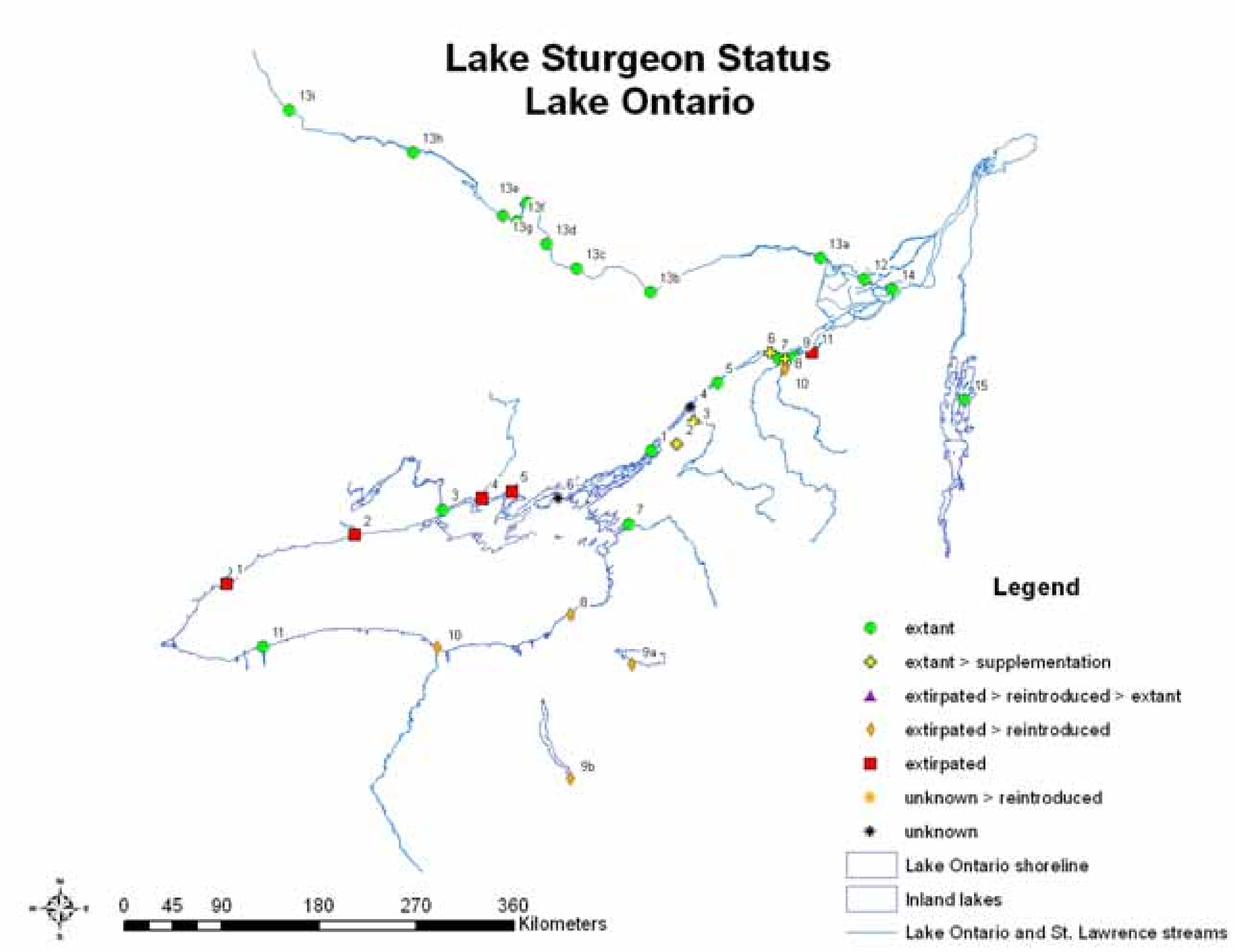

Figure 7. Lake Sturgeon population status in Lake Ontario, Ottawa River and St. Lawrence River, 2012.
Source: New York Lake Sturgeon Working Group, and Tim Haxton, OMNRF

Sub-Indicator: Walleye

Overall Assessment
Status: Good
Trend: Unchanging
Rationale: The health of native Walleye populations in the Great Lakes is quite variable; however, the overall trend is that populations are unchanging. In lakes where non-native species have been on the decline (including alewife) and increases in productivity have been beneficial (i.e., excluding harmful algal blooms), Walleye populations have responded favorably. Where productivity increases or other factors have been deleterious to ecosystem health, Walleye populations have struggled to maintain the robust levels attained previously. Recruitment trends in each Great Lake or in each localized sub-population (i.e., river, embayment or basin) continue to play a large part in the overall health of Walleye populations. Consistent years of good recruitment have helped fortify some populations, while poor recruitment trends in others have resulted in lower than desirable population levels over the short-term. Overall, population trends in Erie, Huron and Superior appear to be consistent (i.e., based on reported harvest) over the long-term, whereas Walleye population has decreased in Lake Ontario but increased in Lake Michigan.

Lake-by-Lake Assessment
Lake Superior
Status: Fair
Trend: Unchanging
Rationale: Assessment efforts are continuing throughout the lake, showing signs of improving conditions in one of the areas, but static population trends in the others. Efforts have been made throughout the lake to address management concerns for Walleye populations including limiting commercial and recreational harvest, nearshore habitat rehabilitation, shoreline remediation and assessment programs to identify other actions. Assessments in the connecting waters have not been included due to lack of monitoring.

Lake Michigan
Status: Good
Trend: Unchanging
Rationale: On a lake-wide basis, Walleye harvest levels have met the target range set by the Lake Michigan Fish Community Objectives (FCOs) for a sustainable harvest of 200,000 to 400,000 pounds since 2011. The average Walleye harvest (biomass) was 311,722 pounds during 2011-2014, with a high of 357,322 pounds in 2012. This includes a 9,357 pound average commercial harvest by the Tribal commercial fishers for the time period, as well as the sport-caught Walleye from the four state jurisdictions. Assessments in the connecting waters have not been included due to lack of monitoring.

Lake Huron
Status: Good
Trend: Unchanging
Rationale: The largest source of Walleye in Lake Huron is the Saginaw Bay stock which achieved recovery targets in 2009. The recovery was fueled by the disappearance of Alewives in the lake beginning in 2003 stemming from profound food web shifts. Walleye reproductive success soared in the absence of Alewives and recovery of this important stock was achieved. In Ontario waters, particularly Georgian Bay and to a lesser extent in the North Channel, most Walleye stocks continue to be depressed; a situation that is being addressed with the initiation of the development of a Walleye Management Plan for Ontario waters.

Lake Erie
Status: Good
Trend: Improving
Rationale: The Walleye population and associated fisheries in Lake Erie are managed individually by four United States state agencies and one Canadian provincial agency. Under the auspices of the Great Lakes Fishery Commission's Lake Erie Committee (LEC), a new stakeholder process, known as the Lake Erie Percid Management Advisory Group (LEPMAG), was initiated in 2010. The purpose of the LEPMAG was to provide Lake Erie managers ad-

vice on fisheries management objectives and associated harvest policies. The work of the LEPMAG resulted in a revised Walleye Management Plan for 2015-2019 (Kayle et al. 2015).

Lake Ontario
Status: Fair
Trend: Unchanging
Rationale: Following declines in juvenile and adult Walleye abundance in the 1990s, associated with reduced young-of-the-year production in the mid-1990s, the Walleye population stabilized in Bay of Quinte and in Ontario and New York waters of eastern Lake Ontario. Walleye performance targets, identified in the Bay of Quinte Fisheries Management Plan (2010) and based on a post-dreissenid time-period (2002-2006), are currently being met or exceeded. Recent hatches should keep the population at current or improved levels of abundance for the next several years. Assessments in the connecting waters have not been included due to lack of monitoring.

Other Spatial Scales
Huron-Erie Corridor (St. Clair River-Lake St. Clair-Detroit River)
Status: Fair
Trend: Unchanging
Rationale: Walleye are an important part of the recreational fishery in the Huron-Erie Corridor. This fishery has been evaluated on an inconsistent basis and no continuous fishery data are available. The most recent Ontario creel survey in 2009 showed that the Walleye catch and catch rate in Lake St. Clair were lower than the early 2000s and the 1980s. However the catch and catch rates in the Detroit River remained high in the 2009 creel compared to the 2000s and early 1990s. Recent (2011-2014) catch rates in the annual voluntary angler diary program remain near the long term average in Lake St. Clair, Detroit River, and St. Clair River.

Sub-Indicator Purpose

- The purpose of this indicator is to measure status and trends in Walleye population abundance and recruitment in various Great Lakes habitats; to infer the status of cool water predator communities; and to infer ecosystem health, particularly in moderately-productive (mesotrophic) areas of the Great Lakes and through their roles in the aquatic food web.

Ecosystem Objective
Protection, enhancement and restoration of historically important, mesotrophic habitats that support natural stocks of Walleye as the top fish predator. These habitats are necessary for a stable, balanced, and properly-functioning Great Lakes ecosystem.

This indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should “support healthy and productive wetlands and other habitats to sustain resilient populations of native species.”

Ecological Condition
The historical dominance of Walleye in mesotrophic habitats in the Great Lakes provides a good basis for a basin-wide evaluation of ecosystem health. Maintaining or re-establishing historical levels of relative abundance, biomass, or production of self-sustaining Walleye populations throughout their native range in the Great Lakes Basin will help ensure dominance of this species in the ecosystem and the maintenance of a desirable and balanced aquatic community in cool water, mesotrophic habitats. Historical data can be used to develop status and trend information on Walleye populations. Commercial catch records for Walleye in the Great Lakes extend back to the late 1800s; recreational catch data and assessment fishing data supplement these commercial catch records in some areas in recent decades and sport fishing data are especially useful in areas where the commercial fishery for the species has been closed.

The “mesotrophic” cool-water fish community is associated with more productive waters in nearshore areas. Mesotrophic communities, along with oligotrophic and eutrophic communities are found to varying degrees in all five of the Great Lakes with more than half of Lake Erie represented by mesotrophic habitat.

The Walleye is the top predator in the cool nearshore and offshore waters of the Great Lakes and is selected as an indicator because they represent one of the original fish communities in the different habitats, they have value to the ecosystem and to fisheries, and they are the focus of fisheries management and restoration efforts. Being co-evolved with the rest of the fish community and the natural ecosystem of the Great Lakes, Walleye represent the natural biodiversity of the lakes. They have been subjected to the full slate of other environmental effects resulted from human disruption of the Great Lakes including habitat loss, nutrient pollution, and persistent toxic pollutants. While restoration efforts like stocking can complicate interpretation of their status, the successes of these species are indicative of progress toward the goals of the GLWQA. Walleye support large commercial and recreational fisheries throughout Lakes Erie and Huron; consequently, trends in harvest are useful for assessing ecosystem health. However, in Lakes Michigan, Ontario, and Superior, where Walleye are constrained to coolwater habitats, harvest information may not be as reflective of ecosystem health as in Lakes Erie and Huron due to their limited spatial distribution. Rather, harvest trends may only reflect the ecosystem health of particular areas in Lakes Michigan, Ontario or Superior because of the limited data available.

Lake Superior
Thunder Bay-Kaministiquia River contains a small but healthy self-sustaining population, with evidence of consistent recruitment. In Black Bay, assessment work is showing an increase in relative abundance of Walleye (creel results are pending). In Nipigon Bay and Nipigon River, Walleye are low in abundance, but assessment work is showing signs of increasing density (high growth rates and low mortality). Due to limited assessment surveys, it is difficult to assess if population targets in the St. Louis River, Bad River and Chequamegen Bay were met during this reporting period.

Lake Michigan
Michigan and Wisconsin sport anglers are the two main user groups contributing to the sport harvest, primarily in the northern end of the lake and Green Bay. Most of the Walleye harvested from Lake Michigan were from the waters of Green Bay. In northern Green Bay, Walleye harvest has shown a declining trend the past four years although harvest has been steady the past two years. In southern Green Bay, harvest has increased during this period because of good recruitment from above average young of year production in most years from 2007-2014. Walleye produced in 2013, the strongest young of year production measured in southern Green Bay since 2003, have just begun to enter the fishery. The harvest trend in Lake Michigan appears to be steady, although data is limited.

Lake Huron
Considerable insights have been gained about the status and behavior of the Saginaw Bay stock since the resurgence in reproductive success. A telemetry study confirmed that about half of the adult Walleyes make an annual migration to the main basin of the lake outside the bay from about May or June until returning in the fall. Bioenergetics modeling indicates that Walleyes account for about 10% of the total prey fish consumption demand in the main basin of Lake Huron since recovery. Advanced stock assessment of the population and fisheries were conducted leading to an improved understanding of the stock's population metrics and dynamics. Models indicate the recovered Saginaw Bay stock of Walleye ranges from 2.5 to nearly 4 million age-2 and older Walleyes in most years. From this, a simulation model was developed enabling the evaluation of new management objectives and strategies. The Michigan DNR, used these tools to shift management of Saginaw Bay Walleyes from a recovery strategy to one that is based on the state of the stock with goals of achieving more full utilization within the recreational fishery and to try and manage Walleye predation for the betterment of Yellow Perch in the bay.

Other sources of Walleye in Lake Huron trace to individual localized reproductive sources usually associated with tributaries. In the Ontario waters, these span the watershed across Georgian Bay and the North Channel. The Ontario Ministry of Natural Resources and Forestry has recently initiated efforts to develop a Walleye Management Plan for Ontario waters of Lake Huron which includes a review and synthesis of historic and contemporary Walleye population assessment data. Preliminary reviews have indicated that the status of individual Walleye stocks is variable with a majority of stocks currently depressed compared to historic levels of abundance. Georgian Bay stocks appear to be more depressed than those in the North Channel. In spite of the disappearance of Alewives, these localized populations have not demonstrated the same sort of recovery that was seen in Saginaw Bay. Factors limiting the abundance of these stocks are uncertain. In some instances it may be recruitment limitations but in others it may be suppression by high rates of total mortality. The status of Walleye in the Ontario waters of the southern main basin appear to be stable as a consequence of these stocks being of mixed origin, primarily immigrants from Saginaw Bay and western Lake Erie.

Overall the trend appears to be unchanging. The overall status of the Lake Huron Walleye population and fisheries has to be characterized as “Good” given the recovery of the Saginaw Bay stock, although there is likely further improvement possible particularly in Ontario waters. Generally yield across all sources has not fully achieved this historic average or the Fish Community Objective of 0.7 million kgs/year.

Lake Erie
Since 2011, the annual Total Allowable Catch (TAC, or fishery quota) set for the west and central basins of Lake Erie has been gradually increasing (no TAC is set for the east basin), resulting in increased Walleye harvest in both the sport and commercial fisheries. The commercial harvest has annually exceeded the 4 million pound management objective as identified in the Walleye Management Plan (Kayle et al. 2015). In 2015 the projected spawner biomass was estimated at 25.858 million kilograms, well above the 11 million kilogram limit reference point of 20% of the unfished spawner biomass.

Across Lake Erie, the annual sport fishing effort remains below the long-term mean, but has been trending upwards since 2011. Similar increasing trends have been observed in the sport fishing catch rates, with catch rates for all management units at or above the long-term mean and meeting the current Walleye management objective of 0.4 Walleye/hour.

Commercial effort across the lake has also been trending upwards over the last five years with the most dramatic increase in effort observed in the 2014. However, effort for all management units remains below the long-term mean. Commercial lake-wide catch rates have been trending down since 2010. The downward trends are strongest in the west with 2014 catch rates falling below the long-term mean, while catch rates in the east-end of the lake remain above the long-term mean and appear to be stable.

Lake Erie Walleye fisheries remain largely dependent on older fish from the 2003 and 2007 cohorts, with more recent contributions by the 2010 and 2011 cohorts. Mean age of Walleye in the sport and commercial harvest continues to rise with the average age for Walleye in the commercial harvest at 7 years of age and the sport harvest at 6 years of age.

Walleye recruitment has improved since 2011 with two of the last four cohorts (2013 and 2014) being moderate to strong year classes. It is expected that these year classes will make strong contributions to the fishery over the next few years. The earlier 2011 and 2012 cohorts were assessed as weak and are expected to contribute little to the fishery.

Some recovery and expansion is apparent in eastern basin Walleye stocks. Sport and commercial harvest and catch rates in the east end of the lake are currently above the long-term mean. This may be the result of recent recruitment patterns as well as the abundance of older, highly migratory stocks of Walleye from the western and central basins of Lake Erie (Kayle et al. 2015).

Lake Ontario
Smaller, local Walleye populations exist in other areas of Lake Ontario. Some embayment areas support small but healthy and self-sustaining populations (e.g., Wellers Bay, West Lake) while other areas with degraded habitat require on-going rehabilitation efforts (e.g., Hamilton Harbour), including Walleye stocking. Stocking to restore Walleye populations in waters they formerly occupied serves to help diversify fish community trophic structure and to enhance recreational fishing.

Huron-Erie Corridor (St. Clair River-Lake St. Clair-Detroit River)
The Ontario Ministry of Natural Resources and Forestry fall trap net survey shows no trend in the catch rate of Walleye in recent years, however the catch rate has declined since the 1970s and 1980s. Similarly the Michigan spring trap net survey shows no trend the catch rate of Walleye in recent years. The growth rate of Walleye in the Ontario fall trap net survey has increased each decade since the survey began. The highest growth rate of Walleye occurred from 2011-2014. Recent recruitment of Walleye in Lake St. Clair has been poor. The last year-class of even moderate strength that was produced in Lake St. Clair was in 1986. Since then, very few age-1 Walleye have been caught in the Ontario fall trap net survey.

Linkages
Linkages to other sub-indicators in the indicator suite include:
- Aquatic Habitat Connectivity

One of the impediments identified as a potential impediment to the continued health of Walleye populations in the Great Lakes Basin is the connectivity between riverine spawning grounds and juvenile habitat. Often this phenomenon may be the result of human-induced alterations (e.g., dam construction) to the landscape.

This sub-indicator also links directly to the other sub-indicators in the Habitat and Species indicator.

Comments from the Author(s)

Fishery yields (Figure 1) are appropriate indicators of Walleye health but only in a general sense. Yield was estimated for the recreational fisheries by multiplying the number of fish harvested by estimating the average size of fish harvested and extrapolating an estimated weight of harvested fish to the total number harvested. Fishery (i.e., dependent and independent) assessments are lacking for some fisheries (recreational, commercial, or tribal) in some years for all of the studied areas. Moreover, measurement units are not standardized among fishery types (i.e., commercial fisheries are measured by mass while recreational fisheries are typically measured in numbers of fish), which means additional conversions are necessary which reduce accuracy. Also, “zero” values need to be differentiated from “missing” data in any figures. Therefore, trends in fishery yields across time (blocks of years) are probably better indicators than absolute values within any year, assuming that any introduced bias is relatively constant over time. Abundance, spawner biomass, recruitment, age/length at maturity, and fishery performance (effort, catch rate, yield) are useful metrics for describing Great Lakes ecosystem and fishery health. However in the absence of absolute abundance and spawner biomass estimates for all lakes, relative measures from fishery dependent (i.e., harvest) and independent (i.e., population assessments) are suitable metrics for reporting on Walleye population health in the event population estimates are lacking.

Many agencies have developed, or are developing, population estimates for many Great Lakes fishes. Walleye population estimates for selected areas (i.e., Lakes Erie, Huron, Michigan and Ontario) would probably be a better assessment of Walleye population health than harvest estimates, thus to the extent that it is possible, future efforts should focus on developing these capabilities.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		LE, LH, LM, LO, HEC	LS			
2. Data are traceable to original sources	LE	LH, LM, LO, HEC	LS			
3. The source of the data is a known, reliable and respected generator of data	LE	LM, LO, HEC	LH, LS			
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		LE, LM, LO	LH, LS, HEC			
5. Data obtained from sources within the U.S. are comparable to those from Canada		LE, LM, HEC	LO, LS	LH		
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	LE	LM, LO	LH, LS, HEC			

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Information Sources

Kayle, K., K. Oldenburg, C. Murray, J. Francis, and J. Markham. 2015. Lake Erie Walleye Management Plan 2015-2019. Great Lakes Fishery Commission, http://www.glfc.org/lakecom/lec/LEC_docs/position_statements/Walleye_managment_plan.pdf.

Fishery harvest and population assessment data were obtained from the following sources:

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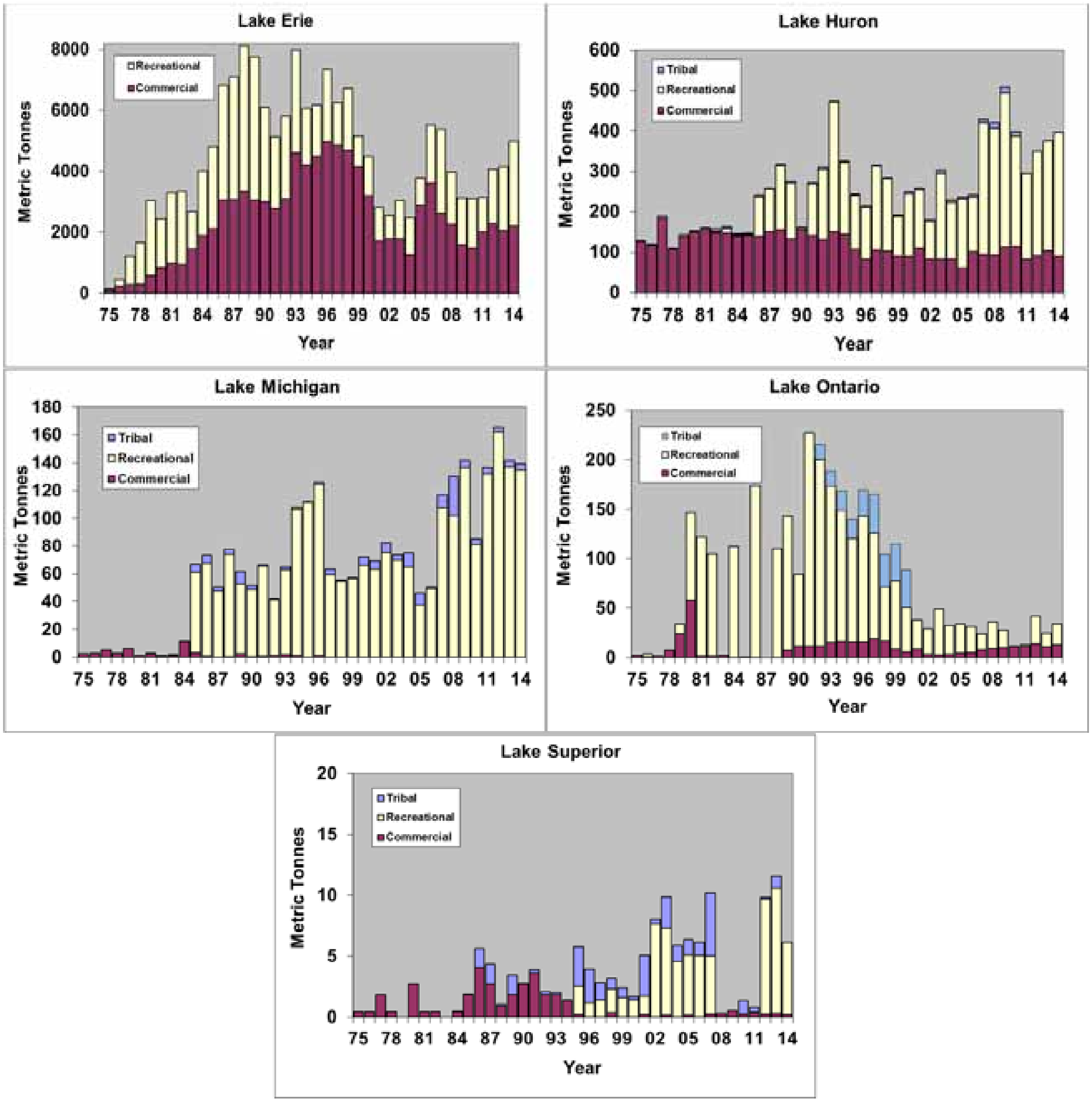

Figure 1. Walleye harvest, reported in metric tonnes, split into contributions from tribal, recreational and commercial fisheries in the five Great Lakes, 1975 – 2014. Fish Community Goals and Objectives are: Lake Michigan, 100-200 metric tonnes; Lake Huron, 700 metric tonnes; Lake Erie, sustainable harvest in all basins; Lake Ontario, maintain early 1990s populations and expand populations into favorable habitats.
Source: Chippewa Ottawa Resource Authority, Michigan Department of Natural Resources, Minnesota Department of Natural Resources. New York State Department of Environmental Conservation, Ontario Ministry of Natural Resources, Ohio Department of Natural Resources, Pennsylvania Fish and Boat Commission, Wisconsin Department of Natural Resources.

Sub-Indicator: Lake Trout

Overall Assessment
Status: Fair
Trend: Improving
Rationale: Self-reproducing populations are present in Lake Superior and natural reproduction is widespread and increasing in Lake Huron. Populations in lakes Michigan, Erie, and Ontario are mostly below Great Lakes Fishery Commission Lake Committee target levels for relative abundance and natural reproduction is low. Some population increases are being observed with support of stocking and other rehabilitation efforts.

Lake-by-Lake Assessment
Lake Superior
Status: Good
Trend: Unchanging
Rationale: Natural reproduction of both nearshore (lean) and offshore (siscowet) populations is widespread and supports all populations. Populations have likely reached carrying capacity given the current available forage base. Overall lake-wide abundance is stabilizing with eastern Michigan populations declining from peak abundance levels and western Lake Superior populations continuing to build. Most stocking has been discontinued. Excessive fishing is occurring in eastern Wisconsin, western Michigan, and in eastern Ontario waters. Sea Lamprey mortality has been increasing. Most agencies are committed to further restoration and conservation.

Lake Michigan
Status: Poor
Trend: Improving
Rationale: Lake-wide densities are stable but well below target. Some natural reproduction being detected in areas with low mortality, older age compositions and higher parental densities; significant recruitment of wild fish to the general population remains elusive. Survival of stocked fish in northern Lake Michigan is poor due to high Sea Lamprey mortality and fishing resulting in inadequate parental stocks. Most agencies are committed to rehabilitation.

Lake Huron
Status: Good
Trend: Improving
Rational: More than 15 year classes of wild Lake Trout have been observed lake wide, and represent more than 50% of survey catches and 50-90% of harvest in recent years. Abundant year classes of wild Lake Trout have entered the adult portion of the population and wild juvenile abundance reached a new high level since the 2010 year class. Post-release survival of stocked fish is low and stocking reductions are being considered. All agencies committed to further rehabilitation and conservation.

Lake Erie
Status: Fair
Trend: Improving
Rationale: Increased stocking levels in recent years and success of the Lake Champlain strain has increased adult stocks to near rehabilitation targets outlined in the rehabilitation plan. Sea Lampreys predation continues to be an issue, and natural reproduction has still not been detected. All agencies remain committed to further rehabilitation and conservation.

Lake Ontario
Status: Fair
Trend: Improving
Rationale: Sea Lamprey predation was strongly related to a collapse in adult stocks during 2004-2005; however abundance increased each year during 2008 – 2014 following improved Sea Lamprey control. Post-release survival

of stocked fish was low from the early 1990s through 2010, but increased 3.4 fold during 2011 - 2014, and the catch of ages-1 and -2 naturally reproduced Lake Trout in 2014 was more than 14 times greater than any previous year since 1994. All agencies remain committed to further rehabilitation and conservation.

Sub-Indicator Purpose

- To estimate the relative abundance of both stocked and wild (naturally reproduced) Lake Trout.
- To measure the success of rehabilitation through catch rates of wild fish
- To infer the control measures on fishing and Sea Lamprey predation through the age structure and abundance of mature fish.
- To infer the basic structure of the cold water predator community and the general health of the ecosystem

Ecosystem Objective

Self-sustaining, naturally reproducing populations that support target yields to fisheries are the goal of the Lake Trout rehabilitation program. Target yields approximate historical levels of Lake Trout harvest or levels adjusted to accommodate stocked naturalized introduced predators such as Pacific salmon. Targets, most centered on desired harvest expectations, are set by Lake Committees of the Great Lakes Fishery Commission in Fish Community Objectives (Horns et al. 2003, Eshenroder et al. 1999, DesJardin et al.1995, Ryan et al. 2003., Stewart et al. 1999), and are revised periodically. These targets are 1.8 million kg (4 million pounds) from Lake Superior, 1.1 million kg (2.5 million pounds) from Lake Michigan, 0.9 million kg (2.0 million pounds) from Lake Huron and 50 thousand kg (0.1 million pounds) from Lake Erie. Lake Ontario has no specific yield objective but has a population objective of 0.5 to 1.0 million adult fish that produce 100,000 yearling recruits annually through natural reproduction. The desired state will be for Lake Trout to serve as the primary top predator in Lake Superior and share this status with other native and established non-native predators in lakes Michigan, Huron, Erie and Ontario.

Ecological Condition

<u>Measure</u>

Trends in the relative abundance of stocked lean Lake Trout in lakes Huron, Michigan, Erie and Ontario, and wild lean Lake Trout in Lake Superior are displayed in Figure 1. Targets are set for most populations of lean Lake Trout as these are perceived to be biologically important to increase the probability of natural reproduction in lakes Huron, Michigan, Erie and Ontario and to maintain wild populations in Lake Superior. Target values are measured and expressed by relative abundances of all or a portion of the population in multiagency gill net surveys that are standardized within each lake. These measures are superior to harvest objectives, which are harder to evaluate and represent desired states that cannot be easily tested for sustainability. Lake Trout abundance dramatically increased in all the Great Lakes after initiation of Sea Lamprey control, stocking, and harvest control. Success to achieve population targets and ultimately to self-sustaining naturally reproducing populations has been mixed among the lakes.

<u>Endpoint</u>

Desired states are populations that are self-sustaining through natural reproduction with minimal or no hatchery supplementation required, that support a sustainable harvest, and serve as a top predator. The resulting population size and sustainable yield compared to historical levels will likely be lower in most lakes since this apex trophic level is now shared by naturalized non-native predators that support a multi-billion dollar fishery.

<u>Background</u>

Historically Lake Trout were the keystone salmonine predator for most of the Great Lakes. Overfishing and predation by non-native sea lamprey, and to a limited extent other factors, destroyed nearshore lean populations and deep water siscowet Lake Trout populations, but many survived in Lake Superior and a few lean Lake Trout populations in Lake Huron (Lawrie and Rahrer 1972, Berst and Spangler 1972, Wells and McLain 1972, Hartman 1972, Christie 1972). Rehabilitation efforts through stocking and controls on fisheries and sea lamprey have been ongoing since the early 1960s (Hansen et al. 1995, Eshenroder et al. 1995, Holey et al. 1995, Cornelius et al. 1995, Elrod et al. 1995).

Status of Lake Trout

Lake Superior

Wild lean Lake Trout populations have recovered from collapse in the 1950s due to an aggressive recovery program employing Sea Lamprey suppression, stocking of hatchery fish, and fishery restrictions (Bronte et al. 2003). Recovery began with the buildup of large populations of hatchery Lake Trout, which were superseded by wild fish. The transition to wild Lake Trout dominance began in the 1980s in Michigan waters and was subsequently followed in Wisconsin, then most recently in Minnesota. Little or no recovery has been observed in the Ontario waters of eastern Lake Superior. In Michigan waters, abundance and recruitment of most Lake Trout populations are near historic high levels with some indications of density-dependent growth declines (Wilberg et al. 2003; Richards et al. 2004; Sitar et al. 2010). The latest progress in recovery was the cessation of most stocking in Minnesota waters.

Siscowet, a deep water morphotype, is the most abundant form of Lake Trout in Lake Superior occupying deep water areas and have recovered from depressed levels in the 1940s (Bronte and Sitar 2008; Ebener et al. 2010). Recent harvest is low, though emerging industrial interest in extracting omega-3 fatty acid from siscowet may develop a demand. Sea Lamprey wounding rates on siscowet are high, though the mortality inflicted may not be higher than that experienced by lean Lake Trout (Moody et al. 2010). Similar to leans, siscowet are at high levels and experiencing density-dependent effects.

Currently, wild Lake Trout abundance has declined in recent years, but remains higher on average than the prior State of the Great Lakes (previously known as SOLEC) reporting period. Fishing mortality has been controlled in most areas of Lake Superior through regulations. Despite continued Sea Lamprey management, wounding rates on Lake Trout in some areas have increased above target levels since 1995 (Sitar et al. 2010). In the near-term, further decline in Lake Trout abundance is expected due to density-dependent effects.

Lake Huron

Lake Trout rehabilitation efforts continue to show signs of success over the past several years. Over 3 million yearlings are stocked annually in the lake, split almost equally in Ontario and Michigan waters. Relative abundance of Lake Trout has increased in recent years (Ji et al. 2013), primarily in the North Channel and the Main Basin. Unfortunately the opposite has occurred in Georgian Bay.

Similarly, Sea Lamprey wounding has decreased significantly since 2000 in the main basin and in particular in the North Channel but have increased in Georgian Bay. However, the relative abundance of age-7 hatchery Lake Trout, corrected for stocking, has decreased since 2002 year class from an average 0.92 to a range of 0.05-0.27. The major food of Lake Trout has switched since 2002 from alewives and rainbow smelt to round gobies and rainbow smelt. The relative abundance of juvenile Lake Trout appears to be negatively influenced by the dominance of adult fish in the population, while a dramatic decline in the recruitment of stocked fish is apparent. The oldest age observed has rapidly increased from less than 10 years in 2002 to more than 25 years recently, and suggests that the combination of natural mortality and Sea Lamprey mortality may be substantially lower now.

Lake wide wild recruitment of Lake Trout has occurred since 2004, after the collapse of alewives and their suspected adverse effects on reproduction via Thiamine Deficiency Syndrome and predation on Lake Trout eggs and fry. The first pulse of wild recruitment did not fully compensate the decline in the recruitment of hatchery fish, but wild recruitment has reached a new high level since 2010 year class. Sufficiently low mortality, relatively stable spawning stock biomass, and continuing increases in the abundance of wild adults have contributed to the recent progress of Lake Trout rehabilitation in Lake Huron.

Lake Michigan

Stocking continues in all jurisdictions. Lake Trout densities measured by spring assessment surveys remain below target in most areas and lakewide. Few wild fish were recovered in assessment surveys (Bronte et al. 2007, Lake Trout Task Group 2015), which indicates that natural reproduction remains low even though fry from reproduction by stocked Lake Trout have been recovered (Jannsen et al. 2006). However, areas (Illinois, Indiana, and southern Wisconsin waters) with advanced age compositions and densities of Lake Trout approaching target levels show some evidence of sustained natural reproduction (Hanson et al. 2012). Northern Lake Michigan is plagued by high fishing and Sea Lamprey mortality that is resulting in very low spawning stock biomass. Recent events that should increase the probability of achieving the Lake Trout rehabilitation objectives include: 1) a revised implementation strategy for the rehabilitation of Lake Trout in Lake Michigan that concentrates stocking and other management efforts in the best habitat areas, 2) egg thiamin levels, thought to be inadequate for hatching success and fry survival, have recently increased lakewide, and 3) Sea Lamprey numbers, which were above the targets levels for many years, have declined.

Sea Lamprey induced mortality, low adult stock size, and lack of sustainable reproduction (Bronte et al. 2003, 2007), continues to limit Lake Trout rehabilitation. Recommendations to advance recovery include minimizing adult mortality from fishing and lamprey, focus hatchery production in refuge areas, restore a native forage base of coregonines and recast FCOs for desired population characteristics rather than harvest levels.

Lake Erie

Directed efforts to restore Lake Trout in Lake Erie began in 1982. Recruitment of stocked fish was good but their survival to adulthood was poor due to excessive Sea Lamprey predation. Adoption of the original Lake Trout rehabilitation plan in 1985 (Lake Trout Task Group 1985) brought higher annual stocking targets, Sea Lamprey control, and standardized assessment programs to monitor the population. The Lake Trout responded quickly to the implementation of Sea Lamprey suppression and increased stocking, building a large population by 1990. However, these accomplishments were short lived as stocking numbers were reduced in 1996 due to concerns about a shortage of forage fishes (Einhouse et al. 1999) while at the same time Sea Lamprey control was relaxed (Sullivan et al. 2003). Adult Lake Trout abundance was quickly reduced to low levels by 2000 where it has since remained.

Overall Lake Trout abundance in Lake Erie has increased in more recent years due to adoption of a revised rehabilitation plan (Markham et al. 2008) that increased stocking numbers back to their original level. Stocking has recently shifted to include all areas of the lake, including the western basin. Recruitment of stocked fish, especially the Lake Champlain strain, has been high, and adult abundance is near targets established in the rehabilitation plan. Sea Lamprey abundance has declined in recent years but still remains well above targets despite increased lampricide treatments, and this continues to suppress the adult Lake Trout population. Achievement of Lake Trout rehabilitation goals will continue to be hampered if Sea Lamprey abundance and wounding rates remain above target levels. Natural reproduction has yet to be detected in Lake Erie.

Lake Ontario

The abundance of hatchery-reared adult lake Trout in Lake Ontario was relatively high during 1986-1998, but declined by more than 30% in 1999 due to reduced stocking and poor survival of stocked yearlings since the early 1990s (Elrod et al. 1995, Lantry and Lantry 2015). Adult abundance remained relatively stable during 1999-2004, but again declined by 54% in 2005 likely due to ongoing poor recruitment and increased mortality from sea lamprey predation. Enhanced control of Sea Lampreys and subsequent decreases in wounding on Lake Trout during 2008-2014 were followed by a sharp recovery in adult Lake Trout numbers, which in 2010-2014 rose to levels similar to those observed during 1999-2004.

Although the abundance of adults reached a peak in 1986, appearance of naturally reproduced Lake Trout in assessment surveys occurred later after the abundance of large adult females exceeded target levels in 1992 (Lantry and Lantry 2015). Despite widespread catches of small numbers of natural recruits nearly every year during 1993-2013, a failure to achieve self-sustaining stocks has been attributed to the dense populations of alewives in Lake Ontario and an associated diet of Lake Trout that favors alewives (leading to Early Mortality Syndrome), the absence of suitable alternative deepwater preyfishes, and colonization of spawning reefs by invasive round gobies (Fitzsimons et al. 2003, Lantry et al. 2003, Schneider et al. 1997, Walsh et al. 2015). Recent meager prospects for restoration have improved with the reappearance of deepwater sculpin in assessment catches (their abundance steadily increased during 2002-2014) (Lantry et al. 2007, Weidel et al. 2015), with the joint US and Canadian efforts currently underway to reestablish cisco and bloater, and with the inclusion of round gobies in Lake Trout diets (Diertrich et al. 2006; Rush et al. 2012). Signs of improving conditions for natural reproduction were realized in 2014 when assessment catches of naturally reproduced age-1 and -2 Lake Trout rose sharply to a level 14.2 times greater than the 1994-2013 mean.

Linkages

The rehabilitation of Lake Trout populations in the Great Lakes has linkages to Sea Lamprey, prey fish, and non-native species. Lake Trout stocking and the building parental stocks would not be possible without sustained levels of Sea Lamprey control, as well as controls on fisheries. Non-indigenous alewives, while at lower levels now, still effect wild recruitment through predation on Lake Trout fry. Alewives also contain high levels of thaiminase that lowers egg viability and fry survival in LakeTrout that consume mostly alewives. The lack of native pelagic and benthopelagic coregonines, lost to overfishing, habitat degradation and non-native invasions, is also hampering recovery as these lost species were conduits for offshore benthic and pelagic production to the nearshore environment and to Lake Trout as prey.

Comments from the Author(s)
Reporting frequency should be every five years. Monitoring systems are in place, but in most lakes the measures do not directly relate to stated harvest objectives. Lake Trout population-objectives need to be redefined as endpoints in units measured by the monitoring activities, are relevant to population characteristics required for restoration to proceed, and should be incorporated into restoration guides and plans. The data time series we present are based on important population targets that can be measured with current assessment activities.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		x				
2. Data are traceable to original sources		x				
3. The source of the data is a known, reliable and respected generator of data		x				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the U.S. are comparable to those from Canada				x		
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				

Acknowledgments
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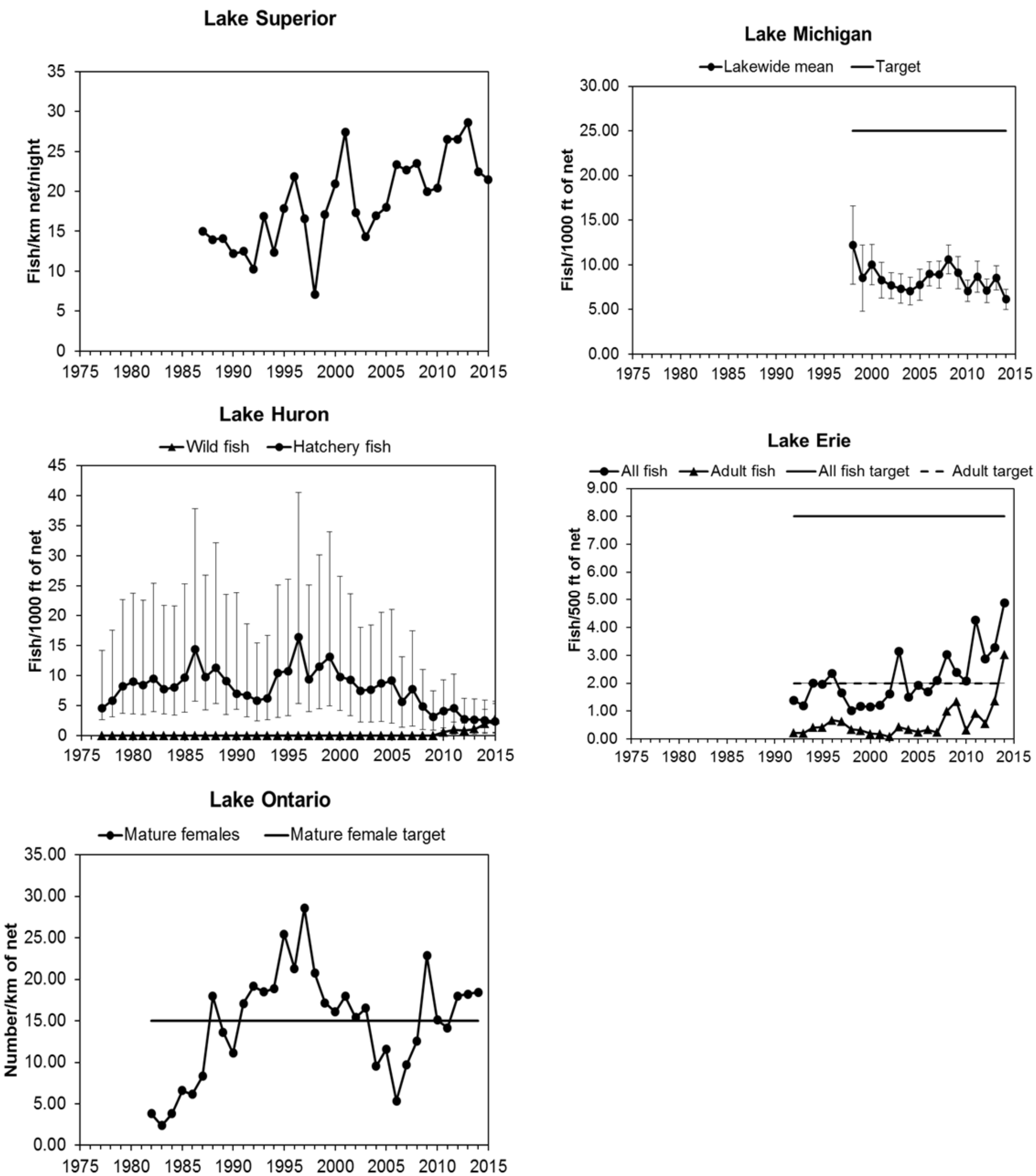
List of Figures

Figure 1. Relative abundance of stocked Lake Trout (wild fish in Lake Superior) in the Great Lakes from 1975 - 2015. The measurements reported vary from lake to lake, as shown on the vertical scale, and comparisons among lakes may be misleading. Overall trends over time provide information on relative abundances for all or part of the population.

Source: Data sources are from biological assessments conducted cooperatively by state, federal, tribal and provincial agencies, and are largely contained in non-peered reviewed reports to the Great Lakes Fishery Commission, Lake Committees , New York Department of Environmental Conservation, Ontario Ministry of Natural Resources, U.S. Fish and Wildlife Service and U.S. Geological Survey.

Last Updated

State of the Great Lakes 2017 Technical Report



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Sub-Indicator: Fish-Eating and Colonial Nesting Waterbirds

Overall Assessment
Status: Fair
Trend: Unchanging
Rationale: Four of eight species are less numerous now than when systematic monitoring began (1976-80; Great Blue Heron, Black-crowned Night-Heron, Herring Gul, Common Tern), although rates of decline have slowed for all over the last decade. Twenty-year (1989-91 to 2007-09) population trends for six of eight species have been assessed as stable. Great Blue Herons exhibited a moderate 20-year decline (-40%). Double-crested Cormorant nests increased 385% since 1989-91, although the rate of increase has slowed over the last decade (a 30% increase since 1997-99).

Lake-by-Lake Assessment

Lake Superior
Status: Fair
Trend: Unchanging.
Rationale: Two species are less numerous now than when systematic monitoring began (1976-80; Great Blue Heron, Common Tern), although rates of decline have slowed for both species over the last decade. Since 1989-91, one species has exhibited a stable trend (Common Terns), two have undergone moderate declines (Great Blue Heron, Herring Gull), one species has had a large decline (Ring-billed Gulls) and one a large increase (cormorants). Unable to calculate trends for night-herons or Caspian Terns; egrets have never nested on this water body.

Lake Michigan
Status: Fair
Trend: Unchanging.
Rationale: Two species are less numerous now than when systematic monitoring began (1976-80; Black-crowned Night-Heron, Common Tern), although rates of decline have slowed for both species over the last decade. Twenty-year populations trends: two species have experienced large declines (Common Tern, Great Blue Heron), one had a moderate decline (Black-crowned Night-Heron), three species were stable (Herring Gull, Ring-billed Gull, Caspian Tern) and one species exhibited a large (> six-fold) increase (cormorants). Unable to calculate a trend for egrets.

Lake Huron
Status: Fair
Trend: Unchanging.
Rationale: Five species are less numerous now than when systematic monitoring began (1976-80; Great Blue Heron, Herring Gull, Ring-billed Gull, Common Tern, Caspian Tern); rates of decline have slowed for all species, except Great Blue Heron, over the last decade. Since 1989-91, one species has undergone a large decline (Great Blue Heron), one had a moderate decline (Caspian Tern), three species were stable (Herring Gull, Ring-billed Gull, Common Tern), one species had a moderate increase (Black-crowned Night-Heron) and two exhibited large increases (cormorants, 2.5x; egrets, 7.8x).

Lake Erie
Status: Fair
Trend: Unchanging.
Rationale: Three species are less numerous now than when systematic monitoring began (1976-80; Great Blue Heron, Black-crowned Night-Heron, Common Tern); rates of decline have slowed for all these species over the last decade. Since 1989-91, three species exhibited a moderate decline (Great Egret, Black-crowned Night-Heron, Herring Gull), three species were stable (Great Blue Heron, Ring-billed Gull, Common Tern) and one species had a large increase (cormorants, 7.5x). Unable to calculate trend for Caspian Tern (colonized water body during the past decade).

Lake Ontario
Status: Fair
Trend: Unchanging.
Rationale: One species is less numerous now than when systematic monitoring began (1976-80; Common Tern); the rate of decline has increased over the last decade. Since 1989-91, two species exhibited a moderate decline (Ring-billed Gull, Common Tern), three species were stable (Great Blue Heron, Black-crowned Night-Heron, Herring Gull) and two species had a large increase (cormorants, 2.3x; Caspian Tern, 1.7x). Unable to calculate trend for Great Egret (colonized this water body during the 1997-99 census).

Sub-Indicator Purpose

- Assessment of ecosystem health by examining long-term trends in the abundance and distribution of colonial waterbird populations breeding on the Great Lakes.
- The sub-indicator tracks changes in the number of breeding pairs (nests), breeding colonies, and populations of nine species of fish-eating birds since the mid-1970s, at multiple geographic scales
- Secondarily, some ecological endpoints will be assessed for representative colonial waterbird species at selected sites on the Great Lakes.

Ecosystem Objective

Conservation of critical island breeding habitat, and maintenance of self-sustaining populations (i.e. no further declines in abundance or reductions in distribution) of each of the eleven waterbird species that comprise that avian community. Fish-eating, colonial waterbirds are distributed across all five Great Lakes, their connecting channels, and the St. Lawrence River, both in Canadian and US waters.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Ecological Condition

Fish-eating, colonial waterbirds are distributed across all five Great Lakes, their connecting channels, and the St. Lawrence River, both in Canadian and US waters. Colonial waterbirds function as apex predators in freshwater systems, and provide an important linkage between aquatic and terrestrial habitats. As a guild, waterbirds derive a large proportion of their diet from fish and other aquatic prey (species range from obligate piscivores to having a mix of aquatic and terrestrial prey). On the Great Lakes, waterbird species differ in the foraging strategies they employ, and thus, differ in the aquatic habitats and trophic levels they utilize (e.g. surface feeders or pursuit divers in open water; sit-and-wait predators in littoral zones and wetlands, surface feeders in wetlands). Another life-history trait that waterbirds share is that they nest in dense aggregations (i.e. colonially), almost exclusively on islands (except for Forster's and Black terns, which nest in wetlands). As such, they can also serve as an important indicator of change in status of this unique habitat within the Great Lakes system.

Changes in waterbird population abundance, distribution and demography can reflect changes in ecosystem trophic structure and/or island or wetland nesting habitat and, therefore, are important metrics for assessing the health of a variety of Great Lakes ecosystem components. Inter-specific differences in foraging and nesting strategies make it possible to assess and integrate trend information across a variety of temporal, spatial and ecosystem scales. Declining waterbird populations (number of breeding pairs or nests) or vital rates (hatching success, fledging success, mortality rates, etc.) can be indicators of local environmental stress. The Great Lakes-wide population of colonial waterbirds has been censused jointly, by the Canadian Wildlife Service and the U.S. Fish and Wildlife Service since the 1970s, approximately every 10 years; four "decadal" censuses have been conducted to date: in the 1970s, 1980s, 1990s and 2000s. For this sub-indicator, population change (over the last 20 years) is defined as: large decline = ≥50% decline; moderate decline = ≥25% to <50% decline; stable: <25% decline to <33% increase; moderate increase: ≥33% to <100% increase; large increase: ≥100% increase.Briefly, in the long-term (1976-2009), these censuses have shown that the breeding numbers of four species have undergone large increases: Double-crested Cormorants, Great Egrets, Ring-billed Gulls and Caspian Terns (population growth has slowed since the 2^{nd} census for the latter two species; Figure 1). Three species, Great Blue Heron, Herring Gull and Great Black-backed Gull (GBBG, an uncommon breeder on the Great Lakes, trend not shown), exhibited a period of population growth followed by a decline; current numbers of breeding pairs for these species are similar to 1970s levels and are considered stable. In contrast, Common Terns and Black-crowned Night-Herons have both undergone long-term declines, although the rates of decline have slowed over the last decade and these populations are currently considered stable. For the six species that have undergone declines since the 1989-91 census (Figure 1; GBBG trend not shown), continued monitoring will determine whether these populations have in fact stabilized or if there is evidence for concern. Currently, drivers such as habitat change and loss, changes in trophic structure and abundance of fish prey (Hebert et al. 2008, 2009), reduced access to alternate sources of food (for gulls, due to changes in agricultural and waste disposal practices), inter-specific competition for nesting space (e.g. increased pressure from hyper-abundant species such as cormorants and Ring-billed Gulls) and stressors in overwintering areas likely play a larger role in regulating waterbird populations than contaminant-related impairments.

Measure

Nine focal species of colonial waterbirds breed at sites (predominantly islands) distributed across all of the Great Lakes: Herring, Ring-billed and Great Black-backed gulls, Caspian, and Common terns, Great Blue Herons, Great Egrets, Black-crowned Night-Herons and Double-crested Cormorants. A complete census of all waterbird colonies on the Great Lakes, their connecting channels and the St. Lawrence River (up to 1 km inland from shorelines) has been conducted, jointly, by the Canadian Wildlife Service and the U.S. Fish and Wildlife Service, approximately every 10 years, since the mid-1970s (four complete census periods; the most recent was completed in 2009; the next comparable survey is planned for 2020). Survey timing and methodologies were coordinated between Canada and the USA. Measures include:

- Nest counts of colonial waterbird species across all water bodies and connecting channels at relevant temporal and spatial scales:
    - Annual: Counts for Herring Gull (13 focal colonies distributed across the Great Lakes) and Double-crested Cormorant (Lake Ontario and the St. Lawrence River to Cornwall, ON) since the late 1970s. Methods are consistent with 'decadal' survey efforts.
    - Decadal: All breeding sites for the nine focal colonial waterbird species are censused at 10-year intervals.

- Periodic measurement of waterbird demographic parameters known to be directly or indirectly impacted by environmental stressors, including (but not limited to): clutch size, egg volume, hatching and fledging success, natal and breeding site fidelity, age at first breeding and age-specific survivorship.
- Additional monitoring considerations include: avian disease surveillance (e.g. botulism type E) and studies tracking adults through the full annual cycle to establish connectivity between breeding and wintering areas.

Endpoints

- Healthy, self-sustaining populations of each waterbird species.
    - Populations of stable or declining species remain stable or increase, respectively
    - Populations of hyper-abundant species (cormorants and Ring-billed Gulls) either remain stable or decline
- Critical island breeding habitat is conserved

There are no specific population objectives for these species, other than within a few Great Lakes Areas of Concern (e.g. Hamilton Harbour, ON).

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Toxic Chemicals in Great Lakes Herring Gull Eggs
- Toxic Chemicals in Great Lakes Whole Fish
- Water Levels

This sub-indicator also links directly to the other indicators in the Habitat and Species indicator, particularly:

- Lake Sturgeon
- Lake Trout
- Walleye
- Preyfish (open water)

Waterbird population trends and breeding habitat are indicators in some of the AOCs, and are used for delisting criteria.

Comments from the Author(s)
This newly-developed sub-indicator, previously reported in conjunction with the historic State of the Great Lakes (previously known as SOLEC) "Contaminants in Waterbirds" sub-indicator, which described trends in chemical contaminants found in the eggs of fish-eating, colonial waterbirds is now being assessed separately to report on progress towards two different general objectives under the 2012 GLWQA.

Data Limitations
- Most waterbird species are migratory. Changes in population status or trends could reflect environmental or anthropogenic stressors experienced during the non-breeding period (or cumulative effects over the full annual cycle, inside and outside of the Great Lakes region)
- Inferences on the effects of climate change on population trends are beyond the scope of this sub-indicator as they would have to include changing food webs and energy cycling though them. In addition, birds could be moving out of the Great Lakes region (i.e. a shift in distribution) in response to climate-related effects, with no net change in abundance at larger spatial scales.
- Data are collected at 10-year intervals, which is longer than the reporting cycle for State of the Great Lakes Reporting (previously known as SOLEC).

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

Acknowledgments
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List of Figures

Last Updated

State of the Great Lakes 2017 Technical Report

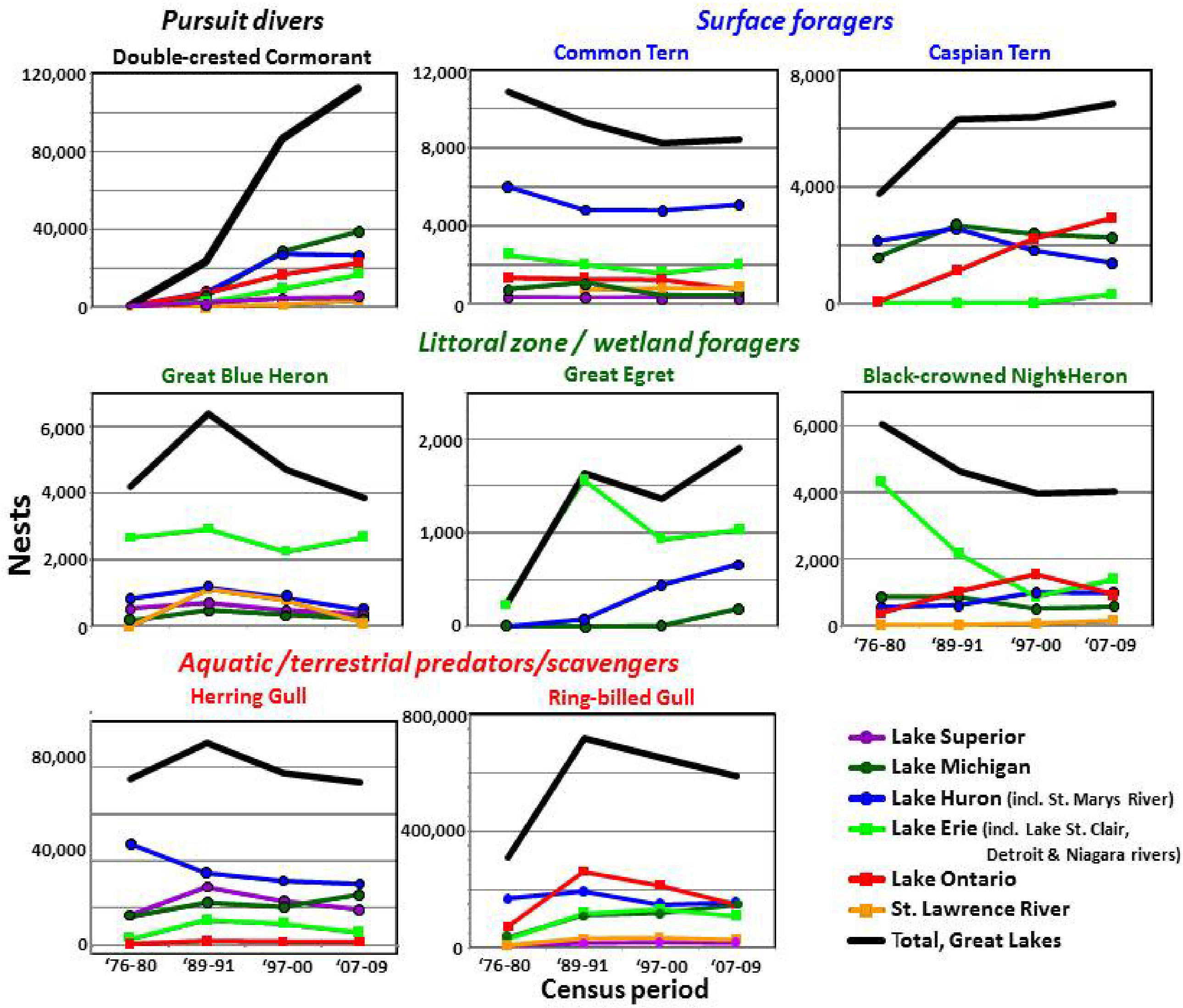
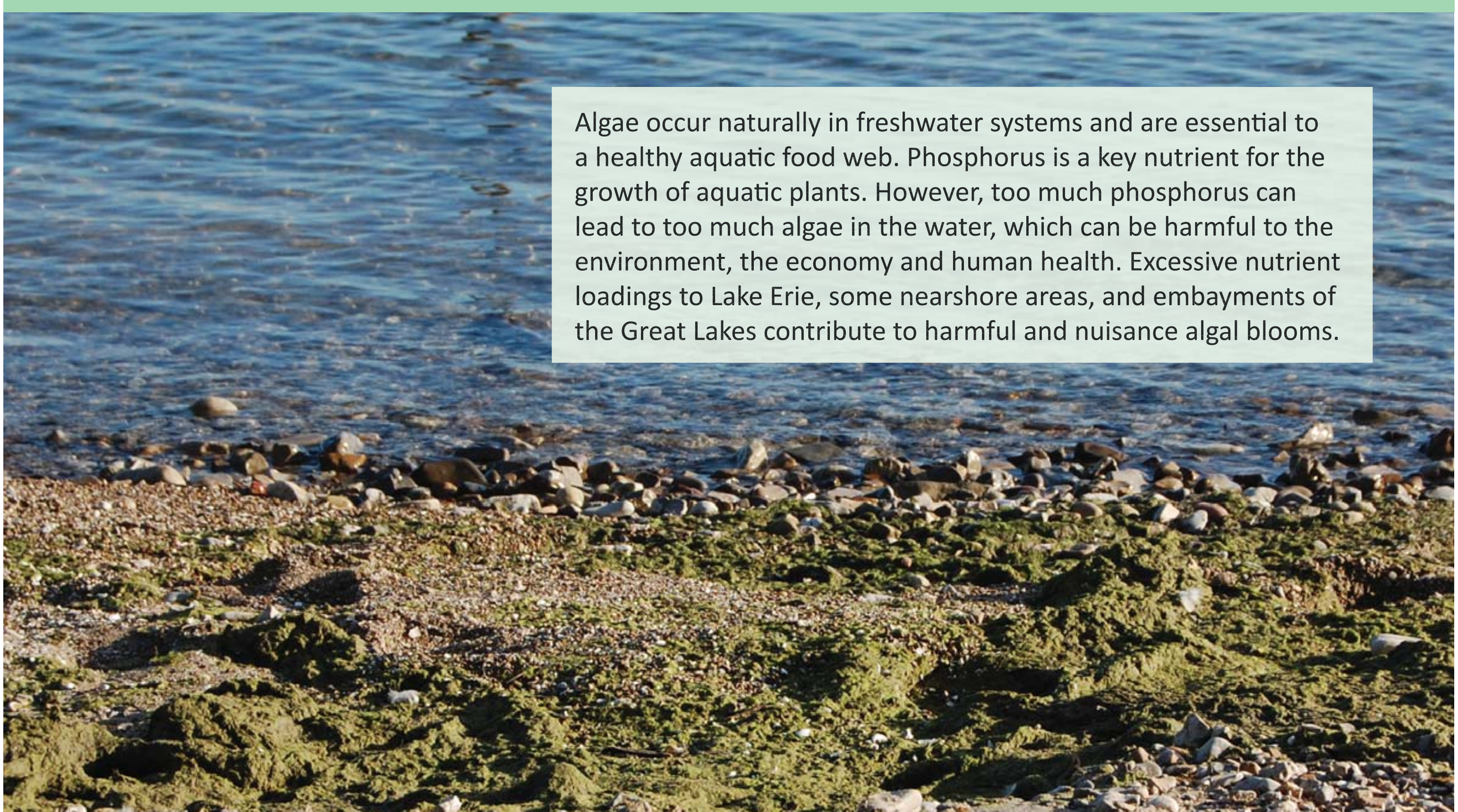


Figure 1. Population trends for the entire Great Lakes region (black line) and by water body (coloured lines, see legend) for eight species of colonial waterbirds censused during four 'decadal' periods, 1976-2009.
Sources: Canadian Wildlife Service- Ontario Region, Environment and Climate Change Canada, Burlington, ON; Cuthbert and Wires (2013).

Nutrients and Algae

Status: Fair   Trend: Unchanging to Deteriorating

The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem"*



Algae occur naturally in freshwater systems and are essential to a healthy aquatic food web. Phosphorus is a key nutrient for the growth of aquatic plants. However, too much phosphorus can lead to too much algae in the water, which can be harmful to the environment, the economy and human health. Excessive nutrient loadings to Lake Erie, some nearshore areas, and embayments of the Great Lakes contribute to harmful and nuisance algal blooms.

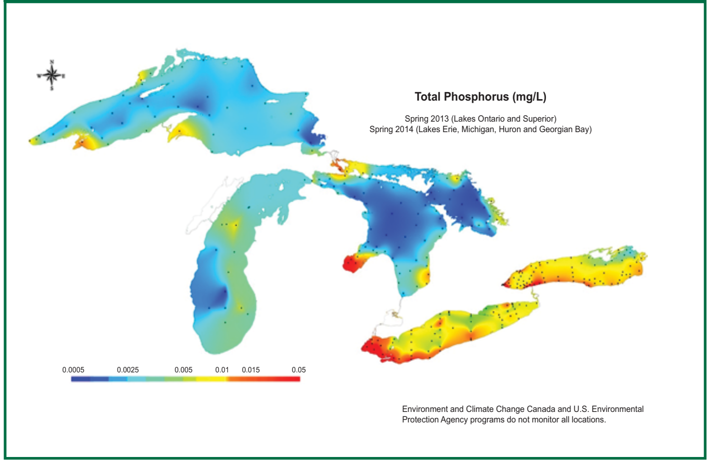
Nutrients and Algae

Assessment Highlights

The 1972 GLWQA focused on phosphorus reductions. In the 1980s and early 1990s, basin-wide restoration efforts were successful in reducing nutrient-related runoff and conditions in the lakes improved. These efforts included the regulation of phosphorus concentrations in detergents, investments in sewage treatment, and the implementation of best management practices on agriculture lands and in expanding urban areas. Despite these efforts, there is a nutrient imbalance in the Great Lakes. With the recent resurgence of the nearshore algal problem in some areas and with other changes in the ecosystem, the problem has become more complicated. Overall, the conditions result in a status of **Fair** and a trend of **Unchanging** to **Deteriorating** for this indicator.

Many offshore regions of some of the Great Lakes have nutrient levels below desired concentrations. In fact, concentrations may be too low in some areas, resulting in insufficient growth of key phytoplankton species which form the base of the food chain. Only in Lake Superior are offshore phosphorus concentrations considered in acceptable condition. Conversely, there are excess nutrients in many nearshore areas. While a certain level of nutrients is good, too much may lead to the development of nuisance and harmful algal blooms (HABs) and hypoxic zones (areas with low oxygen levels). This issue is primarily a concern in Lake Erie, parts of Lake Ontario, Saginaw Bay and Green Bay, along with other nearshore areas that experience elevated nutrient levels. Algal blooms can be harmful to both ecosystem and human health. The western basin of Lake Erie and some parts of Lake Ontario have experienced a resurgence of HABs since 2008, adversely impacting ecosystem health as well as commercial fishing, municipal drinking water systems and recreational activities. Algal blooms are particularly harmful when they are dominated by cyanobacteria (or "blue-green" algae) which can produce toxins such as microcystin. These toxins can impact drinking water safety or can cause gastrointestinal upsets, skin rashes and at elevated levels can be fatal to many organisms.

Total Phosphorus Concentrations in the Great Lakes



Cladophora is a nuisance algae that is broadly distributed over large areas of the nearshore regions of Lakes Erie, Ontario, Huron and Michigan. Large mats of *Cladophora* give the impression that nutrient concentrations are high in the nearshore. However, in some areas, these mats of nuisance algae persist despite low nutrient concentrations in the surrounding water, which is why the management of *Cladophora* has become such a challenge. Excessive *Cladophora* poses many problems including beach and shoreline fouling, clogging of municipal water intakes and unpleasant aesthetics, as well as tourism and recreational fishing impacts. There are also significant ecological impacts of excessive *Cladophora* growth and, when washed up on the shoreline, *Cladophora* may harbour pathogens and create an environment conducive to the development of botulism outbreaks which pose a risk for fish and wildlife.

Warmer temperatures, higher frequency and intensity of precipitation events, and invasive species, in particular Zebra and Quagga Mussels, are confounding factors in the cycling and uptake of nutrients in the lakes. These factors may lead to increased frequency, distribution and severity of HABs, hypoxic zones and *Cladophora*.

Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Nutrients in Lakes	Unchanging	Deteriorating	Deteriorating	Deteriorating	Deteriorating
Cladophora	Unchanging	Undetermined	Undetermined	Undetermined	Undetermined
Harmful Algal Blooms	Undetermined	Undetermined	Undetermined	Deteriorating	Deteriorating
Water Quality in Tributaries	Unchanging	Undetermined	Unchanging	Unchanging	Unchanging

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Nutrients in Lakes

Open water

Overall Assessment
Status: Fair
Trend: Deteriorating
Rationale: Phosphorus remains the growth-limiting nutrient in the Great Lakes. In the past, phosphorus concentrations were elevated throughout many of the lakes. Presently, the problems of excess phosphorus are confined primarily to some nearshore areas and parts of Lake Erie. In Lakes Michigan, Huron and Ontario, offshore total phosphorus concentrations are currently below objectives and may be too low, negatively impacting lake productivity (phytoplankton, zooplankton and fish production). Nearshore, symptoms of nutrient enrichment persist in some locations. In Lake Erie, objectives are frequently exceeded and conditions are deteriorating. Only in Lake Superior are offshore objectives being met and conditions acceptable.

Lake-by-Lake Assessment

Lake Superior

Status: Good
Trend: Unchanging
Rationale: Objectives have consistently been met, and offshore total phosphorus concentrations are similar to historic values, indicating acceptable conditions. There is a very slow rate of decrease over time that is observed in the data.

Lake Michigan

Status: Fair (below objective)
Trend: Deteriorating (further below objective)
Rationale: Offshore phosphorus concentrations are continuing to decrease below objectives. Concentrations have fallen to low levels and may be negatively affecting lake productivity. In some nearshore areas, elevated phosphorus is observed and may be supporting nuisance algae growth.

Lake Huron

Status: Fair (below objective)
Trend: Deteriorating (further below objective)
Rationale: Offshore phosphorus concentrations are continuing to decrease to values that are well below objective. Concentrations may be too low to support a healthy level of lake productivity. In some nearshore areas, elevated nutrients may be contributing to nuisance algae growth.

Lake Erie

Status: Poor (above objective)
Trend: Deteriorating
Rationale: Total phosphorus objectives continue to be exceeded and trends indicate possibly increasing concentrations. Harmful algal blooms have recently plagued the western basin and parts of the central basin, and nuisance benthic algae have resurged in the eastern basin.

Lake Ontario

Status: Fair (below objective)
Trend: Deteriorating (further below objective)
Rationale: Offshore phosphorus concentrations are continuing to decrease to levels too low to support healthy offshore lake productivity. Certain nearshore areas are experiencing recurrent nuisance algae, possibly fueled by locally-high phosphorus discharges or in-lake nutrient cycling.

Sub-Indicator Purpose

- To assess nutrient concentrations in the Great Lakes
- To assess progress in meeting GLWQA General Objective #6, Lake ecosystem Objectives and Substance Objectives for nutrient concentrations for the Waters of the Great Lakes
- To infer progress in meeting nutrient loading targets and allocations
- To support the evaluation of trophic status and food web dynamics in the Great Lakes
- To support assessment of the state of the nearshore waters for the nearshore framework

Ecosystem Objective

General Objective #6 of the 2012 Great Lakes Water Quality Protocol states that the Waters of the Great Lakes should "be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem."

Annex 4 of the 2012 GLWQA Protocol includes Lake Ecosystem Objectives to: maintain an oligotrophic state, relative algal biomass, and algal species consistent with healthy aquatic ecosystems, in the open waters of Lakes Superior, Michigan, Huron and Ontario; maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

Interim Substance Objectives for Total Phosphorus concentrations in open waters are additionally established in Annex 4 for each of the Great Lakes. These interim objectives are shown in Table 1, and comprise objectives for both spring total phosphorus concentrations and summer chlorophyll a concentrations. The resultant nutrient (trophic) states corresponding to the objective concentrations are also displayed. There are no objectives for nearshore nutrient concentrations; Provincial and/or State nutrient objectives will be considered here as benchmarks only.

The establishment of Substance Objectives for phosphorus concentrations and loading targets take into account the bioavailability of phosphorus (and seasonality); therefore, status and trends of the bioavailable phosphorus fraction (soluble reactive phosphorus) and seasonal information are provided here where possible.

There are no current ecosystem objectives for nitrogen. There is a requirement in Annex 4 to establish Substance Objectives for other nutrients, as required, to control the growth of nuisance and toxic algae to achieve Lake Ecosystem Objectives. As an interim measure, and as discussed in Dove and Chapra (2015), the Redfield ratio of 7.2 mgN/mgP is used as a benchmark to assess nitrogen levels; above this level, lakes would tend to be phosphorus limited, below this level, lakes would tend to be nitrogen limited, with nitrogen limitation favoring harmful cyanobacteria. The goal would be to maintain ratios well above this level.

Ecological Condition

The condition of the Great Lakes with respect to nutrients is determined using data collected by the federal agencies Environment and Climate Change Canada and the United States Environmental Protection Agency. The determination of the lakes' current status is based on samples collected during recent spring (late March-May) or summer (generally July-August with some September data) seasons. Data for the determination of trends are restricted to offshore stations (see Dove and Chapra, 2015) sampled at the surface during spring cruises.

Current Status

The current status of spring total phosphorus concentrations in 2013-14 is shown graphically in Figure 1. The objective concentration of 5 µg TP/L is achieved in lakes Superior and Huron as well as Georgian Bay, with the exception of some embayments although it should be noted that these exceedances are single values and in other years the objectives have been met at these sites. In Lake Michigan, current concentrations are well below the objective of 7 µg TP/L. Concentrations in Lake Erie are highly variable. In some years, a majority of the lake at the time of the spring cruise is meeting objectives (e.g., 2012); in other years (e.g., 2011, 2013) all stations exceed objectives, indicating elevated nutrient concentrations. In Lake Ontario, concentrations meet the objectives at most offshore stations and in the northeast portion of the lake, but concentrations in the west, along much of the southern shore and parts of the northern shore exceed the objective. The current status of the bioavailable portion of phosphorus (soluble reactive phosphorus) is very similar to that for total phosphorus, with SRP comprising between 15 – 25% of total phosphorus, depending on location. There is no objective for SRP against which to compare current values.

Temporal Trends

The long-term trends of offshore total phosphorus are shown in Figure 2. All of the lakes show statistically significant long-term declining trends. For Lake Superior, the rate of change is very slow and the statistical significance of the trend relies on the inclusion of certain data points and further time is needed to confirm this result. In Lake Huron, no significant change is noted until the mid- to late-1990s, with a significant and dramatic decline noted since that time. Georgian Bay data are not shown here but the temporal trends closely match those in Lake Huron. In Lake Ontario, two periods of decline are observed. The first occurred in response to the phosphorus management improvements legislated in the 1970s, resulting in dramatic declines of TP in Lake Ontario from approximately 23 µg/L in 1972 to 10 µg/L in 1988. Since that time, concentrations have declined more gradually to approximately 6 µg/L in 2013. In Lake Erie, high spatial and inter-annual variability is observed. The central basin is shown in Figure 2 to represent the lake and we interpret the trends to indicate high concentrations in the 1970s (in the range of 18 µgP/L) and lower concentrations in the 2000s (roughly 12 µgP/L). The variable nature of the data obscure any recent trends.

The long-term trends of offshore soluble reactive phosphorus are similar to those for total phosphorus, but the values are lower. In Lake Ontario, the ratio of SRP:TP also shows a striking linear decline. In the 1970s, about 70% of the total phosphorus in the offshore comprised the soluble reactive fraction. By 2012 the ratio had declined to only 20%. Together, these trends indicate a shortage of phosphorus in offshore regions of the lake.

Trends of spring total oxidized nitrogen (TON) are represented as nitrate (NO_3) in Figure 3 (note that nitrate comprises more than 95% of TON in the Great Lakes). Unlike phosphorus, concentrations of nitrate have increased over time, but those increases have slowed and even reversed in recent years, especially in the lower Great Lakes. Concentrations of nitrate are lowest in Lake Erie, the most productive of the lakes, where it is taken up by algae, phytoplankton and other consumers. High nitrate is protective against blue-green algae blooms, because these algae have a competitive advantage in their ability to use atmospheric nitrogen when nitrogen is low in water. Total nitrogen can be estimated for offshore waters using nitrate concentrations (Dove and Chapra, 2015), and there is an excellent, long-term record of nitrate available. Because nitrate has increased over time and phosphorus has declined, it is therefore phosphorus, not nitrogen, which is increasingly limited in recent years. Currently, all of the lakes are phosphorus limited, with the most extreme limitation occurring in the upper Great Lakes. The ecosystem objective to maintain ratios above the Redfield ratio of 7.2 is currently being met in all of the lakes, with Lake Erie showing greatest risk (ratios closest to the objective; Figure 4).

Inferred Nutrient Loadings

The offshore nutrient objectives represent expected conditions when tributary nutrient loadings targets are achieved. The most recent loadings estimates (obtained by summing all reported sources, scaling these to the lake-wide scale and estimating between-lake transfers) show that loading targets are only occasionally exceeded and that there are no significant temporal trends since the 1980s with the exception of declines noted for Lakes Ontario and Huron (Dolan and Chapra 2012; Maccoux et al. accepted). Despite the recent success of largely meeting the loading targets, there is increasing evidence of nutrient imbalances in the lakes; that is, eutrophic (nutrient-rich) nearshore conditions may be persisting (or resurging) despite low offshore nutrient concentrations. In this way, the existing objectives may not be sufficient to protect all areas of the lakes.

Both the Substance Objectives for Total Phosphorus Concentration in Open Waters and the Phosphorus Load Targets are due for assessment and revision as necessary. Loadings targets have recently been adopted for Lake Erie; these call for a 40% reduction in annual total phosphorus loads to the western and central basins of Lake Erie and a 40% reduction in spring total and soluble reactive phosphorus loads from certain tributaries (Environment and Climate Change Canada and U.S. EPA, 2015). Work on the other lakes is being initiated, where the need to maintain or even enhance offshore nutrients will need to be considered.

Lake trophic status

A lake's trophic state describes its nutritional or growth status. Ranges of phosphorus, together with the response variables of chlorophyll a (an indicator of the amount of algae and phytoplankton in a sample) and Secchi disk depth (an indicator of water clarity) are used in combination to determine the trophic status. The objectives vary between each of the Great Lakes and for Lake Erie the objectives vary by basin. Collectively, the information shows that the open portions of lakes Superior, Michigan and Huron are in the ultraoligotrophic range (i.e., very low in nutrients and below the objective of oligotrophy), Lake Ontario is in the oligotrophic range (i.e., nutrient poor and below the objective) and Lake Erie ranges from eutrophic in the west (nutrient rich and exceeding the objective) to mesotrophic in the central basin (exceeding the objective) and oligotrophic in the east (below objective). This indicates that the offshore regions of the Great Lakes are nutrient deficient with the exception of Lake Erie which suffers from elevated nutrient conditions.

Other Spatial Scales – Nearshore Regions

This sub-indicator report mainly on total phosphorus (TP) concentrations in the offshore. These offshore waters best indicate long-term trends because, in contrast to shallower, nearshore waters, they are less influenced by local pollutant discharges. As demonstrated here, offshore nutrient concentrations in most lakes have declined over time, are below objectives, and may now be too low to support healthy levels of lake productivity.

At the same time as offshore TP concentrations are reaching unprecedented lows, many nearshore regions of the Great Lakes are experiencing nuisance algae problems. The extent of the algae problem seems to be of similar magnitude as was experienced in the 1970s (GLWI 2005), despite significantly lower phosphorus loads since that time (Chapra and Dolan 2012). In Lake Michigan, growth of the benthic alga *Cladophora* remains a problem, making some beaches unswimmable (Bootsma et al. 2015). *Cladophora* blooms appear to be most extensive in eastern Lake Erie, while the western Lake Erie basin is also plagued by the more toxic *Microcystis* algal blooms (Stumpf et al. 2012). In Lake Huron, the benthic alga Chara is flourishing on the east side and additional algal species are associated with other fouling issues in the lake; however *Cladophora* alone is not the only contributor (E.T. Howell, personal communication). In Lake Ontario, nearshore regions on both the south and north shores routinely experience nuisance benthic algae blooms.

The causes of the nearshore algae resurgence are not clear. For example, in Lake Erie, loadings of phosphorus exhibit high inter-annual variability but have decreased since the 1970s and show no temporal trend since the late 1980s (Maccoux et al. 2016). The invasion and proliferation of non-indigenous mussels (Dreissena spp.) may be altering nutrient dynamics, simultaneously depleting offshore nutrients and elevating concentrations in nearshore regions, resulting in a "feast and famine" dichotomy that is unbalanced, especially for lakes Ontario, Michigan and Huron. Lake Erie is an exception, where phosphorus concentrations are above objectives throughout the western basin and much of the central basin and there is no sign of a decline. Symptoms of nearshore eutrophication (elevated nutrients) are observed.

Linkages

- Benthos – nutrient concentrations impact benthic community abundance and composition
- *Cladophora* – high nutrients in the nearshore favour the proliferation of nuisance benthic algae
- Dreissenid Mussels – Dreissenids influence the cycling of phosphorus, which may alter in-lake concentrations, their relationships with loads and may enhance the growth of *Cladophora*
- Harmful Algal Blooms –nutrient concentrations impact the development, timing and severity of harmful algal blooms
- Phytoplankton (open water) – nutrient concentrations impact phytoplankton community abundance and composition
- Wastewater treatment can reduce the nutrient loading to the lakes.
- Water Quality in Tributaries – tributary nutrient concentrations impact nutrient concentrations in Great Lakes Waters
- Zooplankton - nutrient concentrations impact zooplankton community abundance and composition via the food web

Comments from the Author(s)

Continued water quality monitoring in the Great Lakes and measurements of nutrient loads are required in order to inform management, track progress and update status and trend information.

This sub-indicator provides both the long term record and recent trends (where statistically apparent). The emphasis is on recent trends as these are most relevant for contemporary nutrient management. Continued monitoring and reporting of offshore conditions is critical to maintain our ability to assess Great Lakes status and trends.

Possible improvements for future reporting include the incorporation of additional information from the Great Lakes connecting channels because these rivers can be primary drivers of water quality in the lakes. For some of these channels (e.g., St. Clair River, Niagara River, St. Lawrence River), long-term, high-frequency and high-quality information is available and may be used to inform nutrient status and trends and to assess shorter-term (e.g., seasonal, cyclical) fluctuations that cannot be assessed with other available data.

We also aim to incorporate data collected by other State and Provincial environmental agencies in order to report more fully on nearshore nutrient status and trends, including coverage in Green Bay. This will require data integration and further consideration of interagency laboratory comparability.

Integrating nutrient loading information to this sub-indicator will be a challenge without concerted efforts to improve load monitoring in the basin. Important work to coordinate, collect and manage such information has been initiated for Lake Erie

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada		x				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

Clarifying Notes:
Comparison of US and Canadian TP data indicates consistently lower values are obtained by the U.S. EPA relative to Environment and Climate Change Canada. Statistical tests were performed for lakes Ontario and Huron, where some shared stations permit paired t-test comparisons. The results indicated significantly higher values obtained by ECCC compared to the U.S. EPA ($p<0.001$). The differences amount to approximately 1.9 and 1.6 µg P/L for lakes Ontario and Huron, respectively. No significant difference was observed for laboratory quality assurance (filtered) samples over many years (1999-2008), indicating agreement between laboratory instruments used. The difference occurs independently of field sampling date and location and is likely due to differing sample digestion durations. Samples collected by Environment and Climate Change Canada are digested for a minimum of 30 minutes once digestor temperature has reached 121°C. Samples collected by the U.S. EPA are digested for 30 minutes with the oven set to 121°C, but this includes time for the oven to reach high temperature. The longer digestion of ECCC samples may result in more complete breakdown of nutrients attached to particles and higher concentrations are measured.

Acknowledgments

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Contributors: E.T. Howell, Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment and Climate Change.

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Data source: Environment and Climate Change Canada and the United States Environmental Protection Agency

Figure 2. Long-term trends of offshore, spring (April - May) total phosphorus in the Great Lakes (µg/L). The interim GLWQA TP objectives are shown as the horizontal dashed lines. The additional data points (circles) for Lake Michigan prior to 1983 are from Chapra and Dobson (1981), Scavia et al. (1986) and Lesht et al. (1991). Statistically significant temporal trends are shown as solid lines. After Dove and Chapra (2015).
Data source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

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Data source: Environment and Climate Change Canada and U.S. Environmental Protection Agency

Last Updated

State of the Great Lakes 2017 Technical Report

Basin	Total Phosphorus (µgP/L)	Chlorophyll *a* (µgChl*a*/L)	Trophic state
Lake Superior	5	1.3	Oligotrophic
Lake Michigan	7	1.8	Oligotrophic
Lake Huron	5	1.3	Oligotrophic
Western Lake Erie	15	3.6	Mesotrophic
Central Lake Erie	10	2.6	Oligomesotrophic
Eastern Lake Erie	10	2.6	Oligomesotrophic
Lake Ontario	10	2.6	Oligomesotrophic

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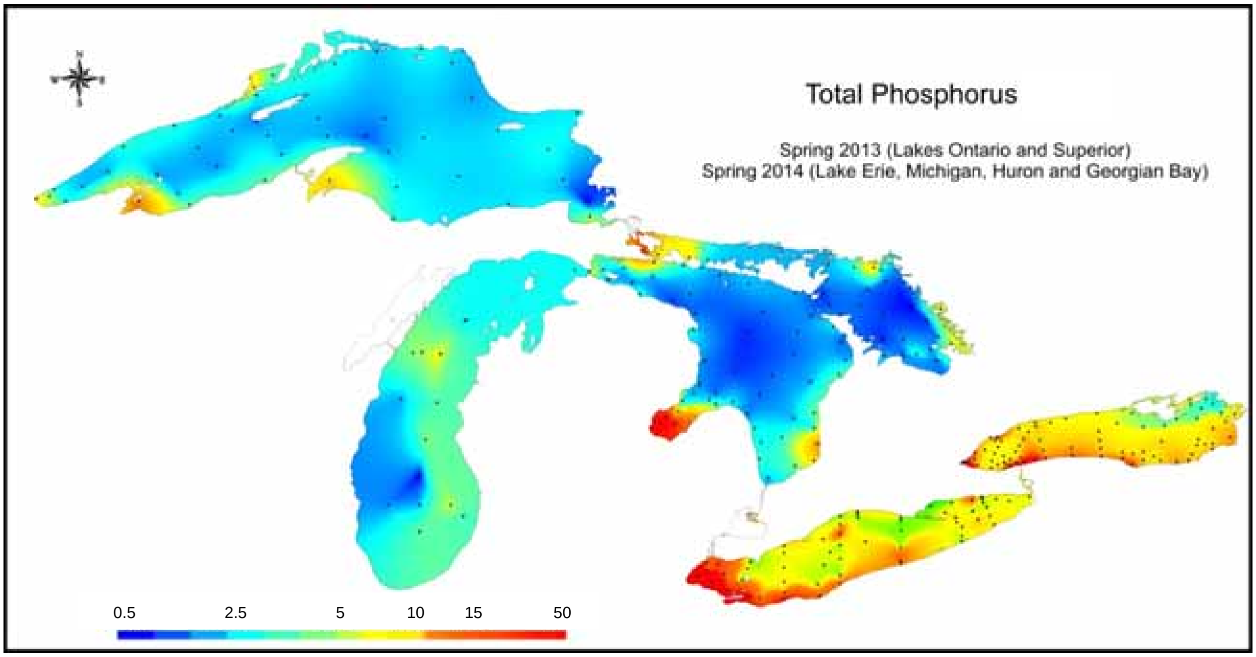

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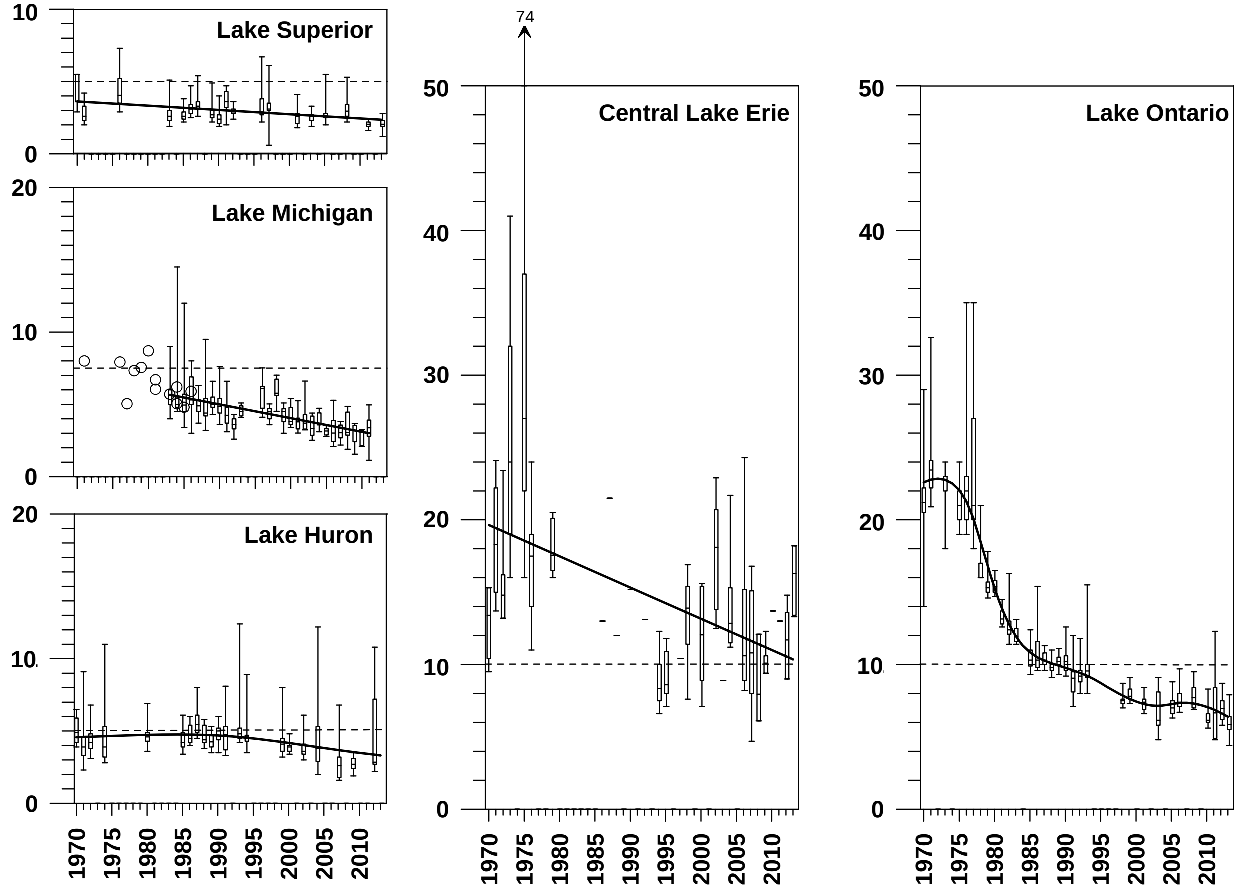

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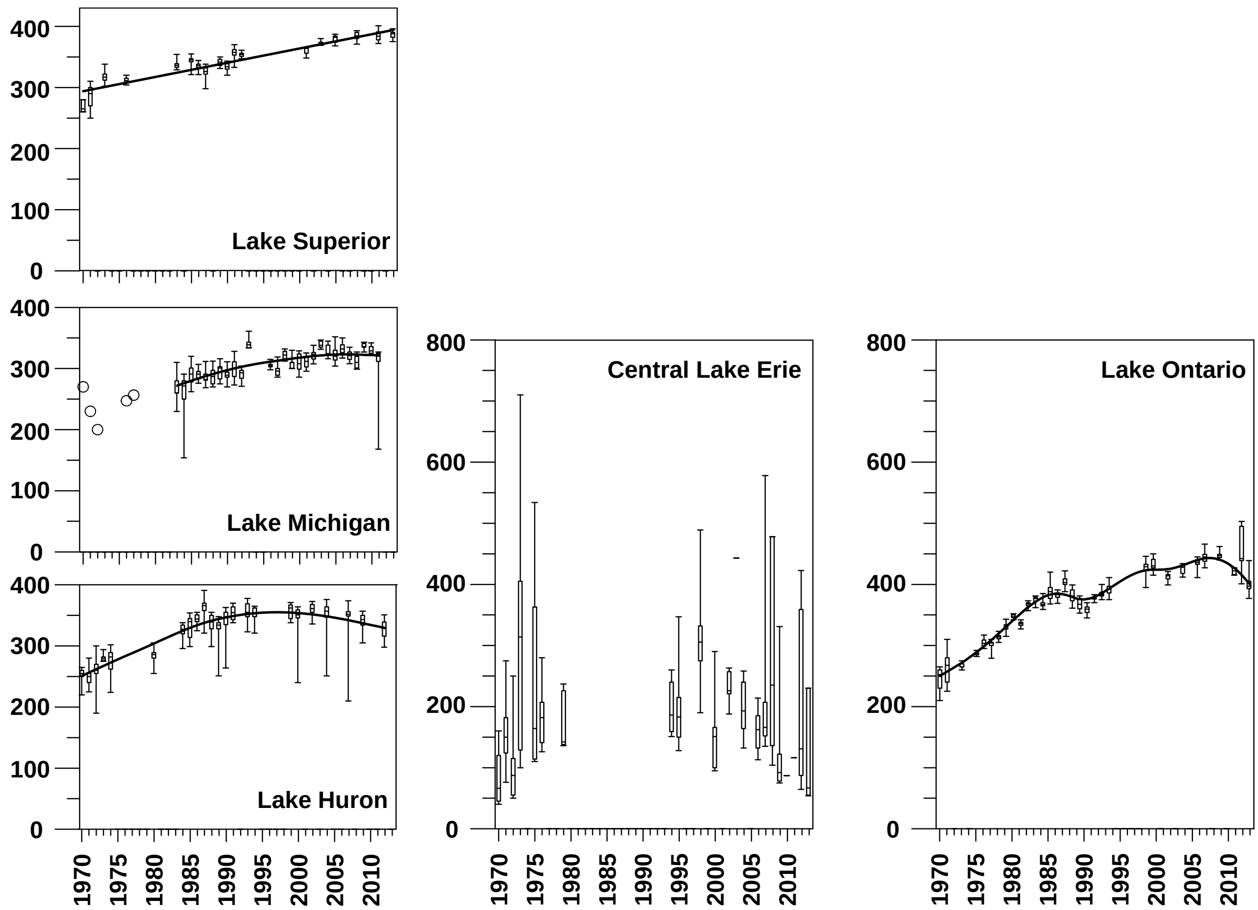

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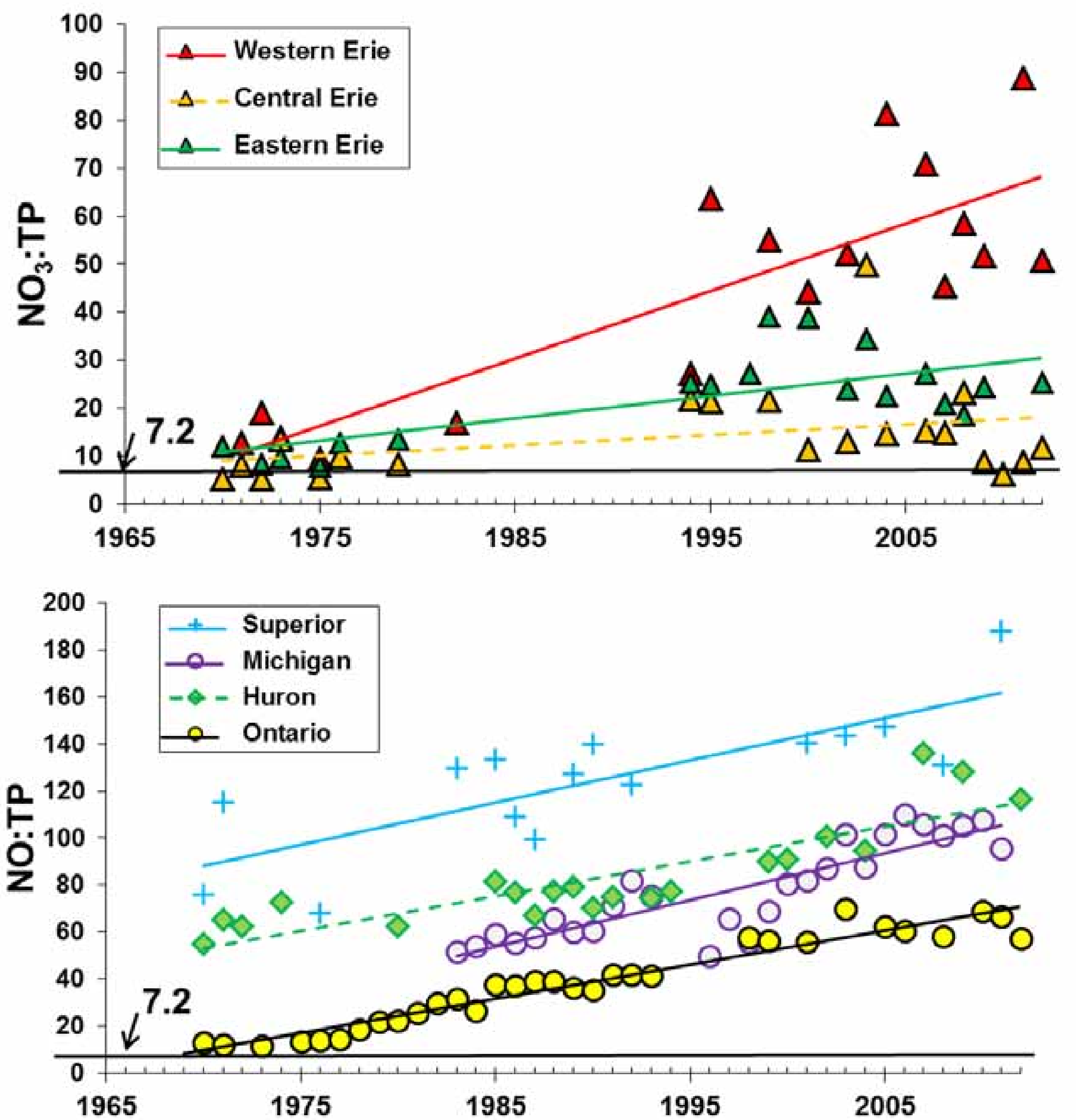

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Data source: Environment and Climate Change Canada and U.S. Environmental Protection Agency.

Sub-Indicator: *Cladophora*

Overall Assessment
Status: Poor
Trend: Undetermined
Rationale: *Cladophora* is broadly distributed over large areas of the near shore regions of Lakes Erie, Ontario, Huron and Michigan. Accrual of biomass to nuisance levels occurs across broad regions of the littoral zones of Lake Ontario, Lake Michigan and the eastern basin of Lake Erie. Nuisance conditions in Lake Huron are limited to isolated locations. No recent information exists for Lake Superior. Temporal trends are difficult to determine because of the lack of binationally consistent monitoring with sufficient spatial and temporal scope to assess trends in distribution or biomass in all lakes. Empirical and anecdotal evidence suggests that biomass levels in Lakes Erie, Ontario, Huron and Michigan are comparable to those observed in the 1960s and 1970s, with lower levels observed in the 1980s and 1990s.

Lake-by-Lake Assessment

Lake Superior
Status: Good
Trend: Unchanging
Rationale: Fouling of shorelines by *Cladophora* has not historically been an issue in Lake Superior. There is no evidence that this status has changed since the last update.

Lake Michigan
Status: Poor
Trend: Undetermined
Rationale: In the two regions of Lake Michigan where regular monitoring of *Cladophora* is conducted (Milwaukee and Sleeping Bear Dunes), biomass varies significantly from year-to-year but peak biomass remains above nuisance thresholds. There is some evidence for a possible declining trend, but this is confounded by high inter-annual variability. Accumulation of *Cladophora* on beaches indicates that algal growth rates remain high in many parts of the lake; however an unchanging trend over the previous 3 years has been seen.

Lake Huron
Status: Fair
Trend: Undetermined
Rationale: *Cladophora* biomass approaches nuisance thresholds in localized areas over the Canadian shoreline of the main basin. *Cladophora* biomass over broader areas of the nearshore zone is generally below nuisance conditions and occurs in waters deeper than 10 metres. Periodic fouling of shorelines can occur but is generally comprised of other macroalgae (e.g. Charophytes) and periphyton. *Cladophora* is not found at macroscopically visible levels in the nearshore of eastern Georgian Bay.

Lake Erie
Status: Poor
Trend: Undetermined
Rationale: *Cladophora* remains broadly distributed along much of the north shore of the eastern basin. Biomass is variable from year-to-year but remains at or above nuisance conditions at most sites sampled. Substantial inter-annual variability in biomass confounds assessment of trends at regional and local scales.

Lake Ontario
Status: Poor
Trend: Undetermined
Rationale: *Cladophora* is widely distributed in Lake Ontario. Biomass routinely exceeds nuisance conditions in the western end of the lake where hard substrate dominates the nearshore lake bottom. Surveys from recent years indicate nuisance conditions both in the vicinity of point source inputs, and also in regions remote from any known

sources. Inter-annual variability is comparable to that observed in Lakes Erie and Michigan and the lack of consistent monitoring hinders assessment of trends.

Other Spatial Scales

Saginaw Bay

Cladophora is part of a cosmopolitan assemblage of benthic macroalgae in Saginaw Bay linked to episodic fouling of beaches with decaying organic matter.

Sub-Indicator Purpose

The purpose of this sub-indicator is to evaluate spatial and temporal trends in biomass of *Cladophora* in the Great Lakes. Data can be used to infer the availability of *Cladophora* to be transported to the lake shore where it may foul beaches and clog water intakes, as well as its potential contribution to other negative impacts such as avian botulism. *Cladophora* is also useful as an integrative measure of nutrient loading and nutrient cycling processes within the Great Lakes.

Ecosystem Objective

Waters and beaches should be safe for recreational use and be free from nuisance algae which may negatively impact drinking water infrastructure and beach use, and which may contribute to negative impacts on ecosystem health, such as avian botulism. This sub-indicator best supports work towards General Objective #6 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem." This sub-indicator also supports General Objective #2 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "allow for swimming and other recreational use, unrestricted by environmental quality concerns."

Ecological Condition

Background

Algae occur naturally in freshwater systems. They are essential to the aquatic food web and healthy ecosystems. However, too much algae can lead to the development of algal blooms, which can be harmful to human health and the environment.

The fouling of shorelines by large rotting mats of filamentous algae (primarily *Cladophora*) in the summer months was a common phenomenon in the lower Great Lakes as far back as the mid-20th century (Taft and Kishler 1973). *Cladophora* is a filamentous green algae that grows on hard substrates in all of the Great Lakes. Generally attributed to excess phosphorus pollution, these blooms elicited public outcry and were identified as an emerging issue under the 1978 Great Lakes Water Quality Agreement. Targeted research in the late 1970s generally concluded that phosphorus (P) load reductions being implemented under the GLWQA would contribute to a reduction of nuisance *Cladophora* growth (Auer 1982). A brief research and monitoring interlude from the mid-1980s to mid-1990s coupled with a small number of documented (Canale and Auer 1982, Painter and Kamaitis 1987) and anecdotal reports (e.g., Painter and McCabe 1987) has been interpreted as an indicator of success of P control programs in reducing *Cladophora* growth. In the 1980s and early 1990s, basin-wide restoration efforts were successful in reducing nutrient-related runoff, and conditions in the lakes improved. These efforts included the regulation of phosphorus concentrations in detergents, investments in sewage treatment, and the development and implementation of best management practices on agriculture lands and in expanding urban areas. However, by the mid-1990s, reports of shore fouling began to appear in Lake Erie (Howell 1998) and by the early 2000s, had extended to Lakes Ontario (DeJong 2000, Malkin et al. 2008) and Michigan (Bootsma et al. 2005). With the recent resurgence of the nearshore algal problem in some areas and with other changes in the ecosystem, the problem has become more complicated. A more detailed and considered history of *Cladophora* in the Great Lakes is provided in Higgins et al. (2008) and Auer and Bootsma (2009).

The negative economic, aesthetic and recreational use impacts of excessive *Cladophora* growth and biomass are well documented and include the fouling of beaches and residential shorelines, clogging of municipal and industrial water intakes, and unpleasant aesthetics associated with rafts of decaying organic matter along the lake shore (Higgins et al., 2008, Peller et al. 2014). The ecological impacts of excessive *Cladophora* growth and biomass are less well understood, but may nonetheless be important. *Cladophora* is generally considered to be a poor food resource for grazers (Dodds and Gudder 1992), thus expansive standing crops may represent a substantial (albeit perhaps temporary) nutrient sink over much of the growing season (Higgins et al. 2005). Accumulation of attached or drifting mats can result in transient hypoxic conditions in shallow littoral regions (Gubelit and Berezina, 2010) which may have deleterious impacts on invertebrate communities (Berezina and Golubkov 2008), while *Cladophora* that is deposited on the shoreline may harbour pathogenic organisms and create an environment conducive to the development of botulism, thus creating a risk for fish and wildlife (Chun et al. 2015).

Current conditions

Locations affected by excessive *Cladophora* biomass continue to be found across much of Lake Ontario and Michigan, as well as the northern shore of eastern Lake Erie. In Lake Huron, reports of excessive biomass are generally restricted to isolated locations along the south-eastern shore of Lake Huron (Figure 1). A recent assessment of satellite imagery from 2008-2011 indicated that *Cladophora* and other submerged aquatic vegetation cover up to 40 % of the neashore lake bottom visible to satellites (Lake Huron - 15%, Lake Erie - 23%, Lake Michigan - 28%, Lake Ontario - 40 %; Brooks et al. 2014).

Lake Michigan

In Lake Michigan, anecdotal evidence (primarily observations of accumulation on beaches and fouling of water intakes) indicates that *Cladophora* has been growing at nuisance levels since the mid-to late 1990s. Biomass has been monitored at one location about 7 km north of Milwaukee Harbor since 2006. These dry weight measurements indicate that peak biomass varies from year-to-year ranging from a high of 268 g m^{-2} in 2008 to a low of 38 g m^{-2} in 2014 (Figure 2). Highest biomass levels were observed between 2006 and 2011. Since 2012, peak biomass levels have been more moderate, but there continue to be problems with fouling of beaches and water intakes. The 10-year record suggests that there may be a trend toward lower peak summer biomass, but the time series is not long enough to confirm whether this is a real trend or simply inter-annual variation.

Lake Huron

Cladophora biomass can reach nuisance conditions in the vicinity of local nutrient inputs in isolated regions along the south-eastern shore. Episodic fouling of beaches has occurred sporadically since 2004 although the degree of shore fouling is considerably less severe than that experienced in Lakes Michigan, Erie and Ontario. In 2013 and 2014, limited measurements were made at a depth of 1 metre near Goderich ON (affected by a municipal WWTP discharge) and Kincardine ON (affected by a small inflowing agricultural drain). Biomass at Goderich was 46 g m^{-2} and 49 g m^{-2} respectively, while at Kincardine biomass was 21 g m^{-2} and 33 g m^{-2} respectively. Similar observations of localized growth of *Cladophora* directly adjacent to nutrient discharge points have been observed over the coastline in recent years as in the past (Barton et al. 2013; Howell personal observations). The spatial extent of growth at these locations was limited. Over broader stretches of the eastern shoreline, *Cladophora* grows to depths of 20 m, although biomass rarely exceeds 10 – 20 g m^{-2} (Barton et al. 2013). A 2014 study by the Ontario Ministry of the Environment and Climate Change of 48 sites in eastern Georgian Bay found little *Cladophora* over the hard and mostly bare substrate surveyed (Figure 1).

Lake Erie

In Lake Erie, *Cladophora* has reached nuisance levels since the mid-1990s, primarily along the northern shore of the eastern basin (Howell 1998). Biomass has been measured infrequently since 1995, with significant effort in 2001 – 2002 (Higgins et al. 2005) comprising the most spatially comprehensive dataset. Since 2010, regular assessment of biomass has occurred at 4-5 transects in the vicinity of the Grand River, extending eastward to Port Colborne, ON by the Ontario Ministry of Environment and Climate Change and Environment and Climate Change Canada. Recent measurements at sites in shallow water (~ 3 m) indicate that inter-annual variability is substantial, and peak seasonal biomass in July ranged from a high of 308 g DW m^{-2} in 2012 to a low of 34.4 g DW m^{-2} in 2014 (Figure 3).

Lake Ontario

It has been apparent for many years that portions of the shallow lakebed of Lake Ontario are widely and extensively colonized by *Cladophora* (Wilson et al. 2006; Malkin et al. 2008; Higgins et al. 2012). The trajectory of changes over the years is broadly similar to Lake Erie and Lake Michigan. The onset of the recent high levels of *Cladophora* by about year 2000 at the latest has been persistent. Measurements of *Cladophora* have been made at a wide range of locations and sporadically over the years, but with no systematic monitoring over time. General features of *Cladophora* over hard substrate, confirmed in more recent surveys by the Ontario Ministry of the Environment and Climate Change and Environment and Climate Change Canada in 2012, 2013 and 2015, include high surface coverage to the point of blanketing substrate, strong attenuation of biomass with depth but persisting cover to depths > 10-20 m, typically co-occurring with high dreissenid mussel cover, and frequently with other filamentous green algae, notably *Spirogyra*. Biomass levels of >50 g m^{-2} have been observed at sites surveyed on the eastern, central and western shores of the main basin of the lake, however, there appears to be less data on the occurrence of *Cladophora* in the eastern basin of the lake. High short-term and spatial variability in biomass levels make inferences on difference among areas or over the years challenging. The finding of Higgins et al. (2012) indicating higher *Cladophora* levels in areas of urbanized shoreline remains a central and significant hypothesis influencing the direction of recent studies (e.g., Auer 2014) given the needs for nearshore phosphorus management over the developed shoreline of the lake.

Summary

The proximal drivers of *Cladophora* growth are reasonably well understood. Numerical models that are driven primarily by three variables – temperature, irradiance, and soluble reactive phosphorus (SRP) concentration – perform moderately well in simulating *Cladophora* growth (Higgins et al. 2006, Malkin et al. 2008, Tomlinson et al. 2010, Auer et al. 2010). However, there remains some uncertainty about the processes that ultimately regulate these drivers. There is strong evidence that dreissenid mussels play an important role, due both to their ability to clear the water column (and hence increase *in situ* irradiance) by removing particulate material, and their recycling of phosphorus, making dissolved phosphorus more available in the near-bottom layer where *Cladophora* grows (e.g., Ozersky et al. 2009, Martin 2010, Dayton et al. 2014). It is unclear at present if the enhanced phosphorus near the lakebed is derived from excretion of soluble nutrients as metabolic wastes (i.e. Conroy et al. 2005) or perhaps enhanced remineralization of non-edible algae and other detritus that accumulates within mussel beds. The role of dreissenids is highlighted by observations of increased production rates of *Cladophora* in the presence of mussels (e.g., Davies and Hecky 2005) and the presence of high *Cladophora* biomass even in regions where there are no major nutrient inputs (Wilson et al. 2006, Depew et al. 2011), unlike the 1960s and 1970s when *Cladophora* was associated primarily with point sources of nutrients. For example, in 2015 *Cladophora* biomass in Good Harbor Bay (near Sleeping Bear Dunes) in Lake Michigan, where there are no major tributary sources of nutrients, peaked at 186 g DW m^{-2}, while peak biomass several kilometres north of Milwaukee Harbor, which is a major nutrient source, was 38 g DW m^{-2}. However, in other regions, (i.e. Lake Ontario) there is evidence that local nutrient inputs do indeed have a local influence on *Cladophora* biomass (Higgins et al. 2012).

Biomass and Phosphorus status as indicators

Monitoring of biomass has been and remains a favored metric for assessing the status of *Cladophora*. Peak standing crops are usually achieved in mid-summer, although the exact timing varies between years and locations. Growth rates and loss processes (i.e. sloughing) are known to vary over short term periods (hours to days) in response to environmental conditions (i.e. wind and wave action, turbidity, nutrient supply, thermal regime). This generally leads to significant spatial and temporal variability in attached biomass at a given point in time (e.g., Figure 3). Comparisons of point-in-time measurements of biomass across spatial and temporal gradients may be misleading without appropriate consideration of environmental conditions.

Approaches for monitoring *Cladophora* were reviewed in the previous status report. These include collection of grab samples at selected monitoring locations (Higgins et al. 2005), hydro-acoustic methods (Depew et al. 2009), and remote sensing (Schuchman et al. 2013). Recent studies suggest that *in situ* monitoring using time lapse imagery may also be a useful method for monitoring *Cladophora* biomass (Bootsma et al. 2015). Each of these approaches has advantages and disadvantages related to spatial coverage, quantitative accuracy and precision, technical difficulty, and cost. For example, remote imaging and acoustic survey methods offer potential to expand the geographic scope of assessment and subsume some of the variability in biomass induced by processes operating on the metre to sub-kilometre scale (i.e. substrate patchiness, degree of exposure, variation in light climate), however they suffer from precision and accuracy issues when estimating biomass. Even among quantitative studies, differences in protocols and approaches to collecting biomass may add additional uncertainty. Specific challenges that remain include: 1) Determining the accuracy with which areal biomass can be determined with satellite imagery; 2) Development of protocols for selection of sentinel sites; 3) Development of sampling / measurement methods and approaches that are relatively simple while accounting for spatial and temporal variability.

The P content (or P status) of algal filaments has long been considered a useful metric for assessing the status of *Cladophora* and the potential for P management to be effective in controlling growth. Expressed most commonly as the proportion of dry weight (% DW; Q_P), the P content of the alga is directly related to its capacity for future growth (Auer et al. 2010). Q_P is thought to provide a time-integrated measure of algal exposure to P that a) removes uncertainty in P supply created by point in time measures of SRP from the overlying water column (which are frequently near or below the detection limit) and b) represents exposure and uptake of P by the alga in its physical habitat (i.e. at the lakebed). In general, values exceeding 1.6 mg g^{-1} (0.16 %) are considered P saturated, values between 1.6 and 0.6 mg g^{-1} (0.16 – 0.06 %) are considered P limited, while values below 0.06 % are considered critically limiting and insufficient to sustain net positive growth rates.

Q_P may be influenced to a large degree by light availability (i.e. water clarity), as the lower growth rates associated with lower irradiance allow for greater P accumulation in *Cladophora* tissue. Research conducted in Lake Michigan in 2015 revealed that *Cladophora* biomass can vary by more than 10 fold within a distance of 10 km. In the same survey, *Cladophora* P content was found to vary more than 3 fold and *Cladophora* biomass was negatively correlated with Q_P, suggesting that Q_P alone is not a good indicator of P availability and growth potential. Similar observations were documented in eastern Lake Erie over 2012-2014, with Q_P increasing (and biomass decreasing) along a gradient toward the Grand River, which is a significant source of turbidity and P to the Lake Erie nearshore (Figure 4). These observations underscore the important role of light as a regulator of *Cladophora* growth, and the importance of considering light climate when interpreting Q_P.

A further question when considering biomass level as an indicator of shore fouling is uncertainty in the degree to which high levels of biomass on the lakebed manifest as shore fouling when biomass extends deeper than the shoreline fringe. In a broad sense, shore fouling concerns map to biomass levels on the lakebed yet the specifics of fouling problems in an area may not. For example, Riley et al. (2015) found that structural development of beaches (i.e. breakwalls, jetties and piers) were important predictors of the degree of *Cladophora* fouling on Lake Michigan beaches and Barton et al. (2013) found that accumulation of algae on Lake Huron beaches was greatest where shoreline features intercepted nearshore currents. Despite these and other limitations, the presence of excessive biomass at a given location is likely to indicate the potential for shore fouling and other negative impacts.

Monitoring

The lack of a framework for *Cladophora* monitoring has been repeatedly cited as a major impediment to understanding the status and trends of *Cladophora* in the Great Lakes. Since the early 2000s, much, if not most of the information on *Cladophora* has been generated as a result of targeted research efforts by academic institutions and/or occasional and opportunistic ad-hoc surveys conducted by government agencies. As a result, there is limited ability to extrapolate results from a particular study site to larger areas or assess differences among studies/surveys as an indicator of spatial variability.

A recent assessment of available historical and contemporary biomass data from Lakes Huron, Erie and Ontario indicates that inter-annual variability is considerably greater than spatial variability (site to site variability) (Figure 5). Such structure in variance implies that, for management relevant time scales (i.e. 5 – 10 years), a large sampling effort would be required to detect trends unless the change in biomass is substantial (Figure 6). This does not mean that current survey approaches are unimportant, as spatial surveys can generally provide information on the spatial extent of nuisance conditions. On the other hand, if temporal trends are of interest, targeted study at a smaller number of sites may be better suited to determining the presence of a trend. Regardless of the approach taken, it will be important that monitoring plans clearly define their objectives as well as the magnitude and type of change that needs to be detected. With this in mind, it may be prudent to consider a tiered or nested approach to monitoring. For example, recently developed approaches (i.e. remote sensing or acoustic measurements) or simple surveillance with underwater video may prove useful for defining broader regions of interest where accumulation of nuisance biomass is an issue, or assessing the extent of problem conditions. Representative sentinel sites can be nested within these broader regions and monitored with sufficient frequency to establish confidence in trends that may be observed and then help to inform programs and policies affecting a larger geographic area. Using this approach can reduce the amount of monitoring that needs to occur. No such framework currently exists, but would be an important development toward management of the *Cladophora* problem.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Benthos (open water) – benthos diversity and abundance may be correlated with the occurrence levels of *Cladophora* and connected by indirect mechanisms that are poorly understood.
- Dreissenid Mussels – *Cladophora* is significantly influenced by the state of water clarity and nutrients in the Great Lakes, which are influenced by dreissenid mussel populations.

- Water Quality in Tributaries – Nutrient loading from tributaries can have both an immediate and long-term effect on *Cladophora* growth. Likewise, tributary loads of suspended sediment and coloured dissolved organic material affect water clarity in the nearshore zone, which in turn affects light availability for *Cladophora* growth.

This sub-indicator also links directly to the other sub-indicators in the Harmful and Nuisance Algae indicator.

Improved wastewater treatment and sustainable agriculture practices which result in decreased nutrient loadings to the Great Lakes may also result in decreases in *Cladophora* biomass.

Comments from the Author(s)

The issue of *Cladophora* in the Great Lakes merits sustained integrated research and monitoring because the symptoms of coastal impairment cannot be easily ignored given the proximity of the problem to recreational and industrial users. Given the apparent sensitivity of *Cladophora* to very low levels of SRP (Auer et al. 2010), the principal challenge is a better understanding of the relative contributions of nutrient supply from both lake-wide and local sources, as well as the internal processes that regulate phosphorus supply to *Cladophora* growth.

Following a robust binational science-based process and extensive public consultation, Canada and the U.S. have adopted phosphorus reduction targets (compared to a 2008 baseline) for the Western and Central basins of Lake Erie to address algal toxins and low –oxygen (hypoxic) areas.

For the Eastern Basin, a target has not been recommended to address nuisance algae (*Cladophora*) at this time. Nonetheless, it is important to note that targets have been recommended for the Western and Central Basins and work in concert, not in isolation. Because all tributaries to Lake Erie, including the Detroit River and the Huron-Erie Corridor, contribute phosphorus loads to the Eastern Basin, the reductions needed to address algal blooms and hypoxia may lower the phosphorus concentrations in the Eastern Basin as well. This may help address nuisance algal issues in the Eastern Basin, while maintaining enough nutrients to support the fisheries. Further work to establish targets that will minimize impacts from nuisance algae in the eastern basin of Lake Erie continues.

Evaluating the current status of *Cladophora* is a somewhat subjective exercise, based on measurements of biomass when and where available, the frequency and magnitude of accumulation on beaches, and the fouling of water intakes. From a management perspective, it would be ideal to designate a biomass target, which would be useful not only for the purpose of assigning a status, but also for developing management strategies with specific, quantitative objectives, the most obvious being nutrient loading targets. As discussed in the previous status report, and in the commentary by Bootsma et al. (2015), a dry biomass of 50 g m^{-2}, which was suggested as a nuisance threshold for Lake Huron in the early 1980's (Canale and Auer 1982), may now be well above the level that leads to a "nuisance" and beneficial use impairment, because nuisance growth is no longer restricted to nearshore regions adjacent to point nutrient sources, and the depth range of *Cladophora* has increased due to greater water clarity. Other factors also confound the use of a single biomass target. In nearshore regions with sparse rocky substrate, biomass on rocks may exceed 50 g m^{-2}, but spatially averaged biomass may be well below that level, resulting in little accumulation on shore. Also, standing biomass may be a poor indicator of the actual amount of biomass available for accumulation on shorelines, because biomass is not necessarily correlated to production. A significant portion of *Cladophora* production may be lost to sloughing (Canale and Auer 1982), and in summers when sloughing rates are high (due to wave-induced turbulence or high temperatures), standing biomass may remain low while the availability of *Cladophora* for accumulation on beaches is high. While this might suggest that the frequency and magnitude of accumulation on the shoreline is a more useful measure, this can also be misleading, as shoreline accumulation is stochastic and subject to the vagaries of nearshore currents and waves. Reliable evaluations of the status of *Cladophora* will ideally depend on measurement of more than one variable, such as biomass. Additional measurements that will support evaluation, and lead to a better understanding of the factors and mechanisms that regulate *Cladophora* include tissue P content, water clarity (along with solar radiation), and growth rate. While direct measurement of growth rate is technically more challenging than measurement of biomass, it may be possible to use a proxy for growth rate, such as the ^{13}C:^{12}C ratio of *Cladophora*.

The designation of *Cladophora* as a nuisance is based primarily on its impact on shoreline conditions, which are the most visible to the public. As discussed above, there are a number of less obvious, and less well understood ways in which *Cladophora* affects nutrient and trophic dynamics (Turschak et al. 2014) and contaminant transfer (e.g. Lepak et al. 2015). These processes ultimately influence ecosystem integrity and beneficial uses, so a rigorous assessment of the status of *Cladophora* will require these factors be increasingly understood.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		X				
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin			X			
5. Data obtained from sources within the U.S. are comparable to those from Canada		X	X			
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X	X			

Acknowledgments

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List of Figures

Figure 1. Locations within the Great Lakes where *Cladophora* has been reported since the year 2000. Empty circles indicate biomass below nuisance threshold of 50 g m^{-2} DW while filled circles indicate biomass above the nuisance threshold. Inset panel denotes higher resolution regions of eastern Georgian Bay where Ontario Ministry of Environment and Climate Change monitoring in 2014 took place.

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Figure 2. Seasonal biomass of *Cladophora* from 2006 to 2015 in the near shore of Lake Michigan (~ 7 km north of Milwaukee, depth = 9m).

Source: H. Bootsma, unpubl. data.

Figure 3. Seasonal plot of *Cladophora* biomass at 3 m depth from 5 transects in eastern Lake Erie (2012 – 2015). Panels are arranged in increasing distance from the Grand River, starting with the western most transect and proceeding eastward (top to bottom). Note different y axis scales on each panel. Notation in upper right corner of each panel indicates approximate distance from Grand River confluence.

Source – Environment and Climate Change Canada, unpubl.data.

Figure 4. Plot of attached biomass and Q_P for sites in eastern Lake Erie for the same stations in Figure 3.

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Figure 5. Estimated percent of total variation attributed to spatial (site to site), coherent temporal (inter-annual), ephemeral temporal (intra-annual at a given site) and residual (error or unmeasured) variation. Estimates are from a mixed model for $\log_{10}$ (*Cladophora* biomass; g DW m^{-2}) versus time for the period 1971 – 2014.

Source: Depew et al. (in prep).

Figure 6. Power curves for detecting temporal trends in *Cladophora* biomass with increasing number of fixed sample sites sampled per year and increasing trend magnitude a) -5 % per year, b) -10 % per year, c) -20 % per year, and d) -40 % per year. Variance components estimated from available data for Lake Erie since 1990, for depths of 0.5 – 3 m during June 1 – Aug 15.

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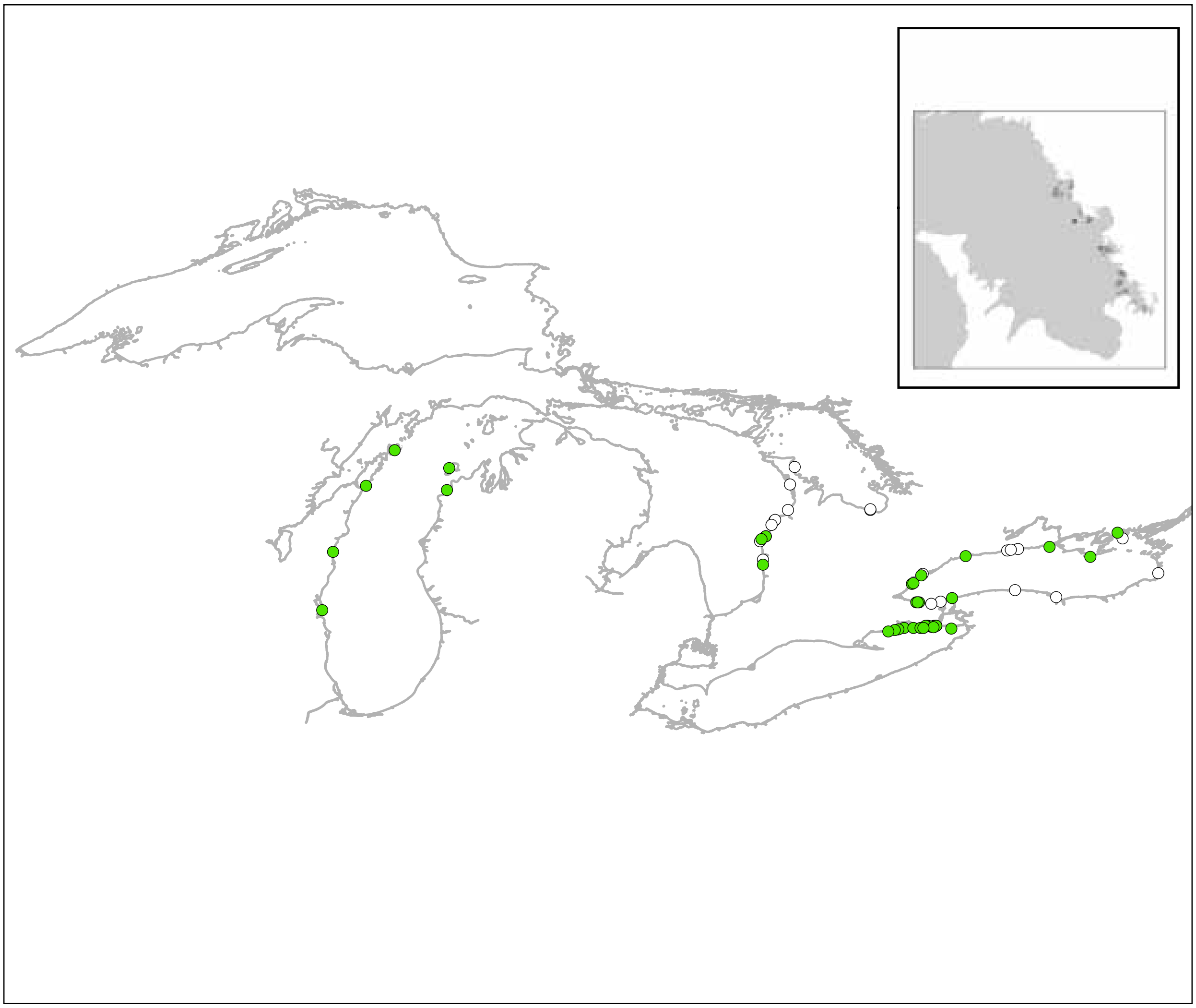
Last Updated

State of the Great Lakes 2017 Technical Report



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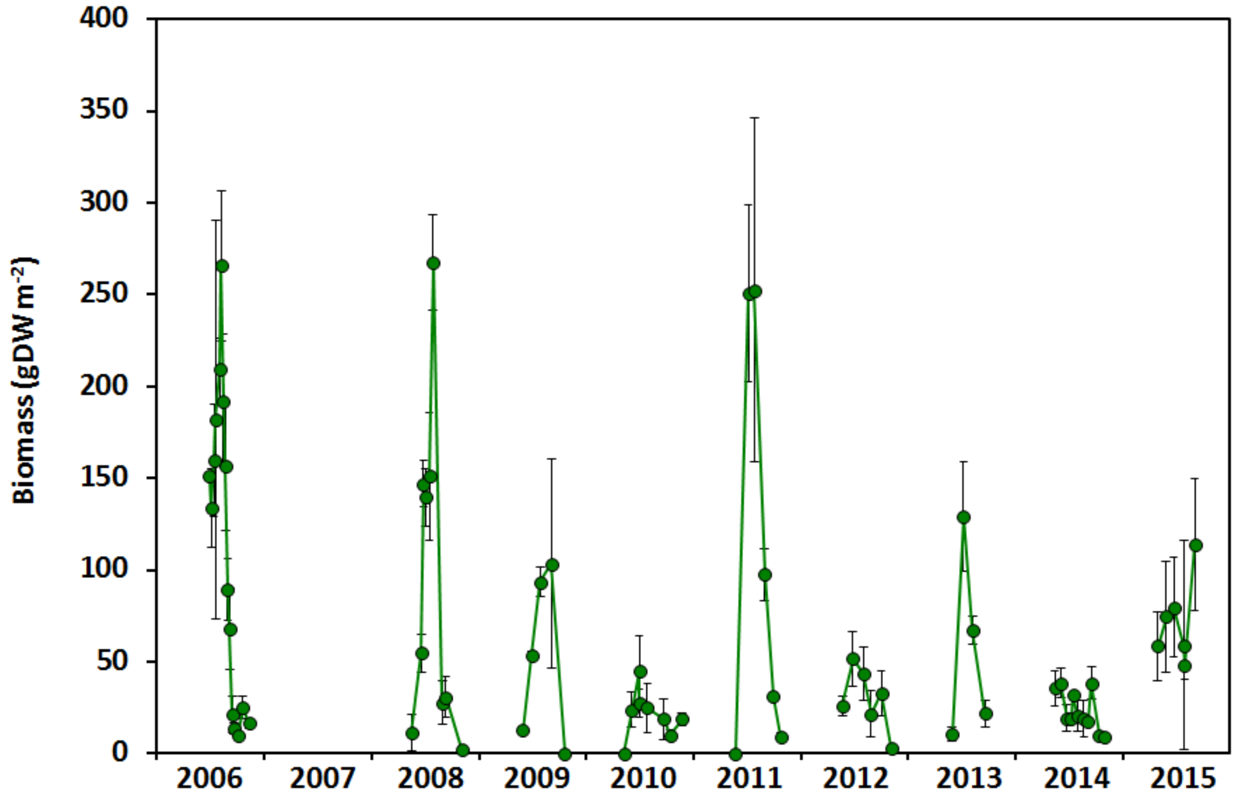

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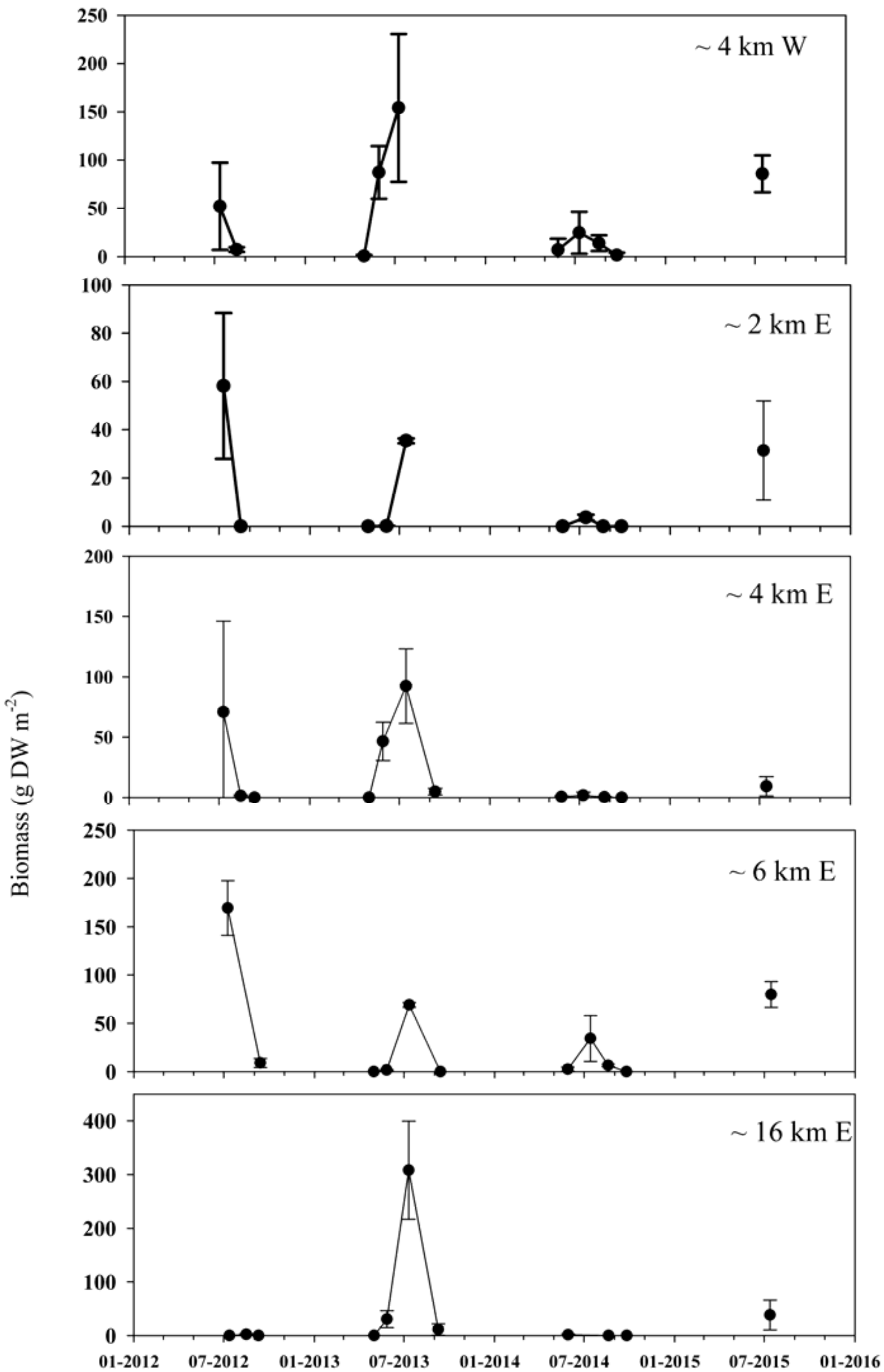

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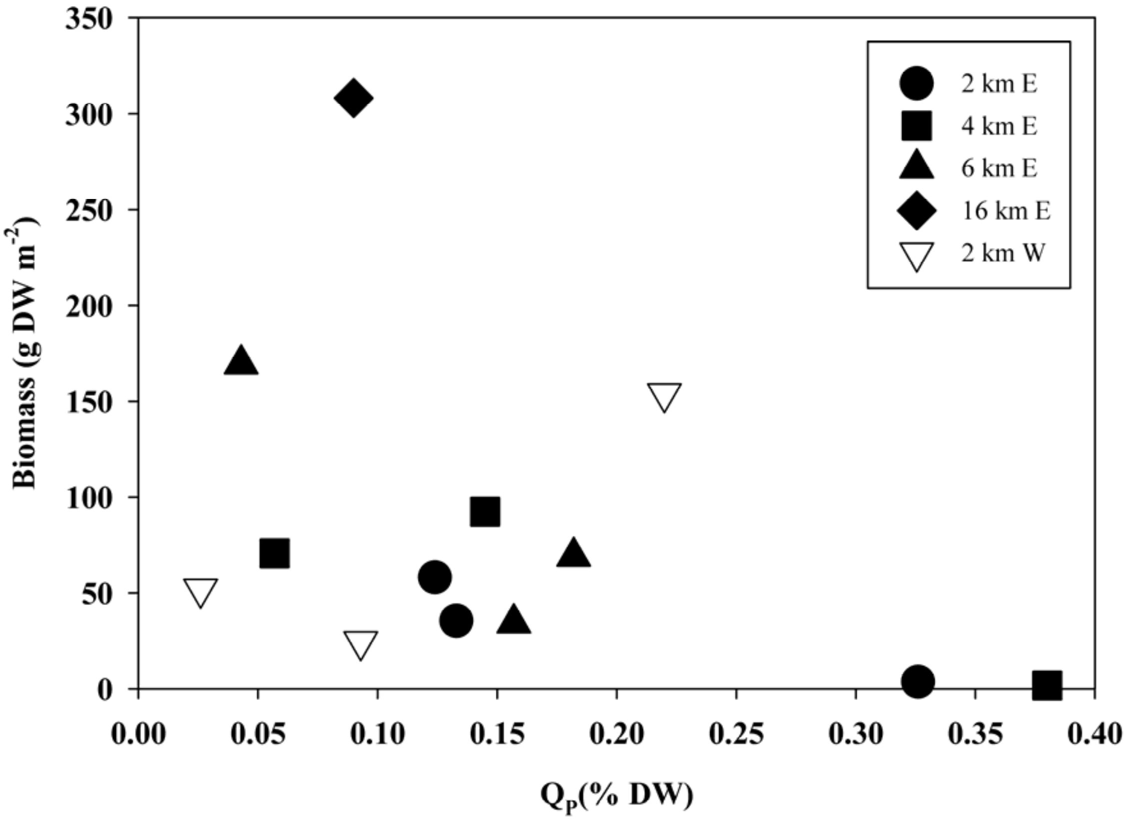

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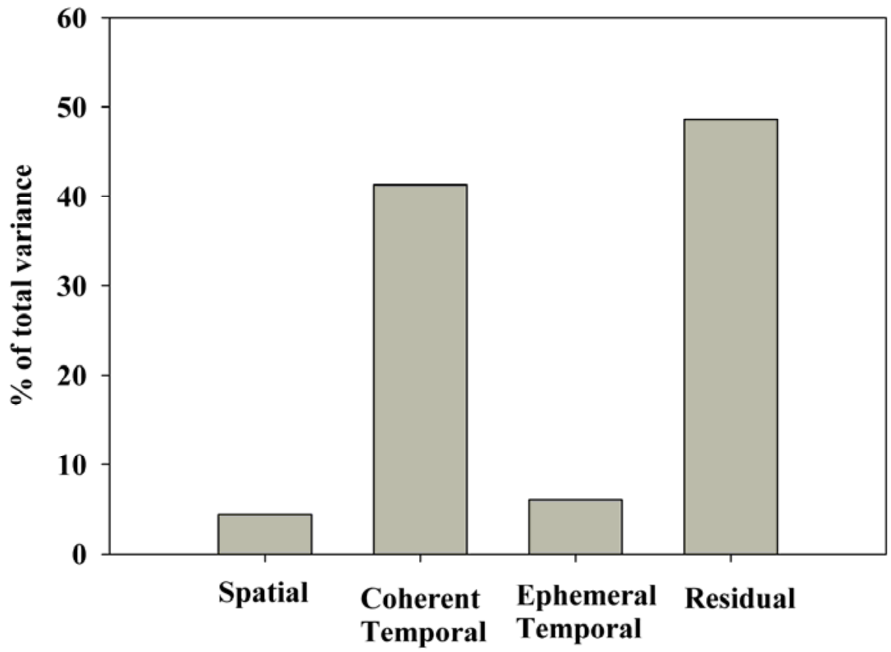

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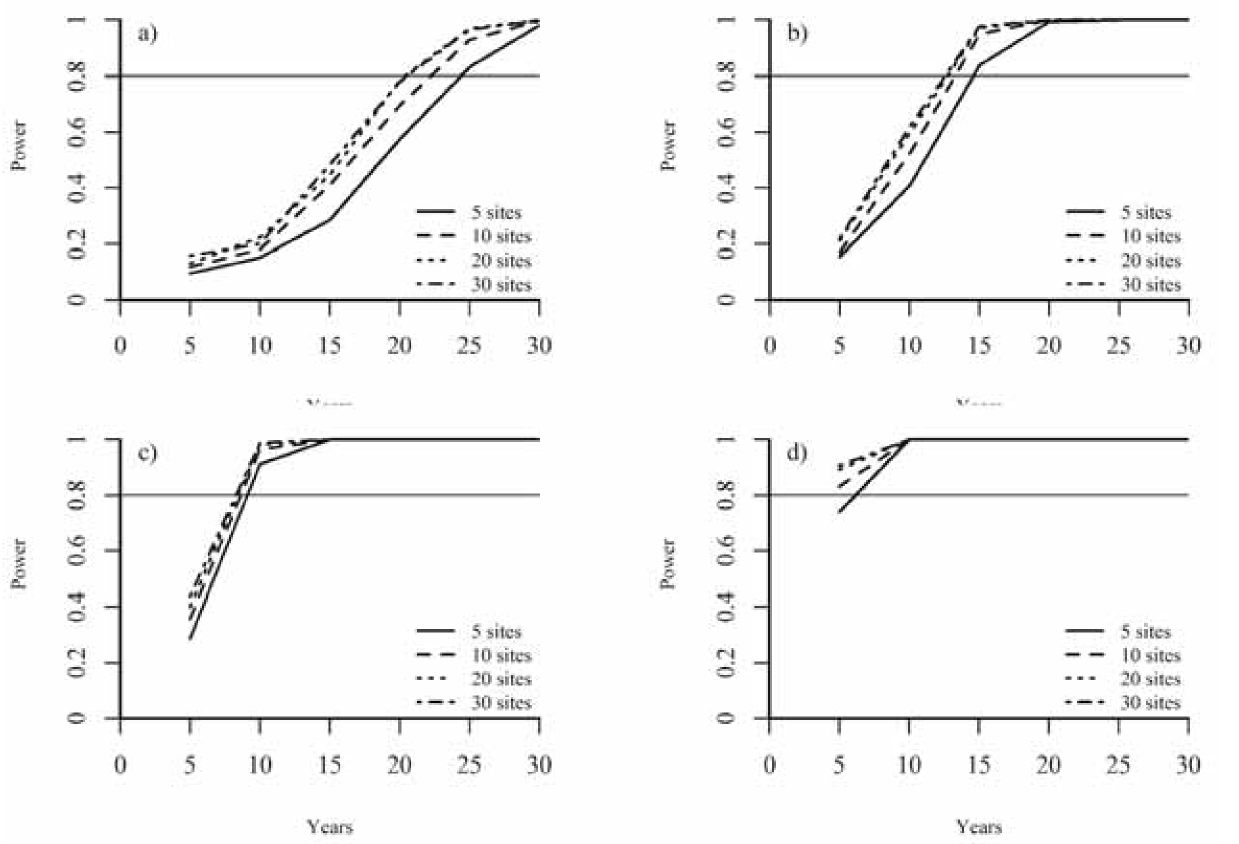

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Source: Depew et al. in prep.

Sub-Indicator: Harmful Algal Blooms
Nearshore

Overall Assessment

Status: Fair

Trend: Undetermined

Rationale: There is little systematic monitoring outside of Lake Erie and Lake Ontario to enable a rigorous evaluation of HABs in the Great Lakes. HABs (toxic and nuisance) have become a major issue for the western basin of Lake Erie and some eutrophic inshore embayments in lakes Michigan, Huron and Ontario and recently, Lake St. Clair. Based on available data and best professional judgement, the overall status of the Great Lakes in deep offshore waters is generally good and although the trend is deteriorating in the embayments, shallower basins or nearshore areas, the overall trend for the Great Lakes is noted as Undetermined.

Lake-by-Lake Assessment

Lake Superior

Status: Good

Trend: Undetermined

Rationale: There is little systematic monitoring for HABs (toxic and nuisance) in Lake Superior; however this waterbody is dominated by pico-cyanobacteria that are less likely to produce toxins than the larger cyanobacteria that typically dominate many of the blooms in the Great Lakes. An occasional local impairment may occur near the shoreline or in connecting channels.

Lake Michigan

Status: Fair

Trend: Undetermined

Rationale: Offshore waters are generally good but cyanobacteria blooms have been reported in some coastal regions and eutrophic embayments such as Green Bay, Muskegon Bay and in many of the drowned river mouths along the western shore. Nuisance algal blooms and beach fouling by *Cladophora* remains a problem for many of the beaches and nearshore regions; this issue is assessed further in a separate sub-indictor report.

Lake Huron

Status: Fair

Trend: Undetermined

Rationale: Lake Huron is generally oligotrophic in most areas, but experiences toxic and nuisance blooms in some nearshore areas, notably Saginaw Bay and Sturgeon Bay (Georgian Bay).

Lake Erie

Status: Poor

Trend: Deteriorating

Rationale: Lake Erie continues to experience toxic and nuisance cyanobacteria blooms throughout the western basin. Blooms in 2013, 2014 and 2015 were ranked as severe in a number of categories, and the 2014 event caused the closure of the City of Toledo water supply system. These blooms often expand into the central basin, and have resulted in loss of economic and ecosystem services provided by the lake. Southwest nearshore areas experience benthic proliferation of the nuisance cyanobacteria *Lyngbya* which has been documented elsewhere as a potential source of toxins.

Lake Ontario

Status: Fair

Trend: Deteriorating

Rationale: Offshore waters remain good with very little cyanobacterial abundance and no reported blooms.

However, toxic and nuisance planktonic blooms have been reported in several of the embayments on the New York side (Sodus Bay, Port Bay), and continue to occur in Hamilton Harbour and the Bay of Quinte on the Canadian side. Nearshore waters continue to experience nuisance algal blooms of *Cladophora*.

Connecting Channels

St. Clair River/Lake St. Clair/Detroit River

Status: Fair-Poor

Trend: Deteriorating

Rationale: Lake St. Clair offshore sites have a low plankton biomass representative of upstream Lake Huron assemblages. Some inshore sites are now experiencing toxic and nuisance planktonic HABs (Thames River mouth and south shore), and benthic *Lyngbya* proliferation (southeast shoreline).

Detroit, Niagara and St. Lawrence Rivers

Status: Undetermined

Trend: Undetermined

Rationale: Monitoring for HAB rarely occurs in riverine systems but the occurrence of pelagic blooms is expected to be low due to the higher flow conditions. Benthic and attached algae are an increasing issue in the St. Lawrence River and have been associated with toxicity though the extent of this issue is currently unknown. Information on benthic algal abundance is sparse in the other connecting channels such as the Detroit and Niagara rivers.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess potential harm to human health, livestock, pets, and other organisms or ecosystems from harmful algal blooms (HABs). This includes: i) cyanobacteria-based harmful algal blooms (cHABs): e.g. blooms that are documented to contain cyanobacterial toxins or are dominated by cyanobacteria species with the genetic potential to produce toxins, and ii) non-toxic nuisance algal blooms (NABs) e.g. episodes of high algal/cyanobacterial biomass e that, while not documented to contain toxins, disrupt ecosystem services provided by the water body.

Ecosystem Objective

Waters should be safe for drinking and recreational use and substantially free from toxic and/or high abundances of noxious cyanobacteria or algae that may harm human, animals or ecosystem health or have other significant adverse effects.

This sub-indicator best supports work towards General Objective #6 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should “be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem.”

Ecological Condition

Background

Harmful cyanobacterial and/or algal blooms (HABs) are a global issue in eutrophic waters with high nutrient loadings. HABs can be differentiated from ‘non-harmful’ (i.e. nuisance) blooms by their impacts on water quality and the associated biota, generally associated with the production of toxins. Nuisance algal blooms (NABs) are a separate subclass of algal blooms whose impact on the ecosystem is generally associated with elevated levels of biomass and not with the production of toxin. HABs and NABs can have detrimental impacts on ecosystem services provided by the lake and negatively impact aesthetics or recreation use of the water body. Prior to remediation in the late 1970s, HABs and NABs were a major problem in many offshore and nearshore areas in the Great Lakes (e.g. Watson et al. 2008) and at that time, the risk of toxins had not been widely recognized and concerns focused on reduced aesthetics, taste and odour (T&O), foodweb structure, beach/intake/net fouling and economic impacts. Lake-wide remediation efforts initiated in the 1980s were mainly directed towards the reduction of point-source nutrient loading, and successfully mitigated many toxic and nuisance algal bloom impairments with progress largely gauged against the management reduction targets for Total Phosphorus (TP) and chlorophyll a (chl-a). This progress changed in 2000 with the identification of the toxins produced by blooms of *Microcystis* in western Lake Erie (Brittain et al. 2000). Because toxin production was not generally recognized as a threat to the Great Lakes in the 1970s, there are no historical data on their occurrence prior to 2000. It is now recognized that many genera of bloom-forming cyanobacteria contain both toxic and non-toxic species and that differentiation between the toxic and non-toxic counterparts may not be possible at the level of light microscopy. Current management approaches which target planktonic (subsurface) chl-a as a measure of total algal biomass and productivity may be using a poor metric for these events. Newer analytical techniques specifically targeting the pigments produced by cyanobacteria (phycocyanin and phycoerythrin) provide a better measure of cyanobacteria biomass but again cannot differentiate between toxic and non-toxic species. Recognizing this issue, many agencies now specifically test for the hepatotoxin microcystins, a family produced by toxic members of the genus *Microcystis*, *Planktothrix* and *Dolichospermum* (syn. *Anabaena*) and extensive monitoring and bloom forecasting programs now exist for Lake Erie, Lake St. Clair and some of the embayments in lakes Huron and Ontario (e.g. http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habsMon.html; https://www.hamilton.ca/parks-recreation/parks-trails-and-beaches/beach-water-quality-in-hamilton) .

Most efforts are focused on visible HABs caused by planktonic toxic cyanobacteria, but HABs also can be caused by benthic/littoral macroalgae. These benthic mats, along with planktonic outbreaks, have shown an apparent resurgence, particularly in the lower Great Lakes. Because these events are often episodic, and vary seasonally and interannually in severity and spatial coverage, it is difficult to implement appropriate research, monitoring and management programs, particularly in large and complex waterbodies such as the Great Lakes where sampling is often subject to weather and vessel access. These blooms are not restricted to the lakes themselves and have been reported in major embayments, tributaries and connecting channels.

Most algal blooms in the Great Lakes are reported in the nearshore areas, which are most prone to shoreline development issues, greater influx of nutrients and to some extent, increased public vigilance. The size of nearshore zones varies from approximately 1-10% in Superior to 60-90% in Erie, as does the influence of physical and climatic factors (runoff, erosion, thermal bar formation, upwelling/down-welling, alongshore/nearshore/offshore currents, circulation patterns, surface/ground water inputs, lake level regulation, ice formation, etc). As a result, the nearshore zones are highly dynamic, and there is significant spatial-temporal variance in the areas supporting littoral and planktonic communities and offshore-nearshore material exchange.

Key aspects of HABs

These are summarized in detail in Watson and Boyer 2008, but some key points are below:

- HABs cause significant economic harm. Annual estimates vary, but range up to annual 4.6 billion USD/year in the USA including monitoring, fisheries, tourism, public health & advisory, lost revenue and property value (Anderson et al. 2000). For the Lake Erie basin alone, a recent report estimated that the major 2011 HAB event cost approximately 71million USD; the smaller 2014 HAB event approximately 65 million USD (Bingham et al. 2015). Lost benefits of 1.3-2.2 billion dollars are predicted over the next 30 years with no management action to control the blooms, a cost which could be reduced by 60-75% if remedial action is taken (Bingham et al. 2015; Smith and Sawyer 2015).
- Not all HABs resemble green paint or pea soup. They are caused by many species, and vary in colour from green to red and brown. Algal blooms do not always appear as surface scums, and can be difficult to identify or anticipate. Some blooms are mixed through the water column, or grow in deep water layers, under ice or as benthic/attached mats.
- Cyanobacteria produce many toxins which fall into three major categories, based on their activity: liver toxins (hepatotoxins), neurotoxins and dermal irritants. These toxins vary greatly in their chemical properties, stability and toxicity. Microcystins (MCs; hepatoxins) are the most stable and prevalent across the Great Lakes. These toxins can persist in the water column after a bloom has died and disappeared. Many cyanobacteria and several classes of algae produce volatile organic compounds (VOCs) that cause unpleasant taste and odour in drinking water supplies, but measures of toxins, taste and odour, visible blooms, cyanobacteria and algal biomass, and chl-a may or may not be correlated. Toxins are odourless and colourless and are often poorly related to malodorous VOCs, which are derived from different biochemical pathways. Both classes of compounds are produced by a diversity of cyanobacteria and algal taxa, and vary in cell production with environmental conditions and growth stage, both among and within species.
- The term 'algal bloom' is a non-quantitative descriptor for visible increases in free-floating or attached algal/cyanobacterial density, often manifested as scums, mats or water colour. (see e.g. Watson and Molot 2012). Blooms are difficult to define, measure and predict. Blooms can show rapid changes in their spatial location and abundance. With calm conditions (or overnight), buoyancy-regulating cyanobacteria can float to the surface and be carried large distances by wind/waves. These may wash onshore, creating patches of very high toxin levels along beaches. Variations in analytical and sampling methods can lead to inconsistencies in the reported levels of these compounds.

- Fluorescence-based, cell counts and other abundance measures (e.g. molecular, biochemical) are often poorly correlated with each other and actual cell biomass, due to wide variance in pigment content, photo-acclimation and cell composition. Taxonomic identification of many of the responsible species may be complex, leading to differences between analysts.
- Harmful algal blooms are differentiated as having harmful socioeconomic or ecological effects, and may be caused by algal/cyanobacteria species belonging to many major taxonomic groups. The greatest concern is with HABs caused by cyanobacteria (cHABs), which include toxic blooms, caused by a subset of cyano-bacterial species with the capacity to produce one or more toxins (neurotoxins, hepatotoxins or dermatotox-ins) and currently are the only known sources of algal toxins in inland waters that directly affect humans. Detrimental health effects from benthic algal accumulations on the shore are more difficult to quantify but may result in significant socioeconomic and ecological damage.

Current State of HABs in Individual Lakes

Although a HABs Index has been developed for this sub-indicator, there are not enough data available to use this index to assess status and trends. There are few long term data or rigorous monitoring programs in place outside of Lake Erie and Lake Ontario, and only a qualitative assessment of the current status in each lake can be made at this time. Recent efforts to use satellite imagery for measuring and quantifying HABs including NABs are increasing (e.g. Stumpf et al. 2012), and offer one potential approach that could help to address this issue. The One Health Harmful Algal Bloom System (OHHABS) will collect data to help health officials understand the severity and extent of illnesses caused by harmful algal blooms both in people and animals and the occurrence of harmful algal blooms. OHHABS development began in 2014 as a collaborative effort between state and federal partners. It has leveraged existing technical capacity for electronic reporting at the Center for Disease Control, lessons learned from a previous HAB-associated illness surveillance effort that ended in 2012, and support from the Great Lakes Restoration Initiative (GLRI), which will use OHHABS data to evaluate and inform restoration efforts for the Great Lakes ecosystem.

Lake Superior: There is very little quantitative current information on HABs in Lake Superior. To our knowledge, severe HABs outbreaks have not been documented recently in this lake and the offshore waters are generally dominated by non-toxic pico-cyanobacteria. Algal biomass, especially for potentially toxic cyanobacterial species remains mostly at low levels, although there may be some local impairment near shoreline development. Localized, low toxicity blooms have been observed in the connecting channels across the Keweenaw Peninsula

Lake Michigan: Cyanobacteria blooms are reported in many of the river mouths along the eastern shore of Lake Michigan and eutrophic embayments such as Muskegon Bay and Green Bay, where there has been an increase in cyanobacterial blooms and hypoxia (e.g. de Stasio et al. 2014). Nuisance algal blooms and beach fouling by *Cladophora* remains an issue for many of the beaches and nearshore regions, especially along the western shoreline and in the area of Sleeping Bear dunes.

Lake Huron: Lake Huron is generally oligotrophic in most areas, but experiences potentially toxic cHABs in some nearshore embayments, notably Saginaw Bay which develops toxic summer outbreaks of *Microcystis aeruginosa* (see http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/SBMicrocystin.html) and Sturgeon Bay (Georgian Bay) where blooms have been reported since the early 2000s, and are largely dominated by N-fixing cyanobacteria; toxin levels in this embayment are generally low or undetected to date (see Township of the Archipelago Sturgeon Bay Project Reports).

St. Clair River/Lake St. Clair/Detroit River's status is Fair-Poor. Seasonal sampling along the south shore from the Thames River to the outflow of the Detroit River into Lake Erie showed high microcystin levels near the Thames mouth, from blooms dominated by *Microcystis* (Davis et al. 2014). *Lyngbya* mats were reported in 2015 along the Eastern shoreline (Vijayavel et al. 2013). NASA and NOAA Coast Watch satellite imagery showed extensive algal blooms again in 2015 that covered much of the southern areas of Lake St. Clair. Nearshore sites vulnerable to HABs have been recently incorporated into the NOAA/GLERL/ECCC tracking and forecasting system; see http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/STCMicrocystin.html.

Lake Erie: Lake Erie is the most heavily impaired by planktonic cHABs, particularly over the last few years when satellite images of extensive surface blooms of *Microcystis* and other cHAB species such as *Dolichospermum* have been widely posted (e.g. NOAA; http://coastwatch.glerl.noaa.gov). Toxic cHABs and their causes/management are a major focus of the IJC and US-Canada working groups and a number of recent studies and initiatives (e.g. IJC Science Advisory Board 2013; MERHAB-LGL, Stumpf et al. 2012; Steffen et al. 2014; Watson et al. 2016). Currently, highly resolved data on chlorophyll and toxin levels in the west basin are available online (http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/WLEMicrocystin.html) along with a 'HAB tracker' and weekly HAB bulletins posted (http://www2.nccos.noaa.gov/coast/lakeerie/bulletin/bulletin_current.pdf).

General trends for Lake Erie: Data indicates a high year-to-year variability in bloom intensity, coverage and timing with a general deterioration in overall status since 2008. Shifts in the physical/chemical/ biological regimes (e.g. Michalek et al. 2013; Watson et al. 2016) are evident – notably in the western basin. Overall, satellite imagery indicates an increase in the severity of cyanobacteria blooms in the western basin (Figure 1) and some nearshore areas of the north shore (Point Pelee, Rondeau Bay, Long Point), and a general decline or no change in overall chl-a and total and/or eutrophic species biomass in the offshore regions of the central and eastern basins. Immense surface blooms (>20 km^2) are now annually recorded in the western basin of Lake Erie near the Maumee and Sandusky rivers (e.g. Stumpf et al. 2012; Michalek et al. 2013; Steffen et al. 2014;Watson et al. 2016). Microcystins (MCs) are the most common cyanobacterial toxins measured in Lake Erie. Data from 2000–2004 measured a wide range in MC levels from detection limits (in 2002) to >20 µg/L (in 2003). Toxicity is not restricted to the western basin and has been reported in Sandusky Harbor, Presque Isle and in Long Point Bay. Neurotoxins (anatoxin–a, saxitoxin, neosaxitoxin) occurred at or near detection limits in the open lake waters. Samples collected across the lake between 2003 and 2015 showed the greatest proportion of samples with detectable MC levels from the western basin, although only a small fraction of these samples exceed the drinking water guidelines of 1.5 µg/L and even fewer exceed the recreational contact level of 20 µg/L.

Wind driven material from west basin blooms intermittently impair central and northern shorelines (e.g. Figure 2) – although some of these events may be of local origin e.g. near Point Pelee. Blooms are frequently dominated by potentially toxic non nitrogen-fixers, notably *Microcystis* and *Planktothrix* spp., suggesting increased Nitrogen loading or dreissenid activity, although significant blooms of nitrogen-fixers (*Dolichospermum* and *Aphanizomenon)* also occur in both western and eastern basins (Allinger and Reavie 2013). Severe impairments by thick mats of the cyanobacterium *Lyngbya wollei* reported in the mouth of the Maumee River between 2006-2009 appear to have abated (Western Lake Erie Waterkeeper Association unpublished). However, extensive mats of attached green algae, notably *Cladophora* are showing an increase in abundance along some northern shorelines (Depew et al. 2011; Watson et al. 2016).

Most impairment occurs at shorelines and beaches and can be manifested as fish/bird kills. Lyngbyatoxins (inflammatory/vesicatory and tumour-promoting) were not detected in the mats of *Lyngbya wollei* proliferating in the Maumee and Detroit rivers. Geosmin and 2-methylisoborneol (MIB) occur in several areas of the lake (Kutovaya and Watson 2014) and are likely the cause of annual musty-muddy odour problems in drinking water in supplies in the western basin (e.g. Toledo). Significant odour is also produced by extensive rotting mats of shoreline attached algae. In 2014, a *Microcystis* bloom in the western basin of Lake Erie near the Collins Park Water Treatment facility serving the City of Toledo resulted in measureable levels of microcystin toxin in the finished drinking water in excess of 2.5 µg/L, which is significantly higher than the 1.5 µg/L drinking water guideline. This resulted in the City of Toledo being placed under an emergency drinking water degree and severely disrupted city services for nearly 500,000 residents for a period of 5 days.

Lake Ontario: Blooms of cyanobacteria and related impairments (toxins, shoreline fouling, taste and odour) occur on an annual basis in some nearshore areas, notably Areas of Concerns (AOCs) of Lake Ontario. Outbreaks of high MC levels and cyanobacteria blooms have been recorded most years in Hamilton Harbour, Bay of Quinte, Oswego Harbor and the southern shore embayments of New York (Watson and Boyer 2008, Perri et al. 2015). Toxic cHAB-related beach closures occur annually in Hamilton Harbour, where the Health Agency has established a systematic beach monitoring program which includes toxin testing (City of Hamilton 2014).

Spatial and temporal levels of MCs in the Bay of Quinte, Hamilton Harbour, Oswego Harbor (now delisted), Sodus Bay, and the Rochester Embayments continue to indicate periods of severe impairment of nearshore sites by wind-blown accumulations of toxic material, where MC levels can reach levels in excess of 500 µg/L (Watson et al. 2009; Figure 3). Microcystins and toxigenic *Microcystis* are also commonly found in many of the nearshore regions and embayments that span the northern coast of New York State (Perri et al. 2015). While microcystins are certainly the toxin of most concern in Lake Ontario, recent surveys indicate the widespread occurrence of low concentrations of anatoxin-a in nearshore embayments (Boyer 2007). The organism responsible for anatoxin-a production is currently unidentified. Cylindrospermopsins have not been detected (Figure 3).

Connecting Channels

There are few studies or reports of HABs in connecting channels although a number of papers report significant blooms in tributaries to Lake Erie (Maumee, Sandusky; e.g. Kutovaya et al. 2012; Davis et al. 2015). Toxin-producing *Microcystis* blooms have been reported recently in the Detroit River, likely derived from upstream blooms in Lake St. Clair (Davis et al. 2014) although MC levels reported to date have been below the WHO guideline. Toxin-producing (saxitoxin analogues) and taste and odour producing *Lyngbya* has been reported in the St. Lawrence River (e.g. Lajeunesse et al. 2012), along with frequent impairments of drinking water and shoreline odour produced by benthic and epiphytic cyanobacteria (Watson et al. 2008).

Linkages

Increasing nutrient inputs from diffuse and point sources, climate change (severe storm events, differences in insulation/harmful irradiation, ice-cover and mixing), and invasive species (e.g. dreissenid mussels) in the Great Lakes may lead to an increased risk of more frequent, widespread and severe nearshore (attached/benthic) and offshore algal blooms and favour the predominance of cyanobacteria, particularly in the more eutrophic areas of the lower lakes.

Comments from the Author(s)

There are few long term data collected on HABs and more specifically, toxins, in the Great Lakes, making trend analysis difficult. Differences in sampling regimes and analytical protocols (e.g. surface or integrated sampling; taxa enumeration; toxin analyses) utilized in past studies affects the ability to compare data and determine long term trends in toxins and bloom occurrences. Event or response-based sampling also tends to inflate the severity of the issue by only focusing on times when blooms are in high abundance.

Attention is most often focused on shoreline scums or algal material visible at the surface, particularly for inland waters where many reported blooms are caused by attached macroalgae (*Cladophora*, *Lyngbya*) or large, buoyancy-regulating cyanobacteria. These buoyancy-regulating taxa can produce rapid surface accumulations from populations through the mixed layer or deep living/benthic populations. Concentrated surface scums appear, disappear and migrate rapidly with changes in vertical mixing, currents and wind activity. These can produce rapid changes in toxin levels along a waterfront or cover extensive areas in large lakes, and are difficult to sample, quantify or predict.

Beach and shoreline sampling programs require multiple subsites to capture this envelope of spatial/temporal variance in risk and impairment, which are poorly represented by basin-wide seasonal means. Sampling regimes in the Great Lakes are often sparse (both temporally and spatially) and are likely to miss spatial and temporal peaks in cyanobacterial/algal abundance.

Potential new sources of data that could be used in future evaluations of this sub-indicator, with the application of the developed index to assess status and trends, include: i) the expanded HABtracker data, available online (http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habsTracker.html); ii) the increased number of drinking water treatment plants now monitor toxins in the raw water in compliance with state or provincial regulations; ii) beach closure statistics iii); and more specific data from proactive beach monitoring programmes which are now incorporating HAB or toxin measures into coliform surveys.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization			X*			
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data			X			

4. Geographic coverage and scale of data are appropriate to the Great Lakes basin					X	
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report				X		

Clarifying Notes: The sources of data are varied and in many cases, use different sampling and analytical methods. Monitoring in the lower lakes is generally good but monitoring in the upper lakes Michigan, Huron and Superior is sparse and largely reactive. * Increasingly, the data are validated and quality controlled by recognized agencies e.g. NOAA-GLERL, SYNY, ECCC, USGS.

Acknowledgments
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Greg Boyer, State University of New York (glboyer@esf.edu)

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List of Figures

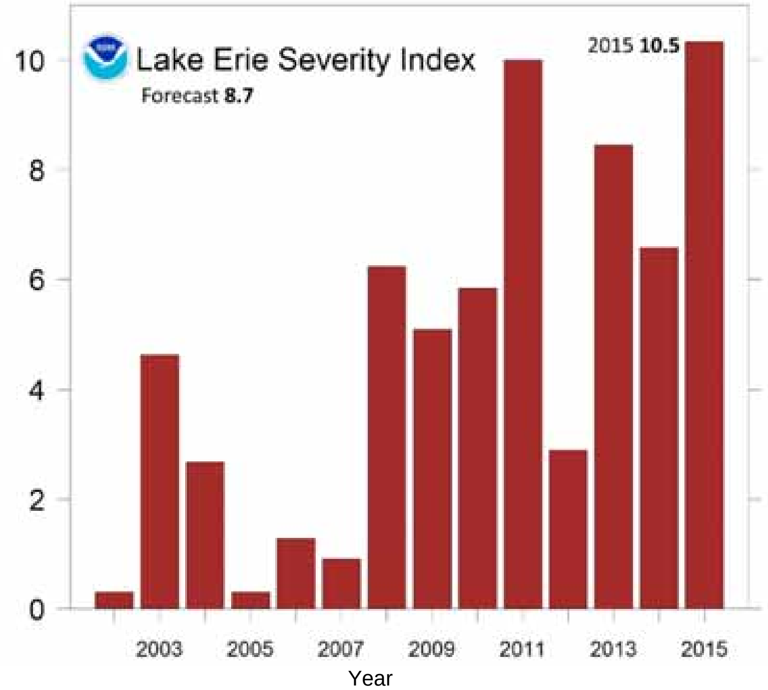
Figure 1. Bloom severity index for 2002-2015, based on the amount of biomass over the peak 30-days.
Source: NOAA-GLERL Experimental Harmful Algal Bloom Bulletin;
https://www.glerl.noaa.gov//res/HABs_and_Hypoxia/lakeErieHABArchive/bulletin_2015-027.pdf

Figure 2. The maximum extent of the bloom on 6 September 6, 2015 shown as a true colour image. The bloom was less concentrated at this time than in August.
Source: Raw data was obtained from NASA's Modis-Terra sensor:
https://www.glerl.noaa.gov//pubs/brochures/bluegreenalgae_factsheet.pdf

Figure 3. Seasonal (June-September) average (±standard deviation) levels of microcystin and geosmin from 2009 in the Bay of Quinte (1m) grouped by station.
Source: Watson et al. (2009)

Last Updated

State of the Great Lakes 2017 Technical Report



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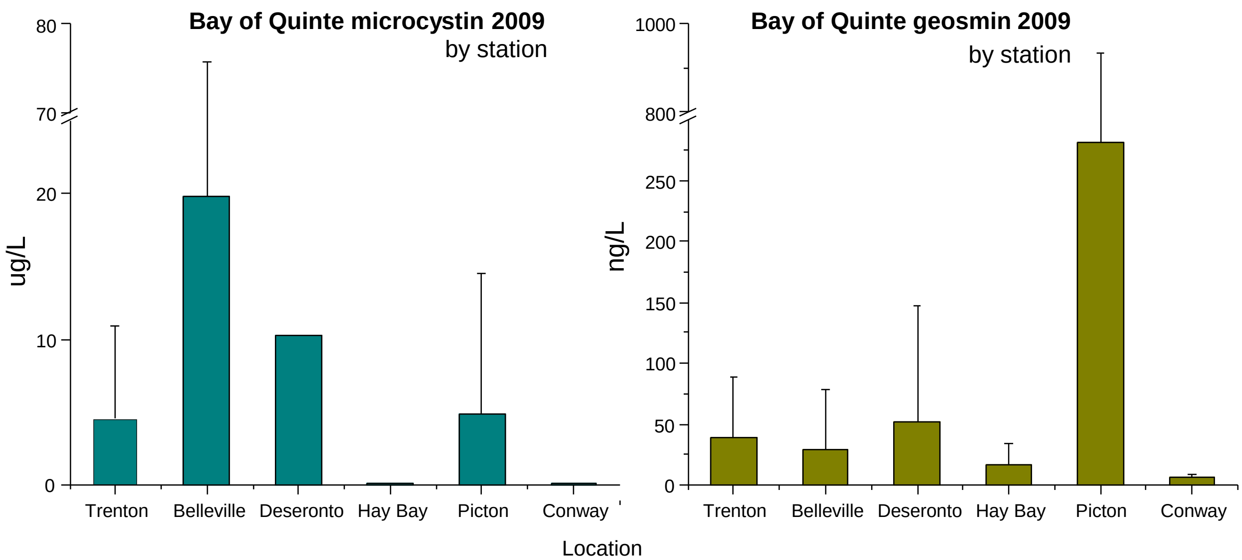

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Source: Watson et al. 2009

Sub-Indicator: Water Quality in Tributaries

Overall Assessment
Status: Fair
Trend: Unchanging
Rationale: The overall water quality status of tributaries to the Great Lakes was described as Fair which is unchanged since the previous indicator report in 2011. The average Water Quality Index (WQI) score for 92 Canadian tributaries to the Great Lakes was 67/100. The WQI scores ranged from 11 to 100 (Poor to Good). Overall, 30% of the tributaries were categorized as having Good water quality, 51% as Fair, and 19% were Poor (Figures 1 and 2). Good water quality was found in certain tributaries to lakes Superior, Huron, and Ontario, and the St. Lawrence River. Poor water quality was found in certain tributaries of lakes Erie and Ontario and in one tributary of Lake Huron.

Lake-by-Lake Assessment
Lake Superior
Status: Fair
Trend: Unchanging
Rationale: The average WQI score for 9 tributaries was 78/100. WQI scores ranged from 65 to 100 (Fair to Good). There were only a few sites monitored, therefore those sites assessed as fair may be under-represented. In 2011, the average WQI value was 80/100.

Lake Michigan
Status: Undetermined
Trend: Undetermined
Rationale: No tributaries to Lake Michigan are monitored by the Ontario Provincial Water Quality Monitoring Network (PWQMN).

Lake Huron
Status: Good
Trend: Unchanging
Rationale: The average WQI score for 28 tributaries was 81/100. WQI scores ranged from 44 to 100 (Poor to Good). In 2011, the average WQI value was 83/100, noting one less tributary was used for the 2016 assessment.

Lake Erie
Status: Poor
Trend: Unchanging
Rationale: The average WQI score for 18 tributaries was 43/100. WQI scores ranged from 11 to 75 (Poor to Fair). In 2011, the average WQI value was 45/100.

Lake Ontario
Status: Fair
Trend: Unchanging
Rationale: The average WQI score for 31 tributaries was 65/100. WQI scores ranged from 29 to 93 (Poor to Good). In 2011, the average WQI value was 66/100, noting that 2 less tributaries were included in the 2016 assessment.

Other Spatial Scales
St. Lawrence River
Status: Fair

Trend: Deteriorating

Rationale: The average WQI score for 6 tributaries was 73/100. WQI scores ranged from 55 to 85 (Poor to Good). In 2011, the average WQI value was 81/100.

Sub-Indicator Purpose

The purpose of this sub-indicator is to communicate water quality status relative to guidelines and support the evaluation of aquatic ecosystem health in Great Lakes tributaries.

Ecosystem Objective

The surface waters in the Great Lakes Basin should be of a quality that is protective of aquatic life and healthy aquatic ecosystems.

This sub-indicator best supports work towards General Objective #6 and # 4 of the 2012 Great Lakes Water Quality Agreement. General Objective # 6 states that the Waters of the Great Lakes should "be free from from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem" and General Objective # 4 states that the Waters of the Great Lakes should " be free from pollutants in quantities or concentrations that could be harmful to human health, wildlife, or aquatic organisms, through direct exposure or indirect exposure through the food chain."

Ecological Condition

Measure

Inland water quality is evaluated using the Water Quality Index (WQI). The WQI provides a mathematical framework for synthesizing water quality monitoring results for multiple samples and parameters into one value that represents overall water quality for the protection of aquatic life at a given site. The WQI uses three measures of compliance with water quality criteria (guidelines and objectives) to assess water quality:

1. Scope: measures the percentage of the number of parameters that comply with water quality criteria;
2. Frequency: measures the percentage of individual water quality tests that comply with criteria; and
3. Magnitude: measures by how much criteria are exceeded.

The three factors are combined into a single unit-less value between 0 and 100 where higher numbers indicate better water quality. The WQI is computed using the Canadian Council of Ministers of the Environment's Water Quality Index (v. 1.2; CCME 2011a), which is described in detail in CCME (2001a, b). The sensitivity of the WQI to variations in its formulation and application has been studied extensively (e.g. Davies, 2006; Gartner Lee Limited, 2006; de Rosemond et al. 2009; Kilgour and Associates Limited, 2009; etc.).

For the Canadian tributaries assessed for this report, the WQI values were calculated at sites with four years of data and a minimum of 10 observations for total concentrations of the following eight (8) site-relevant parameters: ammonia (un-ionized), chloride, copper, iron, nitrates, nitrites, phosphorus, and zinc. Inland stream water quality results for these parameters were acquired from the Ontario Provincial Water Quality Monitoring Network (PWQMN) (OMOE, 2013). For the calculation of the WQI , the water quality results are compared with guidelines from the Canadian Council of Ministers of the Environment (CCME)'s Water Quality Guidelines for the Protection of Aquatic Life (CCME, 2011b) or, in the absence of CCME Guidelines, the Ontario Interim Provincial Water Quality Objectives (PWQO) (i.e. for total phosphorus) (OMOE, 1994) (Table 1).

The WQI was calculated for the most downstream monitoring site for streams draining to the Great Lakes, including tributaries to the Great Lake connecting channels and the St. Lawrence River as an indication of water quality entering the Great Lakes. The most recent four years of water quality monitoring results that are available online (as of Winter 2015; OMOE, 2013) were used for the index calculations. For most (81/92) sites, the WQI was computed using monitoring results from 2009-2012 but for sites that were monitored infrequently (< 10 samples) between 2009 and 2012, results from 2002-2005 or 2006-2009 were used (11/92 sites).

Background

The Ontario Ministry of the Environment and Climate Change's Provincial (Stream) Water Quality Monitoring Network (PWQMN) measures water quality in rivers and streams at hundreds of sites across Ontario in partnership with Ontario's Conservation Authorities. Most of these sites are located in the Great Lakes Basin, and many are located at or near the outlets of tributaries to the Great Lakes. Stream water samples are collected on an approximately monthly basis and delivered to the Ministry of the Environment and Climate Change's laboratory where they are analyzed using consistent analytical methods for a consistent suite of water quality indicators. Water quality indicators are selected to indicate the influence of land-use activities on stream water quality. For example, chloride is measured as an indicator of the influence of salt loading from winter de-icing. Field measurements including water temperature and pH are also taken at the time of sample collection using portable water quality meters. Water quality data for all stream monitoring sites is available on the Ontario Ministry of the Environment and Climate Change public website (https://www.ontario.ca/data/provincial-stream-water-quality-monitoring-network).

Targets or Endpoint

Desirable outcomes are the absence of undesirable water quality conditions in streams. The Water Quality Index (WQI) score is from 0 to 100 with rankings for poor, fair and good. The category ranges describe sites where the water quality complies with criteria virtually all of the time (Good) or hardly any of the time (Poor).

Status Assessment and Justification

The calculated values fit into five categories that describe water quality conditions as used by the CCME:
Excellent (95-100);
Good (80-94);
Fair (65-79);
Marginal (45-64); and
Poor (0-44).

For this sub-indicator, the five original categories developed by CCME were dissolved into three descriptive categories:
Good: 80-100
Fair: 45-79
Poor: 0-44

Status of Water Quality in the Great Lakes Tributaries

The WQI was computed for 92 Canadian tributaries to the Great Lakes. The overall water quality status of tributaries to the Great Lakes can be described as Fair (WQI_{avg}=67, WQI_{range}=11-100). 30% of the tributaries were categorized as having Good water quality, 51% as Fair, and 19% were Poor (Figures 1 and 2).

Good water quality was found in certain tributaries to lakes Superior, Huron, and Ontario, and the St. Lawrence River. Poor water quality was found in certain tributaries of lakes Erie and Ontario and in one tributary of Lake Huron. The WQI scores ranged from 11 (Sturgeon River, Lake Erie) to 100 (Montreal and Michipicoten rivers, Lake Superior; Mississagi and Serpent rivers, Lake Huron).

On a lake-by-lake basis, tributaries to Lake Huron can be described as having Good water quality (WQI_{avg}=81, WQI_{range}=44-100, n=28). Tributaries to Lake Superior (WQI_{avg}=78, WQI_{range}=65-100, n=9), Lake Ontario (WQI_{avg}=65, WQI_{range}=29-93, n=31), and the St. Lawrence River (WQI_{avg}=73, WQI_{range}=55-85, n=6) had Fair water quality. Tributaries to Lake Erie (WQI_{avg}=43, WQI_{range}=11-75, n=18) were categorized as having Poor water quality.

The overall water quality status of tributaries to the Great Lakes was described as Fair which is unchanged since the previous State of the Great Lakes (previously known as SOLEC) report (EC and USEPA, 2014). On a lake-by-lake basis, the description of the water quality for tributaries to lakes Huron and Ontario has not changed since the previous State of the Great Lakes report but the status of tributaries to lakes Superior and Erie and the St. Lawrence River has changed. For tributaries to lakes Superior and Erie, the average WQI scores reported in 2011 were at the lower boundary of the Good and Fair categories, respectively. In this current report, the average WQI scores for tributaries to these lakes decreased by 2 and are described as Fair (Lake Superior) and Poor (Lake Erie). However, since the WQI score only decreased by 2, the trend was reported as 'unchanging' irrespective of the change in status. The water quality of tributaries to the St. Lawrence River was Good in 2011 and Fair in this current report. This change in status for the St. Lawrence River is likely attributed to the WQI scores in certain tributaries where more recent water quality results showed non-compliance of water quality criteria for multiple parameters whereas non-compliance in earlier results was for one parameter only (i.e. phosphorus).

Linkages

The WQI values for the 92 tributaries show a statistically significant negative relationship with percent of the watershed occupied by human land uses (Figure 3). This relationship suggests that overall water quality in the Great Lakes tributaries is influenced by human land use where minimally developed watersheds have higher WQI scores than the more heavily developed watersheds.

The WQI scores suggest the potential for substances in stream water to impact aquatic life based on compliance with water quality criteria. However, the WQI values are not a direct measure of impacts to aquatic communities, such as changes in fish and benthic invertebrate communities. The WQI values (and the water quality in tributaries) also infer the potential for discharge of nutrients or other substances from tributaries into the Great Lakes and the associated impacts of these discharges, particularly at the tributary mouths and nearby nearshore areas.

However, it should be noted that there are some linkages that can be made to impacts on aquatic life. For example, freshwater mussels are particularly sensitive to chloride (a component of road salt) exposure compared to other aquatic life, especially during their early life stages. Chloride concentrations in many of our rivers and streams have been increasing since the mid-1990s. (Water Quality in Ontario, 2014 Report).

Comments from the Author(s)

The WQI is a communication tool that was designed to report complex water quality information about multiple variables in a simplified format. While the WQI can provide a broad overview of water quality, it is not intended to replace rigorous technical analyses of water quality data for water resource management.

Although the water quality of many Great Lakes tributaries has been monitored since the 1960s, assessing long-term trends in water quality is challenging due to inconsistent laboratory methods and detection limits over time and incomplete datasets. At this time, the utility of using the WQI for the statistical analysis of trends in water quality in Ontario tributaries continues to be explored.

For this Water Quality in Tributaries report, the WQI has been computed only for Canadian tributaries. The application of the WQI to assess water quality in U.S. tributaries to the Great Lakes depends on the availability of monitoring data. An anticipated challenge is that WQI results are not directly comparable between jurisdictions where different water quality parameters and criteria are used.

Most of the PWQMN's monitoring sites are purposefully located where water quality impacts are known or expected, such as areas with a high population or where land is used for agriculture. Minimally-impacted reference watersheds are likely under-represented in this sub-indicator. The sub-indicator may also under-represent tributaries to the upper Great Lakes (especially Lake Superior). For future reports, a redundancy or other analysis could be undertaken to eliminate some sites from the lower Great Lakes to ensure all lakes are more equally represented.

Water quality criteria can be exceeded in areas that are naturally rich in a given nutrient or metal. The calculation of the WQI does not take into account naturally-occurring elevated concentrations of some parameters.

This current Water Quality in Tributaries report is a status update from 2011 (EC and USEPA, 2014). This report uses the same eight (8) site-relevant parameters as the previous report. The WQI was recalculated for this report using the most recent water quality monitoring results for these parameters with current water quality criteria for the protection of aquatic life. For chloride, the guideline for the protection of aquatic life is now 120 mg L-1 (CCME, 2011) whereas a guideline value of 110 mg L-1 was used previously (EC and USEPA, 2014). For this current report, WQI scores are computed for 92 tributaries whereas scores were computed for 95 tributaries used previously (EC and USEPA, 2014). Although fewer tributaries to Lakes Ontario (n_{2011}=33, n_{2017}=31) and Huron (n_{2011}=29, n_{2017}=28) were included in this current report, there continues to be ample representation of these lakes.

Because the WQI can be influenced by factors other than water quality (i.e. the particular parameters selected for the calculation, the number of parameters included, the specific sites used, and the water quality criteria for a given jurisdiction), using changes in the WQI scores over time to identify trends can be potentially more indicative of changes based on how the index was calculated than changes in the quality of the water. However, in this case, the locations and criteria used the same 8 criteria and for the most part, the same locations.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the U.S. are comparable to those from Canada						x
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					
Clarifying Notes: WQI calculations for Ontario tributaries to the Great Lakes were computed using monitoring data from the PWQMN (https://www.ontario.ca/data/provincial-stream-water-quality-monitoring-network). The WQI may be calculated independently for U.S. tributaries if data are available.						

Acknowledgments

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Last Updated

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Parameter	Criterion	Source
Ammonia (un-ionized)	0.0152 mg L^{-1}-N	CCME
Chloride	120 mg L^{-1}	CCME
Copper	2 µg L^{-1} at water hardness of 0-120 mg L^{-1}-$CaCO_3$ 3 µg L^{-1} at water hardness of 120-180 mg L^{-1}-$CaCO_3$ 4 µg L^{-1} at water hardness of >180 mg L^{-1}-$CaCO_3$	CCME
Iron	300 µg L^{-1}	CCME
Nitrate	2.9 mg L^{-1}-N	CCME
Nitrite	0.06 mg L^{-1}-N	CCME
Phosphorus	0.03 mg L^{-1}	OMOE
Zinc	30 µg L^{-1}	CCME

Sources: CCME = Water quality guidelines for the protection of aquatic life (CCME 2011*a*); OMOE = Interim provincial water quality objective (OMOE 1994).

Table 1. Water quality criteria for the eight parameters used in the CCME Water Quality Index (WQI) calculations. Source: Ontario Ministry of the Environment and Climate Change

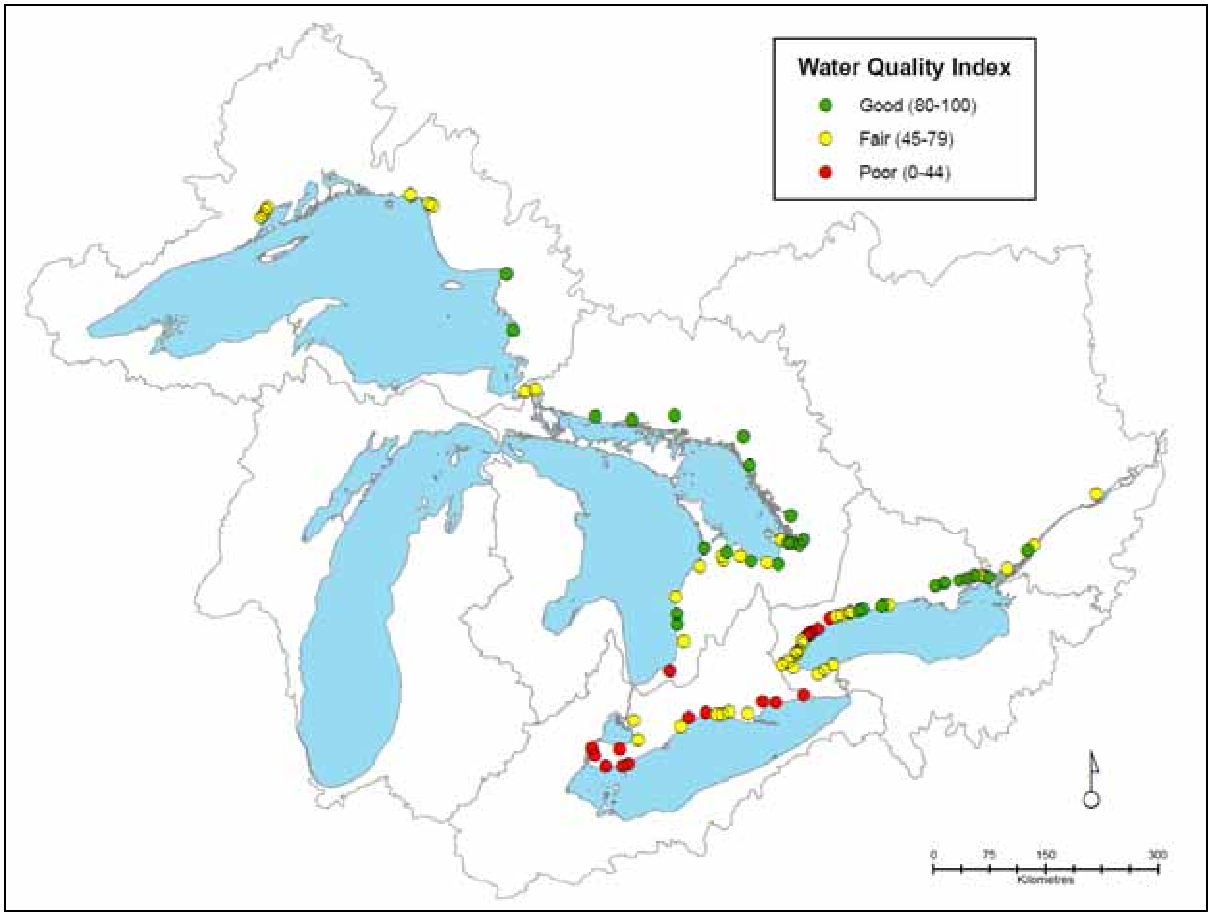


Figure 1. CCME Water Quality Index (WQI) values for 92 Canadian tributaries to the Great Lakes. Source: Ontario Ministry of the Environment and Climate Change

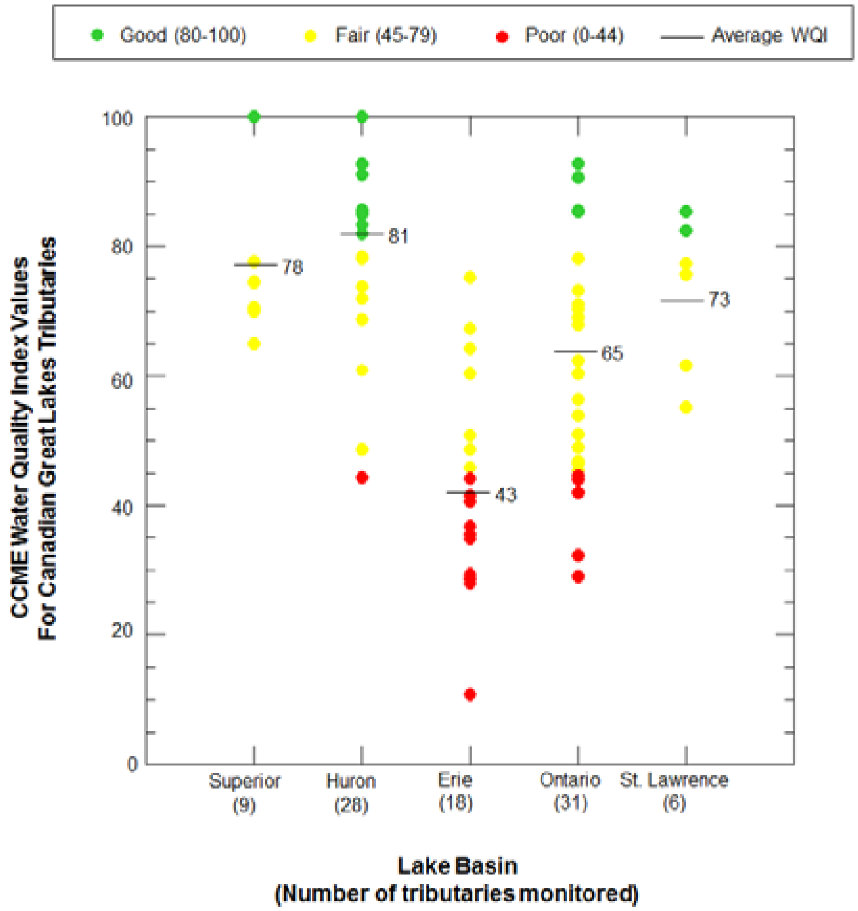


Figure 2. CCME Water Quality Index (WQI) values for 92 Canadian Great Lakes tributaries by lake basin. Source: Ontario Ministry of the Environment and Climate Change

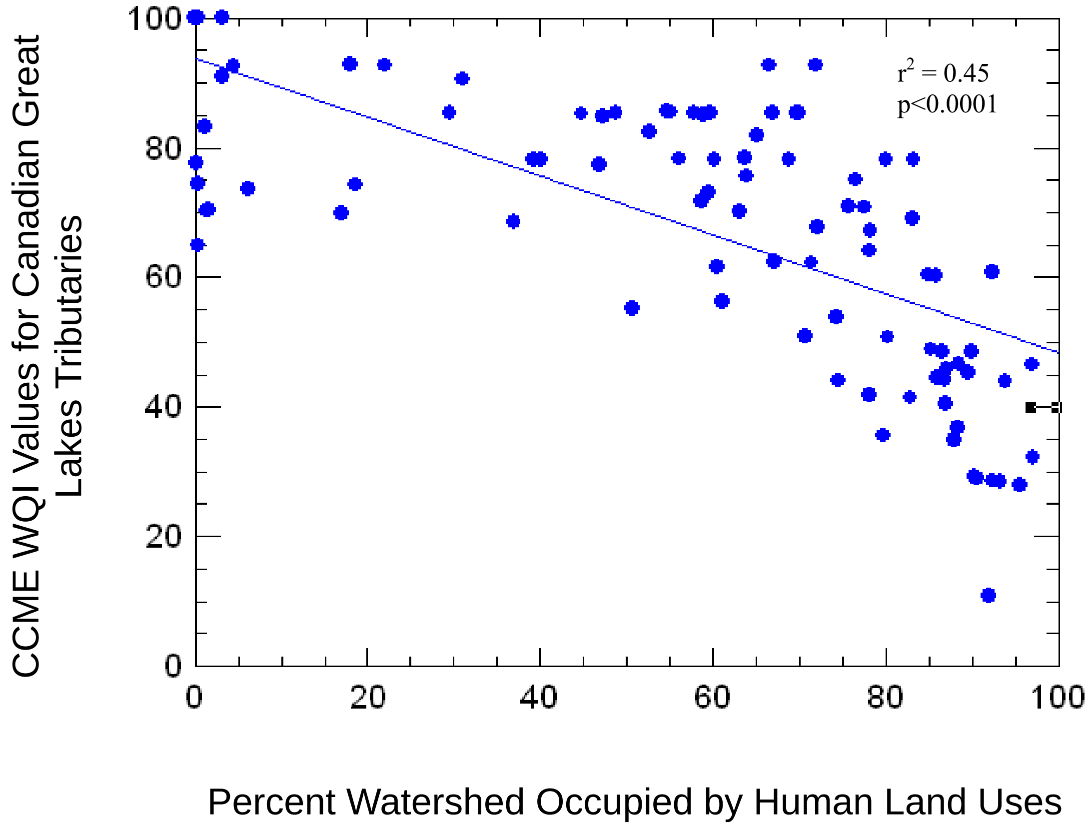
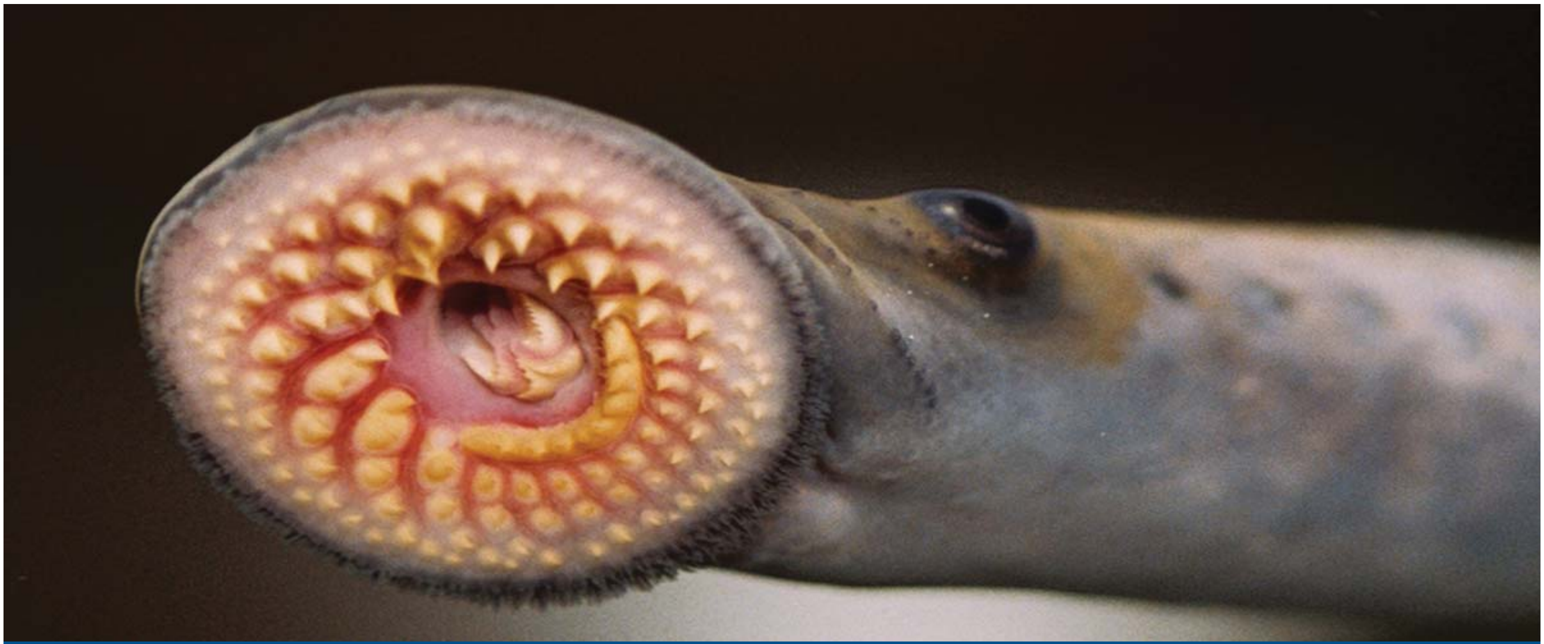


Figure 3. CCME Water Quality Index (WQI) values for Canadian Great Lakes tributaries (n=92) versus percent watershed occupied by human land uses.
Source: Ontario Ministry of the Environment and Climate Change



Invasive Species

Status: Poor   Trend: Deteriorating

The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes"*

The number of new invasive species entering the Great Lakes has been significantly reduced; however, those invasive species already in the Great Lakes such as Sea Lamprey, Zebra Mussels and Purple Loosestrife continue to cause more than $100 million annually in economic impacts in the U.S. alone.

Invasive Species

Assessment Highlights

The Invasive Species indicator highlights that the spread and impact of aquatic and terrestrial invasive species continues to be a significant stress to biodiversity in the Great Lakes region. As such, the Invasive Species indicator is assessed as **Poor** and the trend is **Deteriorating**.

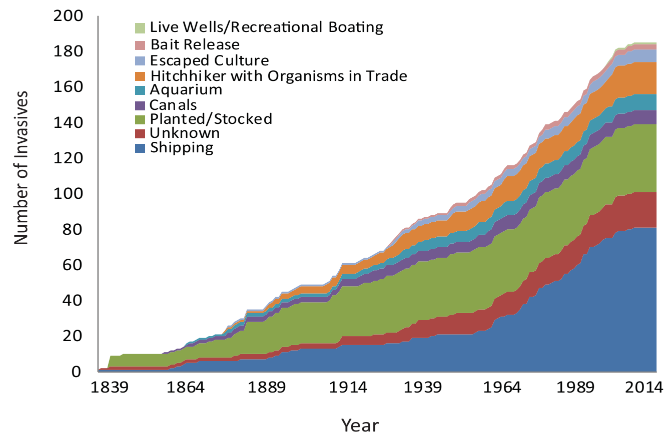
To date, over 180 aquatic non-native species have become established in the Great Lakes Basin. Only **one** new non-native species has been discovered since 2006, a zooplankton called *Thermocyclops crassus*. This tremendous success in reducing the introduction of invasive species is largely due to the regulation of ballast water from trans-oceanic ships. Additionally, the Asian carp species established in the Mississippi River, which are threatening the Great Lakes, have not become established. This success is attributed to the important prevention efforts in both countries, including the U.S. Army Corps of Engineers electrical barrier on the Chicago Sanitary and Ship Canal.

Despite the significant slowdown in recent introductions, the impacts of established invaders persist and their ranges within the lakes are expanding. It is believed that at least 30% of the aquatic non-native species found in the Great Lakes have significant environmental impact.

For several decades, Sea Lamprey have been causing severe ecological impacts. However, Sea Lamprey abundance has been reduced significantly in the five lakes through active, on-going, and basin-wide control measures. But, native fish such as Lake Trout, Walleye and Lake Sturgeon are still subject to Sea Lamprey predation. Sea Lamprey remain an impediment to achieving critical fish community and ecosystem objectives and therefore continuation of and improvements to Sea Lamprey control are required.

Dreissenid mussels, also known as Zebra and Quagga Mussels, are prominent invasive species in the Great Lakes as well. In many offshore regions, Zebra Mussels have been displaced by increasing populations of Quagga Mussels. While in some nearshore regions, populations of both species seem to be stable or declining. Overall, dreissenids are a dominant component of the bottom-dwelling community. Consequently, they have played an instrumental role in the alteration of the zooplankton and phytoplankton communities as well as disrupting the nutrient cycle and increasing water clarity.

Aquatic Invasive Species - Establishments Have Slowed Down



On the land, terrestrial invasive species have a significant impact and continue to spread throughout the Great Lakes Basin. Five terrestrial invasive species were assessed collectively—*Phragmites*, Purple Loosestrife, Garlic Mustard, Emerald Ash Borer and Asian Long-horned Beetle. These species are widely distributed and their ranges appear to be expanding. All five of these species have a detrimental impact on the surrounding ecosystem, including degrading habitat and water quality.

Limiting the impact of existing invaders is critical. However, binational prevention efforts, including continuing early detection and rapid response programs, are where the biggest difference can be made to ensure the Great Lakes are healthy, safe and sustainable.

Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Impacts of Aquatic Invasive Species	Deteriorating	Deteriorating	Deteriorating	Deteriorating	Deteriorating
Dreissenid Mussels	Unchanging	Deteriorating	Deteriorating	Improving	Deteriorating
Sea Lamprey	Improving	Improving	Improving	Improving	Unchanging
Terrestrial Invasive Species	Deteriorating	Deteriorating	Deteriorating	Deteriorating	Deteriorating

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Impacts of Aquatic Invasive Species

Overall Assessment
Status: Poor
Trend: Deteriorating
Rationale: While new species have been prevented from entering the Great Lakes, those which are established are continuing to expand within the basin. Although no new aquatic nonindigenous species (ANS) have become established in the Great Lakes in nearly a decade, the impacts of established invaders persist and their ranges within the lakes are expanding resulting in a Poor status and Deteriorating trend. Great Lakes Aquatic Nonindigenous Species Information (GLANSIS) includes more than 15,000 records for species in new locations in the last decade. To date, 185 nonindigenous species have become established in the Great Lakes basin, however no new species are reported to have become established since 2006 (GLANSIS 2015). Parrot feather (*Myriophyllum aquaticum*) was established in Meserve Lake, IN (within the Lake Michigan drainage) in 2006, but has not been reported elsewhere within the basin. This species was an escaped ornamental pond plant. Bloody red shrimp (*Hemimysis anomala*) was reported for the first time in the Great Lakes in 2006 in Lake Michigan, however surveys done that same year found the species to already be widespread (with populations in Lakes Michigan, Erie and Ontario) throughout the Great Lakes; introduction of this species is attributed to ballast water. Note that one new species, *Thermocyclops crassus*, was discovered in Lake Erie in 2016, after the analysis done for this report. Examination of archived samples by EPA scientists place our current best estimate for the introduction of *Thermocyclops crassus* as 2014 and revises the total number of species to 186.

Lake-by-Lake Assessment
Lake Superior
Status: Poor
Trend: Deteriorating
Rationale: Lake Superior is the site of greatest ballast water discharge in the Great Lakes, but this pathway has led to comparatively few direct ANS establishments (Grigorovich et al. 2003). Intrabasin movement of ANS is likely to be of greater consequence. Species established within the Great Lakes basin continue to expand their ranges into and within Lake Superior. GLANSIS records 19 species as new introductions to Lake Superior within the last decade although these species were already present elsewhere in the Great Lakes (some likely reflect reporting time lags). Records indicate range expansion within the Superior basin accounting for 67 species in the same period. Many of these represent significant expansions of high impact species. Since 2010, only two new nonindigenous species have been identified in Lake Superior; the deadly infectious fish disease (i.e. VHS) was discovered in 2010; the Banded Mystery Snail was detected and reported in 2015. Note that addition of Banded mystery snail (*Viviparus georgianus*) in Lake Superior in 2016 (back dated to a 2014 introduction), reported after the analysis for this report, would revise the number of new introductions to Lake Superior within the last decade to 20 – but the entire dataset was not re-analyzed systematically (additional species may also have expanded ranges and/or introduction dates may have been revised).

Lake Michigan
Status: Poor
Trend: Deteriorating
Rationale: Species established within the Great Lakes basin continue to expand their ranges into and within Lake Michigan. No new species have been reported for Lake Michigan since 2009. GLANSIS records more than 30 species as first reported in the Lake Michigan watershed within the last decade (some likely reflect reporting time lags), most recently Brittle Waternymph (*Najas minor*) and red swamp crayfish (*Procambarus clarkia*) in 2009. Records indicate range expansion within the Lake Michigan basin recording 86 species in the same period. Many of these represent significant expansions of high impact species.

Lake Huron
Status: Poor
Trend: Deteriorating

Rationale: Species established within the Great Lakes basin continue to expand their ranges into and within Lake Huron. GLANSIS records 23 species as first reported in Lake Huron within the last decade (some likely reflect reporting time lags), most recently Chain Pickerel (*Esox niger*) in 2015 and Tubenose Goby (*Proterorhinus semilunaris*) in 2012. Records indicate range expansion within the Lake Huron basin (including the St. Marys River) recording 54 species in the same period. Many of these represent significant expansions of high impact species.

Lake Erie
Status: Poor
Trend: Deteriorating
Rationale: Species established within the Great Lakes basin continue to expand their ranges into and within Lake Erie. GLANSIS records 29 species as first reported in Lake Erie within the last decade (some likely reflect reporting time lags), most recently a parasitic copepod (*Neoergasilus japonicus)* in 2011. Records indicate range expansion within the Lake Erie basin recording 76 species in the same period. Many of these represent significant expansions of high impact species. Note that the addition of *Thermocyclops crassus* (back-dated to 2014, but discovered after the analysis for this report was complete) would revise the number of species first reported in Lake Erie within the last decade to 30 – but the entire dataset was not re-analyzed systematically (additional species may also have expanded ranges and/or introduction dates may have been revised).

Lake Ontario
Status: Poor
Trend: Deteriorating
Rationale: Species established within the Great Lakes basin continue to expand their ranges into and within Lake Ontario. GLANSIS records 19 species as first reported in Lake Ontario within the last decade (some likely reflect reporting time lags), most recently Tubenose goby *(Proterorhinus semilunaris)* in 2011. Records indicating range expansion within the Lake Ontario basin (including the Niagara River) have been recorded for 79 species in the same period. Many of these represent significant expansions of high impact species.

Lake St-Clair, Detroit and St. Clair Rivers
Status: Poor
Trend: Deteriorating
Rationale: Species established within the Great Lakes basin continue to expand their ranges into and within Lake St. Clair (including the Detroit and St. Clair Rivers). GLANSIS records 26 species as first reported in this corridor within the last decade (some likely reflect reporting time lags), most recently Yellow Floating Heart *(Nymphoides peltata)* in 2015, Western Mosquitofish (*Gambusia affinis*) in 2013, Chinese Mystery Snail (*Cipangopaludina chinensis*) in 2012, and faucet snail (*Bithynia tentaculata*) in 2011. Records indicating range expansion within the Lake St. Clair corridor have been recorded for 48 species in the same period. Many of these represent significant expansions of high impact species.

Sub-Indicator Purpose
The purpose of this sub-indicator is to assess the presence, number, distribution and impact of aquatic invasive species (AIS) in the Laurentian Great Lakes. The rate of invasion will also be measured as the number of new AIS arriving in the Great Lakes since the last assessment, a retrospective analysis to identify the likely pathway by which the species arrived, and an evaluation of the longer record to quantify any trend in the rate of invasion.

Ecosystem Objective
The goal of the Great Lakes Water Quality Agreement is to restore and maintain the biological integrity of the Great Lakes Ecosystem. Fundamental to this goal is to control existing, and prevent further introduction of, aquatic invasive species.

This sub-indicator best supports work towards General Objective #7 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes."

Ecological Condition

Background

The National Oceanic and Atmospheric Administration (NOAA) currently reports a total of 186 established Great Lakes ANS (plus at least 17 species native to some part of the basin which have expanded their ranges to other parts).

In the Great Lakes, transoceanic ships (including solid ballast, packing materials, ballast water and ballast residuals) have been the primary invasion vector responsible for 44% of the total established ANS. Historically, deliberate introductions (stocking fish and agricultural/horticultural plants) have been a significant vector (21%) and both accidental releases and hitchhikers with such organisms in trade (e.g., parasites, diseases, contaminants in shipments) have also been significant vectors (10% and 5%, respectively).

During the 1980s, the importance of ship ballast water as a vector for ANS introductions was recognized, prompting ballast management measures in the Great Lakes. In the wake of Eurasian ruffe and zebra mussel introductions, Canada introduced voluntary ballast exchange guidelines in 1989 for ships declaring “ballast on board” (BOB) following transoceanic voyages; this action followed recommendations by the Great Lakes Fishery Commission and the International Joint Commission. In 1990, the United States Congress passed the Nonindigenous Aquatic Nuisance Prevention and Control Act, producing the Great Lakes’ first ballast exchange and management regulations in May of 1993. The National Invasive Species Act (NISA) followed in 1996. Following initiation of voluntary guidelines in 1989 and mandated regulations in 1993, the overall rate of Great Lakes invasion did not decline until recently (Grigorovich et al. 2003; Holeck et al. 2004; Ricciardi 2006). However, more than 90% of transoceanic ships that entered the Great Lakes during the 1990s declared “no ballast on board” (NOBOB; Colautti et al. 2003; Grigorovich et al. 2003; Holeck et al. 2004) and were not required to exchange ballast, despite their tanks containing residual sediments and water that could be discharged in the Great Lakes. Residual water and sediment in these ships were found to contain several species previously unrecorded in the basin; such species could be discharged after the ship undergoes sequential ballasting operations as it travels between ports within the Great Lakes to offload and take on cargo (Duggan et al. 2005, Ricciardi and MacIsaac 2008). In June 2006, Canada implemented new regulations for the management of residuals contained within NOBOB tanks and requires the salinity of all incoming ballast water to be at least 30 parts per trillion (Government of Canada 2006). In the decade since, we have seen no new ballast water ANS introductions (the last being *Hemimysis anomala,* collected in May 2006) despite a fairly steady number of NOBOB transits. Ballast water regulation appears to have been largely successful in preventing new introductions from this vector – there has been only one new introduction attributed to this vector in the last decade (2006-2015); in comparison there were 9 introductions attributed to this vector in the previous decade (1996-2005) and 18 in the decade prior to that (1986-1995). However, ballast water movement within the basin, which is not currently regulated, may pose a relatively high risk of spreading ANS (Casas-Monroy et al. 2014).

Second to shipping, release, transfer, and escape have introduced ANS into the Great Lakes. Of particular concern are private sector activities related to aquaria, garden ponds, baitfish, and live food fish markets. Silver and bighead carp escapees from southern United States fish farms have developed large populations in the middle and lower segments of the Illinois River, which connects the Mississippi River to Lake Michigan via the Chicago Sanitary and Ship Canal (CSSC). A prototype electric barrier on the CSSC was activated in April 2002 to block the transmigration of species between the Mississippi River system and the Great Lakes basin. The U.S. Army Corps of Engineers (partnered with the State of Illinois) completed construction of the second and third permanent barriers in 2005 and 2011, respectively. Since 2009, environmental DNA (eDNA) surveillance has been used to complement the use of traditional monitoring and suppression tools. Between 2009 and 2010, DNA of both bighead and silver carp was detected past the electric barriers; however, only a single bighead carp was subsequently found (Lake Calumet, June 2010). As of August of the 2011 monitoring year, only silver carp DNA had been detected on the lake side of these barriers for that year; despite an intensive sampling effort in response to three consecutive rounds of positive eDNA tests in the Lake Calumet area, no Asian carp were seen or captured. Nearly a million Asian carp, including bighead and black carp, are sold annually at fish markets within the Great Lakes basin. Until recently, most of these fish were sold live. All eight Great Lakes states and the province of Ontario now have some restriction on the sale of live Asian carp. Enforcement of many private transactions, however, remains a challenge. The U.S. Fish and Wildlife Service published a final rule in March 2011, officially adding the bighead carp to the federal injurious wildlife list and codifying the Asian Carp Prevention and Control Act. Bighead, silver, and black carp are now listed as nuisance species under the Lacey Act, prohibiting interstate transport. There are currently numerous shortcomings in legal safeguards relating to commerce in exotic live fish in Great Lakes and Mississippi River states, Quebec, and Ontario, as identified by Alexander (2003). These include: express and de facto exemptions for the aquarium pet trade; de facto exemptions for the live food fish trade; inability to proactively enforce import bans; lack of inspections at aquaculture facilities; allowing aquaculture in public waters; inadequate triploidy (sterilization) requirements; failure to regulate species of concern (e.g., Asian carp); regulation through "dirty lists" only (e.g., banning known nuisance species); and failure to regulate transportation.

Status

The total number of ANS introduced and established in the Great Lakes increased steadily from the 1830s to 2006, but has stabilized in the last decade (Figure 1). Although there have been 34 invasions since the GLWQA was signed in 1987, no **new** species have been discovered since 2006. However, species introduced in the previous decades continue to spread – each of the Great Lakes has seen new species become established in its waters in the last decade (ranging from 19 new species for Superior to 30 for Lake Michigan) and nearly every watershed in the entire basin has seen at least one new species in that decade.

A NOAA-developed impact assessment tool (NOAA 2014 was applied to 182 of the Great Lakes' established ANS. Briefly, this questionnaire-style assessment considered three main categories of impact: environmental, socio-economic, and beneficial. Scores under criteria for each impact category were determined based on literature review and expert evaluation, with the results assigned a qualitative score of High, Moderate, Low, or Unknown. At least 31% of the nonindigenous species found in the Great Lakes have significant (moderate to high) environmental impact, as seen in Figure 3. While substantially higher than the often cited estimate of '10% of established nonindigenous species have significant impacts' this estimate is likely also an under-estimate of the true environmental impact. If the 88 species which are currently unable to be fully assessed (due to lack of data) follow the trends of the assessed species this number will be closer to 60%. While less substantial, socio-economic impacts are also likely higher than the 10% figure–we estimate between 14 and 16% of the nonindigenous species found in the Great Lakes have moderate to high socio-economic impact (NOAA 2014).

The overall economic impact of ANS on the Great Lakes region—spanning direct operating costs, decreased productivity, and reduced demand within sport and commercial fishing, power generation, industrial facilities, tourism and recreation, water treatment, and households—is estimated at well over $100 million annually (Rosaen et al. 2012). This figure includes both basinwide efforts such as that of Great Lakes Fishery Commission's sea lamprey control program, with an annual budget of about $18 million, and local responses, such as the $1,040-$26,000 cost per acre of Eurasian watermilfoil removal (Rosaen et al. 2012). Economic impacts from dreissenid mussel control and monitoring are estimated at $1.2 million annually per power plant, $1.97 million for removal of 400 cubic yards at a paper plant, and $480,000-$540,000 annually at a water treatment plant (Rosaen et al. 2012).

Linkages

Invasion Meltdown: Evidence indicates that newly invading species may benefit from the presence of previously established invaders. That is, the presence of one ANS may facilitate the establishment or population growth of another (Ricciardi 2001). For example, the sea lamprey (*Petromyzon marinus*) may have created enemy-free space that facilitated the alewife's (*Alosa pseudoharengus*) invasion, and the round goby (*Neogobius melanostomus*) and *Echinogammarus ischnus* (amphipod) have thrived in the presence of previously established zebra (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*). In effect, dreissenids have set the stage to increase the number of successful invasions, particularly those of co-evolved species in the Ponto-Caspian assemblage. This result may be a critical factor contributing to the continued spread of species across lakes within the Great Lakes system.

Multi-stressors: Changes in water quality, global climate change, and land use also may make the Great Lakes more hospitable for the arrival of new invaders. We are particularly concerned that climate change may be facilitating the northward spread of both invasive species and the spread of native species into adjacent habitats to which they are not native (e.g., range expansion).

Secondary Shifts in Native Populations: ANS may exert significant direct and indirect pressures upon native species including facilitation of parasitism, transmission of viral/bacterial infections, magnification of toxins, competition, food-web alteration, genetic introgression, degradation of water quality, and degradation of physical habitat. ANS have promoted the proliferation of native nuisance species, including green algae (*Cladophora*); cyanobacteria (Skubinna et al. 1995; Vanderploeg et al. 2001), and bacteria (botulism).

The potential for ANS to colonize new locations is increased with removal of dams. In contrast, ecological separation of the Great Lakes from the Mississippi River basin is currently being discussed as a way to limit transfer of ANS between these basins.

Many nonindigenous plants are capable of forming dense mats that may exclude fish from nearshore habitats. Colonization of lakebed areas by dreissenid mussels and the consequent filling of remaining interstitial spaces with pseudofeces and fine-grained sediments led to the exclusion of lake trout from some of their native spawning grounds (S. Mackey, Habitat Solutions NA, pers. comm.).

Comments from the Author(s)
ANS have invaded the Great Lakes basin from regions around the globe. Increasing world trade and travel elevates the risk that additional species will continue to gain access to the Great Lakes. Existing connections between the Great Lakes watershed and systems outside the watershed, such as the Chicago Sanitary and Ship Canal, and growth of industries such as aquaculture, live food markets, and aquarium retail stores will also increase the risk that new ANS will be introduced. New vectors may arise as the face of industry in the region changes. Climate change may also facilitate the northward migration of species as well as altering habitat in a way that favors some invaders over natives or alters their impacts. Increasing lake temperatures associated with climate change will lead to increased potential for ANS introduced from warmer climates to establish overwintering populations (Adebayo et al. 2011; Mandrak 1989). The rate of invasion may increase if positive interactions involving established ANS or native species facilitate the establishment of new ANS. Each new invader can interact in unpredictable ways with previously established invaders, potentially creating synergistic impacts (Ricciardi 2001, 2005). For example, recurring outbreaks of avian botulism in the lower Great Lakes are thought to result from the effects of dreissenid mussels and round gobies, in which the mussels create environmental conditions that promote the pathogenic bacterium and the gobies transfer bacterial toxin from the mussels to higher levels of the food web.

Data on range expansion populations (those native or cryptogenic to a portion of the basin but introduced to other areas of the basin) is currently still lacking – GLANSIS tracks only 12 such species (mostly those that invaded the upper lakes via the Welland Canal. More monitoring data will be needed to assess potential expansion of these populations due to climate change.

Authors of the previous report recommended additional discussion of prevention, spread and control options for ANS. We have made a preliminary attempt to include information here on spread and impact as indicators of ecosystem pressure. While GLANSIS has begun to serve information on regulation and control options (pending NOAA Tech Memo 2015) that remains beyond the scope of this report in that it would shift the focus to one of response.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		X				
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin		X				
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				

6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				

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Source: GLANSIS

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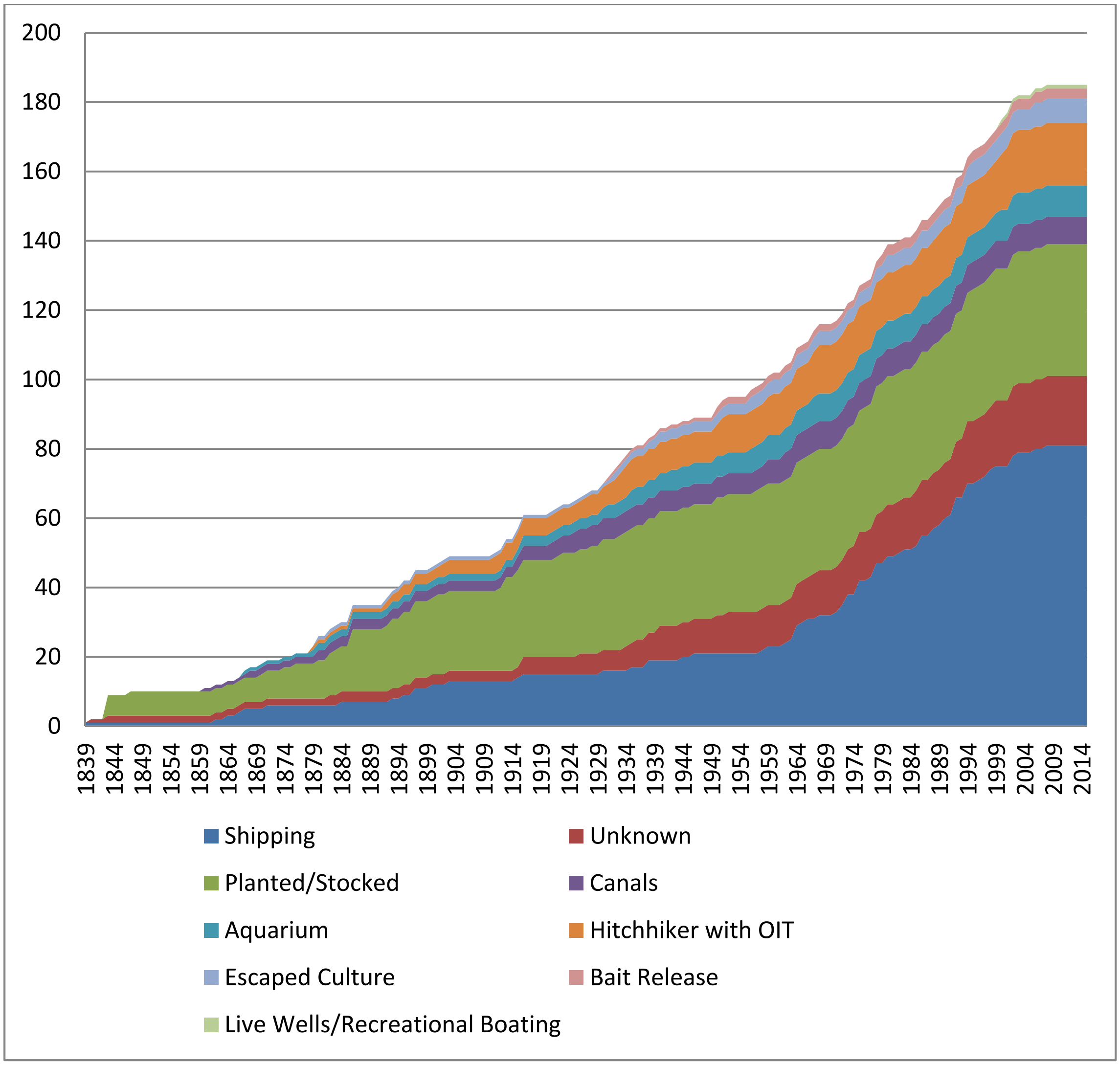

Figure 1. Cumulative Invasions to the Great Lakes Basin by Vector. OIT – Organisms in Trade.
Source: GLANSIS

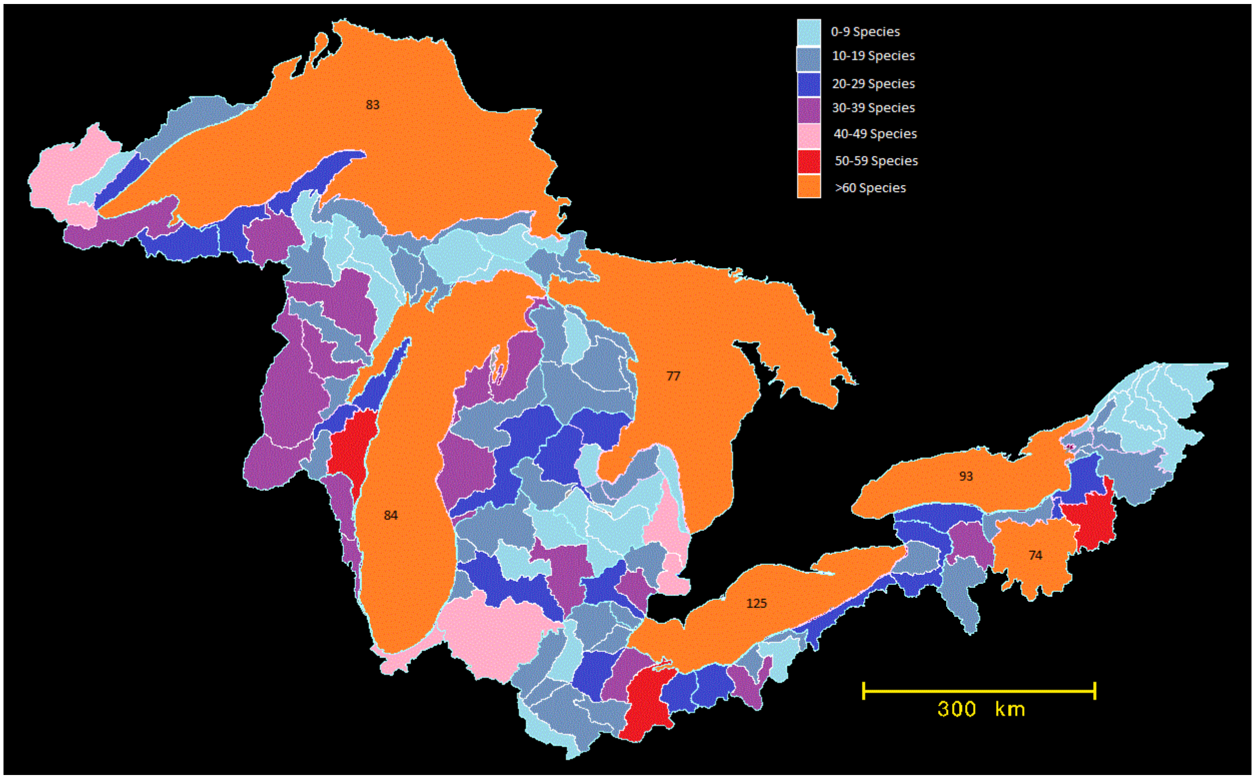

Figure 2. Number of AIS Present in the Great Lakes Basin for each lake.
Source: GLANSIS

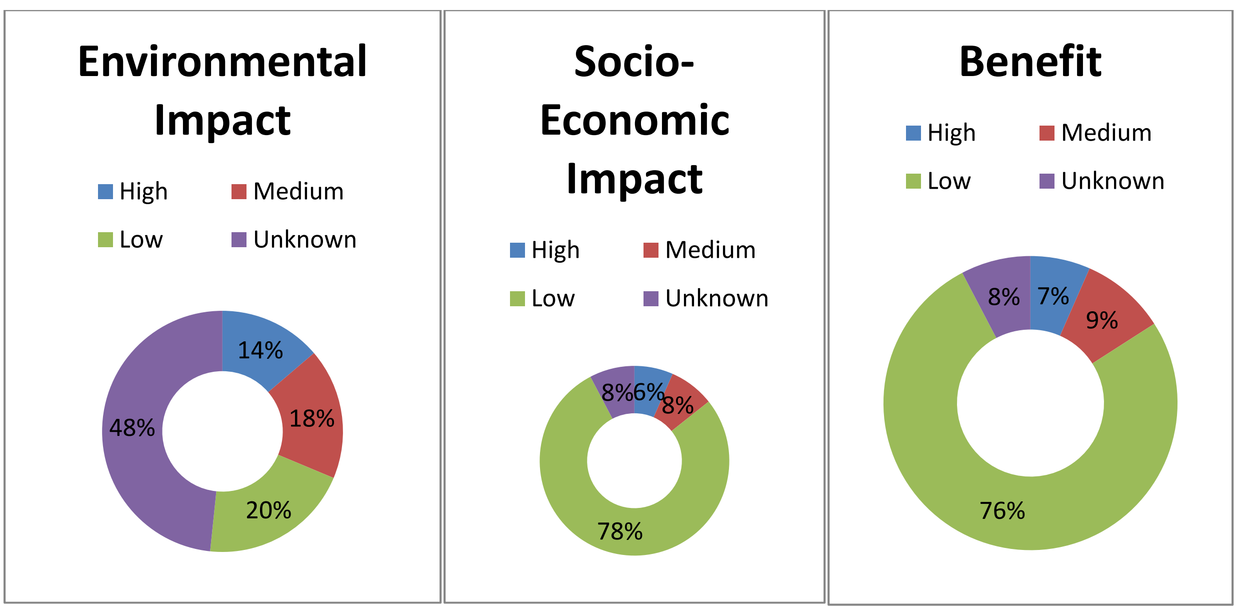

Figure 3. Environmental and Socio-Economic Impact and Benefit of AIS
Source: GLANSIS

Sub-Indicator: Dreissenid Mussels

Overall Assessment
Status: Poor
Trend: Deteriorating
Rationale: Over all the lakes, the status of dreissenid mussel populations varies depending upon the water depth and particular lake region. In general, populations in lakes Michigan, Huron, and Ontario appear to have stabilized or are decreasing at depths < 90, but are gradually increasing in offshore regions at depths > 90 m. The deep zone appears to be a continuing invasion front for quagga mussels, though the rate of population growth is slower than what was observed in more shallow depths. These assessments are mostly based on lake-wide surveys conducted every 5 years. In these three lakes, quagga mussels have displaced zebra mussels except in shallow, nearshore areas and bays. Because the offshore region of these lakes (> 90 m) comprises a relatively large proportion of total lake area and quagga mussels are still expanding in this region, the overall status would indicate a deteriorating status. It is also worth noting that although mussel biomass has been declining in some of the lakes in the 30-90 m depth zone, dreissenid mussels remain a dominant component of the benthos. Depending on the lake basin, dreissenid populations in Lake Erie are stable or declining, while populations in Lake Superior remain at low levels. In regions of all the lakes where populations are stable or declining, it is not clear if mussel impacts are becoming less severe. Population trends are mostly derived from density estimates, but biomass estimates give a better evaluation of trends. However, biomass estimates are often not available, or methods of determination are not consistent. Herein, trends in biomass are given only when estimates are temporally consistent. Further, assessments are limited to the main basins of the lakes and exclude the connecting channels. There are few, if any, regular monitoring programs in the connecting channels and, even so, physical factors such substrate variability, current patterns, etc. do not provide the best conditions to assess temporal trends in populations. In the main lake basins, emphasis will be placed on trends at depths > 30 m. Wide variations in populations occur at shallower depths making assessments of temporal trends difficult. Finally, since lake-wide assessments are mostly based on surveys every 5 years, temporal trends can be considered mainly at this level of detail. Some regional assessments are made on an annual basis, and these are included if data are available.

Lake-by-Lake Assessment

Lake Superior

Status: Good
Trend: Unchanging
Rationale: Zebra mussels were first found in Duluth-Superior Harbor in 1989, and quagga mussels were subsequently found in the same area in 2005. Since then, the spread and population growth of both dreissenid species has been minimal. Both species are most abundant in the Duluth Harbor area or just outside the harbor in the immediate vicinity of nearshore Lake Superior. Mussels have spread from the Duluth Harbor region. Some zebra mussels were found in the east side of the lake in Whitefish Bay in 2002, and in a bay of Isle Royale in 2009. It is believed that calcium concentrations in Lake Superior are too low to support high abundances.

Lake Michigan

Status: Poor
Trend: Deteriorating
Rationale: The status of dreissenid populations in Lake Michigan is routinely assessed by two major surveys. One survey is conducted over the entire lake every 5 years, while the other survey is conducted in the southern basin on a yearly basis. The last 5-year survey with reported results was in 2010. When densities in 2010 were compared to densities in 2005, the dreissenid population (all quagga) at 31-90 m appeared to have stabilized (Figure 1), but the population at > 90 m continued to increase (Figure 2). More recent data on density and biomass from the annual survey in the southern basin indicate populations are now in the state of decline at 30-90 m (Figures 3 and 4). Density also shows a slight decline at > 90 m since 2012 (Figure 3), but biomass seems to be holding relatively steady (Figure 4), indicating that mean biomass per mussel (i.e., mean size) is increasing at these greater depths. Despite declines at sites in the 31-90 m interval, the quagga mussel population still well exceeds maximum densities previously reached by zebra mussels in that interval. A lake-wide survey was conducted in 2015 (5 years since 2010) and future results will confirm whether these patterns are apparent throughout the entire lake.

Lake Huron

Status: Poor

Trend: Deteriorating

Rationale: The last lake-wide survey of dreissenid populations in Lake Huron occurred in 2012. Between 2007 and 2012, dreissenid densities (all quagga) appear to have stabilized at 31-90 m, but are still increasing at > 90 m (Figures 1 and 2). At the former depth interval, decreased densities at 31-50 m were compensated by increased densities at 51-90 m (Figure 5). In Georgian Bay, densities at 31-90 m decreased two-fold between 2007 and 2012, while mussels were not present in North Channel at the sites sampled, which is similar to the finding in 2007.

Lake Erie

Status: Fair

Trend: Improving

Rationale: An update on trends in dreissenid populations in Lake Erie was provided by Karatayev et al. (2014). In 2009-2012, zebra mussels were rarely found outside of the western basin, and even there it comprised only 30 % of the total dreissenid density. Overall, lake-wide densities of dreissenids were lower in 2009-2012 compared to 2002, which is a continuation of a trend first observed between the late 1990s and 2002.

The lake-wide decrease was mostly a function of decreases in the eastern basin. In this basin, mean densities were about 9,000 m^{-2} in 2002 but only 442 m^{-2} in 2009-2012. Historically, densities in the eastern basin tended to be greater than in the western and central basins, but in 2012, the eastern basin densities dropped below those observed in the western basin. Potential explanations included food limitation, predation by round goby, and sampling site bias, but none have been demonstrated definitively (Karatayev et al. 2014).

Populations in the central basin are limited because of seasonal hypoxia.

Populations in the western basin are limited because of poor food quality (cyanophytes, inorganic particulates). Based on annual USGS surveys in just the western basin, the dreissenid population appears to be stable, with annual densities fluctuating around 1,000 m^{-2} since 2006 (Figure 6). Also, while quagga mussels have displaced zebra mussels as the dominant dreissenid species, the percentage of sampled sites with dreissenids present has fluctuated around a mean level since the early 2000s, indicating the total population is not spatially expanding within the western basin (Figure 6).

Lake Ontario

Status: Poor

Trend: Deteriorating

Rationale: The last lake-wide survey of dreissenid populations in Lake Ontario occurred in 2013. Dreissenid densities (all quagga) at 31-90 m were lower in 2013 compared to densities in 2008 (Figure 1). Densities at this depth interval appear to have peaked in 2003. On the other hand, the population at > 90 m still seems to be expanding as densities at these deep depths in 2013 were the highest ever recorded (Figure 2). While densities at 31-90 m were lower in 2013 compared to 2008, biomass was slightly higher. Mean biomass was 31.2 g m^{-2} in 2013 compared to 19.3 g m^{-2} in 2008. This can be attributed to the greater mean size of mussels in the former year.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess the population status of the invading *Dreissena rostriformis bugensis* (quagga mussel) and *Dreissena polymorpha* (zebra mussel) in the Great Lakes.

Ecosystem Objective

Dreissenids are actively changing the integrity of Great Lakes ecosystems by altering nutrient and energy cycling, promoting nuisance algal blooms and benthic algae, and negatively impacting native species of invertebrates and fish. Such changes to ecosystem integrity create uncertainty in effective resource management. Thus, the sub-indicator addresses the objective of maintaining healthy and sustainable ecosystems.

This sub-indicator best supports work towards General Objective #7 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes."

Ecological Condition

Dreissenid populations in the Great Lakes are presently in various stages of change. In many offshore regions, populations are increasing, but in some nearshore regions populations seem to be stable or declining. While some year-to-year variability can be expected, a goal of this sub-indicator is to determine at what level of abundance/biomass populations become stable and at equilibrium with the surrounding environment. Such levels, along with associated degrees of uncertainty, can then be used in predictive models to better manage Great Lakes resources.

Many sampling efforts have sought to provide data on population abundances and biomass. While abundances are the most common reporting measure of population status, biomass is more valuable for assessing ecological impacts and for input to predictive models. Biomass is calculated from the soft tissue of these organisms. Some protocols call for separating soft tissue from shell and directly determining soft tissue weight, while others determine the size frequency of the populations (shell length) and infer tissue biomass based upon a predetermined relationship between shell length and soft tissue weight. Data used to obtain biomass with the latter protocol can also be used to assess population dynamics and predict the direction of populations over time. For example, a population with a large number of individuals and a size distribution skewed toward smaller individuals demonstrates high recruitment and possibly low survivability (or if survivability is not compromised then it may illustrate recent colonization). In contrast, populations showing a size-frequency distribution skewed towards larger individuals with fewer numbers suggests an aging population with relatively lower recruitment and greater survivability. Traditional population ecology suggests that stable populations move from a size-frequency distribution of low mean biomass towards one of higher mean biomass. As a population colonizes a new area, high resource availability promotes high recruitment. As resources are sequestered into the population, recruitment decreases with decreasing resource availability and mean biomass increases as fewer new (low biomass) individuals are added to the population and surviving members continue to grow.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Benthos (open water) – the relative abundance of the benthic community other than dreissenids can be affected by dreissenids.
- *Cladophora* – *Cladophora* is significantly influenced by increases in mussel populations and the corresponding state of water clarity and nutrients in the Great Lakes.
- *Diporeia* (open water) – *Diporeia* is an important component of the native benthic community that has been affected by dreissenids.
- Harmful Algal Blooms – the filtering and nutrient excretion activities of dreissenids may lead to increased frequency, distribution and severity of both inshore (attached/benthic) and offshore algal blooms and favour the predominance of cyanobacteria.
- Phytoplankton – the abundance and composition of phytoplankton has dramatically changed in areas of the Great Lakes where dreissenids have become abundant.

This sub-indicator also links directly to the other sub-indicators in the Invasive Species category, particularly Aquatic Invasive Species.

Comments from the Author(s)

Dreissenid mussels may be responsible for adverse impacts to several other indicators. Dreissenid mussels have directly or indirectly impaired native species and therefore have negatively impacted biological integrity. Further they have impaired several beneficial uses listed under Annex 2, (1) of the Great Lakes Water Quality Agreement including fish and wildlife consumption, and fish and wildlife populations. Aquatic invasive species, including dreissenid mussels, have been given a high priority in the renewed Water Quality Agreement. In 2014, the U.S. Invasive Mussel Collaborative (http://invasivemusselcollaborative.net/) was formed to advance scientifically-sound technologies to control invasive mussels. The Collaborative also aims to improve communication and coordination among researchers and resource managers.

Because of the rapid rate at which *Dreissena* populations have expanded in many areas, and because of the ability of dreissenids to cause ecosystem-wide changes, agencies committed to documenting trends should report data in a timely manner. Besides abundance, biomass should be routinely monitored. This allows comparisons across lakes and other food web components, and is most useful for predictive models. Since dreissenids are found on hard as well as on soft substrates, various sampling methods may be needed to truly assess population mass in a given lake or lake region, particularly in the nearshore.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		X				
5. Data obtained from sources within the U.S. are comparable to those from Canada						X
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Acknowledgments

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Figure 2. Mean densities (number per square metre) of *Dreissena* from sites at > 90 m in lakes Michigan, Huron, and Ontario. Data are from lake-wide surveys conducted mostly at 5-year intervals. Lake Michigan = blue triangles, dashed line; Lake Huron = red squares, dot-dash line; Lake Ontario = black circles, solid line. Sources: Watkins et al. 2007; Birkett et al. 2015; Great Lakes Environmental Research Lab, NOAA

Figure 3. Mean (± SE) density (number per square metre) of dreissenids at each of four depth intervals in southern Lake Michigan, 1992-2014. The number of sites in each depth interval was 16-30 m = 9-12, 31-50 = 11-13, 51-90 m = 11, > 90 m = 6. Zebra mussels = black; quagga mussels = blue. Two outlier stations were removed: H-14 in 2012 (31-50 m interval, density = 50201/m^2); and H-18 in 2013 (16-30 m interval, density = 45403/m^2). In both cases, one of the replicates contained >5000 newly settled mussels (length <1mm), which inflated density and standard error values.
Source: Great Lakes Environmental Research Lab, NOAA

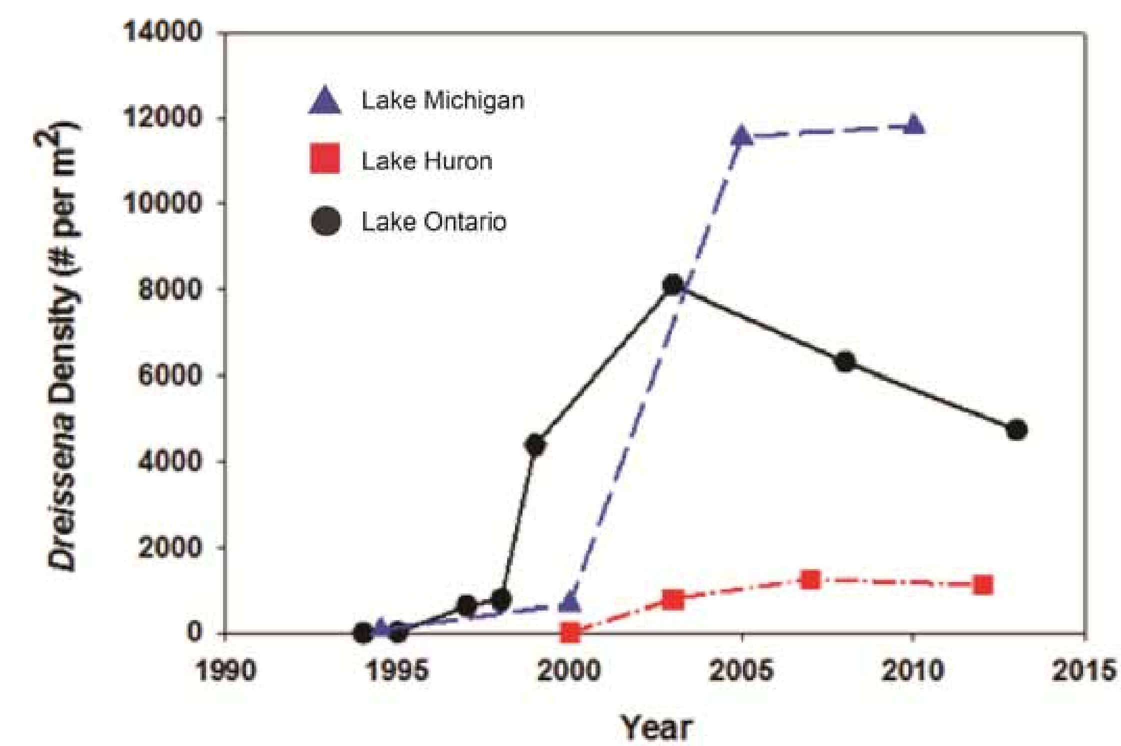
Figure 4. Mean (± SE) biomass (shell-free grams per square meter) of dreissenids at each of four depth intervals in southern Lake Michigan, 1998-2014. The number of sites in each depth interval was 16-30 m = 9-12, 31-50 = 11-13, 51-90 m = 11, > 90 m = 6. Zebra mussels = black; quagga mussels = blue.
Source: Great Lakes Environmental Research Lab, NOAA

Figure 5. Densities (No. m^3) of zebra (top) and quagga (bottom) mussels in Lake Huron from 2000-2012.
Source: Nalepa et al. (in prep)

Figure 6. Percentage of sites with *Dreissena* (top panel) and mean density of *Dreissena* (number per square metre) (bottom panel) in western Lake Erie, 1991-2013; n=30. Zebra mussels = blue squares; quagga mussels = black circles.
Source: Great Lakes Science Center, USGS

Last Updated

State of the Great Lakes 2017 Technical Report



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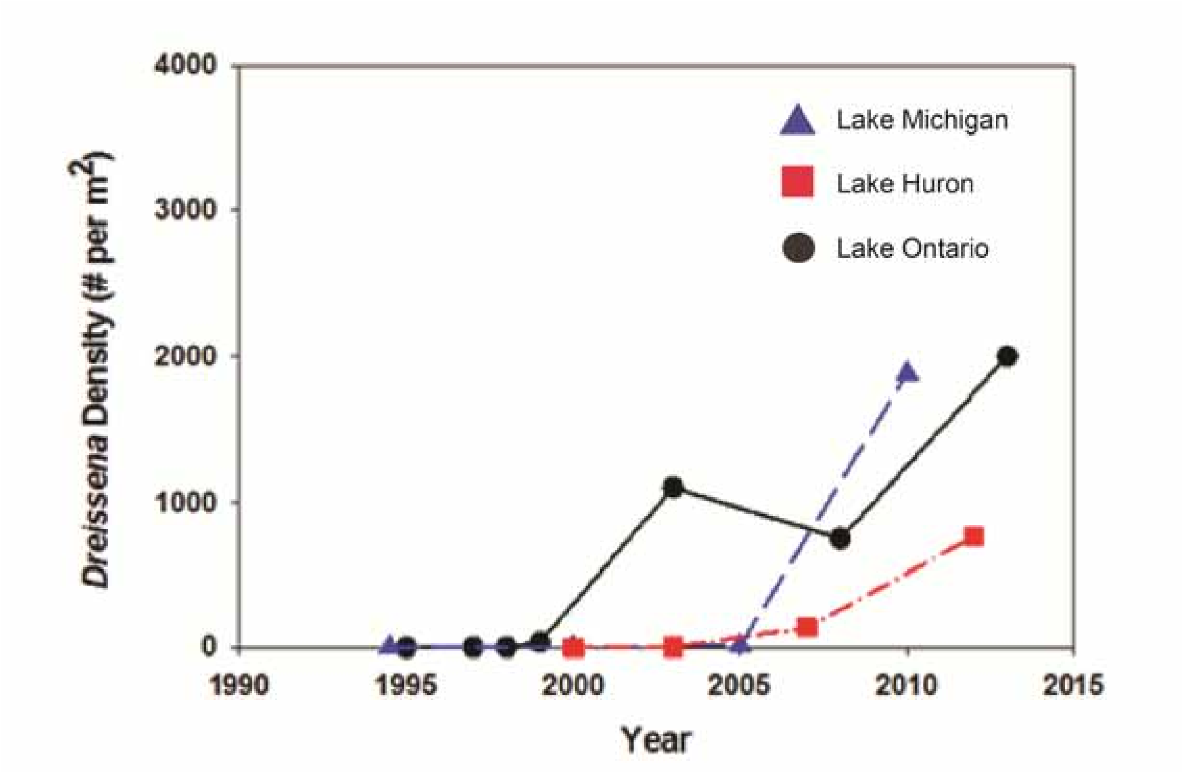

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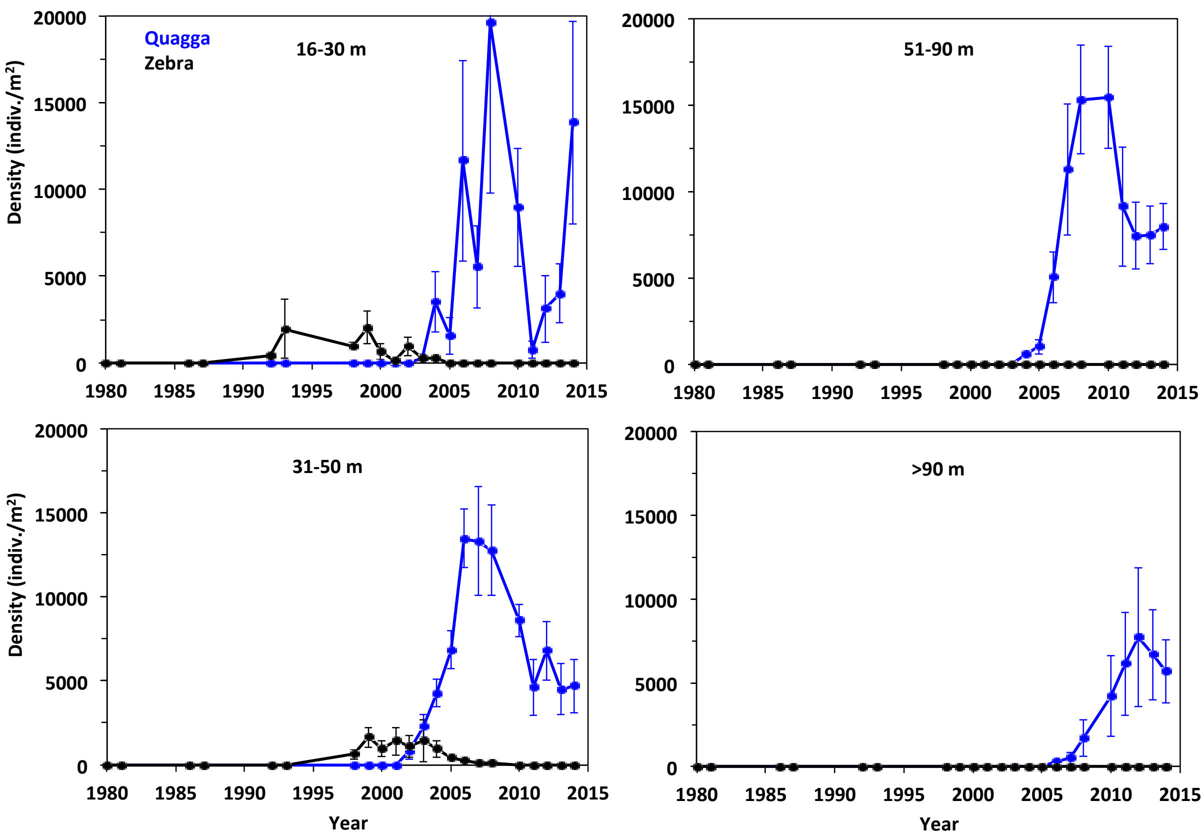

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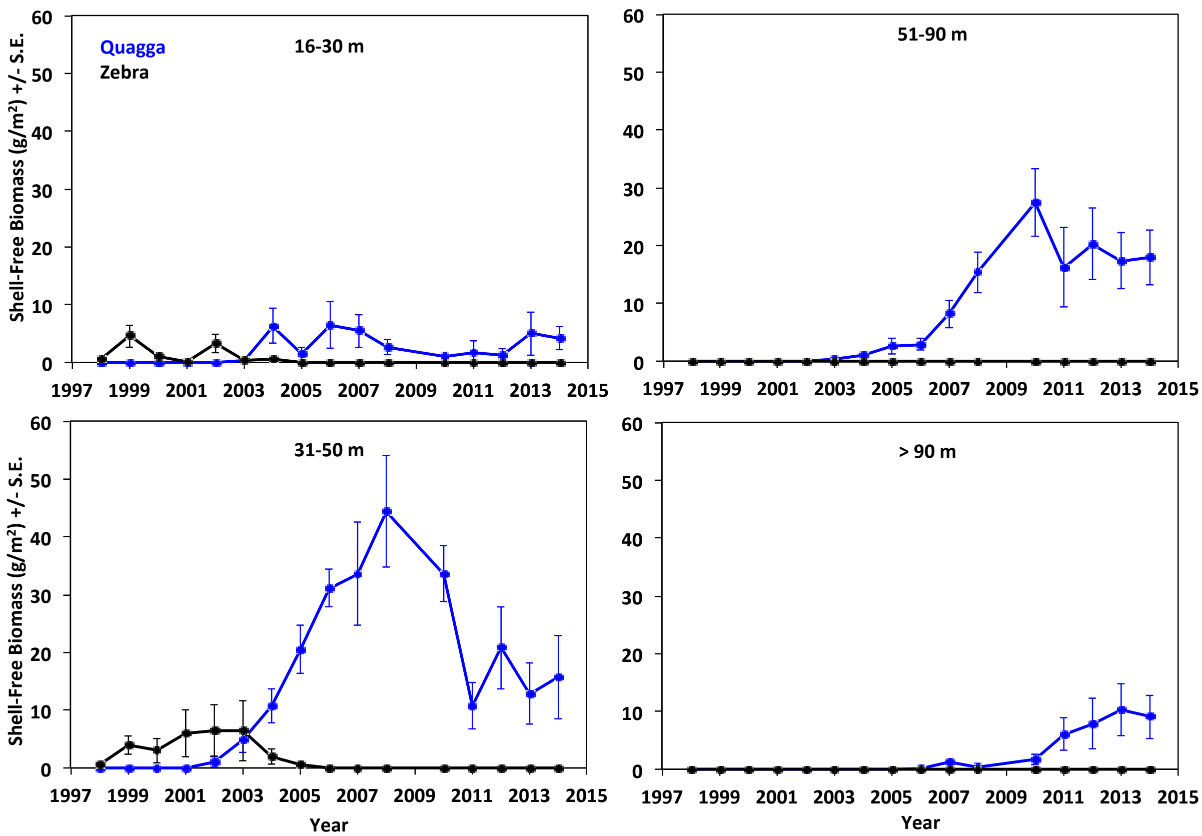
Source: Great Lakes Environmental Research Lab, NOAA



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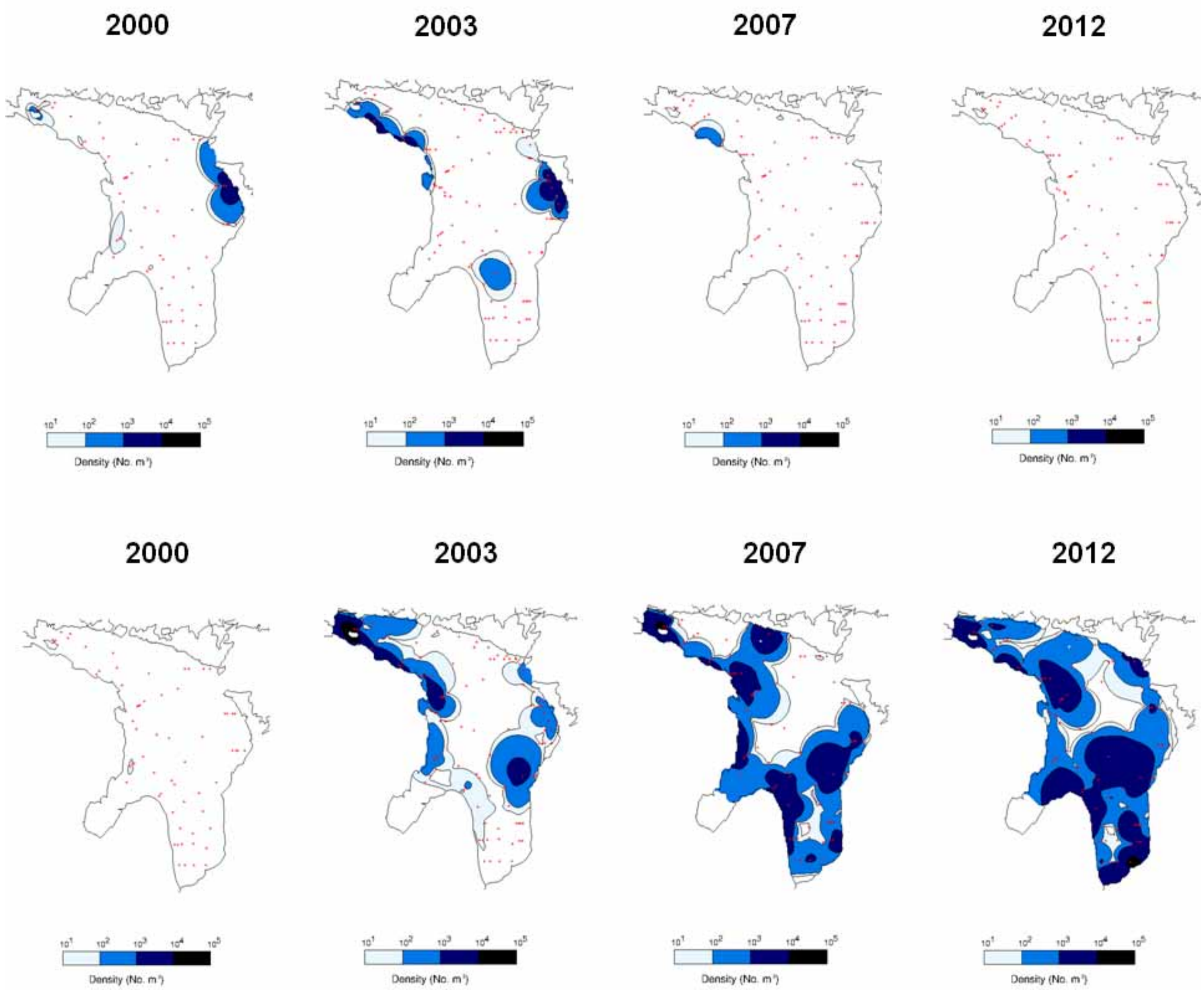

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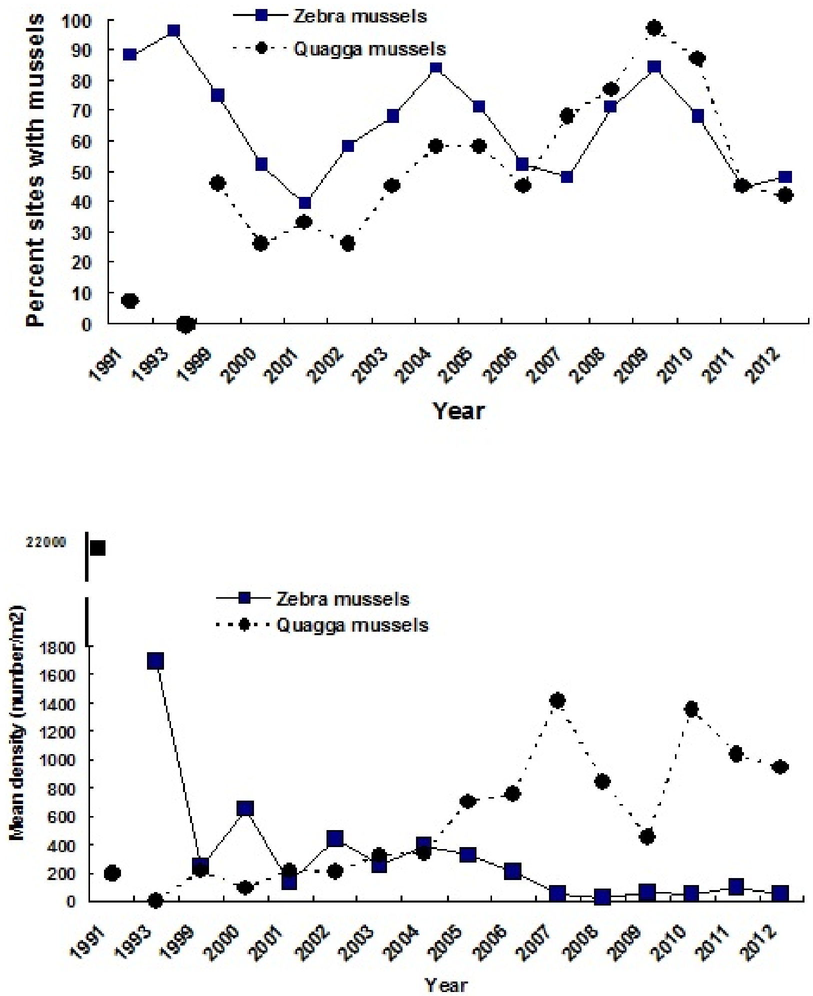

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Source: Great Lakes Science Center, USGS.

Sub-Indicator: Sea Lamprey

Overall Assessment
Status: Fair
Trend: Improving
Rationale: Annual sea lamprey control activities in the Great Lakes have successfully suppressed sea lamprey populations from peak levels by about 90%. Currently, index estimates of adult sea lamprey abundance are meeting targets in Lakes Huron, Michigan, and Ontario and are above targets, but declining in Lakes Superior and Erie. More suppression is needed to bring adult indices to targets in all lakes.

Lake-by-Lake Assessment

Lake Superior
Status: Fair
Trend: Improving
Rationale: Index estimates of adult sea lamprey abundance are above the target, but have declined since 2012.

Lake Michigan
Status: Good
Trend: Improving
Rationale: Index estimates of adult sea lamprey abundance are meeting the target and have declined since 2012.

Lake Huron
Status: Good
Trend: Improving
Rationale: Index estimates of adult sea lamprey abundance are meeting the target and have declined since 2012.

Lake Erie
Status: Fair
Trend: Improving
Rationale: Index estimates of adult sea lamprey abundance are above the target, but have declined since 2010.

Lake Ontario
Status: Good
Trend: Unchanging
Rationale: Index estimates of adult sea lamprey abundance are meeting the target and have been holding steady since 2013.

Sub-Indicator Purpose

- To estimate and track the relative adult sea lamprey abundance for each lake.
- To monitor the damage caused by sea lamprey to the aquatic ecosystem.
- To monitor the success of sea lamprey control actions.

Ecosystem Objective

This sub- indicator supports Great Lakes Fishery Commission (GLFC) and fishery management agencies fish community objectives that were established under A Joint Strategic Plan for the Management of Great Lakes Fisheries. Fish community objectives call for suppressing sea lamprey populations to levels that cause only insignificant mortality on fish to achieve objectives for Lake Trout and other members of the fish community.

This sub-indicator best supports work towards General Objective #7 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should "be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes."

Ecological Condition

The sea lamprey is a non-native species and a lethal parasite of many fish species in the Great Lakes (e.g. Bergstedt and Schneider 1988; Kitchell 1990), and has caused ecologic and economic tragedy in terms of its impact on the Great Lakes fish communities and ecosystem (Smith and Tibbles 1980). Before control, sea lampreys killed an estimated 103 million pounds (47 million kilograms) of fish per year with the average sea lamprey killing up to 40 pounds (18 kg) of fish during its parasitic stage. Sea lampreys prefer trout, salmon, whitefish, and Lake Sturgeon but they also attack smaller fish like cisco, Walleye, and perch (GLFC). The first complete round of stream treatments with the lampricide TFM (as early as 1960 in Lake Superior) successfully suppressed sea lamprey populations to less than 10% of pre-control abundances in all of the Great Lakes except Lake Erie, and subsequent lampricide treatments conducted on a regular basis across the Great Lakes have successfully maintained sea lamprey populations at this level in all lakes except Lake Erie. The sea lamprey, however, continues to be a significant source of mortality for many fish species (Bergstedt and Schneider 1988; Kitchell 1990) and its continued control is needed to restore and maintain the Great Lakes fish communities and ecosystem.

Index estimates of adult sea lamprey abundance relative to lake-specific targets is the primary performance indicator of the sea lamprey control program (Figure 1). Index estimates are calculated as the sum of the spawning run estimates for a subset of streams in a given lake basin. The numbers of adult sea lampreys migrating into each index stream are estimated with traps using mark/recapture methods. Index estimates are updated on an annual basis.

On all lakes except Huron and Michigan, index targets are the average index estimate in each lake during times when whole-lake sea lamprey wounding rates on Lake Trout were tolerable, that is, causing less than 5% annual mortality (or when Lake Trout wounding rates were less than or equal to five wounds per 100 fish). For Lake Huron, Lake Trout wounding rates have not been at tolerable levels, so the index target is set at 25% of the average index estimate during the late 1980s. For Lake Michigan, sea lamprey index estimates are not available during times when Lake Trout wounding rates were tolerable, so the index target is set using index data from late 1990s corrected for the higher than tolerable Lake Trout wounding rates. Index targets are only updated when an index stream is either added and/or removed from the estimation procedure.

In past years, the sea lamprey sub-indicator encompassed whole-lake adult sea lamprey abundances calculated as the sum of spawning run estimates for all sea lamprey-producing streams in a given basin. Abundances were obtained in streams with traps using mark/recapture estimates or extrapolation from previous trap capture efficiency estimates, and in streams without traps using a model that relates spawning run size to stream discharge, larval abundance, and year since last treatment (spawner model; Mullett et al., 2003). The majority of the abundances were obtained using the spawner model. Recently, the GLFC changed their adult sea lamprey monitoring protocols, moving away from the spawner model in favor of an adult sea lamprey index on a subset of streams in a given basin. The change was made because of the high amount of uncertainty inherent to the spawner model. The index provides a means to track adult sea lamprey populations using the best available data - actual population assessment data, reducing uncertainty and providing a better method to track adult sea lamprey populations and assess the impacts of the sea lamprey control program. Indices have been back calculated so that historical data matches the new data. It is important to note that the previous indicator report (2011) would not have significantly changed if the adult index method was used. Therefore, the change in trends from the previous indicator report are not due to the change in methodology, but are a result from increased sea lamprey control efforts in all lakes, especially Lakes Huron, Michigan, and Erie.

Sea lamprey wounding rates on Lake Trout have also been previously included as another measure of the abundance of sea lamprey in relation to their prey. However, wounding rates were not used directly to assess sea lamprey abundance in previous sea lamprey indicator reports. Lake Trout wounding rate trends do not always match sea lamprey abundance trends. Lake Trout wounding rates are dependent on sea lamprey abundance and abundances of ALL host fish. These relationships are hard to reconcile because of the lack of abundance data on hosts other than Lake Trout, which leads to inconsistencies between sea lamprey abundance and Lake Trout wounding rates (e.g., a Lake Trout wounding rate can increase in the presence of a steady sea lamprey population if the abundance of other host fish declines). However, sea lamprey wounding rates on Lake Trout for each lake along with their targets are graphically summarized in Figure 2 as additional information to show some of the impact sea lamprey have on Great Lakes fish, specifically Lake Trout.

Lake Superior
In Lake Superior, the adult index estimate is above the target, but has been decreasing since 2012. Sources of sea lampreys that are of concern include the Bad River and lentic populations in the Kaministiquia, Nipigon, Gravel, and Batchawana rivers where populations are sparsely distributed and granular Bayluscide treatment is less effective than conventional TFM applications. Overall lampricide control effort has increased since 2005 with additional tributary and lentic (estuaries, bays, and slower moving tributaries) areas being treated, likely leading to a reduction in the adult sea lampreys.

Lake Michigan
In Lake Michigan, the adult index estimate is meeting the target. Sources of sea lampreys that are of concern include the Manistique River, other productive tributaries in the northern part of the lake, and the St. Marys River (Lake Huron). Lampricide control effort has increased starting in 2006 with additional treatments. In addition, the Manistique River has been treated six times since 2003 with the most recent treatment during 2014. Reductions in sea lamprey abundance during the past nine years are likely due to the repeated treatment of the Manistique River.

Lake Huron
In Lake Huron, the adult index estimate is meeting the target. Sources of sea lampreys that are of concern include the St. Marys River, other productive tributaries in the northern part of the lake (e.g. Cheboygan and Mississagi rivers), and the Manistique River (Lake Michigan). Lampricide control effort has increased starting in 2006 with additional treatments. Additionally, a large-scale effort to treat the North Channel area of Lake Huron (including the St. Marys River) occurred from 2010-2011 along with geographically expanded treatment in the northern parts of Lakes Huron and Michigan in 2012-2013 and 2014-2015. Application of this strategy successfully reduced larval sea lampreys in the St. Marys River to all-time lows and the adult index estimate for Lake Huron to target levels.

Lake Erie
In Lake Erie, the adult index estimate is above the target, but has been decreasing since 2010. Sources of sea lampreys that are of concern include hard-to-treat tributaries (e.g. Cattaraugus Creek), tributaries with non-target species of concern (Conneaut Creek), and the St. Clair and Detroit River System. Lampricide control effort dramatically increased during 2008-2010 with the implementation of a large-scale treatment strategy where all known sea lamprey-producing tributaries to Lake Erie were treated in consecutive years. Increased control effort was also applied during 2013 with the treatment of twelve tributaries. The adult sea lamprey index has yet to meet the target as expected. Assessment and treatment strategies are being developed for the Huron-Erie Corridor.

Lake Ontario
In Lake Ontario, the adult index estimate is meeting the target. A source of sea lampreys that is of concern is the Niagara River – the larval sea lamprey population is currently small, but could become an issue with improved habitat and water quality. Steady lampricide control effort on Lake Ontario has maintained the adult sea lamprey index at or near the target.

Linkages

Lake Trout; Walleye; and Lake Sturgeon;
Sea lampreys remain a significant source of mortality on many fish species of the Great Lakes including Atlantic, Chinook, and Coho Salmon, Burbot, Ciscoes, Lake Sturgeon (threatened in some parts of the Great Lakes basin), Lake Trout, Steelhead, Walleye, Whitefish, etc. Short lapses in sea lamprey control can result in rapid increases in sea lamprey abundance and the damage they inflict on fish. Continued stream and lentic area treatments are necessary to overcome the reproductive potential of the sea lamprey and to ensure the achievement of population management objectives for many different species, and to preserve functioning ecosystems.

Aquatic Habitat Connectivity; Water Quality:

The potential for sea lamprey to colonize new locations is increased with improved aquatic habitat connectivity through the removal of dams and improved water quality. The failure of the Manistique River dam to block sea lampreys and the subsequent sea lamprey production from the river is an example of the linkages between sea lamprey and aquatic habitat connectivity. Additionally, as water quality improves, streams and lentic areas once inhospitable to sea lampreys may become viable spawning and nursery habitats. As examples, during the mid-2000s, a significant larval population requiring regular lampricide treatment was established for the first time in the estuary of the Kaministiquia River (Lake Superior) after a local paper mill began tertiary treatment of its effluent. The establishment of larval populations in the St. Marys, St. Clair, and Lower Niagara rivers followed concerted efforts to improve water quality, and with observations of successful reproduction by lake sturgeon, whitefish, and brindled madtom, it is likely only a matter of time before sea lamprey reproduction is documented in the Detroit River.

Climate Change:

Rising temperatures in the Great Lakes have recently been associated with increasing size of adult sea lampreys (Kitchell et al. 2014). As temperatures rise, sea lampreys may grow larger increasing metabolism and becoming more fecund, which may increase the number of sea lampreys and the damage they cause to host fish.

Comments from the Author(s)

Increases in lampricide treatments have reduced index estimates of adult sea lamprey abundance to within target ranges in three of the five Great Lakes (Huron, Michigan, and Ontario). The effects of increased lampricide treatments are observed in index estimates beginning two years after they occur. Efforts to identify new/unidentified sources of sea lampreys also need to continue. In addition, research to better understand sea lamprey/prey interactions, recruitment dynamics, population dynamics of sea lampreys that survive treatment, and refinement of and research into other control methods are all keys to achieving and maintaining index estimates at targets.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada	X					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Acknowledgments

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List of Figures

Figure 1. Index estimates of adult sea lamprey abundance plotted on sea lamprey spawning year. Horizontal lines represent the targets for each lake. Note the scale differences for each lake.
Source: Great Lakes Fishery Commission

Figure 2. Number of A1-A3 sea lamprey wounds per 100 Lake Trout > 532 mm (Superior, Huron, Michigan, and Erie) and number of A1 sea lamprey wounds per 100 Lake Trout > 432 mm (Ontario) from standardized assessments. Horizontal lines represent the wounding rate target for each lake. Note the scale differences for each lake.
Source: Great Lakes Fishery Commission

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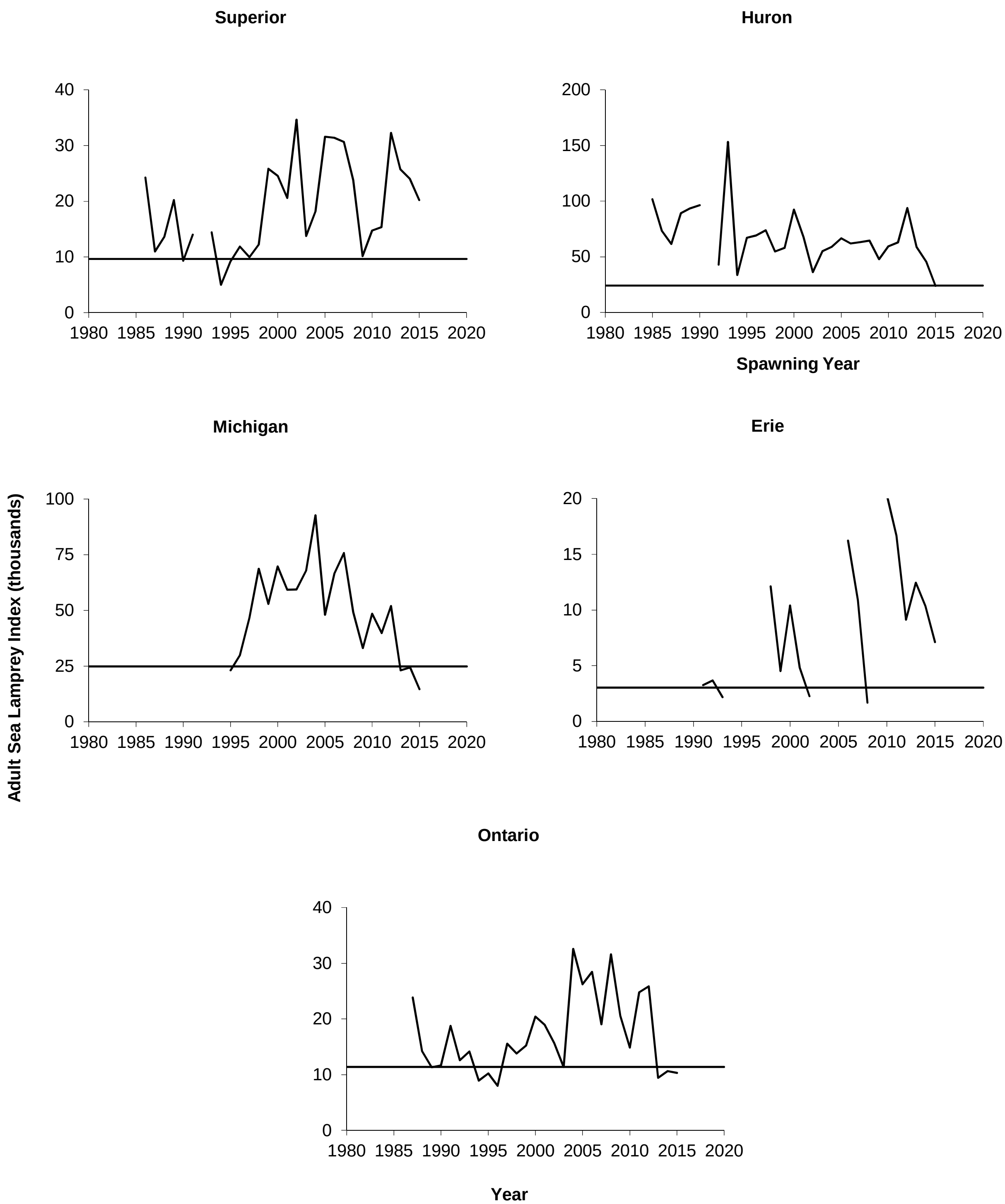

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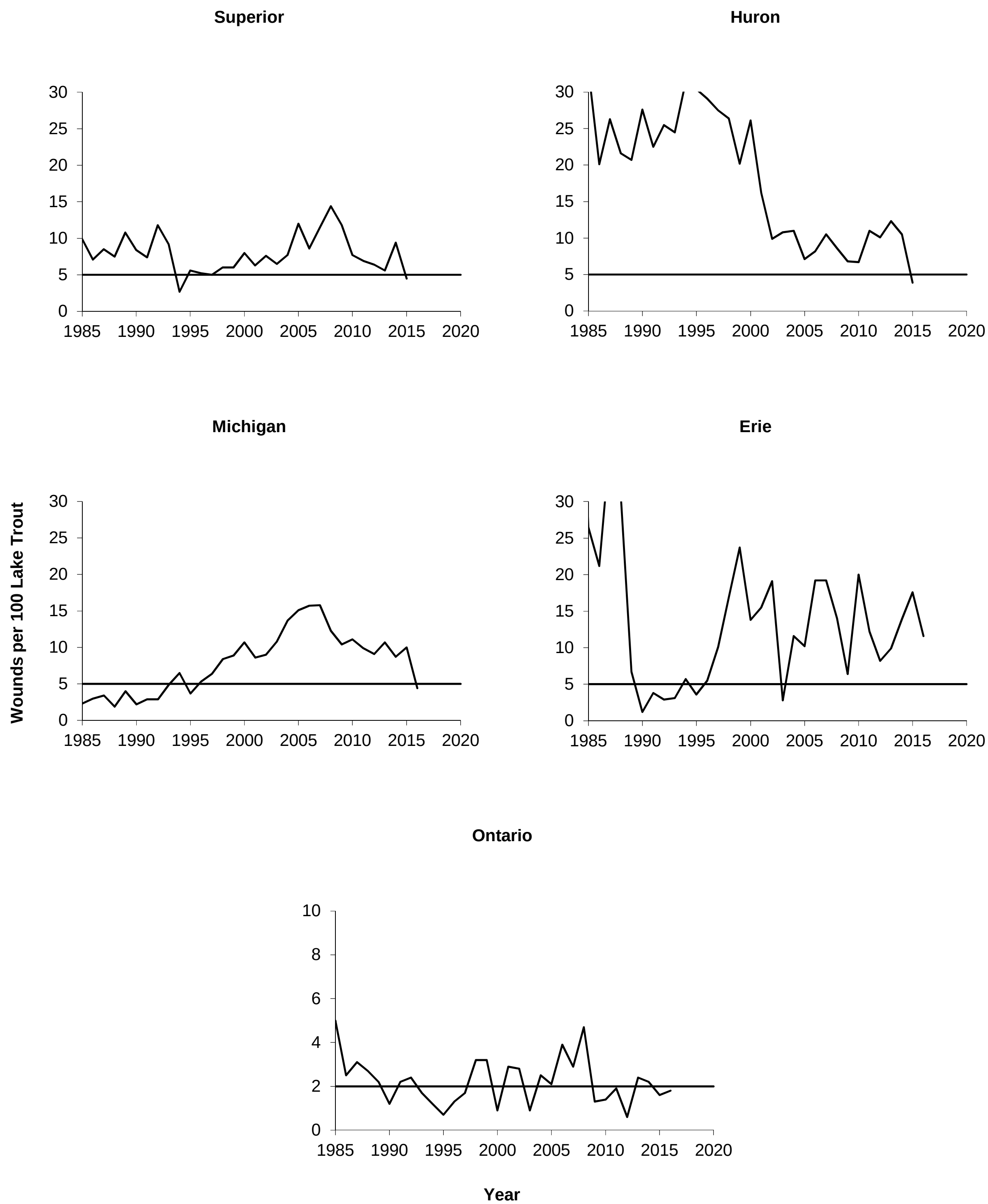

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Source: Great Lakes Fishery Commission

Sub-Indicator: Terrestrial Invasive Species

Overall Assessment
Status: Poor
Trend: Deteriorating
Rationale: Based on the five species of interest – Asian longhorned beetle, emerald ash borer, garlic mustard, *Phragmites* and purple loosestrife, terrestrial invasive species are having significant negative impacts and continue to spread throughout the Great Lakes Basin ecosystem.

Lake-by-Lake Assessment

Lake Superior

Status: Fair

Trend: Deteriorating
Rationale: The impact of the five species of interest has been less significant in the Lake Superior basin than in the other Great Lakes basins. The limited amount of impact and number of introductions of the five species may be attributed to the fact that the basin has few major population centres, which reduces the potential for anthropogenic movement of terrestrial invasive species. Nevertheless, the threat of the five terrestrial invasive species remains high and warming temperatures due to climate change may increase the habitat range for invasive species. Garlic mustard and purple loosestrife threaten to further spread their ranges in the basin. There have also been a few sites south of Lake Superior with confirmed emerald ash borer infestations and strict regulation is important to limit its spread. Furthermore, data from the Early Detection and Distribution Mapping System (EDDMapS) suggest that since 2003, there has been an increase in *Phragmites* observations in the lake basin. No infestations of the Asian longhorned beetle have been reported in the Lake Superior basin.

Lake Michigan

Status: Poor
Trend: Deteriorating
Rationale: The five species of interest continue to have considerable negative impacts on the Lake Michigan basin ecosystem. It appears that emerald ash borer, garlic mustard and *Phragmites* continue to spread through the Lake Michigan basin. In the Lake Michigan basin, over 6000 hectares of monotypic *Phragmites* stands were detected by satellite imagery in 2010. The vast range of *Phragmites* is likely impacting the quality of both wetland and riparian habitat. However, the Asian longhorned beetle was declared eradicated from the Chicago, Illinois area after 10 years of eradication efforts beginning in 1998. The magnitude of purple loosestrife infestations has also been successfully limited by biocontrol programs, but they are not capable of complete eradication.

Lake Huron

Status: Poor
Trend: Deteriorating
Rationale: Emerald ash borer, garlic mustard and *Phragmites* are having significant negative impacts on the Lake Huron basin. The emerald ash borer exists in numerous locations along the south shore of Lake Huron near Sarnia, Ontario. Based on volunteered geographic information (VGI) observations from the Early Detection and Distribution Mapping System, garlic mustard and purple loosestrife have been spreading in the basin. Though it is difficult to discern the magnitude of infestations based on VGI data (an observation could represent one plant or hundreds of plants), it provides insight into potential distribution and spread of the two plant invasive species. In the U.S. Lake Huron basin, over 10 000 hectares of dense *Phragmites* stands were detected by radar imagery in 2010. The extensive range of *Phragmites* likely impacts the habitat and populations of wildlife. No infestations of the Asian longhorned beetle have been reported in the Lake Huron basin.

Lake Erie

Status: Poor
Trend: Deteriorating

Rationale: Garlic mustard continues to have considerable negative impact on the Lake Erie basin ecosystem. Furthermore, the impacts of emerald ash borer on forests in southwestern Ontario have been particularly devastating; from 2004-2012, over 66 000 hectares of forests in the Aylmer and Guelph Ministry of Natural Resource Districts have experienced moderate- to-severe defoliation and decline. Quarantine areas exist throughout the Lake Erie basin and education and eradication campaigns have been crucial in slowing the spread of the emerald ash borer. *Phragmites* has also had considerable negative impact on the U.S. Lake Erie basin; more than 8200 hectares of dense *Phragmites* stands were detected by satellite imagery in 2010. A study by the Canadian Wildlife Service of Environment and Climate Change Canada suggests that *Phragmites* continued to spread in the Canadian Lake Huron-Erie corridor in the areas around the St. Clair River, Lake St. Clair and Detroit River from 2006-2010. Meanwhile, the extent and severity of purple loosestrife infestations has been controlled by two leaf-eating beetles, *Galerucella calmariensis* and *Galerucella pusilla*, which feed exclusively on this wetland perennial. No infestations of the Asian longhorned beetle have been reported in the Lake Erie basin.

Lake Ontario
Status: Poor
Trend: Deteriorating
Rationale: Garlic mustard and *Phragmites* have continued to negatively impact the Lake Ontario basin ecosystem and the extent of these 2 species has spread across this basin. By comparison, purple loosestrife has been effectively controlled by the two leaf-eating beetles (noted above) in the Lake Ontario basin. This perennial plant may continue to spread through the basin, but the beetles can limit the severity of infestations. In the Lake Ontario basin, emerald ash borer was detected in the Niagara Region in 2012. While its impacts have not been as severe as the Lake Erie basin, there are large areas in the region that are experiencing moderate-to-severe decline and mortality in ash trees. The emerald ash borer has the ability to spread quickly and negatively impact forest ecosystems. For the Asian longhorned beetle, two infestation areas exist in the basin; the infestation in the Toronto-Vaughan area was declared eradicated. The other infestation in Toronto-Mississauga is under quarantine and the pest will be declared eradicated if there are no detections after 5 years of surveys.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess the presence, number, and distribution of five selected terrestrial invasive species (TIS) in the Laurentian Great Lakes watershed, and to understand the means by which these species are introduced and persist.
- It is also to aid in the assessment of the status of biotic communities, as invasive species alter both the structure and function of ecosystems thereby compromising the biological integrity of these systems.
- This sub-indicator provides insight into the complex relationships between land and water that impact Great Lakes water quality.

Ecosystem Objective

To reduce and further prevent expansion of five selected terrestrial invasive species: Asian Long-horned Beetle, Emerald Ash Borer, Garlic Mustard, Phragmites (Common Reed) and Purple Loosestrife, in the Great Lakes because they can negatively impact the biodiversity, habitat, chemical loads, nutrient cycling, and hydrogeology of terrestrial and other ecosystems within the Great Lakes watershed.

This sub-indicator best supports work towards General Objective #7 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should “be free from the introduction and spread of aquatic invasive species and free from the introduction and spread of terrestrial invasive species that adversely impact the quality of the Waters of the Great Lakes.”

Ecological Condition

The proliferation of terrestrial invasive species in the Great Lakes Basin has occurred as an unintended consequence of global trade and movement of people. As the movement of goods and people continues to grow, a greater number of species are transported from their native ranges to introduced ranges. Though not all alien species are a threat to their introduced range, a small number of these alien species are invasive and have the ability to significantly disturb ecosystems (Canadian Food Inspection Agency, 2005; Great Lakes Regional Collaboration Strategy, 2005). Since the1800s, there has been a dramatic increase in the number of invasive alien plant species introduced into Canada

(Canadian Food Inspection Agency, 2005; Figure 1). This trend is also supported by data analyzed from the World Wildlife Fund's Invasive Species database, which indicates that there has been a 55% increase in the number of terrestrial invasive species introductions in the Great Lakes Basin from 1900 to 2000 (World Wildlife Fund 2003).

The status and trends of terrestrial invasive species will be assessed based on the impacts and distribution of the Asian longhorned beetle, emerald ash borer, garlic mustard, *Phragmites* and purple loosestrife. These species were selected because of their significant and widespread impact on the Great Lakes Basin. It must be noted that though the species selected would predominantly result in poor and deteriorating assessments, there is an opportunity to realize improvement through limiting their spread and impact.

Asian Longhorned Beetle

Asian longhorned beetles (ALB) are native to China and Korea and have been discovered in Ontario and Illinois. The preferred hosts of ALB are maple trees, but they have been known to infest and kill other hardwood trees, such as poplars, willows, birches, horse chestnuts and elms. Because the ALB has no natural predators in North America, they pose a substantial threat to millions of trees. The United States Department of Agriculture (2006) estimates that the ALB could have a potential market economic impact of more than $41 billion in the United States. However, the intangible economic losses associated with ALB, such as ecosystem service and aesthetic losses, are estimated to have a greater impact than market economic losses (Animal and Plant Health Inspection Service [APHIS], 2015). In North America, extensive eradication measures have been introduced to ensure that the number and spread of ALB is limited. Treatment options include strict regulation of quarantine areas and tree removal. In Ontario, susceptible and infested trees located in the two identified infestation sites were removed; one of the infestations was declared eradicated as no beetles or infested trees were discovered after 5 years of surveys. The other infestation site is being monitored to ensure that further eradication measures are implemented if warranted. Since 2008, the ALB has been eradicated from Illinois. Outside the Great Lakes Basin, efforts continue in nearby southern Ohio and New York to limit the spread of the ALB.

Emerald Ash Borer

The emerald ash borer (EAB) was first discovered in North America in the Detroit-Windsor area in the early 2000s. These wood-boring pests are believed to have arrived from East Asia in wood shipping containers. EAB feeds on green, red, white, black and blue ash and is responsible for the destruction of millions of ash trees across Ontario and all eight Great Lakes States. In Ontario, Canadian Forest Service scientists estimate that $2 billion over a 30-year horizon will be required to remove and replace trees (Natural Resources Canada [NRCAN], 2015). Moreover, high mortality rates are typical once an infestation occurs; after 6 years of initial infestation, roughly 99% of ash trees are killed in the woodlot (NRCAN, 2015). In 2001, Toronto had approximately 860,000 ash trees throughout the city. In 2016, approximately 9,500 viable trees remain. The effects of EAB on the Great Lakes ecosystem are wide-ranging, particularly in areas that are dominated by ash trees. It is also expected that urban areas will be affected since ash trees are often planted for their quick-growing nature. The loss of ash trees will increase the amount of stormwater runoff and exacerbate the urban heat island effect (Wisconsin Department of Natural Resources, 2015). Forests play a key role in stabilizing soil and limiting the amount of sediment-bound pollutants into receiving waters (Turner & Rabalais 2003). These forests also protect water quality as well as the habitats of a number of native species (The Nature Conservancy). The emerald ash borer is significantly impacting the Lake Erie ecosystem (Figure 2); it is estimated that more than 65 000 acres across southern Ontario have experienced moderate-to-severe decline and mortality in ash trees (Figure 3). The impacts of EAB have also been having a severe impact in the Lake Huron basin in the area surrounding Sarnia, Ontario (Figure 2). Areas west of London, Ontario have been particularly affected and there is concern that the emerald ash borer will continue to spread east into the Lake Ontario basin and north into the Lake Superior basin. The Canadian Council of Forest Ministers [CCFM] (2015) predicts that EAB will spread to Thunder Bay, Ontario and into other parts of Northern Ontario due to the lack of biological prevention tools and regulation. However, the rate of spread for EAB in Northern Ontario will be slower than in the south because of cooler climatic conditions (CCFM 2015). Quarantine areas, strict regulation, education programs and removal of ash trees in infested areas are some important measures to limit the spread of emerald ash borer in the Great Lakes Basin and beyond.

Garlic Mustard

Garlic mustard was likely introduced to North America from Europe in the late 19th century for culinary or medicinal purposes. It is considered one of the most invasive exotic species in North America as it out-competes native plants and disrupts natural understory growth (Yates & Murphy, 2008). The invasive nature of garlic mustard results in altered forest composition since garlic mustard can control the nutrient supply in soil, making it difficult for tree seedlings to germinate (Rodgers, Stinson & Finzi, 2008). Further, two native species – the wood poppy and wood aster have been designated as endangered and threatened, respectively, by the Committee on the Status of Endangered Wildlife in Canada in part due to the spread of garlic mustard. This invasive species is also toxic to the larvae of some butterflies, which results in a reduction of plant pollination (Lake Huron Centre for Coastal Conservation n.d.). Tracking the distribution of garlic mustard is an important step in eradication efforts as it highlights areas that require management. The Early Detection & Distribution Mapping System (EDDMapS) is one important platform that collects volunteered geographic information about garlic mustard observations in Canada and the United States. Data derived from EDDMapS indicates that there has been a spread of garlic mustard in the Great Lakes Basin as it has now been observed across Ontario and in all eight Great Lakes States (Figures 5 and 6). The Greater Toronto Area and southern and western Michigan appear to have a number of garlic mustard observations. Over time, the range of garlic mustard in Ontario has spread to the northern shores of Lake Superior. It is predicted that garlic mustard will continue its spread across North America as it possesses a specific combination of traits, making it a successful competitor in a number of different ecosystems (Rodgers et al. 2008). Because garlic mustard can grow in numerous diverse ecosystems, unique management options are required for each site (The Nature Conservancy of Canada, 2007).

Phragmites

Two varieties of *Phragmites* exist in the Great Lakes Basin, the native subspecies (*americanus*) and the invasive subspecies (*australis*). *Phragmites australis* subsp. *australis* form dense stands in roadside ditches, along the water's edge and in wetlands, decreasing biodiversity by choking out native plant species. In 2005, Agriculture and Agri-food Canada declared that *Phragmites australis* subsp. *australis* (herein Phragmites) was the worst invasive plant species in Canada. Invasive *Phragmites* is responsible for changes in the hydrologic cycle, alterations to the nutrient cycle as well as losses to biodiversity and habitat (Ontario Ministry of Natural Resources [MNR], 2011). The spread of *Phragmites* occurs quickly as it can grow up to 4 centimetres a day vertically and can establish root systems that measure several metres (MNR, 2011). The rhizomes of its roots release toxins that inhibit the growth of native species, resulting in the formation of a dense monoculture. Invasive *Phragmites* seeds are easily transported by the wind, water or birds and can rapidly colonize disturbed environments. Once it is established in an area, multiple management controls are typically required for eradication because of their large root systems (MNR, 2011). Based on data analyzed from EDDMapS, Lake Ontario and Lake Erie have the most observations of *Phragmites* in the Great Lakes Basin. In Ontario, this perennial grass has begun to migrate north to Georgian Bay and Lake Superior. It appears that over a period of 67 years beginning in 1948, the distribution of observations has expanded to multiple locations in Ontario and into five of the eight Great Lakes States (Figures 7 and 8). The presence of *Phragmites* across the Great Lakes Basin has been supported by research undertaken by a team at the Michigan Tech Research Institute, led by Laura Bourgeau-Chavez. The locations of mature stands of invasive *Phragmites* on the U.S. side of the Great Lakes Basin were mapped using satellite imagery (Figure 4). Data collected in 2008-2010 was used to detect invasive *Phragmites* that dominated 90% of 0.2 hectare mapping units. Significant stands were mapped in Lake Huron (10 395 ha), Lake Erie (8233 ha) and Lake Michigan (6002 ha), while little to none were mapped in the Lake Ontario and Lake Superior basins (Bourgeau-Chavez 2011). It should be noted that the radar imagery can only detect large, dense stands of *Phragmites*. It can also be difficult for the researchers to determine whether the imagery depicted *Phragmites* as other monotypic aquatic plants. The overall accuracy of the basin-wide map was 87%, illustrating that radar imagery is an effective means to detect the presence of large, mono-typic invasive *Phragmites* stands in the Great Lakes Basin. Wilcox et al. (2010) investigated the change in plant communities on the northern shores of Lake Erie in Long Point, Ontario and found that areas of predominantly cattails and marsh were replaced by *Phragmites*. Long Point is noted as an important staging area for waterfowl, which may be negatively impacted by dense monocultures of *Phragmites* (Wilcox et al. 2010).

Purple Loosestrife

Purple loosestrife is a perennial plant native to Asia and Europe, which was initially introduced in North America as a decorative plant. It has spread extensively to wetlands and disturbed environments due to its small, easily-transported seeds. Purple loosestrife weaves thick mats of roots that cover vast areas, impacting the quality of habitat for birds, insects and other plants (Government of Ontario, 2012). Furthermore, purple loosestrife threatens wetland ecosystems by altering water levels and reducing food sources for both aquatic and terrestrial native species (Thompson, Stuckey & Thompson, 1987). According to data collected by EDDMapS, purple loosestrife is present across Ontario and in all eight Great Lakes States. It appears that beginning in 1900, purple loosestrife has expanded its range over a 115-year period as it is now ubiquitous along the shorelines of all five Great Lakes (Figures 9-10).

However, there is an effective control measure to combat the spread of purple loosestrife, which has been the use of their natural predators, *Galerucella calmariensis and G. pusilla* beetles. Multiple studies were carried out to ensure that the use of *Galerucella calmariensis* and *G. pusilla* would not impact native species (Michigan Sea Grant). It was determined that these particular varieties of beetle only target purple loosestrife, making it a viable biocontrol option. They have been used at multiple sites in the Great Lakes Basin and can significantly reduce purple loosestrife populations (Government of Ontario, 2012). In 2006, the Ontario Federation of Anglers and Hunters reported that this perennial invasive has been successfully controlled by *Galerucella calmariensis* and *G. pusilla* in more than 80% of the 300 control sites located in Ontario. It must be noted that the beetles can only reduce purple loosestrife to manageable populations and are not capable of complete eradication.

Linkages

Climate change may expand the current habitat ranges of terrestrial invasive species as temperatures warm and growing seasons become longer (Clements & DiTommaso, 2012). Based on spatial data from EDDMapS, it appears that invasive *Phragmites* has begun to move north into the Lake Superior basin, perhaps as a result of warmer temperatures. Smith et al. (2012) have described the need to better study the impacts of climate change on terrestrial invasive species and stressed the need to bridge the gap between policy and science.

Forest cover can be negatively impacted by the Asian longhorned beetle and the emerald ash borer, which increases the amount of runoff and sediment-bound pollutants into the Great Lakes and its tributaries (Turner & Rabalais 2003). Forests also play a key role in carbon sequestration by absorbing and removing greenhouse gas emissions (Natural Resources Canada 2015).

The invasion of purple loosestrife and *Phragmites* in the Great Lakes can alter the structure and function of coastal wetland ecosystems (Keil & Hickman 2015). Wetlands provide ecosystem services that are significant to the Great Lakes Basin including filtering nutrients that stimulate algal growth and limiting eutrophication in lakes and tributaries (Zedler & Kercher 2005). Furthermore, wetlands are unique habitats for plants and animals and help store large quantities of carbon in their soils (Zedler & Kercher 2005).

Comments from the Author(s)

Because EDDMapS is a repository of volunteered geographic information, it may not provide a perfect picture of the extent of terrestrial invasive species in the Great Lakes region. However, the assessments strive to depict the status and trend of terrestrial invasive species in each lake basin as accurately as possible given the data available. This report was supported by data from both EDDMapS and qualitative information from government reports, non-governmental agencies and journal articles.

EDDMapS is an important platform that gathers volunteered geographic information about terrestrial and aquatic invasive species in Canada and the United States. It is currently supported by a number of organizations, including the National Park Service, U.S. Forest Service, U.S. Fish & Wildlife Service, Nature Conservancy, U.S. Department of Agriculture and Ontario Federation of Anglers and Hunters. The data is validated by one of their partner organizations to ensure its accuracy. Some limitations must be noted since the data is volunteered geographic information. The maps may not depict a complete portrait of the spatial distribution of terrestrial invasive species in the Great Lakes Basin since monitoring efforts are not uniform. Also, the locations of the observations are contingent upon the users who submit the data and the amount of resources expended in an area (a greater amount of resources will generally result in a greater amount of observations). The data only reflects observations that were made and does not reflect treatment options that have been applied; for instance, a strand of *Phragmites* may have been eradicated after the observation was submitted to EDDMapS. An observation may also represent one plant or hundreds of plants. EDDMapS does however provide some spatial data that helps ecosystem managers to track the spread of terrestrial invasive species and to identify areas that require greater intervention.

It is also important to note that agencies have increased their level of public education and outreach for the time period shown in the species-specific figures and thus the public is far better informed about invasive species. The development of tools such as EDDMapS and associated Applications has made it much easier for the public to report observations of invasives. While there is evidence that garlic mustard and others is increasing on the landscape, the frequency of reports and the distribution of the reports may have considerably outpaced the actual spread of the species. EDDMapS is likely the best information available and it is a great tool, but the limitations should be carefully considered and explained so that the information is not misrepresented – especially for tracking spread and trends.

It is difficult to fully appreciate the status and spread of terrestrial invasive species in the Great Lakes region due to the extent of the region, the number of terrestrial invasive species and the differences in monitoring efforts across space and time. The management of invasive species is essential as they are one of the greatest threats to biodiversity in the Great Lakes region. Consequently, a greater amount of research is required to not only understand where terrestrial invasive species are located, but to also understand what impact terrestrial invasive species are having on different habitats and water quality.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		X				
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		X				
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this indicator report		X				

Acknowledgments
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State of the Great Lakes 2017 Technical Report

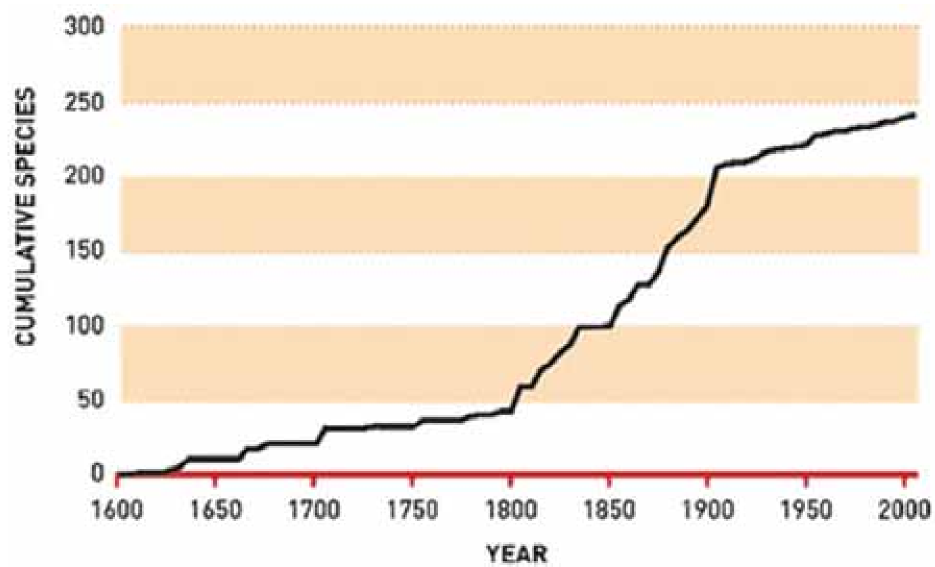


Figure 1. Cumulative Number of Invasive Alien Plant Species Introduced into Canada from 1600 to 2005 – Estimated.
Source: Canadian Food Inspection Agency

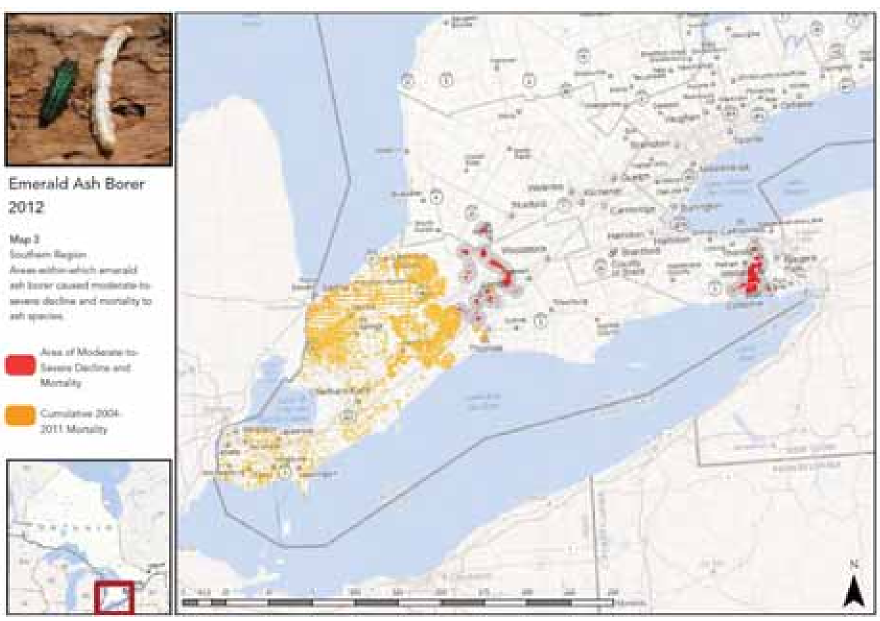
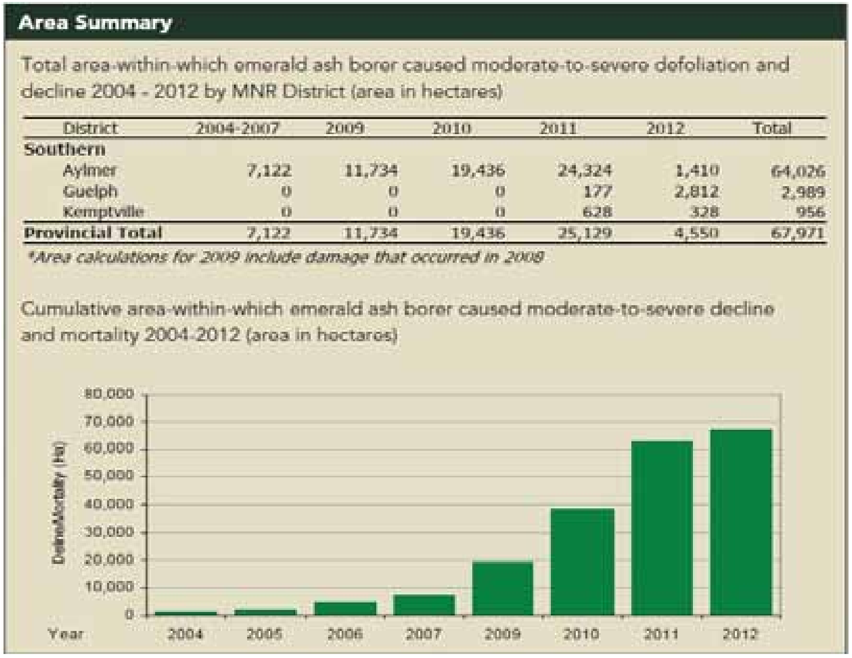


Figure 2. Areas where emerald ash borer has caused moderate-to-severe decline and mortality to ash species.
Source: Ontario Ministry of Natural Resources



Area Summary

Total area-within-which emerald ash borer caused moderate-to-severe defoliation and decline 2004 - 2012 by MNR District (area in hectares)

District	2004-2007	2009	2010	2011	2012	Total
Southern						
Aylmer	7,122	11,734	19,436	24,324	1,410	64,026
Guelph	0	0	0	177	2,812	2,989
Kemptville	0	0	0	628	328	956
Provincial Total	7,122	11,734	19,436	25,129	4,550	67,971

**Area calculations for 2009 include damage that occurred in 2008*

Cumulative area-within-which emerald ash borer caused moderate-to-severe decline and mortality 2004-2012 (area in hectares)

Figure 3. Cumulative amount of area in specific regions of the province of Ontario where emerald ash borer has caused moderate-to-severe decline and mortality to ash species.
Source: Ontario Ministry of Natural Resources

Figure 4. Potential distribution of invasive phragmites (may include dense, mono-typic stands of other wetland plants) in the U.S. Great Lakes Basin using remotely sensed data, 2008-2010.
Source: Bourgeau-Chavez et al.

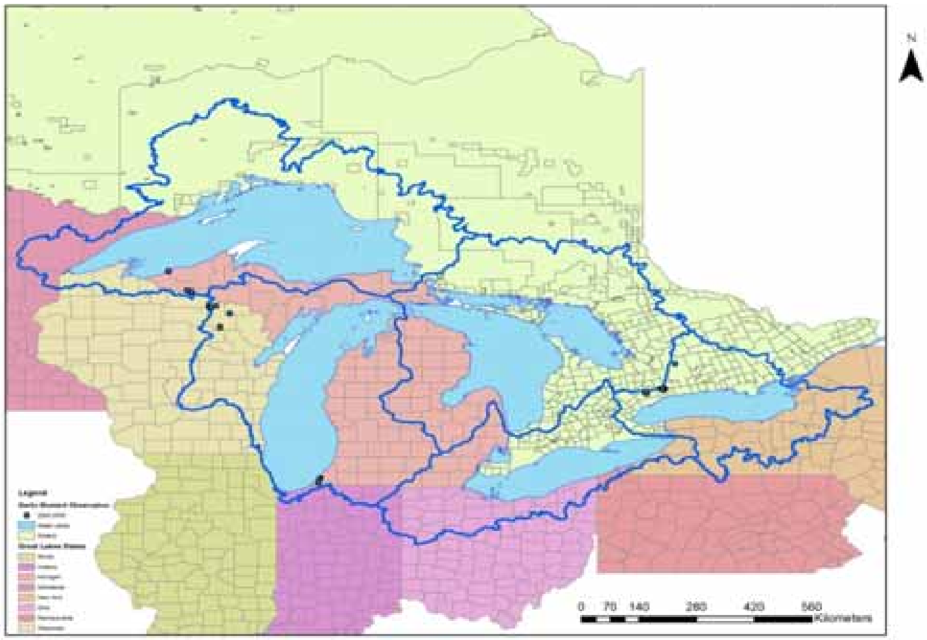


Figure 5. Garlic Mustard Observations in the Great Lakes Basin (2002-2005).
Source: EDDMapS

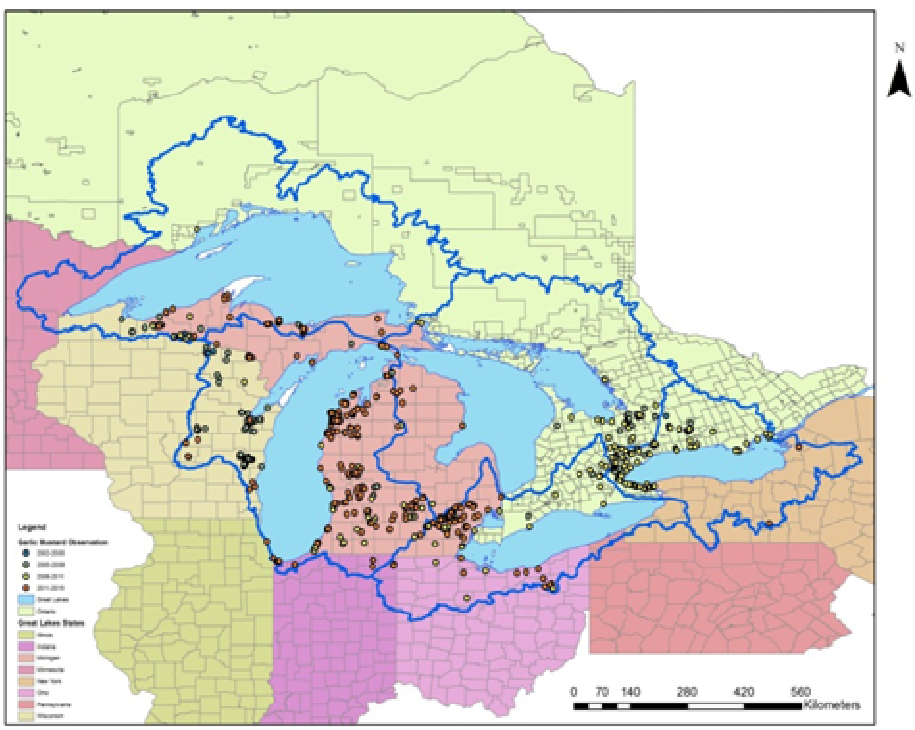


Figure 6. Garlic Mustard Observations in the Great Lakes Basin (2002-2015).
Source: EDDMapS

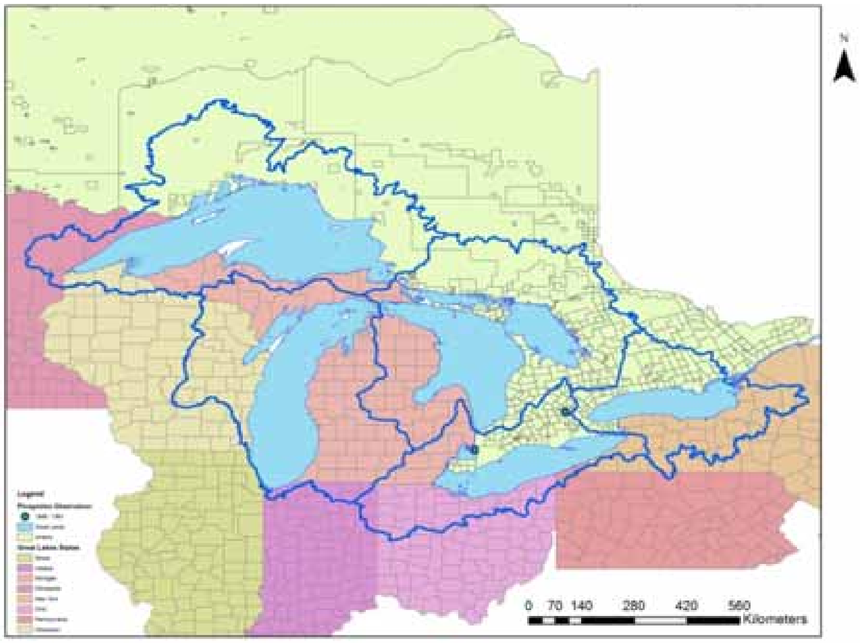


Figure 7. *Phragmites* Observations in the Great Lakes Basin (1948-1961).
Source: EDDMapS

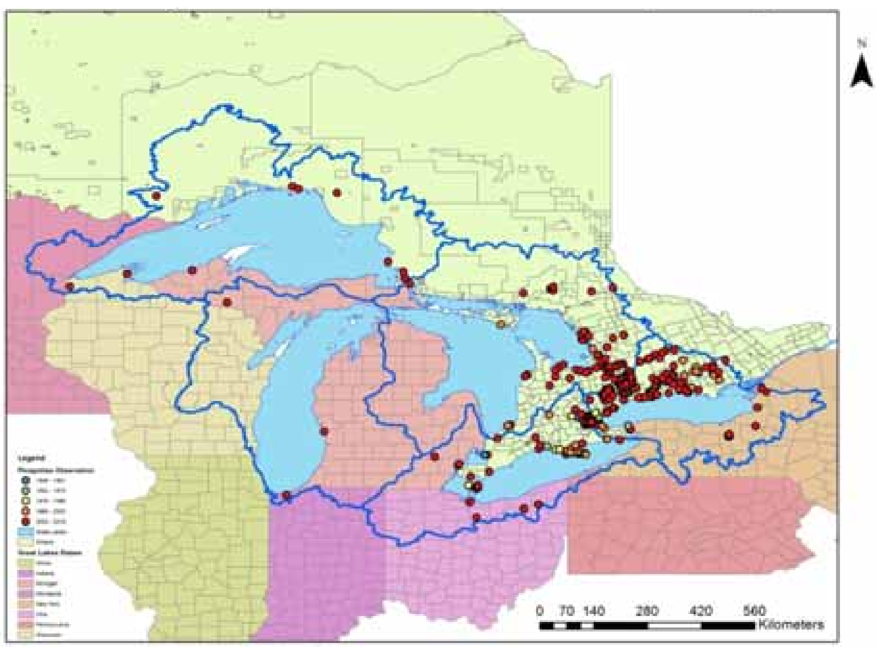


Figure 8. *Phragmites* Observations in the Great Lakes Basin (1948-2015).
Source: EDDMapS

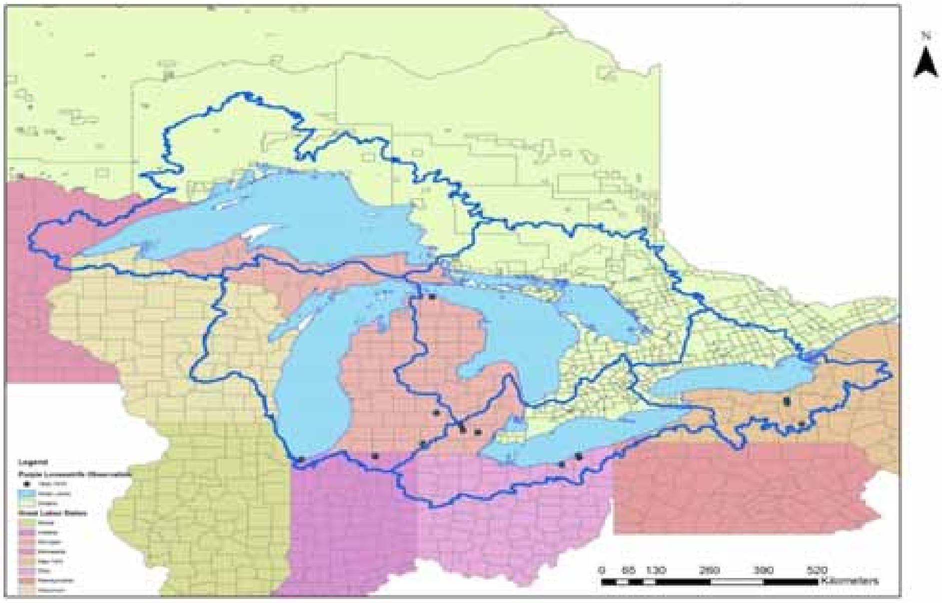


Figure 9. Purple Loosestrife Observations in the Great Lakes Basin (1900-1979). Source: EDDMapS

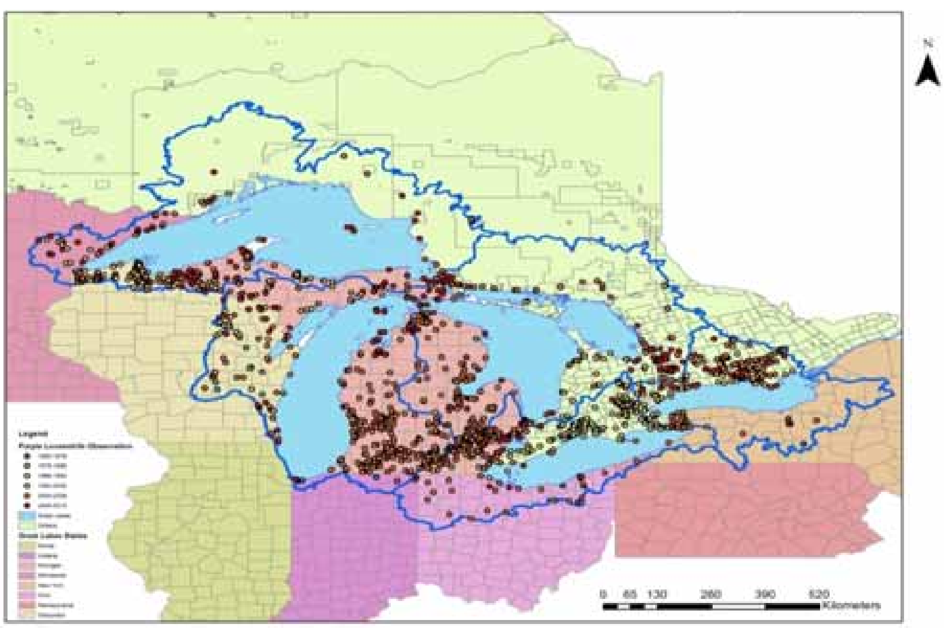
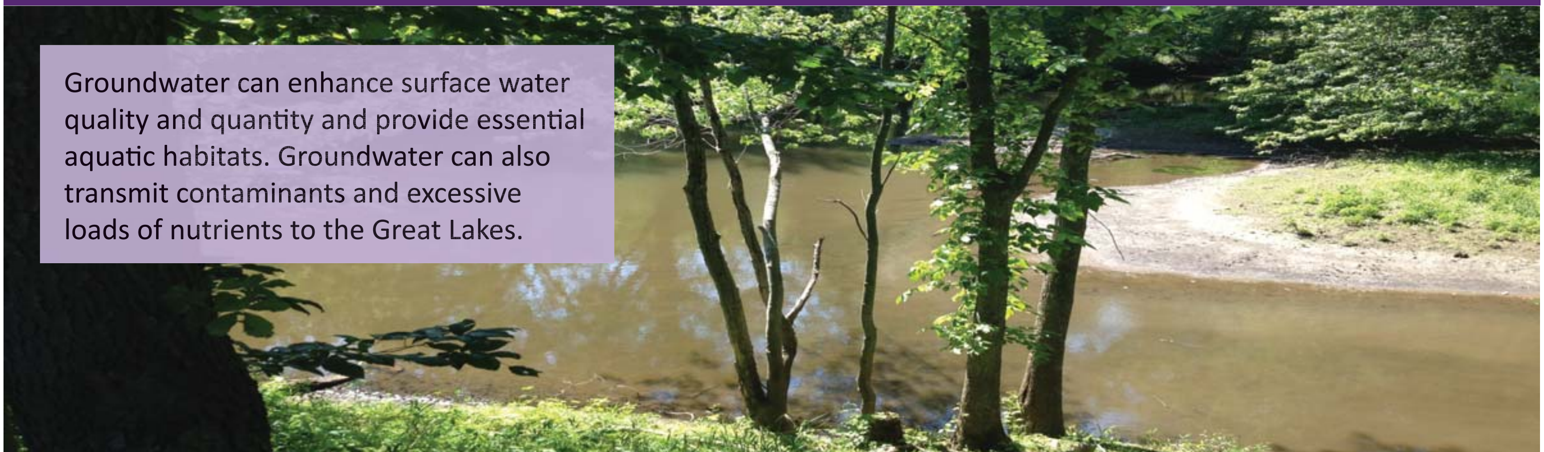


Figure 10. Purple Loosestrife Observations in the Great Lakes Basin (1900-2015). Source: EDDMapS

Groundwater

Status: Fair   Trend: Undetermined



Groundwater can enhance surface water quality and quantity and provide essential aquatic habitats. Groundwater can also transmit contaminants and excessive loads of nutrients to the Great Lakes.

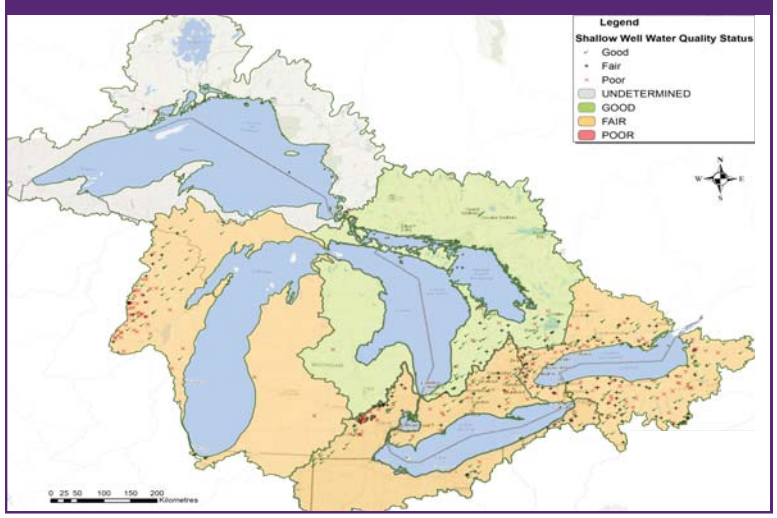
The 2012 Great Lakes Water Quality Agreement states that *“the Waters of the Great Lakes should be free from the harmful impact of contaminated groundwater”*

Assessment Highlights

The Groundwater Quality indicator is assessed as **Fair** but the trend is **Undetermined** due to insufficient long-term data. The concentrations of nitrate, primarily from agricultural practices, and chloride, mainly from the urban use of de-icing salt, are being used to assess groundwater quality. Elevated concentrations of both of these constituents in water can have detrimental impacts to ecosystem and human health.

Portions of the Great Lakes Basin with more intense development, such as areas within the basins of Lakes Michigan, Erie and Ontario, are generally assessed as fair. Groundwater quality is generally assessed as good in the less developed areas, such as portions of the Lake Huron basin. A better understanding about the impacts of contaminated groundwater and its interaction with the waters of the Great Lakes is needed, particularly for the nearshore zone.

Groundwater Quality Assessment by Lake Basin



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Groundwater Quality	Undetermined	Undetermined	Undetermined	Undetermined	Undetermined

Status:	GOOD	FAIR	POOR	UNDETERMINED

Sub-Indicator: Groundwater Quality

Regional-scale assessment

Overall Assessment
Status: Fair
Trend: Undetermined
Rationale: The overall status of groundwater quality, based on current knowledge and data in the Great Lakes Basin, is assessed as fair. Of the 670 monitoring wells in the basin that were included, the groundwater quality was assessed to be Poor in 203 (30%), Fair in 173 (26%), and Good in 294 (44%). Given that no single category captured more than 50% of wells, the overall assessment is fair (following the criteria as explained on page 3). Caution must be used when interpreting and applying this overall assessment, due to the large spatial gaps in the data, particularly in the northern and central portions of the basin, as shown in Figure 1 where hundreds of kilometres/miles exist between wells in the Lake Superior basin, for example. In large areas of the basin where groundwater quality data are missing (Figure 1), the status of groundwater quality should be considered to be undetermined. The overall trend in groundwater quality in the basin is undetermined for two reasons: (1) a lack of available long-term sample analysis for many of the monitoring locations; (2) a statistical analysis of the available data has not yet been completed. However, as noted in this report, trends of increasing (or upward trends in) chloride and nitrate concentrations in groundwater have been reported previously for various watersheds within the basin.

Lake-by-Lake Assessment

Lake Superior
Status: Undetermined
Trend: Undetermined
Rationale: Data (22 wells) are insufficient for assessing overall groundwater quality in the Lake Superior basin (Figure 2).

Lake Michigan
Status: Fair
Trend: Undetermined
Rationale: The status assessment as fair should only be considered valid within the **western portion** of the Lake Michigan basin, given that this is where almost all of the available data were collected (Figure 3). Of the 136 wells that were assessed, the groundwater quality was poor in 64 (47%), fair in 29 (21%), and good in 43 (32%). On the eastern side of Lake Michigan (Figure 3), the status should be considered as undetermined. Trend analysis is not part of this initial assessment (2016-17), but is anticipated to be a component of future assessments.

Lake Huron
Status: Good
Trend: Undetermined
Rationale: The status assessment as good should only be considered valid within the **southeast portion** of the Lake Huron basin (Ontario) for which data were available (Figure 4). Of the 77 wells that were assessed, the groundwater quality was poor in 14 (18%), fair in 16 (21%), and good in 47 (61%). Where data gaps exist (Figure 4), the status should be considered as undetermined. Trend analysis is not part of this initial assessment (2016-17), but is anticipated to be a component of future assessments.

Lake Erie
Status: Fair
Trend: Undetermined
Rationale: The status assessment as fair should only be considered valid within the areas of the basin for which data were available (Figure 5). Of the 177 wells that were assessed, the groundwater quality was poor in 50 (28%), fair in 49 (28%), and good in 78 (44%). Where data gaps exist (Figure 5), the status should be considered as undetermined. Trend analysis is not part of this initial assessment (2016-17), but is anticipated to be a component of future assessments.

Lake Ontario

Status: Fair

Trend: Undetermined

Rationale: Of the 258 wells that were assessed, the groundwater quality was poor in 74 (29%) fair in 78 (30%), and good in 106 (41%) (Figure 6). Trend analysis is not part of this initial assessment (2016-17), but is anticipated to be a component of future assessments.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess the general status of the quality of shallow groundwater in the Great Lakes Basin (GLB), which is interactive with other components of the water cycle, and has potential to impact the quality of the Great Lakes waters. Select chemical constituents of groundwater can be used to provide information about ecosystem health and potential risks to the waters of the Great Lakes Basin.

Ecosystem Objective

This sub-indicator supports work towards General Objective #8 of the 2012 Great Lakes Water Quality Agreement (GLWQA), which states that the waters of the Great Lakes should be "free from the harmful impact of contaminated groundwater."

Ecological Condition

Groundwater can become contaminated with various substances including nutrients, salts, metals, pesticides, pharmaceuticals and other contaminants. Groundwater plays an important role as a reservoir of water that, if contaminated, can become a continuous source of contamination to the Great Lakes. Chemical parameters, such as nitrate and chloride, can be used to assess groundwater quality and to provide information about ecosystem health and potential risk to Great Lakes water quality. Nitrate is mainly from agricultural practices and chloride is mainly an urban contaminant as a result of de-icing road salt.

Elevated concentrations of nitrate in water have been shown to have detrimental effects on aquatic organisms and aquatic ecosystems (e.g., direct toxicity and increasing the risk of algal blooms and eutrophication; CCME, 2012), and human health (Health Canada, 2013). Elevated concentrations of chloride in water have been shown to have detrimental effects on aquatic organisms and aquatic ecosystems (e.g., toxicity; CCME, 2012).

Nitrate and chloride are considered to be key indicator contaminants in groundwater for the following reasons:

- They are two of the most prevalent and widespread contaminants in groundwater that have been measured and reported in the GLB (and elsewhere);
- They both are derived from multiple contaminant sources in both rural (agricultural) and urban areas;
- As anions, they are both extremely mobile (soluble) in water, including the subsurface environment;
- They are stable contaminants that do not have much physical or chemical interaction with the material they flow through;
- Chloride in particular, is persistent – chloride is not subject to attenuation in the subsurface by processes such as biodegradation, sorption or precipitation, and therefore may have an adverse effect on the water quality of streams, rivers and lakes in the GLB;
- Although nitrate is potentially reduced or eliminated by denitrification in some subsurface environments, nitrate also may have an adverse effect on surface-water quality in the GLB; and
- Even though some natural sources of these compounds exist in the environment (e.g., geological), nitrate and chloride are considered as general indicators of anthropogenic impact to aquatic systems.

As noted in a recent report on "Groundwater science relevant to the Great Lakes Water Quality Agreement" (Grannemann and Van Stempvoort, 2016):

"The natural flux of groundwater to the Great Lakes and their tributaries can enhance water quality and water quantity and provide essential habitats for Great Lakes ecosystems. Groundwater can also be a transmitter (vector) of contaminants and excessive loads of nutrients, which are derived from both non-point sources and point sources, to the Great Lakes. In addition to the direct flux of groundwater that transports contaminants and nutrients to the Great Lakes, the flux of groundwater to streams flowing into the Great Lakes also must be considered because the ecology and habitats of streams are interconnected with ecology of the Great Lakes (for example, fish spawning and migration)".

This sub-indicator regional-scale assessment was based on measurements (2000-2015) of the dissolved concentrations of two water quality constituents in groundwater in the GLB, nitrate and chloride, as part of ongoing monitoring of groundwater quality. For this initial assessment, the data were obtained from groundwater monitoring networks maintained by (1) the U.S. Geological Survey (USGS) and its partners, and (2) the Ontario Ministry of the Environment and Climate Change (MOECC) and its partners.

For each monitoring location/well, the groundwater quality was assessed, on the basis of concentrations of chloride (Cl^-) in milligrams per litre (mg/L) and nitrate (NO_3^-) in milligrams nitrogen per litre (mg N/L) as being:

Good: less than or equal to (≤) 0.8 mg N/L NO_3^- AND ≤ 30 mg/L Cl^-
Fair: greater than (>) 0.8 BUT less than (<) 3 mg N/L NO_3^- AND/OR >30 BUT < 120 mg/L Cl^-
Poor: greater than or equal to (≥) 3 mg N/L NO_3^- AND/OR ≥120 mg/L Cl^-

In this approach, the distinction between fair and poor is based on the CCME (2012) water quality guidelines for the protection of aquatic life (120 mg/L for chloride; 3 mg N/L for nitrate) and the distinction between good and fair is based on concentrations equivalent to one-quarter (25%) of these guidelines (i.e., 30 mg/L for chloride; 0.75, rounded up to 0.8 mg N/L for nitrate) (see sub-indicator description for additional information). These "25% of guideline" criteria provide an interim, protective approach for this sub-indicator assessment, based on judgement rather than directly on previously established criteria. They may be modified in future, if sufficient support for alternative criteria becomes available.

For each individual lake or entire Great Lakes Basin, the overall groundwater quality is assessed as follows:

- GOOD: If the percentage of wells assessed as GOOD is more than 50 (>50), THEN the basin is assessed as GOOD.
- POOR: If the percentage of wells assessed as POOR is more than 50 (>50), THEN the basin is assessed as POOR.
- FAIR: If the percentage of wells assessed as FAIR is more than 50 (>50), then the basin is assessed as FAIR
- If the basin is not assessed as Good, Fair, or Poor by the above definitions, THEN by default the basin is assessed as FAIR.
- UNDETERMINED: Data are not available or are insufficient to assess conditions of the ecosystem.

As illustrated in Figure 7, the definition of FAIR is more inclusive than POOR or GOOD, because FAIR includes all cases where there is no majority of individual wells assessed as poor, fair, or good (i.e., the central portion of this diagram, coloured in orange, where each of these three classifications is < 50%).

Only "shallow" groundwater samples (collected from wells screened at depths less than (<) 40 metre) were included in this assessment, given that shallow groundwater is the most interactive with the rest of the hydrologic system, including surface water in the Great Lakes Basin (Conant et al. 2016). Most of the shallow groundwater in the basin flows towards and will eventually discharge into the Great Lakes. This connection has many implications for water quality. Shallow groundwater tends to be "younger," or in other words, more recently recharged, and therefore it better reflects the groundwater quality impacts of recent activities in the recharge area (e.g., land use practices). That said, it should be understood that it can sometimes take years or decades for changes in land management practices to measurably impact the shallow groundwater (e.g., Zebarth et al. 2015).

The spatial distribution of data used in this assessment was uneven (Figures 1-6). Given that there were very few data points for the Lake Superior basin, the groundwater quality in this basin was assessed as "undetermined." The Lake Michigan basin was assessed using data from only the western portion of the basin given the lack of data on the east side. Likewise, the Lake Huron basin was assessed using data from the southeast portion of the basin, given that there were only two scattered data points throughout the northern and western portions of this basin. In the Lake Erie basin, data were concentrated in the north, resulting in large areas (especially the southwest portion) where groundwater quality data were limited. The Lake Ontario basin had sufficient, distributed data and thus has no caveats to note on the whole basin assessment for this lake.

There was a stronger tendency for groundwater quality to range from poor to fair in those portions of the basin that had more intense development, including urbanization (e.g., areas within the Michigan, Erie, and Ontario basins), and a tendency for groundwater quality to range from fair to good in the less developed areas (e.g., Huron and Superior basins) (Figure 1). For example, although only 22 data points (wells) were available for the Lake Superior basin, 90.9% of these (20) had good groundwater quality.

For the Canadian monitoring wells included in this study, statistical tests indicated no significant difference (probability value less than 0.05) between the depths of the wells and the concentrations of nitrate and chloride (Figure 8). The lack of correlation may reflect differences in the settings of the well sites (e.g., differences in land uses and in nitrate loadings from surface, and differences in subsurface conditions such as permeability of geologic units and in intensity of microbial activity).

It is important to note that if only one of the two constituents that were combined for this sub-indicator (chloride and nitrate) was assessed individually, the results would be very different. For example, in the western portion of the Lake Michigan basin, many of the wells have excessive nitrate concentrations resulting in the overall assessment of poor water quality. But, if only the chloride concentrations were considered, many of these wells would have been assessed as having fair to good groundwater quality (data not shown). This example illustrates that different areas in the basin have different contaminant issues that may drive the overall assessment when combined into a multi-contaminant approach. However, for reasons noted on page 2 of this report, it is informative to analyze both contaminants together, in particular, as it provides a fairly representative assessment of ambient groundwater quality in the Great Lakes Basin with the inclusion of these two contaminants from multiple sources. Consequently, the addition of other chemicals/constituents in the future would likely affect the assessments. This may require explanation when comparing updated results (that include additional constituents) to earlier sub-indicator reports.

Reported Trends of Chloride and Nitrate Concentrations in Groundwater in the Great Lakes Basin

Over the past several decades, various studies and status reports have provided information about trends of chloride and nitrate in surface water and groundwater in the Great Lakes Basin. For example, in a recent national study in the United States, which included the Great Lakes Basin, DeSimone et al. (2014) stated that "concentrations of .. chloride, and (or) nitrate in groundwater increased in two-thirds of groundwater well networks that were sampled at 10-year intervals between the early 1990s and 2010" (Figure 9). Similarly, on the Canadian side of the Great Lakes Basin, Sawyer (2009) reported that "increasing concentrations of nitrate and chloride are obvious" in groundwater throughout the Grand River watershed. Ongoing monitoring of water quality in Ontario has shown that chloride concentrations have increased in lakes and streams over the past several decades (Ontario Ministry of the Environment and Climate Change, 2016).

Chloride

One of the early studies to document chloride trends in the Great Lakes Basin was Bubeck et al. (1971), who reported that "salt used for deicing streets near Rochester, New York, had increased the concentration of chloride in Irondequoit Bay at least fivefold over two decades."

Thomas (2000a) investigated groundwater quality in the Detroit metropolitan area, and found that "young, shallow waters…. had significantly higher median concentrations of ….chloride ….than older, deeper waters." Based on analysis of chloride/bromide ratios, Thomas (2000a) concluded that the elevated salinities were "due to human activities rather than natural factors, such as upward migration of brine."

Kelly and Wilson (2008) reported that the majority of shallow public supply wells in some counties in northeastern Illinois have had increasing chloride concentrations since the 1960s. The increases were attributed primarily to "road salt runoff." DeSimone et al. (2014) reported that in the glacial aquifer system, which extends across the northern United States, including the Great Lakes Basin, "chloride concentrations were highest in shallow groundwater beneath urban areas, reflecting the use of deicing salt and the many other manmade sources of chloride in urban and suburban areas." Similarly, Mullaney et al. (2009) also reported evidence for increasing chloride concentrations in streams in urbanized and urbanizing areas of the United States, including the Great Lakes Basin.

On the Canadian side of the Great Lakes Basin, Howard and Beck (1993) reported that background concentrations of chloride in groundwater in glacial deposits in southern Ontario were in the range of 15–20 mg/L, but chloride concentrations were as great as 700 mg/L in domestic wells, as great as 2,840 mg/L in urban springs, and as great as 13,700 mg/L in pore waters extracted from beneath shallow urban areas. The potential sources of the chloride included road salts, landfill leachates, agricultural fertilizers, and saline bedrock waters. There was "extensive association of high chloride concentrations with urbanization in Metropolitan Toronto" (Howard and Beck, 1993). Bowen and Hinton (1998) reported that long-term monitoring of surface water in the Greater Toronto area showed a "gradual increase in chloride concentrations" and that "detailed baseflow water chemistry surveys….confirm that lower chloride concentrations occur predominantly in the rural portions of the watersheds."

In a more detailed study of a watershed in Metropolitan Toronto, Howard and Haynes (1993) estimated that 55% of the deicing salt applied each winter to roads, highways, and parking lots entered "temporary storage in shallow sub-surface waters." Howard and Haynes (1993) predicted that if salt application was maintained at the same rate, the average steady-state chloride concentrations in groundwater discharging as springs in the basin would exceed 400 mg/L, possibly within 20 years. In a follow-up study of the same watershed (20 years later), Perera et al. (2013) reported that chloride concentrations in base flow ranged widely, peaking at 500–600 mg/L in late spring, and then declining to around 250–300 mg/L. This was evidence that "a component of the groundwater, elevated in salinity due to the prior season's salting activity, moves…. rapidly to the stream via relatively shallow, preferential flow zones within the aquifer". Perera et al. (2013) reported that if "current road salt application rates are continued, late summer baseflow chloride concentrations will reach around 505 mg/L, almost double present levels," and would be above the drinking water guideline and the CCME (2012) aquatic chronic toxicity guideline. Similarly, Eyles and Meriano (2010) reported that in an urbanized watershed at Pickering, Ontario (Lake Ontario basin), 52% of the deicing salt applied "accumulates in groundwater where it continues to be released as brackish baseflow to creeks in summer."

By 1998, the Ontario Ministry of the Environment (1998) reported that a high percentage of water quality monitoring stations along Lake Erie had increasing chloride concentrations "indicative of the significant amount of urbanization and development that has occurred in watersheds in southern Ontario since the early 1980s." In the 2009 "State of the Great Lakes" report, Sawyer et al. (2009) noted that chloride levels in groundwater in the Grand River watershed of Ontario "can be linked to urban growth and its associated land uses." Sawyer et al. (2009) reported that increasing chloride concentrations have been observed in most municipal wells in the Grand River watershed, and that this increase has been attributed to winter deicing of roads with sodium chloride. Similarly, at Barrie, Ontario, one of the municipal wells has an upward trend in chloride concentrations that has become a drinking water issue (South Georgian Bay-Lake Simcoe Source Protection Committee., 2015). Another example is in the town of Orangeville, Ontario, where increasing chloride concentrations were documented in 5 of the 12 municipal supply wells for the 1982–2012 period (Credit Valley Conservation Authority, 2015).

Nitrate

Nitrogen is an essential nutrient for plants and animals. Nitrogen promotes rapid growth, increases seed and fruit production, and improves the quality of leaf and forage crops. Nitrogen exists in the environment in many forms as a part of the nitrogen cycle, with nitrate (NO_3^-) and ammonium (NH_4^+) being important inorganic species in water systems.

Nitrate is highly soluble in water and weakly absorbed by soil particles so it easily infiltrates through the soil profile and subsequently enters the groundwater system. The ability of nitrate to move through the soil can depend on the biological activity in the soil, the type of soil, and on the concentration of nitrate in the infiltrating water (Mikolajkow, 2003).

A study of groundwater quality in agricultural areas of Ontario was initiated by Agriculture Canada in 1991. Approximately 1,300 domestic farm wells were sampled in 1991 and 1992 and the groundwater samples were analyzed for nitrate, total and fecal coliforms, and several pesticides (Rudolph and Goss, 1993). Nitrate concentrations exceeded the drinking water quality standard of 10 mg N/L in samples from 15% of the domestic farm wells. The occurrence and concentration of nitrate in groundwater were found to be associated with the following:

- Most of the nitrate contaminated wells were shallow dug or bored wells;
- The nitrate concentrations tended to be higher in areas where the soils had high permeability;
- The nitrate concentrations were consistent at the same location and did not show a seasonal variation; and
- The nitrate concentrations decreased linearly with depth.

Similarly, a survey in Ontario in the late 1990s showed 14% of drinking water supply wells on farms had nitrate concentrations above the drinking water quality limit (Goss et al. 1998). Nitrate concentrations in groundwater are often elevated in urban and agricultural areas (Dubrovsky et al. 2010; IJC, 2010).

Sawyer et al. (2009) noted a linkage between "increased agricultural activity and groundwater contamination and its impact on surface water quality." Some elevated nitrate concentrations are linked to agricultural practices, but some may also be linked to "rural communities with a high density of septic systems that leach nutrients to the subsurface."

In a study of nitrate concentrations in groundwater in an agricultural region within the western Lake Erie basin, Thomas (2000b found that 37% of the samples had elevated nitrate concentrations that indicated human effects (e.g., fertilizer, manure, septic systems), and that 7% of the samples had nitrate concentrations that exceeded the U.S. Environmental Protection Agency's Maximum Contaminant Level of 10 mg N/L (U.S. Environmental Protection Agency, 2015).

Similar to chloride, increasing nitrate concentrations in some of the municipal supply wells in the Town of Orangeville have also been seen from 1982-2012 (Credit Valley Conservation Authority, 2015).

Linkages

Linkages to other Great Lakes sub-indicators include:

- Treated Drinking Water
- Water Quality in Tributaries. This sub-indicator is based the Water Quality Index (WQI), which is calculated using a total of eight parameters, including both chloride and nitrate concentrations.
- Coastal Wetlands: Extent and Composition
- Aquatic Habitat Connectivity
- Nutrients in Lakes (open water)
- Watershed Stressors – to some extent, the pattern of groundwater quality status appears to be associated with land-use and development patterns. Poorer groundwater quality tends to be in areas of more intense land use, including urban and agricultural land use. Additional statistical analysis is warranted to confirm linkages in future reports.
- Human Population – Similarly, poorer groundwater quality tends to be in areas that are more densely populated. Additional statistical analysis is warranted to confirm linkages in future reports.

Future consideration of the above linkages may be useful in terms of demonstrating how regional groundwater quality patterns are related to surface water quality, habitats and various stressors.

Comments from the Author(s)

The new "USGS Online Mapper" (https://www.usgs.gov/news/usgs-online-mapper-provides-decadal-look-groundwater-quality, release date: June 2, 2016) is a "first of its kind" online interactive mapping tool that provides "summaries of decadal-scale changes in groundwater quality" across the United States, including areas in the Great Lakes Basin (U.S. side only).

Limitations

This sub-indicator takes into account only two contaminants (nitrate and chloride) and is therefore not meant to capture all possible groundwater contamination issues or problems at a given location. Groundwater can be contaminated by many other substances including natural chemicals (e.g., petroleum hydrocarbons and arsenic), synthetic chemicals (e.g., organic pesticides and pharmaceuticals), or other substances, such as pathogenic microorganisms. Also, the impact of some sectors on groundwater quality is not well assessed by the two chemicals that have been selected (e.g., mining sector).

In future assessments, where sufficient data are available, the basic spatial (geographic) unit of observation for this sub-indicator should be sub-watersheds within the Great Lakes Basin. However, due to large gaps in spatial distribution of currently (2016) available groundwater quality data (USGS and MOECC monitoring networks), this sub-watershed component was not included in this initial status report.

Also, how the contaminated groundwater impacts and interacts with the water of the Great Lakes, in particular in the nearshore zone, requires a better understanding.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the United States are comparable to those from Canada				x		
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				
Clarifying Notes: The networks of monitoring wells that were used for this assessment differ on the U.S. and Canadian sides of the border. Specifically, the ages of the wells, their construction methods, and the criteria that were used for selecting these monitoring wells were different. Although the methods of analyses used for the U.S. and Canadian data also differed, this is not likely to have had a substantial effect on the outcome of the assessment.						

Acknowledgments
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Contributor:
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Information Sources

Bowen, G.S., and Hinton, M.J. 1998. The temporal and spatial impacts of road salt on streams draining the Greater Toronto area. Proceedings of the Groundwater in a Watershed Context symposium, A.R. Piggott (ed.), p. 303-310.

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Source: DeSimone et al. (2014)

Last Updated

State of the Great Lakes 2017 Technical Report

		Poor groundwater quality		Fair groundwater quality		Good groundwater quality	
Canadian data	**Total # wells**	**# wells**	**%**	**# wells**	**%**	**# wells**	**%**
Superior	9	1	11%	1	11%	7	78%
Huron	75	12	16%	16	21%	47	63%
Erie	54	15	28%	8	15%	31	57%
Ontario	114	35	31%	34	30%	45	39%
All basins	252	63	25%	59	23%	130	52%

		Poor groundwater quality		Fair groundwater quality		Good groundwater quality	
US data	**Total # wells**	**# wells**	**%**	**# wells**	**%**	**# wells**	**%**
Superior	13	0	0%		0%	13	100%
Michigan	136	64	47%	29	21%	43	32%
Huron	2	2	100%	0	0%	0	0%
Erie	123	35	28%	41	33%	47	38%
Ontario	144	39	27%	44	31%	61	42%
All basins	418	140	33%	114	27%	164	39%

		Poor groundwater quality		Fair groundwater quality		Good groundwater quality	
Binational data	**Total # wells**	**# wells**	**%**	**# wells**	**%**	**# wells**	**%**
Superior	22	1	5%	1	5%	20	91%
Michigan	136	64	47%	29	21%	43	32%
Huron	77	14	18%	16	21%	47	61%
Erie	177	50	28%	49	28%	78	44%
Ontario	258	74	29%	78	30%	106	41%
Entire Great Lakes Basin	670	203	30%	173	26%	294	44%

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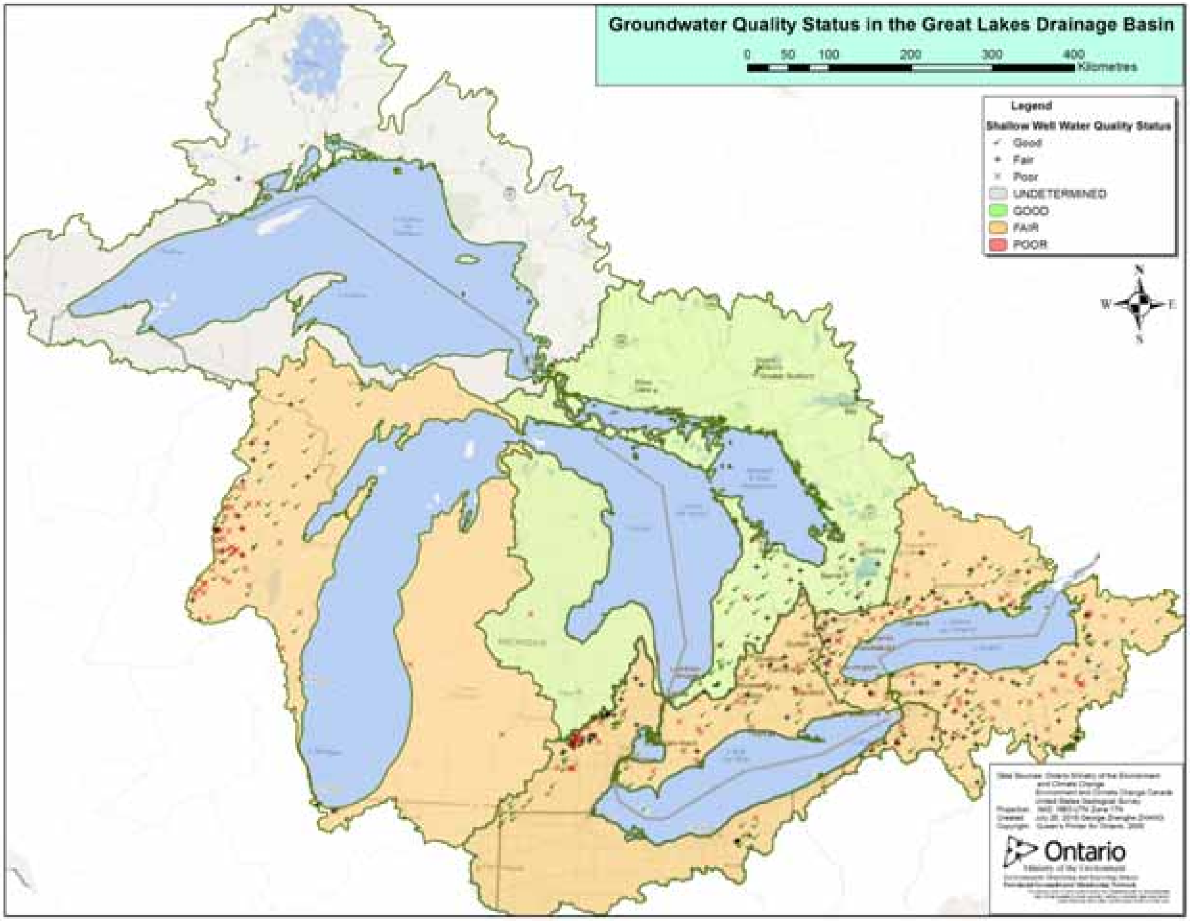

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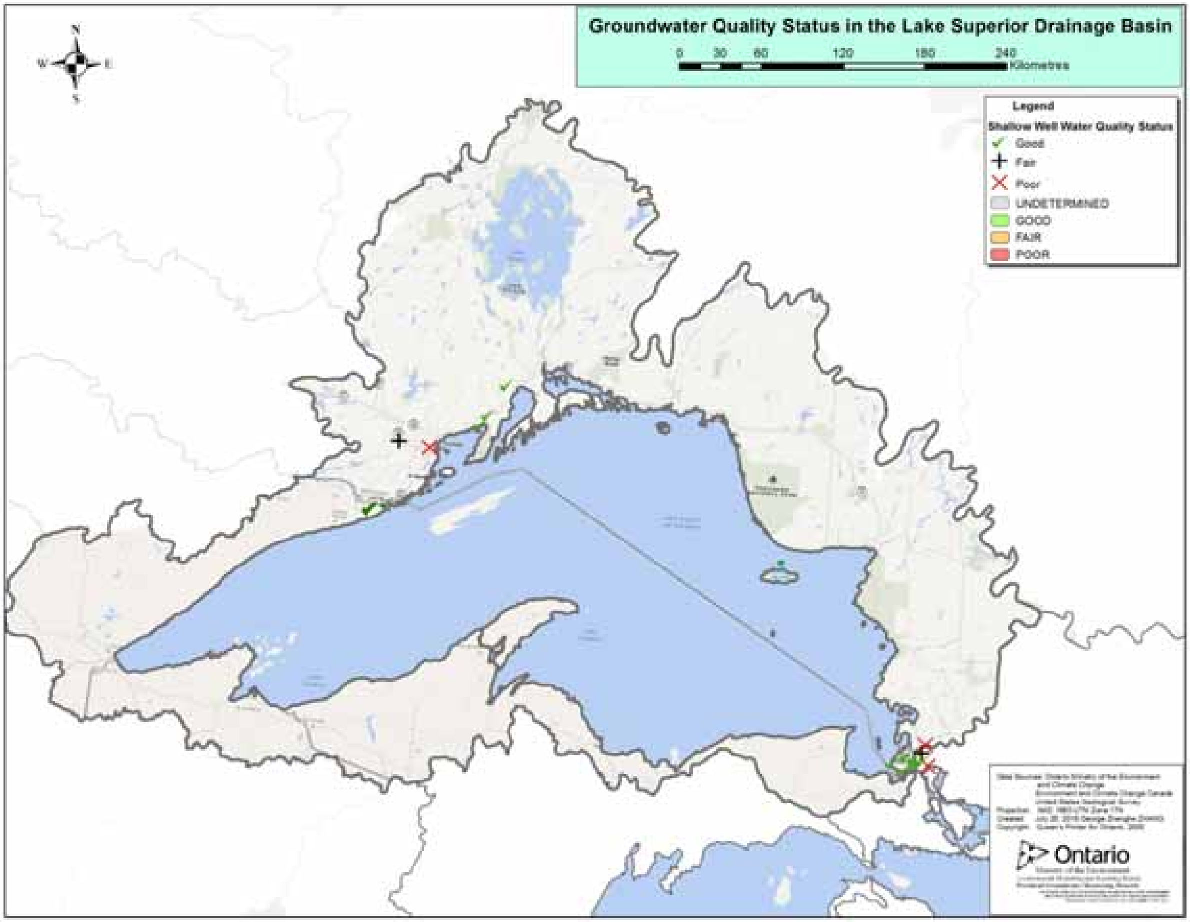

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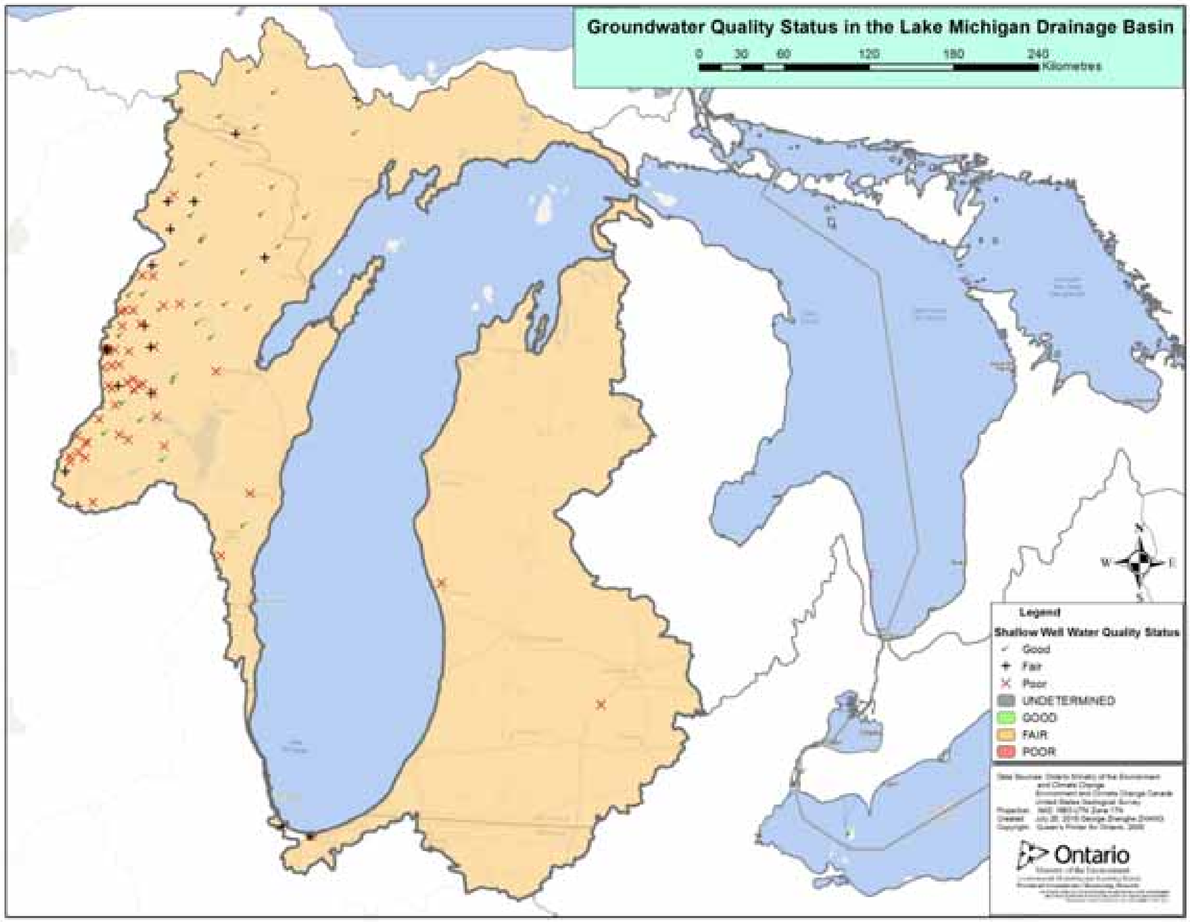

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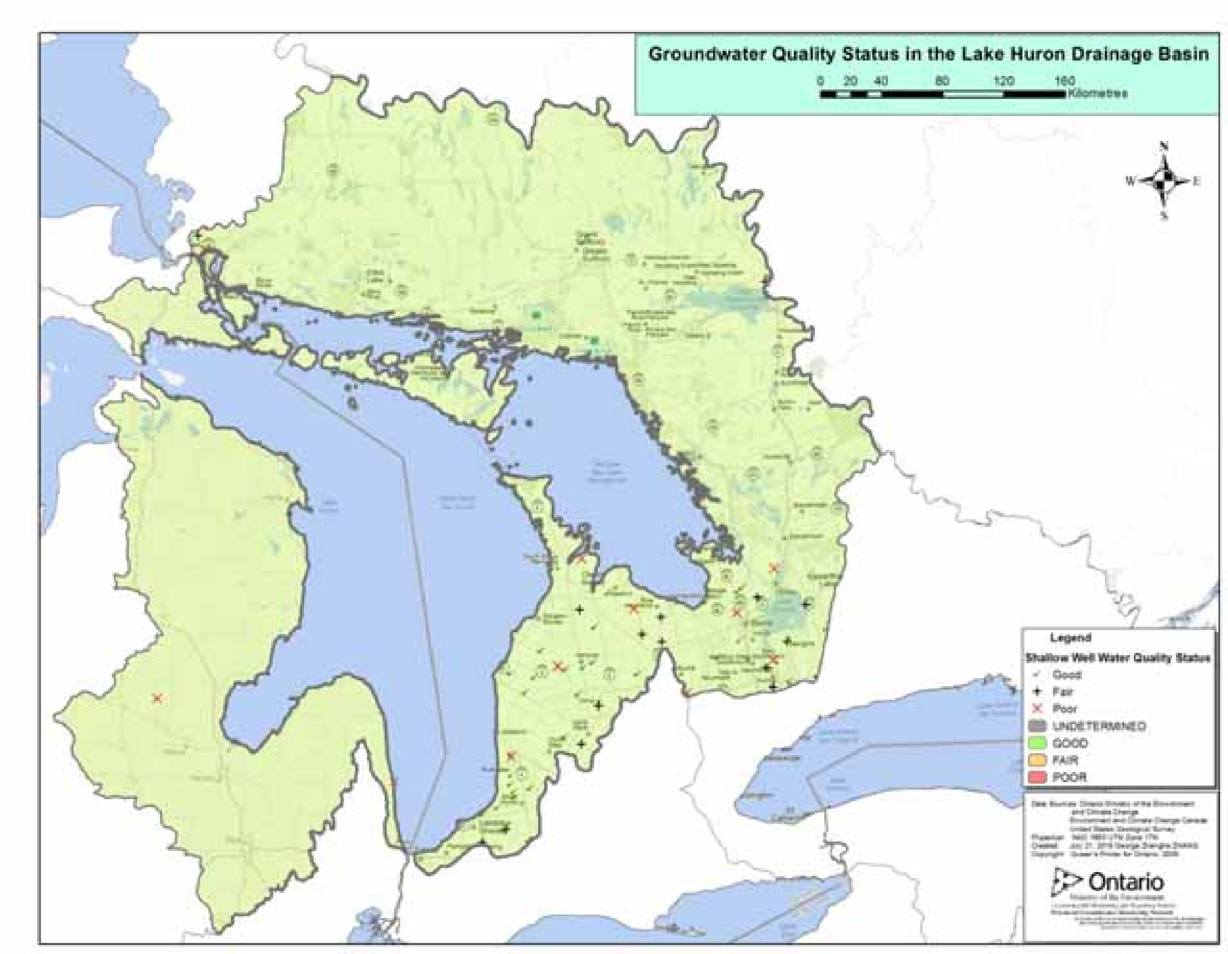

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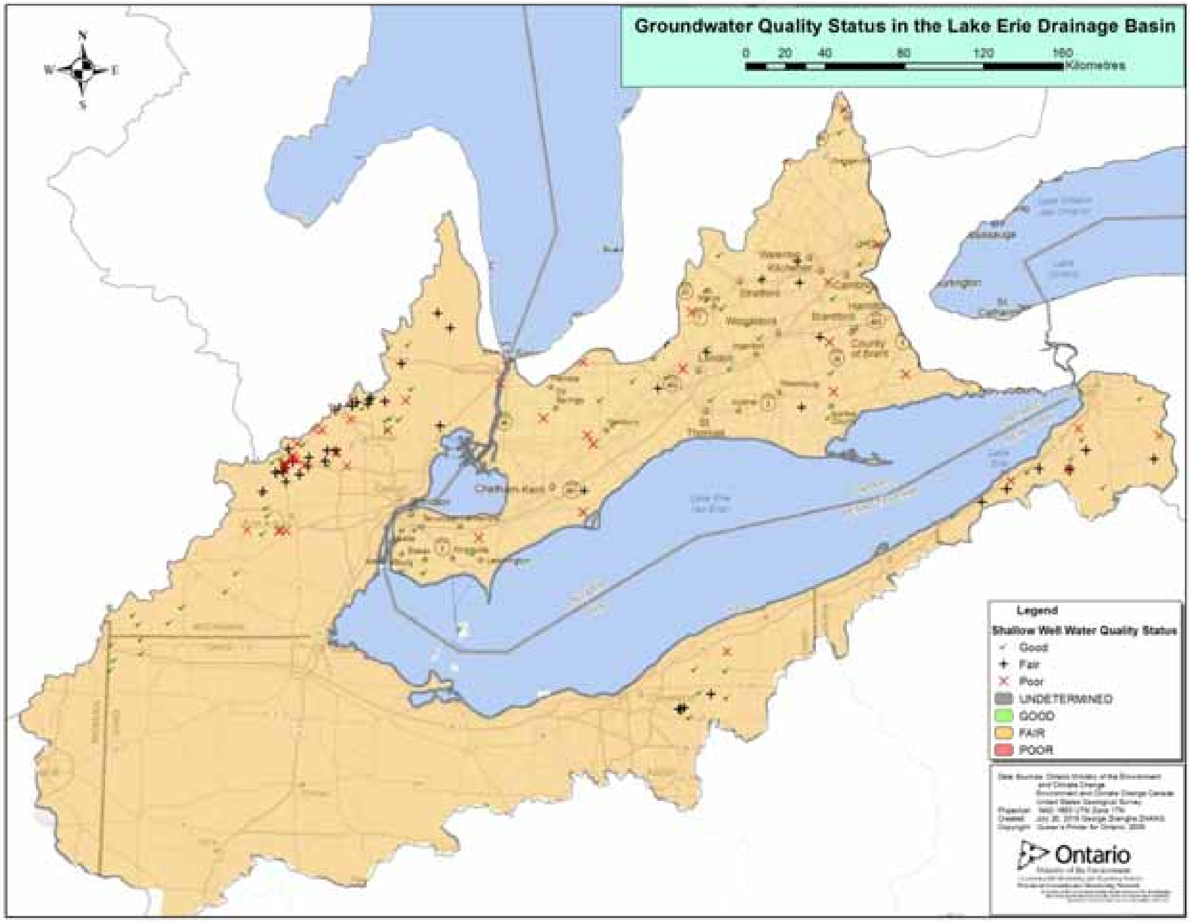

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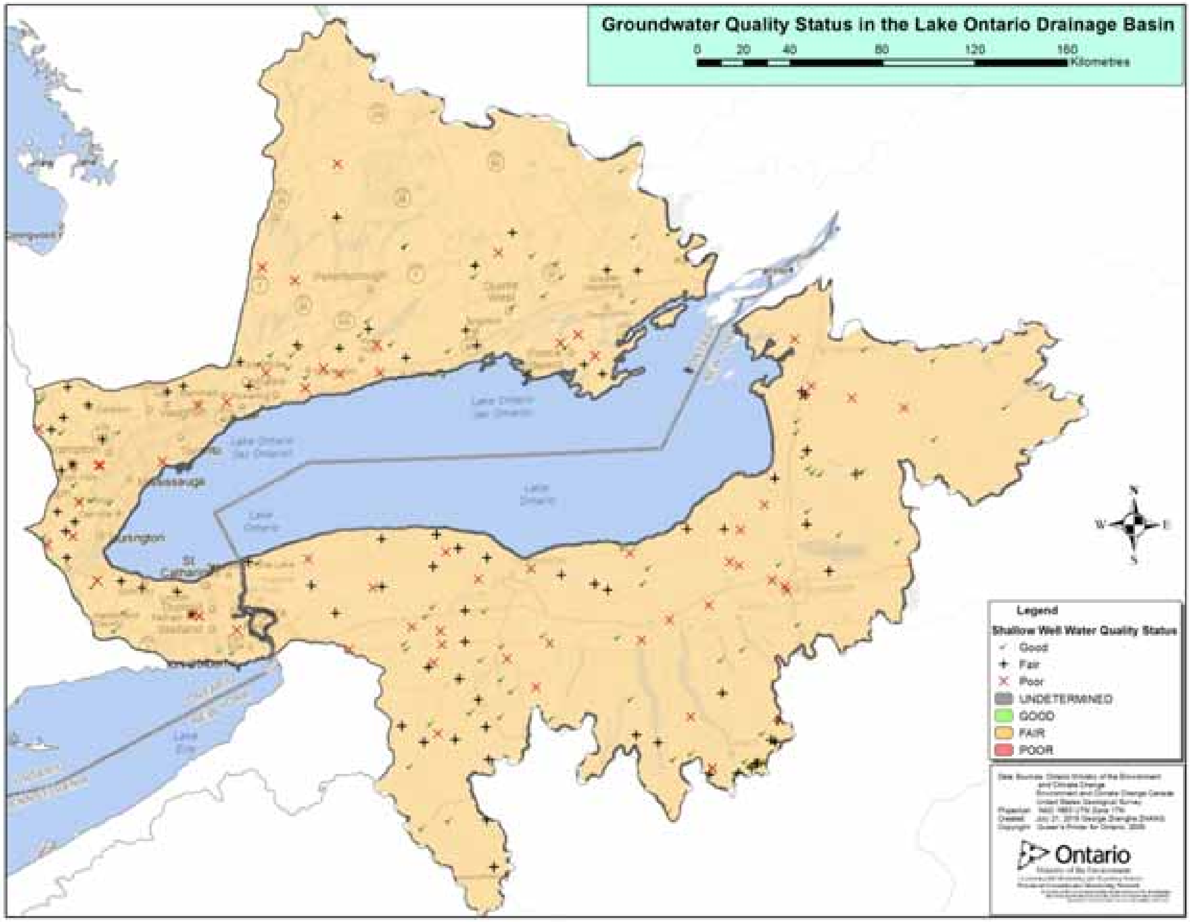

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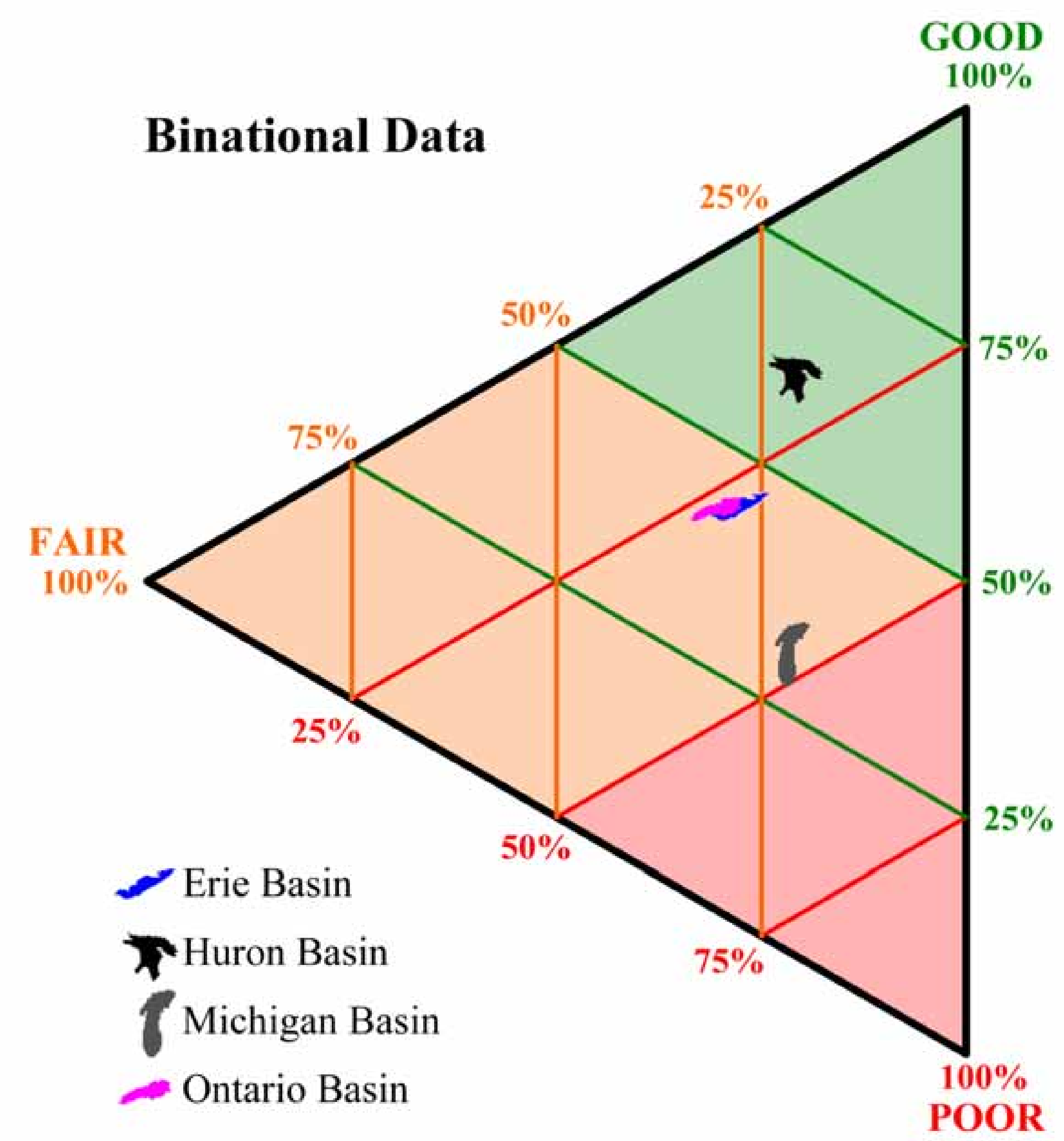

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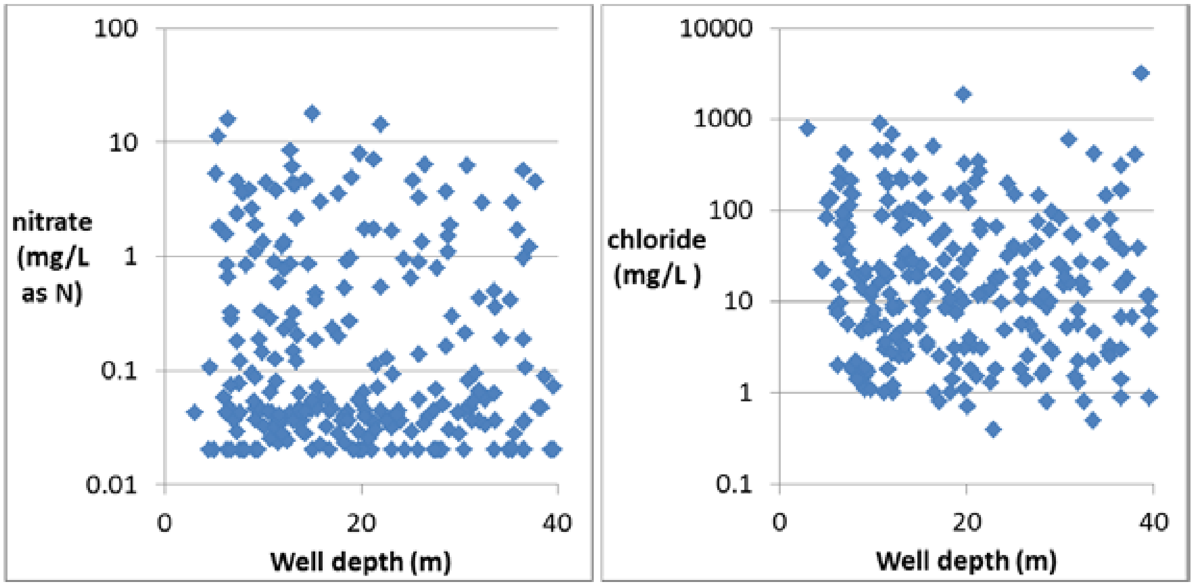

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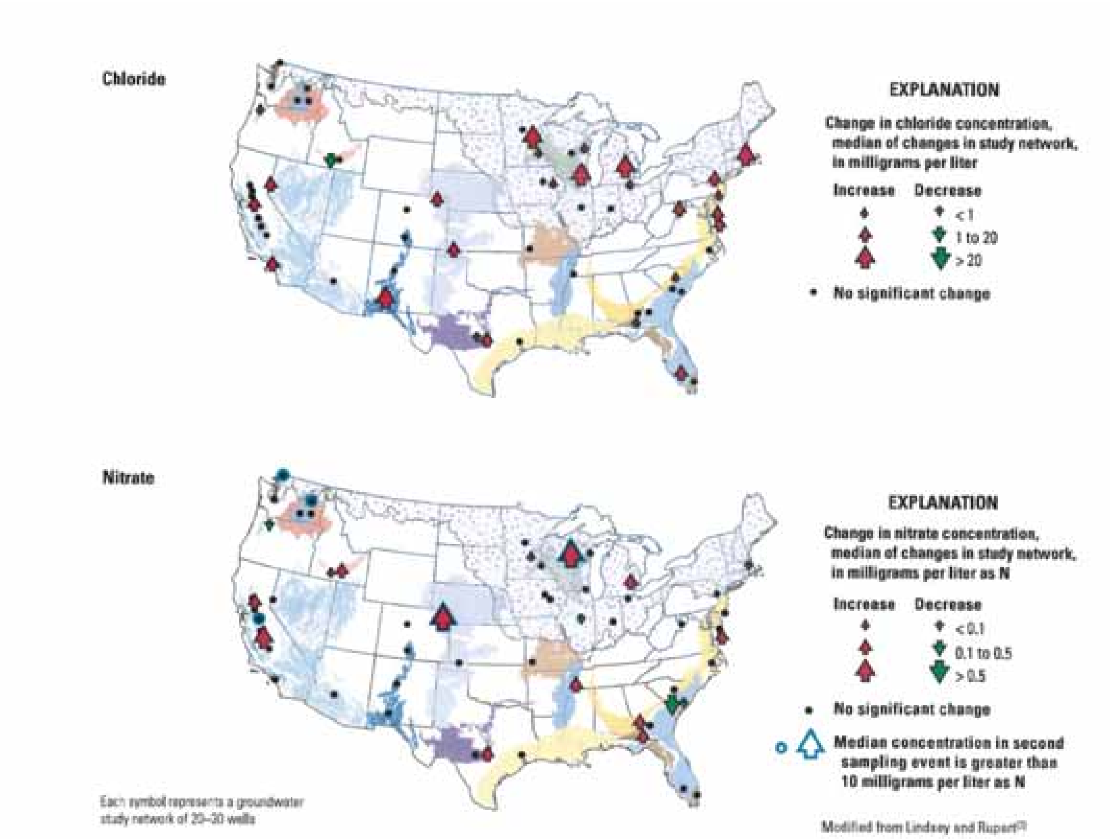

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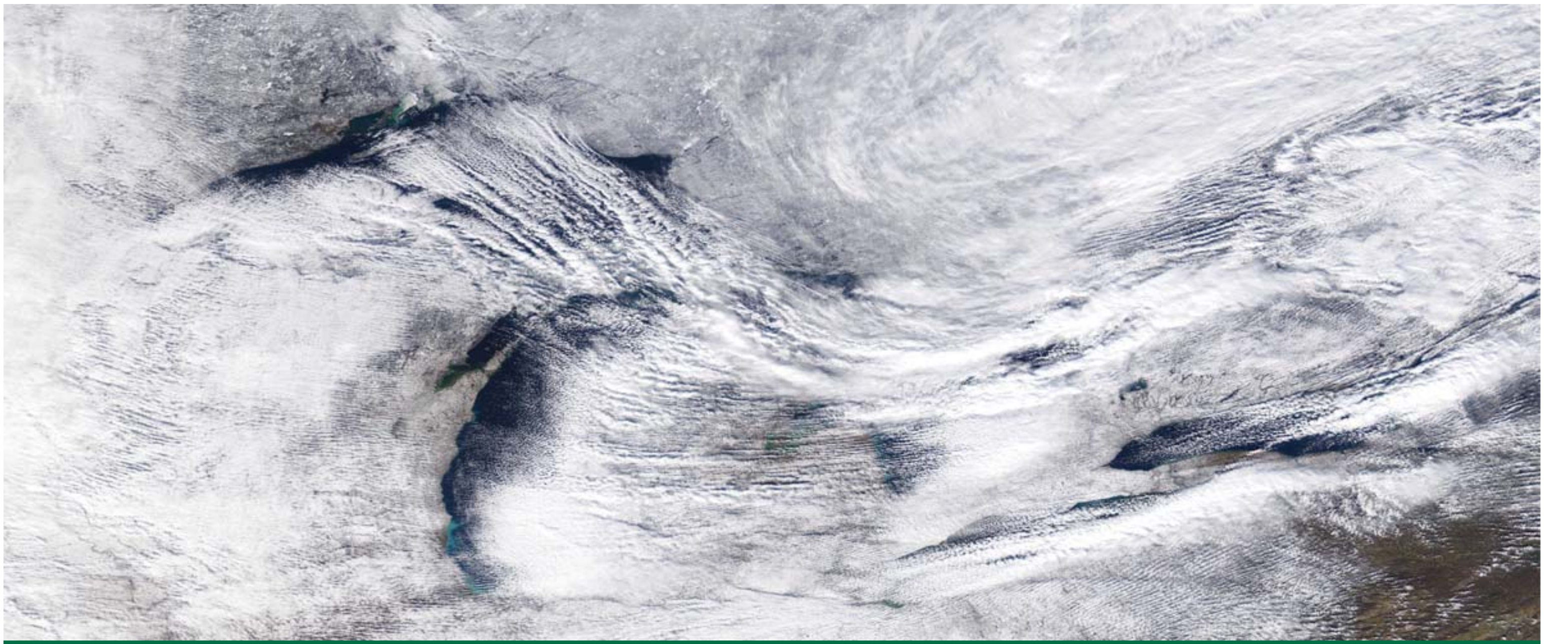
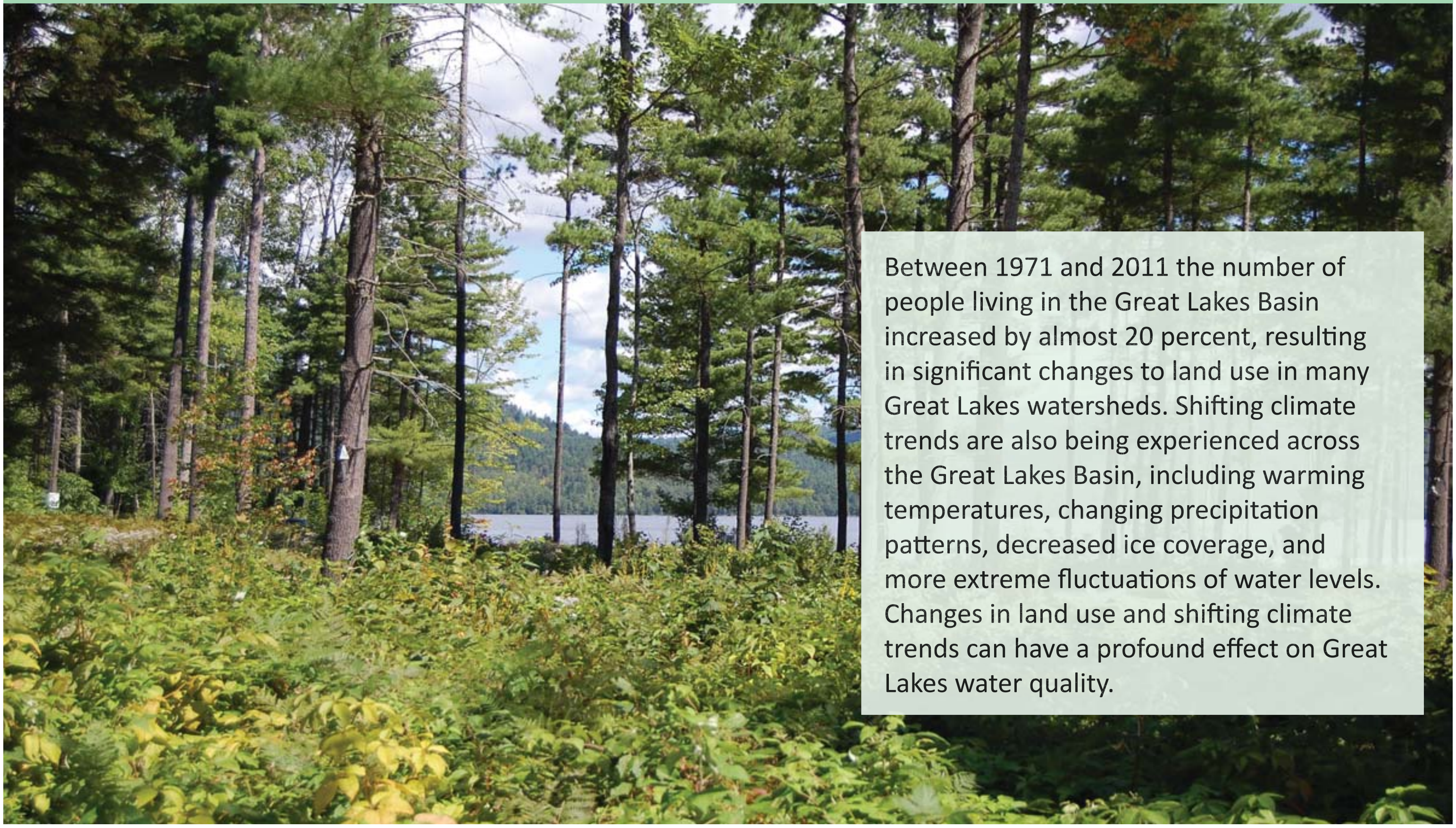


Watershed Impacts and Climate Trends

Status: Fair Trend: Unchanging

The 2012 Great Lakes Water Quality Agreement states that *"the Waters of the Great Lakes should be free from other substances, materials or conditions that may negatively impact the chemical, physical or biological integrity of the Waters of the Great Lakes"*



Between 1971 and 2011 the number of people living in the Great Lakes Basin increased by almost 20 percent, resulting in significant changes to land use in many Great Lakes watersheds. Shifting climate trends are also being experienced across the Great Lakes Basin, including warming temperatures, changing precipitation patterns, decreased ice coverage, and more extreme fluctuations of water levels. Changes in land use and shifting climate trends can have a profound effect on Great Lakes water quality.

Watershed Impacts and Climate Trends

Assessment Highlights

Overall, the Watershed Impacts and Climate Trends indicator is assessed as **Fair** and **Unchanging**. This indicator includes all "other substances, materials or conditions" that are not highlighted in the eight other indicators noted on page 2, but are important with respect to the state of the Great Lakes. The indicator currently includes an array of land-based conditions which can affect water quality as well as climate trends which can impact all parts of the ecosystem.

Watershed Impacts

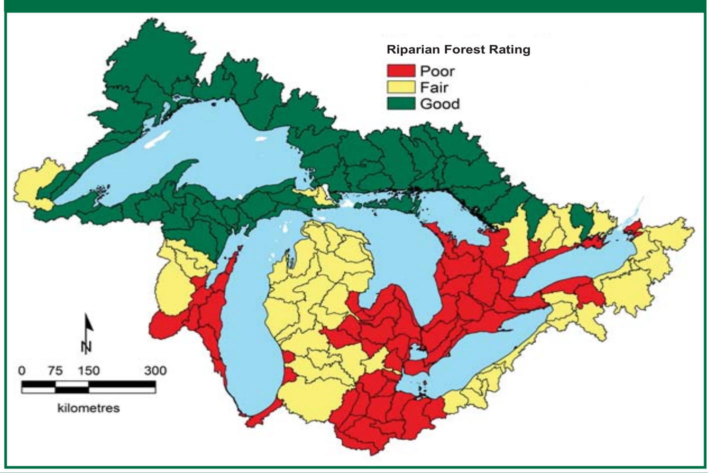
Population, development, agriculture and road density can cause land-based pressures on the Great Lakes ecosystem, especially in areas with larger population centres. Although urban and agricultural lands are important to the Great Lakes region because they help support people and the economy, the water quality in these areas, in particular the lower lake basins, is more susceptible to impairments or threats. Conversely, the northern part of the Great Lakes Basin has lower relative amount of stress since it remains largely undeveloped and is dominated by natural cover.

Across the entire basin, almost 400 square kilometres (154 square miles) or 40,000 hectares of natural lands were converted to developed land cover between 2001 and 2011. The latest analysis shows a growing trend of increasing development, resulting in a loss of agricultural, forested and natural lands.

Research has shown that an increase in forest cover improves water quality. In particular, forest cover within a riparian zone (i.e. land along a lake, river or stream), plays a key role in stabilizing soil and can help reduce the amount of runoff from the land and reduce nutrient loadings and other non-point source pollutants. Forest cover in the riparian zones varies with the Lake Superior watershed having the highest amount at 96% and the Lake Erie watershed having the least with 31%. With half of the Great Lakes Basin currently in agricultural or developed land use, and with much less forest cover in the more southern parts of the Great Lakes Basin, it is evident that land-based pressures can significantly impact water quality.

Agricultural Lands in the Southern Parts of the Great Lakes Basin

Forest Cover Helps to Improve Water Quality



Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Forest Cover	Unchanging	Unchanging	Unchanging	Improving	Deteriorating
Land Cover	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging
Watershed Stressors	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging
Hardened Shorelines	Undetermined	Undetermined	Undetermined	Undetermined	Deteriorating
Tributary Flashiness	No lake was assessed separately Great Lakes Basin trend is **Unchanging**				
Human Population	Decreasing	Increasing	Increasing	Increasing	Increasing

Status:	GOOD	FAIR	POOR	UNDETERMINED

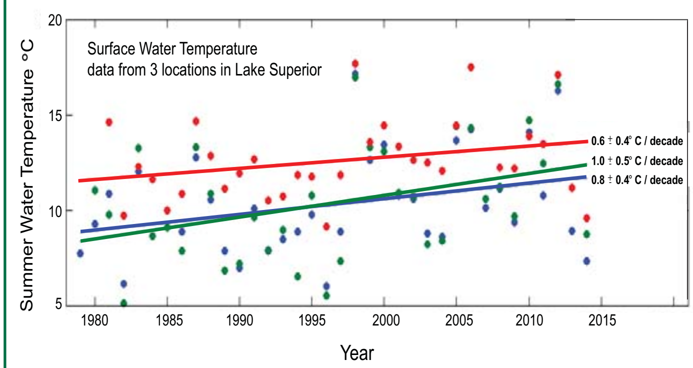
Watershed Impacts and Climate Trends

Climate Trends

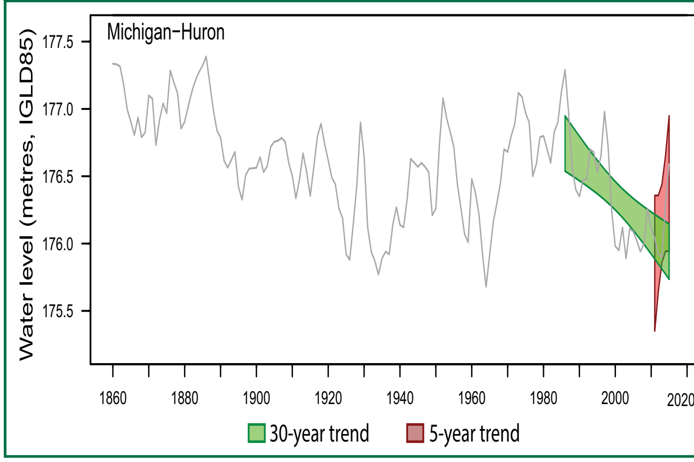
Data collected over the past 30-40 years in the Great Lakes Basin show increases in the amount of precipitation, increases in summer surface water temperature and a reduction in ice cover. Lake levels have also generally decreased, although there has been a recent rebound in water levels in the past few years. It is not yet possible to say with any certainty, however, if changes in water levels are due to human activity or natural long-term cycles.

These changes can affect the health of the Great Lakes Basin including impacts to spawning and other habitats for fish species, the amount and quality of coastal wetlands and changes in forest composition. Shifts in climate trends can also lead to the northward migration of invasive species and alter habitat in a way that favours some invaders over native species. An extended growing season, increases in runoff and nutrient loads and changes to contaminant cycling could also result from a shift in climate trends.

Surface Water Temperatures are Increasing



Water Levels Fluctuate



Assessing Climate Trends

Climate information is not assessed in the same manner as other indicators in this report. For example, the ecosystem has adapted to and needs both high and low water levels and neither condition can be assessed as **Good** or **Poor**. However, prolonged periods of high or low water levels may cause stress to the ecosystem. Therefore, climate trends are simply assessed as **Increasing**, **Unchanging** or **Decreasing** over a defined period of time.

Sub-Indicators Supporting the Indicator Assessment

Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Precipitation Amounts (1948-2015)	No lake was assessed separately Great Lakes Basin trend is ↑				
Surface Water Temperature (1979/1980-2014)	↑	↑	↑	**Undetermined**	**Undetermined**
Ice Cover (1973-2015)	↓	↓	↓	↓	↓
Water Levels (1985-2015)	↓	↓	↓	↓	**No significant change**
Baseflow Due to Groundwater	No lake was assessed separately Great Lakes Basin trend is **Undetermined**				

Sub-Indicator: Forest Cover

Forest Cover in the Riparian Zone

Overall Assessment
Status: Fair
Trend: Unchanging
Rationale: Forested cover in the riparian zone of water bodies is high in the Lake Superior basin (96%), moderate in the Michigan, Huron and Ontario basins (61 – 73%) and low in the Lake Erie basin (31%) based on satellite imagery. Trends in forested cover (2006 – 2011 in U.S. and 2002 – 2011 in Canada) in riparian zone are showing unchanging conditions in the Lake Superior, Michigan and Huron basins, small decrease in the Ontario basin (-1.7%) and an increase in the Erie basin (+4.5%). The northern watersheds have much higher rates of forested riparian zones than watersheds in the south, where there is much greater development and agriculture.

Similarly, forested lands are a large percentage of land area within the Lake Superior basin (93%), a moderate amount in the Lake Michigan, Huron and Ontario basins (48 - 65%) and low in the Lake Erie basin (19%) based on satellite imagery. Trends in forest cover across the lake basins are very similar to the riparian zone assessments, showing unchanging conditions in the Superior and Huron basins. However, losses in forest cover were seen in Lakes Michigan (-1.2%), Erie (-1.2%) with the largest losses in the Ontario basin (-3.9%).

Lake-by-Lake Assessment
Lake Superior
Status: Good
Trend: Unchanging
Rationale: With riparian zones of water bodies in this basin having high forest cover, these waters are likely to be well protected. The Lake Superior basin also has a high overall forest cover. These data suggest that there is unlikely to be long-term impairment of water quality due to forest cover change.

Lake Michigan
Status: Fair
Trend: Unchanging
Rationale: Northerly watersheds within this basin have high forest cover in riparian zones, while southern watersheds have reduced cover that may decrease water quality and ecosystem integrity. There is a similar pattern for forest cover in this basin, with high forest cover in the northern watersheds, while southern watersheds have low forest cover. These data suggest there is some potential in southerly watersheds to have impairments in water quality and ecosystem integrity due to forest cover change.

Lake Huron
Status: Fair
Trend: Unchanging
Rationale: Northerly watersheds within this basin have high forest cover in riparian zones, while southern watersheds have reduced cover that may decrease water quality and ecosystem integrity. There is a similar pattern for forest cover in this basin, with high forest cover in the northern watersheds, while southern watersheds have low forest cover. These data suggest there is some potential in southerly watersheds to have impairments in water quality and ecosystem integrity due to forest cover change.

Lake Erie
Status: Poor
Trend: Improving
Rationale: A low proportion of forest cover in riparian zones suggests heightened threat to water quality and ecosystem integrity. However, the trend (between 2002 and 2011) is improving on the Canadian-side of the basin. This basin also has a low coverage by forests, which has declined over the 2002 to 2011 period on the Canadian-side of

the basin despite increase in riparian forest cover. These data suggest that there is a large potential for water quality problems and risks to ecological integrity due to forest cover change.

Lake Ontario
Status: Fair
Trend: Deteriorating
Rationale: There is a moderate level of forest cover in riparian zones in this basin which suggests there a moderate risk to water quality and ecosystem integrity. Similarly, most watersheds in the Lake Ontario basin have moderate forest cover, which has declined over the 2002-2011 period on the Canadian-side of the basin. These data suggest there is a potential for water quality problems and risks to ecological integrity due to forest cover, particularly in Canada where losses have been larger while the U.S. has remained unchanged.

Sub-Indicator Purpose
The purpose of this sub-indicator is to quantify forest cover in riparian zones in relation to its role in performing hydrologic functions, providing essential processes (e.g., evapotranspiration and nutrient transport), and protecting the physical integrity of the watershed (e.g., erosion control), all of which are necessary for supplying high quality water.

Ecosystem Objective
To have a forest composition and structure that reflects the natural ecological diversity (i.e., under present climate conditions) of the region.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes."

Ecological Condition
This sub-indicator includes the percent of forested lands within riparian zones by watershed, over time as the main component being assessed. The percent of forested lands within watershed by lake basin, over time is also included to support and provide context for the lake-by-lake and overall assessments.

Decades of research and monitoring have shown that water draining forested watersheds is of high quality, as measured by sediment yields, nutrient loadings, contaminant concentrations and temperatures. Forest cover also contribute to many other ecosystem services, including controlling soil erosion, increasing groundwater infiltration, stabilizing shorelines and mitigating storm run-off. Leaf litter and woody debris provide critical food and habitat for fish and other aquatic wildlife. Although there are different roles of non-forest vegetation in maintaining water quality and quantity, forest cover in riparian areas is a good representation of water protection.

In general, an increase in forest cover improves water quality. Ernst (2004), in a small survey of municipal water systems, showed that water treatment costs can be directly related to the degree of forest cover in the source watershed. The function she developed suggests that treatment costs are lowest at levels of forest cover above ~60%. Other studies have been less successful in discovering empirical relationships between forest cover and the economics of municipal water supplies.

Where watersheds have experienced large land-use changes due to agricultural activities or urban and suburban development, increased forest coverage within a riparian zone can mitigate many of the potentially harmful impacts on water bodies. Forested riparian zones can decrease the amount of surface runoff to water bodies (reducing erosion), mitigate nutrient loadings from fertilizer application and other non-point source pollutants and increases the capacity of the ecosystem to store water. Riparian zones are also important sources of energy and material to aquatic systems and help regulate water temperatures. Thus the amount of forest in riparian zones (30 metre buffer around all water bodies which includes water polygons, rivers, streams and intermittent streams where identified) within each lake basin is the component being used to assess the conditions within this sub-indicator. The status assessment is determined using the following criteria: Good = >80% forest cover in riparian zones; Fair = 50 – 80% forest cover in riparian zones; and Poor = <50% forest cover in riparian zones. For trends, a trend is considered unchanging if change is ≤ ± 1% and changing if >± 1%. Overall forest cover in a lake basin is used as additional information to provide a larger context.

The riparian zone was assessed by creating a 30 metre buffer around all waterbodies and using it as a mask on the forest cover data layers. On a lake basin level (Figure 1), the Lake Superior basin has 96% of its riparian zones identified as forested, with moderate level of forest in riparian areas for Michigan (63%), Huron (73%), and Ontario (61%). Only 31% of riparian zones in the Lake Erie basin is forested (Table 1). There is also substantial variation at the tertiary watershed level with each of the lake basins (Figure 2). The northern watersheds have much higher rates of forested riparian zones than watersheds in the south, where there is much greater development and agriculture.

Assessing trends in the forest cover within the riparian zone sub-indicator has proven difficult. Whereas the status of forest cover can be readily assessed through analysis of carefully checked and referenced satellite data, these data are usually available for single points in time. For this report, satellite imagery data was employed for the U.S. portions of the lake basins from 2006 to 2011 and for the Canadian portions of the basins from 2002 and 2011. Trend analysis showed that riparian forest is unchanging for northern basins, a small increase in Erie (4.5%) and small decrease in Ontario (-1.7%) basins. Changes were small in the U.S. (<1.1%) and larger in Ontario (range from -3.3% to +16.3%) (Table 2). These trends should be interpreted with some caution, realizing the short span of time in which they are calculated (5 years for U.S. and 9 years for Canada). A longer record (>20 years) is required in order to identify trends with any degree of reliability.

Patterns in forest cover within watersheds show similar findings to the forest cover in riparian areas. Figure 3 shows the tertiary watersheds draining into the Great Lakes and their level of forest cover. There is a strong N-S gradient evident in the degree of forest cover as would be expected given a similar gradient in population and agricultural activity. In the Lake Superior basin, 93% of the land area is forested (Table 2). In all the other basins, forests have been replaced by development and agriculture, leaving forest to occupy 49% (Michigan), 65% (Huron), 19% (Erie) and 48% (Ontario) of the basins (Table 2). However, it must be noted that within any given basin, there are watersheds with fair to good forest cover (Figure 4). Table 2 shows that in the U.S. portion of all lake basins, there is a trend of unchanging (Erie, Ontario) or small declines (Superior, Huron, Michigan), whereas in Canadian basins there are unchanging (Superior, Huron) to some larger declines (Erie, Ontario) in forest cover (Table 2).

Linkages

The well-documented ability of forested lands to produce high quality water and in particular for forested riparian areas to protect water resources has linkages to many other sub-indicators. In particular, forest cover within riparian areas contribute directly to reducing nutrient, and other non-point source pollutant, loadings to the tributaries and lakes and help to improve the negative effects of atmospheric deposition. Indirectly, the high quality water emanating for forested areas supports diverse aquatic communities. Climate change, through its effects on forest composition and function and on local hydrological processes is likely to affect the ability of forests to produce high quality water, although the magnitude and direction of these affects are not well known. For example, the decline to total annual runoff in many Great Lakes basins may lead to increased concentrations of nutrients and contaminants in tributary waters. Also, changes in forest composition, due human activities (e.g., forest management) or natural agents (e.g., emerald ash borer), may affect water quality and/or quantity.

Comments from the Author(s)

Estimating forest cover by remote sensing is widely used and generally reliable. However, many of the available datasets do not contain the long time series needed to adequately assess trends. Regular assembly of cross-border data sets are needed to measure changes in forest cover and to understand the drivers of change. Forest inventory data (e.g., USFS FIADB) is also useful but Canada lacks an equivalent system. There also remains the challenge of integrating both forest inventory systems and remote sensing data across jurisdictions due to differences in goals and methodologies.

It is acknowledged that forest type and the age structure and composition of forests as a function of types and intensity of disturbance influence water quality and quantity. Although it may be desirable to expand the analysis to include these factors, devising a way compile and calculate indicators given the different sources of data will be a challenge. It is also recognized that a standard 30 m buffer may not be sufficient to protect water bodies and assessing different or variable buffer sizes might be more beneficial.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		X				
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin				X		
5. Data obtained from sources within the U.S. are comparable to those from Canada			X			
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				

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List of Tables

Table 1. Percent of forest cover in riparian zones and percent change by basin for U.S. (2006 and 2011) and Canada (2002 and 2011) and combined U.S. and Canada Great Lakes region. Data was based on summing forest cover types in a 30 m buffer around all water bodies. Forest cover was identified from Landsat satellite imagery for U.S. and Canada (Ontario).
Sources: U.S. National Land Cover Database 2006 (Fry et al. 2006), 2011 (Homer et al. 2015) and Ontario Landcover 2002 and SOLRIS 2002 (OMNRF 2006, Forest Sustainability and Information Section, unpublished data) and Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)
Table 2. Percentage of forest cover and percent change by lake basin for U.S. (2006 and 2011) and Canada (2002 and 2011) and combined U.S. and Canada Great Lakes region. Forest cover was identified from Landsat satellite imagery for U.S. and Canada (Ontario).
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Figure 1. Percentage of forest cover within riparian zone (30 m buffer around water bodies) for tertiary watersheds (HUC8 in U.S. and 4 digit in Ontario) of the Great Lakes. Forest cover was estimated from satellite imagery and includes a variety of forest types (i.e. deciduous, conifer, mixed) and treed wetlands.
Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

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Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

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Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

Figure 4. Forest cover rating in tertiary watersheds (HUC8 in U.S. and 4 digit in Ontario) of the Great Lakes.
Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

Last Updated

State of the Great Lakes 2017 Technical Report

U.S. Basin	Riparian Forest 2006 (ha)	Riparian Forest 2011 (ha)	% Change in Riparian Forest	Amount of Riparian Forest 2011	Class Value
Superior	172,927	171,014	-1.1%	85.9%	Good
Michigan	270,484	268,988	-0.6%	62.5%	Fair
Huron	93,021	92,367	-0.7%	56.4%	Fair
Erie	95,593	95,421	-0.2%	35.1%	Poor
Ontario	95,857	96,807	1.0%	58.0%	Fair
Total:	727,882	724,597	-0.5%	58.8%	Fair

Canada Basin	Riparian Forest 2002 (ha)	Riparian Forest 2011 (ha)	% Change in Riparian Forest	Amount of Riparian Forest 2011	Class Value
Superior	619,980	626,200	1.0%	98.8%	Good
Michigan					
Huron	607,694	611,857	0.7%	75.8%	Fair
Erie	37,571	43,689	16.3%	23.8%	Poor
Ontario	163,564	158,216	-3.3%	62.1%	Fair
Total:	1,428,808	1,439,963	0.8%	76.6%	Fair

Great Lake Basin	Riparian Forest 2006/02 (ha)	Riparian Forest 2011/11 (ha)	% Change in Riparian Forest	Amount of Riparian Forest 2011	Class Value
Superior	792,907	797,214	0.5%	95.7%	Good
Michigan	270,484	268,988	-0.6%	62.5%	Fair
Huron	700,715	704,224	0.5%	72.5%	Fair
Erie	133,164	139,110	4.5%	30.5%	Poor
Ontario	259,421	255,023	-1.7%	60.5%	Fair
Total:	2,156,690	2,164,560	0.4%	69.6%	Fair

Table 1. Percent of forest cover in riparian zones and percent change by basin for U.S. (2006 and 2011) and Canada (2002 and 2011) and combined U.S. and Canada Great Lakes region. Data was based on summing forest cover types in a 30 m buffer around all water bodies. Forest cover was identified from Landsat satellite imagery for U.S. and Canada (Ontario).
Sources: U.S. National Land Cover Database 2006 (Fry et al. 2006), 2011 (Homer et al. 2015) and Ontario Landcover 2002 and SOLRIS 2002 (OMNRF 2006, Forest Sustainability and Information Section, unpublished data) and Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

U.S. Basin	All Forest 2006 (ha)	All Forest 2011 (ha)	% Change in Forest	Amount of Forest 2011	Class Value
Superior	3,539,252	3,483,919	-1.6%	83.5%	Good
Michigan	5,577,078	5,507,977	-1.2%	48.9%	Fair
Huron	2,048,628	2,006,615	-2.1%	49.8%	Fair
Erie	1,107,959	1,100,254	-0.7%	20.7%	Poor
Ontario	1,533,078	1,537,099	0.3%	46.1%	Fair
Total:	13,805,995	13,635,864	-1.2%	48.5%	Fair

Canada Basin	All Forest 2002 (ha)	All Forest 2011 (ha)	% Change in Forest	Amount of Forest 2011	Class Value
Superior	7,038,011	7,037,552	0.0%	98.9%	Good
Michigan					
Huron	6,278,642	6,289,194	0.2%	72.3%	Good
Erie	296,517	287,027	-3.2%	14.2%	Poor
Ontario	1,330,982	1,215,674	-8.7%	49.3%	Fair
Total:	14,944,151	14,829,448	-0.8%	73.0%	Good

Great Lake Basin	All Forest 2006/02 (ha)	All Forest 2011/11 (ha)	% Change in Forest	Amount of Forest 2011	Class Value
Superior	10,577,263	10,521,471	-0.5%	93.2%	Good
Michigan	5,577,078	5,507,977	-1.2%	48.9%	Fair
Huron	8,327,270	8,295,809	-0.4%	65.2%	Good
Erie	1,404,476	1,387,281	-1.2%	18.9%	Poor
Ontario	2,864,060	2,752,773	-3.9%	47.5%	Fair
Total:	28,750,146	28,465,312	-1.0%	58.8%	Fair

Table 2. Percentage of forest cover and percent change by lake basin for U.S. (2006 and 2011) and Canada (2002 and 2011) and combined U.S. and Canada Great Lakes region. Forest cover was identified from Landsat satellite imagery for U.S. and Canada (Ontario).
Sources: U.S. National Land Cover Database 2006 (Fry et al. 2006), 2011 (Homer et al. 2015) and Ontario Landcover 2002 and SOLRIS 2002 (OMNRF 2006, Forest Sustainability and Information Section, unpublished data) and Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

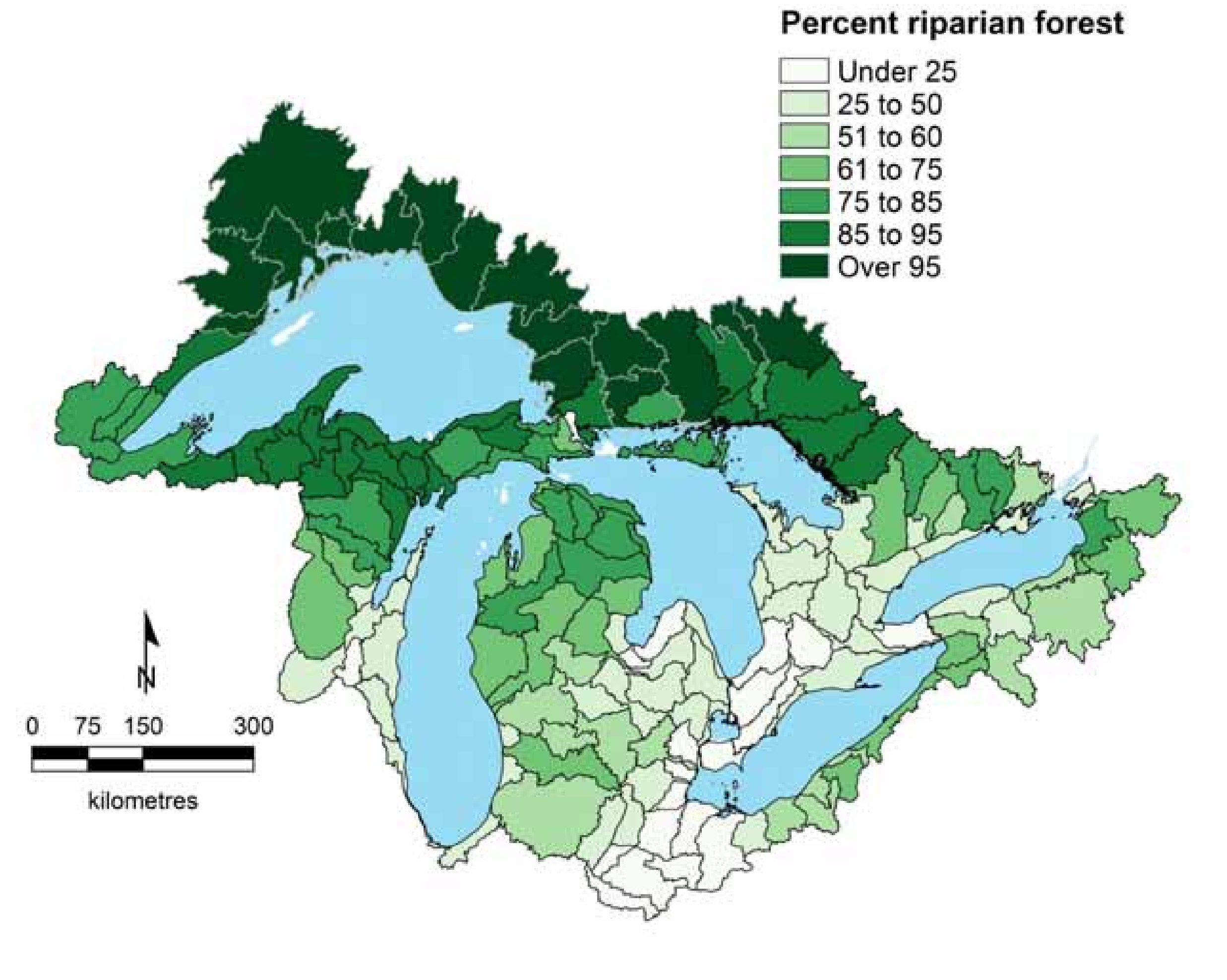

Figure 1. Percentage of forest cover within riparian zone (30 m buffer around water bodies) for tertiary watersheds (HUC8 in U.S. and 4 digit in Ontario) of the Great Lakes. Forest cover was estimated from satellite imagery and includes a variety of forest types (i.e. deciduous, conifer, mixed) and treed wetlands.
Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

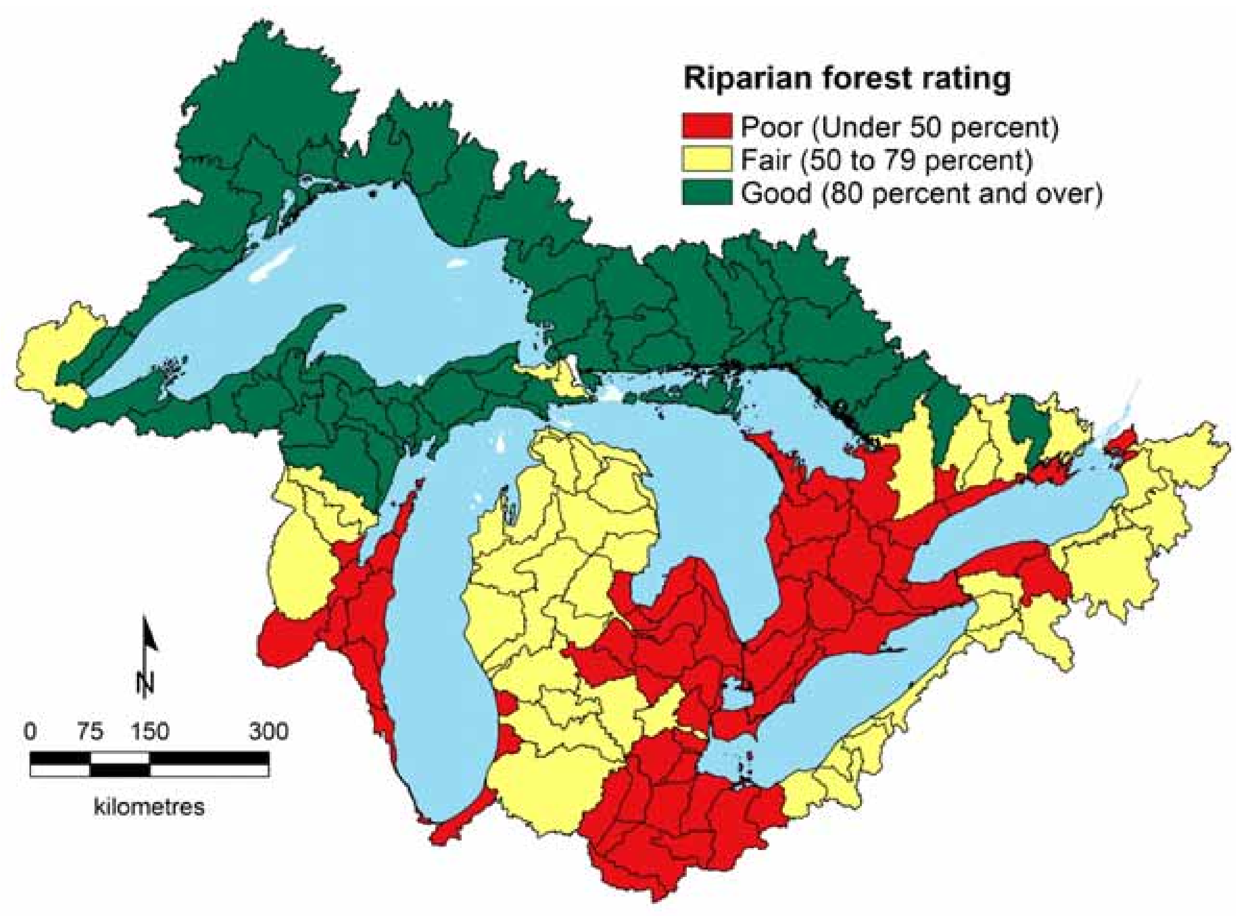

Figure 2. Forest cover within riparian zone (30 m buffer around water bodies) rating for tertiary watersheds (HUC8 in U.S. and 4 digit in Ontario) of the Great Lakes. Forest cover was estimated from satellite imagery and includes a variety of forest types (i.e. deciduous, conifer, mixed) and treed wetlands.
Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

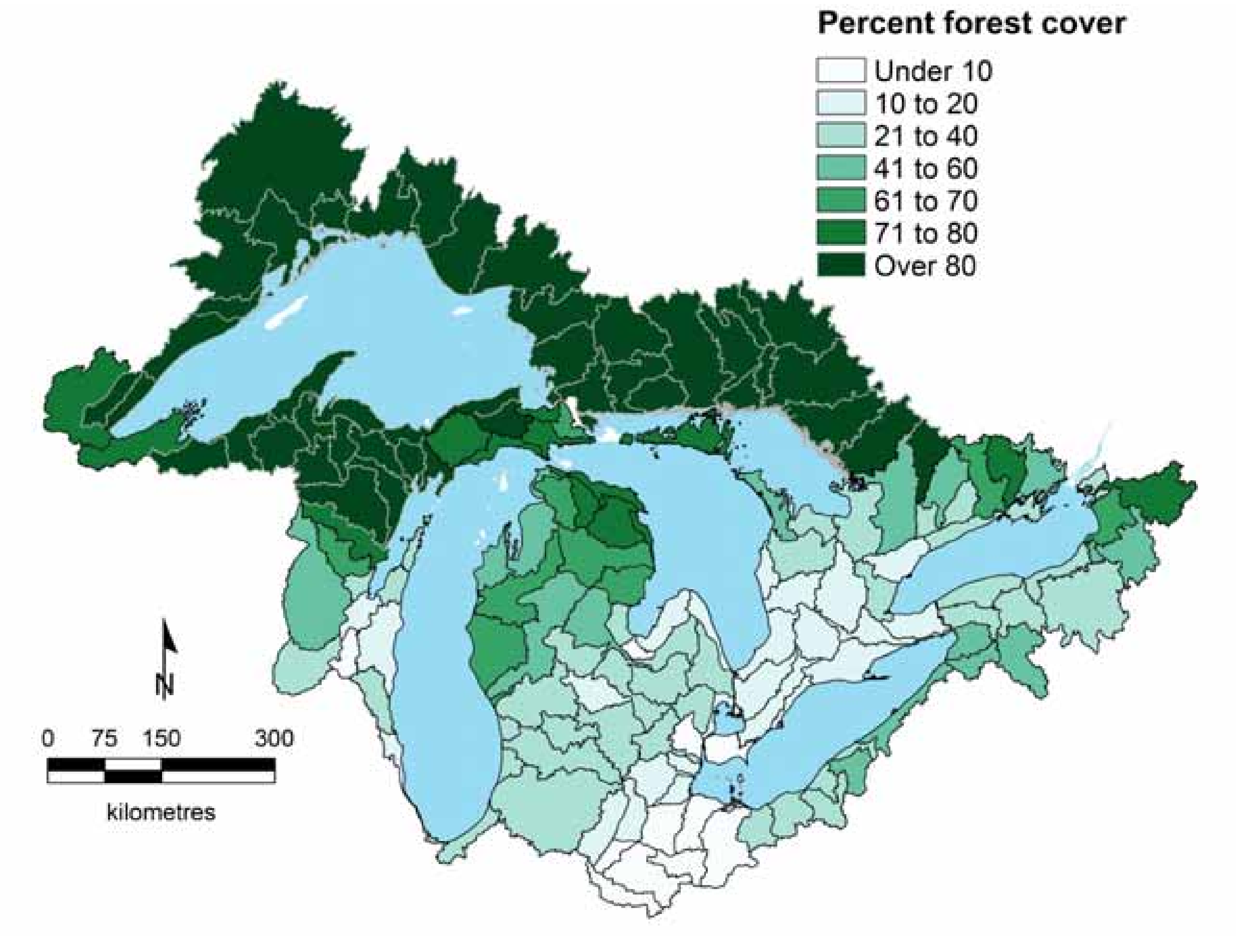

Figure 3. Percentage of forest cover in tertiary watersheds (HUC8 in U.S. and 4 digit in Ontario) of the Great Lakes. Forest cover was estimated from satellite imagery and includes a variety of forest types (i.e. deciduous, conifer, mixed) and treed wetlands.
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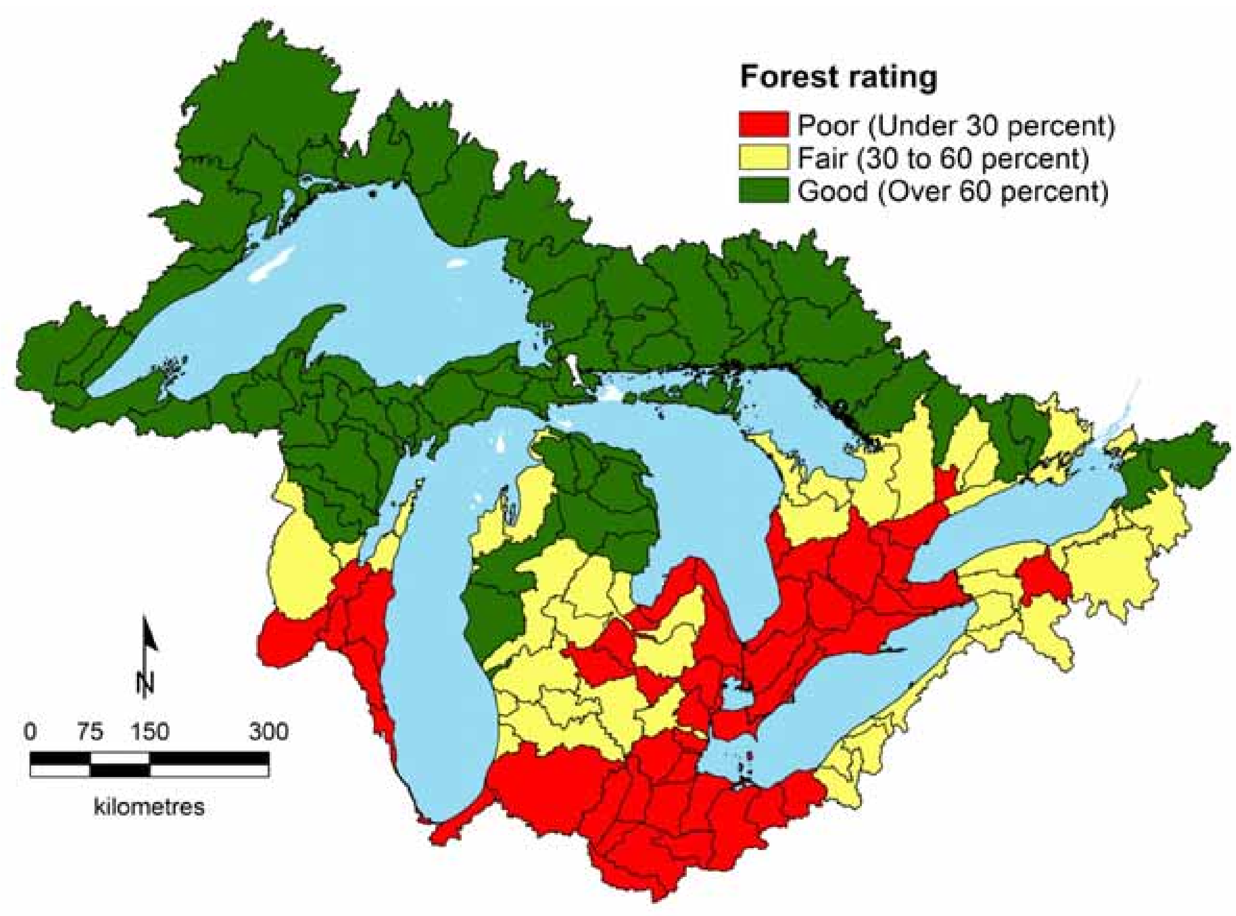

Figure 4. Forest cover rating in tertiary watersheds (HUC8 in U.S. and 4 digit in Ontario) of the Great Lakes. Source: U.S. National Land Cover Database NLCD 2011 (Homer et al. 2015) and Ontario Landcover 2008 and SOLRIS 2011(OMNRF 2015, Forest Sustainability and Information Section, unpublished data)

Sub-Indicator: Land Cover

Overall Assessment

Status: Fair

Trend: Unchanging

Rationale: Across the entire basin, between 2001 and 2011, there was a net conversion of 393 km^2 from natural land cover to developed land cover. This decrease in natural land cover constituted 0.05% of the assessed land area (see explanation of the geographic extent considered under "Ecological Condition), resulting in a determination of "unchanging". With 50% of the basin in agricultural or developed land use, the status by definition is "Poor" however, this percentage is straddling the Fair – Poor threshold. Based on the lake-by-lake assessments below, the overall sub-indicator assessment will remain as "Fair" for this reporting cycle.

Lake-by-Lake Assessment

Lake Superior

Status: Good

Trend: Unchanging

Rationale: Land cover change was assessed only on the U.S. side of the basin as there are no 2012 era land use data available for Canada in the Lake Superior basin. Forest land in the U.S Lake Superior basin decreased by approximately 400 km^2 or 0.93% of the watershed, but this conversion was predominately to grass/shrub land cover, which increased by 384 km^2 or 0.089%. With 93% natural land cover, the status is "Good" and the trend is "Unchanging".

Lake Michigan

Status: Fair

Trend: Unchanging

Rationale: Forest land cover decreased by 600 km^2 and developed land increased by 450 km^2. However the predominant transition of forest was to grass/shrub, whereas the increase in developed land came from conversion of agricultural land. For this reason the trend is "Unchanging". With 42% of the watershed in agriculture and 11% in developed land, the status is "Fair".

Lake Huron

Status: Fair

Trend: Unchanging

Rationale: Land cover data were unavailable for the Canadian portion of the basin outside of the SOLRIS coverage. Forest land cover decreased by 450 km^2, with much of this converting to grass/shrub. Developed land increased by 117 km^2 but agricultural lands decreased by 90 km^2. With essentially no net change between developed and natural land covers, the trend is unchanging. With 42% of the watershed in agriculture and 8% in developed land, the status is "Fair".

Lake Erie

Status: Poor

Trend: Unchanging

Rationale: Land cover data were unavailable for the Canadian portion of the basin outside of the SOLRIS coverage. Lake Erie's largest land use change was an 458 km^2 increase in developed land, largely due to the conversion of agricultural land, which decreased by almost 300 km^2. Forest land decreased by 225 km^2, primarily by conversion to developed land or agriculture. With 62% of the watershed in agriculture and 17 % in developed land, the status is characterized as Poor and the trend is Unchanging.

Lake Ontario

Status: Fair

Trend: Unchanging

Rationale: Land cover data were unavailable for the Canadian portion of the basin outside of the SOLRIS coverage. The largest land use change was a 300 km^2 increase in developed land, due to conversion from agricultural land, and to a lesser degree, forestland. Forest land cover decreased overall by 100 km^2. With 42% of the watershed in agriculture and 11% in developed land, the status is characterized as Fair and the trend is Unchanging.

Other Spatial Scales

This sub-indicator pertains primarily to risk of degradation of the coastal margins and nearshore waters. The importance of land use condition (especially as a source of nutrients and contaminants) declines with increasing distance away from the coastal margin since substances are typically transported by the water contributed by tributaries.

Sub-Indicator Purpose

- Assess the status of natural land cover within the Great Lakes Basin
- Inform inferences about the major proximate causes of changes and trends in other biological communities, physical habitat, and water quality indicators that are more directly reflective of the health of the Great Lakes ecosystem

Ecosystem Objective

Sustainable development is a generally accepted land use goal for the Great Lakes Basin. This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes."

Ecological Condition

For the previous analysis, a common land cover classification was developed to allow an integrated comparison of land use in both Canada and the U.S. This involved integrating the detailed but distinct classifications of the U.S. system (24 land use classes as delineated by Wolter et al. 2006) with the Canadian system (The Ontario Ministry of Natural Resources' Ontario Provincial Land Cover, consisting of 27 (in 1990) or 28 (in 2000) classes). The resulting unified assessment consisted of six land classes (Developed, Agriculture, Grassland/ Shrubland, Forest, Wetland, and Water (Ciborowski et al. 2011)). Using this common land cover classification for the year 2000, we calculated the total and proportional amounts of each land cover class by lake and across the Great Lakes Basin.

In the present assessment, temporally comparable (i.e., 2000-2002 era) datasets derived from U.S. National Land Cover Dataset (NLCD) and Ontario Land Cover Compilation v.2.0 were merged into a single binational land cover product by the Great Lakes Aquatic Habitat Framework project (GLAHF; *http://ifr.snre.umich.edu*) (Wang et al. 2015). Subsequently, a more contemporary product was created utilizing 2011 NLCD (Homer et al. 2015) and 2012 (SOLRIS v2.0) data. The SOLRIS land cover dataset however, is not a complete coverage of the Canadian side of the Great Lakes Basin - it excludes approximately 175,000 km^2 of the largely forested northern regions of the Lake Superior and Lake Huron watersheds. This is 34% of the land area within the Great Lakes basin watershed. It is expected that outside of forest harvest activities, this region has experience relatively little land use change. The assessments of land cover change presented below however, only reflect that portion of the basin where 2001 and 2011 data are directly comparable.

Over the extent of our study area there was a net conversion of 393 km^2 from natural to human-modified land cover. This change came largely at the expense of forest land, which decreased by 1780 km^2. The area of the basin in agricultural land use also decreased by 948 km^2. Increases were seen in the amount of developed land (1341 km^2) and grass/shrub land cover (1257 km^2). Rates of land use change provide an important integrated indicator of the degree and location of both loss and gain of natural lands, representing increases and reductions in the risks of degradation. These latest analysis reflect a growing trend of increasing developed lands, at the expense of both agricultural and forest lands.

As might be expected, the large variations in land cover across the Great Lakes noted in the previous report has remained constant, with the Lake Superior basin continuing to be predominately forested (Figure 1) and Lake Erie predominantly agricultural (Figure 4). Forest and Agricultural land uses are more evenly distributed in lakes Michigan and Ontario (Figures 2 and 5). This large variation in land use among lakes reflects the underlying climatic and soil gradients across the Great Lakes Basin that have historically constrained the conversion of the native vegetation (forest or grassland) to agricultural land use.

The distribution of land use classes for each Great Lake is shown in Figures 1-5. The greatest change toward human-modified land use uses on both an absolute and percentage basis occurred in the Lake Erie basin, with a net change of 165 km^2. This change was entirely due to increases in developed lands, which increased by 458 km, largely due to the conversion of agricultural (-292 km^2) and forested (-225 km^2) lands. Similar changes occurred in the Lake Ontario basin, which saw a 298 km^2 increase in developed land, again due to loss of agricultural land (-226 km^2) and forest land (-106 km^2). In fact, with the exception of Lake Superior, all lakes experienced declines in agricultural land and increases in developed lands (Table 1). The row totals in Table 1 show the total area in a land use class in 2001, whereas the column totals show the total area by class in 2010. The barren land class was too uncommon to show in the figures but included in Table 1 for completeness.

Linkages

The importance of land use condition (especially as a source of nutrients and contaminants) is greatest at shorelines and coastal margins, and declines with increasing distance away from the shore since substances are typically transported by the water contributed by tributaries. Natural land cover is an indicator of good conditions because it incorporates nutrients into biomass and slows the rate of water runoff into the lakes, together with materials (sediments, pollutants) that the water transports. This sub-indicator also relates to the Forest Cover sub-indicator, and indirectly to Tributary Flashiness, which is influenced by conversion to human-modified land covers.

Comments from the Author(s)

Issues with data registration and classification criteria between 1992 and 2000-era data precluded meaningful land cover change analysis in the 2011 report, as noted in Ciborowski 2011.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				
Clarifying Notes: Re: geographic coverage – the SOLRIS land cover dataset is not a complete coverage of the Canadian side of the Great Lakes Basin. It excludes the largely forested northern regions of the Lake Superior and Lake Huron watersheds, north of N 45.88334 and west of W83.10000.						

Acknowledgments

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The project on which these data were based was originally funded by the U.S. Environmental Protection Agency Science to Achieve Results (STAR) Estuarine and Great Lakes (EaGLe) program through funding to the Great Lakes Environmental Indicators (GLEI) and Reference Condition projects (U.S. EPA Agreements EPA/R-8286750 and EPA/R-82877701, respectively). More recent work was supported by the second stage GLEI-II Indicator Testing and Refinement project funded by a Great Lakes Restoration Initiative grant from the U.S. Environmental Protection Agency Great Lakes National Program Office to Lucinda.B. Johnson (GL-00E00623-0). Although the research described in this work has been partly funded by the U.S. EPA, it has not been subjected to the agency's required peer and policy review and therefore does not necessarily reflect the views of the agency and no official endorsement should be inferred. The GLAHF project was funded by the Great Lakes Fisheries Trust.

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Data Sources

The integrated and reclassified NLCD 2011 and SOLRIS 2012 land use/land cover data were obtained from the Great Lakes Aquatic Habitat Framework; *http://ifr.snre.umich.edu*

The following credits for land cover circa 2000 and 2010 were posted with on the GLAPH metadata page:

- National Land Cover Dataset, 2001 *v11 http://www.mrlc.gov/nlcd01_data.php*;

- The 2000 Provincial Landcover Ontario PLO *https://www.javacoeapp.lrc.gov.on.ca/geonetwork/srv/en/main.home;*
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Last Updated

State of the Great Lakes 2017 Technical Report

Lake Erie	Agriculture	Barren	Developed	Forest	Grass/Shrub	Wetland	Water	Totals
Agriculture	46314	38	487	192	8	95	18	**47151**
Barren	23	172	8	1	3	2	4	**213**
Developed	214	1	12234	23	0	13	3	**12488**
Forest	200	7	149	10320	55	123	7	**10860**
Grass/Shrub	4	2	27	5	886	2	1	**927**
Wetland	99	2	38	92	2	3939	6	**4178**
Water	4	1	3	2	0	16	615	**641**
Totals	**46858**	**222**	**12945**	**10635**	**955**	**4190**	**653**	**76457**

Lake Huron	Agriculture	Barren	Developed	Forest	Grass/Shrub	Wetland	Water	Totals
Agriculture	26284	34	270	276	25	122	13	**27024**
Barren	31	175	4	1	5	4	5	**227**
Developed	190	1	4727	48	0	21	3	**4990**
Forest	287	10	71	16682	474	172	9	**17706**
Grass/Shrub	11	3	4	95	2538	1	1	**2652**
Wetland	124	5	29	147	5	10690	10	**11010**
Water	7	3	2	5	0	18	852	**888**
Totals	**26934**	**231**	**5107**	**17255**	**3048**	**11029**	**893**	**64497**

Lake Michigan	Agriculture	Barren	Developed	Forest	Grass/Shrub	Wetland	Water	Totals
Agriculture	37112	38	308	11	34	15	14	**37532**
Barren	15	379	7	0	3	1	10	**415**
Developed	0	0	11486	0	0	0	0	**11486**
Forest	33	17	61	34731	768	7	4	**35621**
Grass/Shrub	25	9	46	281	4581	5	2	**4949**
Wetland	3	5	24	1	8	23086	10	**23138**
Water	1	6	2	1	1	12	3448	**3470**
Totals	**37189**	**453**	**11934**	**35024**	**5395**	**23127**	**3488**	**116611**

Lake Ontario	Agriculture	Barren	Developed	Forest	Grass/Shrub	Wetland	Water	Totals
Agriculture	22617	23	497	429	10	193	15	**23783**
Barren	32	110	5	1	1	1	1	**151**
Developed	263	2	5393	79	0	35	5	**5777**
Forest	442	7	120	16077	43	305	16	**17010**
Grass/Shrub	6	3	8	28	2102	6	3	**2156**
Wetland	186	3	49	275	3	6217	12	**6745**
Water	9	2	4	15	0	27	1216	**1272**
Totals	**23556**	**149**	**6075**	**16904**	**2159**	**6783**	**1267**	**56893**

Lake Superior	Agriculture	Barren	Developed	Forest	Grass/Shrub	Wetland	Water	Totals
Agriculture	1411	1	2	2	5	1	0	**1420**
Barren	0	153	1	0	6	1	5	**167**
Developed	0	0	1535	0	0	0	0	**1535**
Forest	10	13	12	25303	895	7	1	**26241**
Grass/Shrub	2	6	3	529	472	2	0	**1015**
Wetland	1	3	3	4	20	11346	1	**11378**
Water	0	10	0	0	3	5	1379	**1397**
Totals	**1423**	**188**	**1556**	**25839**	**1400**	**11361**	**1387**	**43153**

Table 1. Changes in area of land use/land cover classes between 2001 and 2011. Row totals show the total area in a land use class in 2001, column totals show the total area by class in 2010. Values are area in square kilometres. Data Source: 2011 NLCD and 2012 SOLRIS; integrated classification by Wang et al. 2015; regions north of the SOLRIS demarcation line represent 2001-era data.

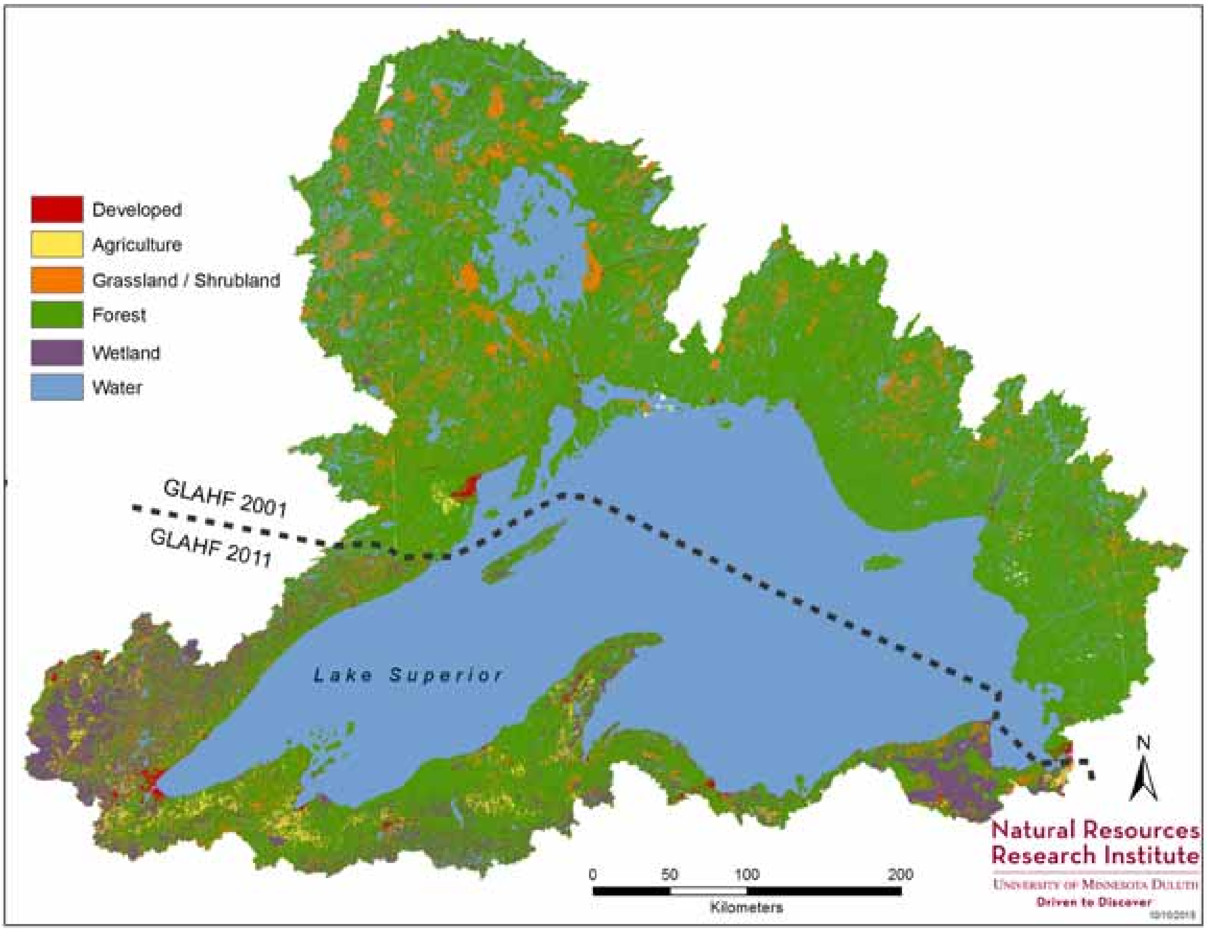

Figure 1. Distribution of land use/land cover across the Lake Superior Basin.
Source: GLAHF 2001 are an integration of the National Land Cover Dataset (NLCD) and the Ontario Land Cover Compilation v 2.0 data from 2001, whereas GLAPH 2011 incorporate 2011 NLCD and 2012 SOLRIS data (Wang et al. 2015); the GLAPH 2011 dataset does not cover the area north of the demarcation line.

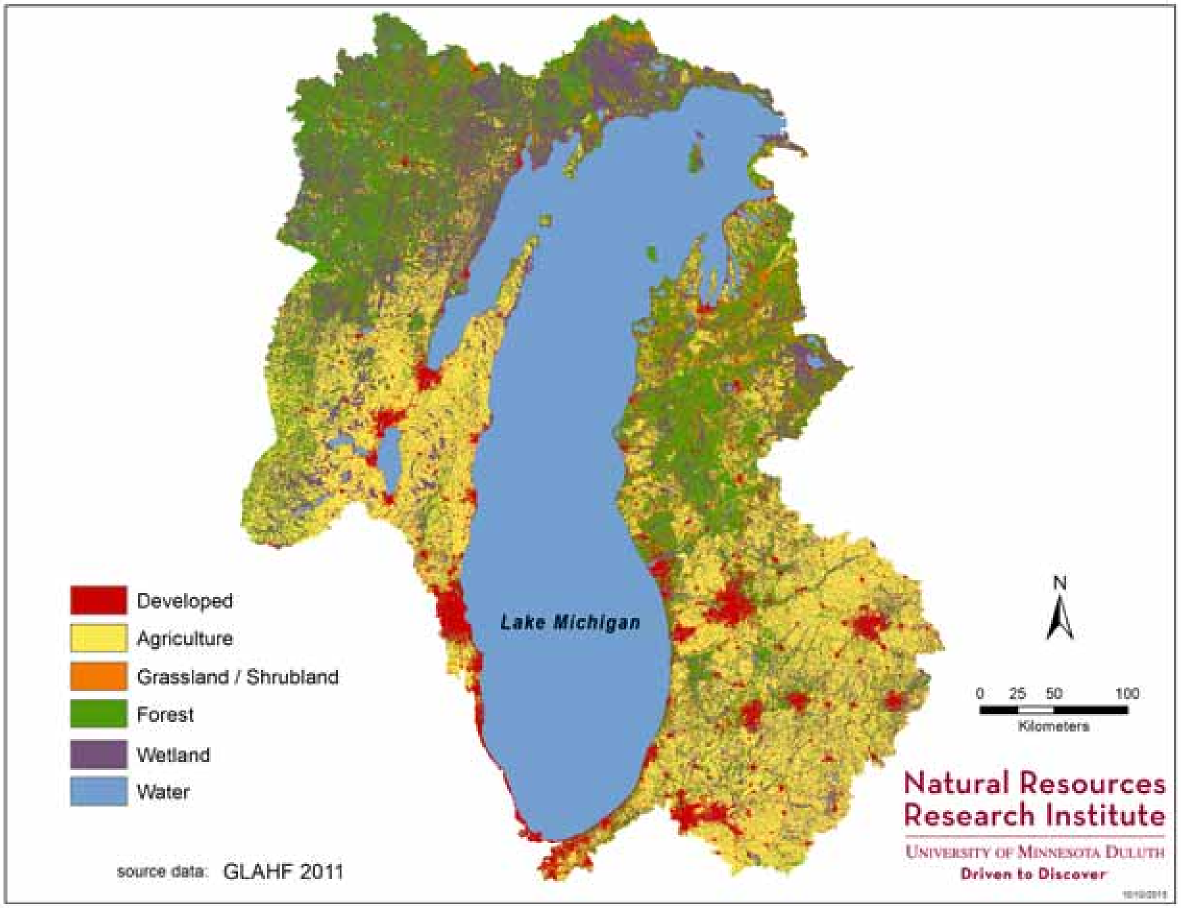

Figure 2. Distribution of land use/land cover across the Lake Michigan Basin in 2011.
Source: 2011 NLCD and 2012 SOLRIS; integrated classification by Wang et al. 2015; regions north of the SOLRIS demarcation line represent 2001-era data.

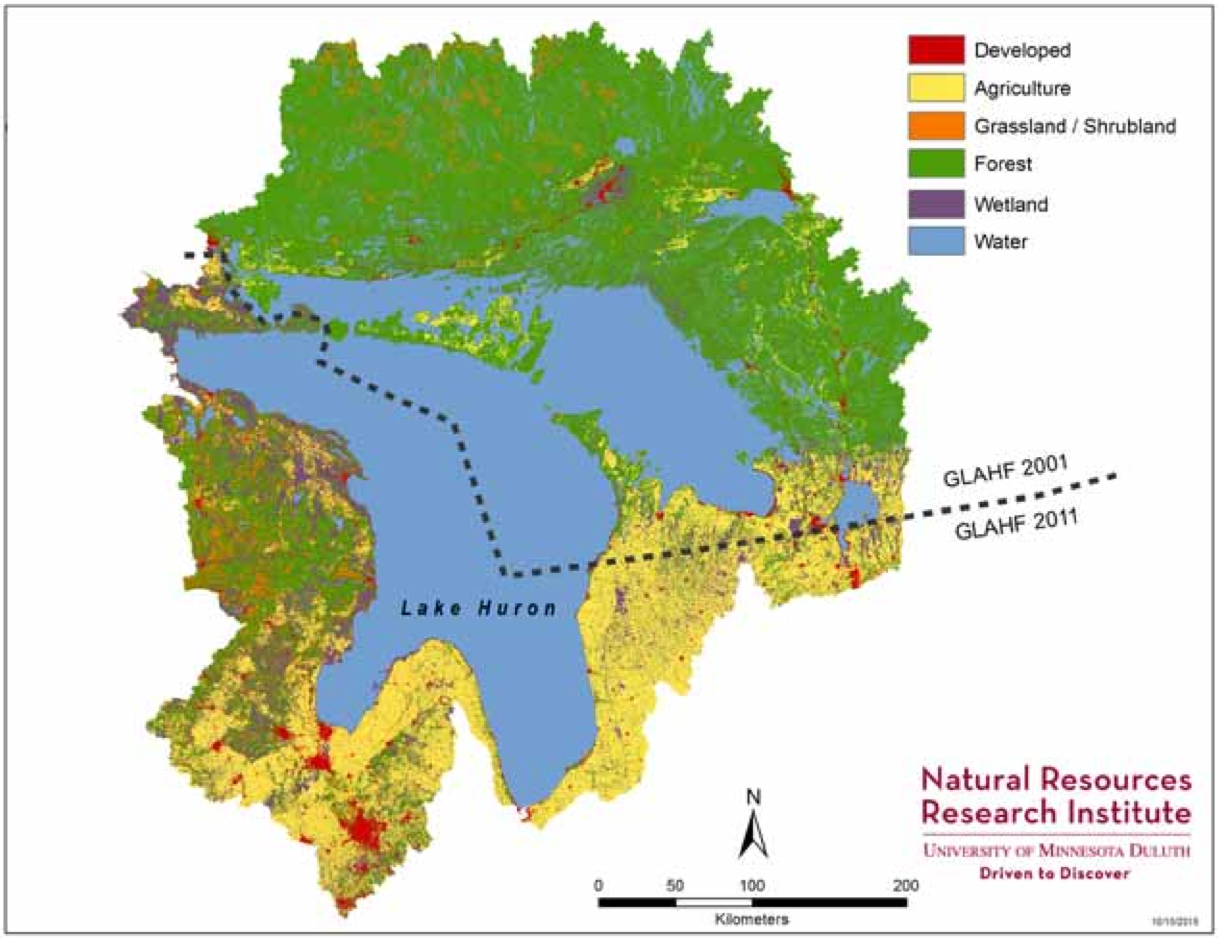

Figure 3. Distribution of land use/land cover across the Lake Huron Basin.
Source: GLAHF 2001 are an integration of the National Land Cover Dataset (NLCD) and the Ontario Land Cover Compilation v 2.0 data from 2001, whereas GLAPH 2011 incorporate 2011 NLCD and 2012 SOLRIS data (Wang et al. 2015); the GLAPH 2011 dataset does not cover the area north of the demarcation line.

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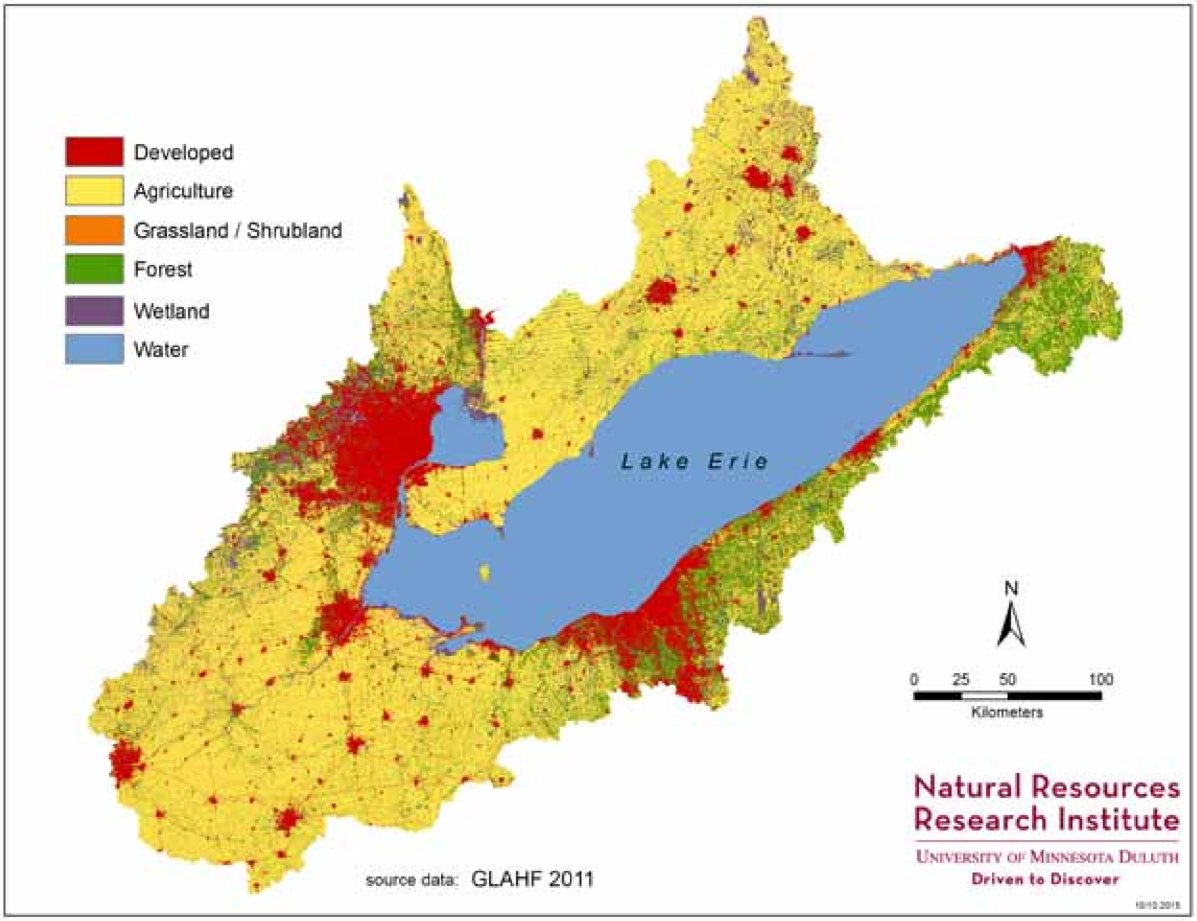

Figure 4. Distribution of land use/land cover across the Lake Erie Basin in 2011.
Source: 2011 NLCD and 2012 SOLRIS; integrated classification by Wang et al. 2015; regions north of the SOLRIS demarcation line represent 2001-era data).

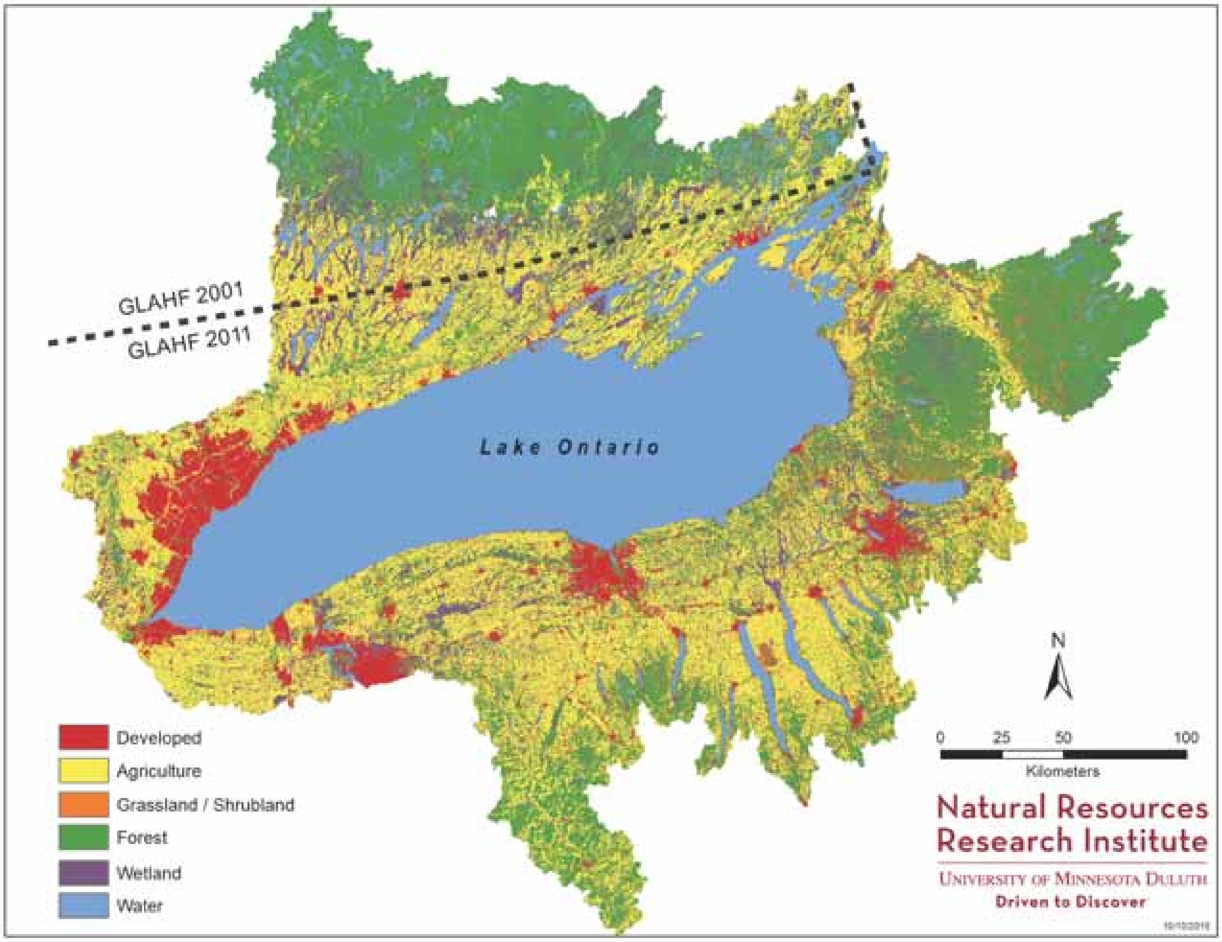

Figure 5. Distribution of land use/land cover across the Lake Ontario Basin.
Source: GLAHF 2001 are an integration of the National Land Cover Dataset (NLCD) and the Ontario Land Cover Compilation v 2.0 data from 2001, whereas GLAPH 2011 incorporate 2011 NLCD and 2012 SOLRIS data (Wang et al. 2015); the GLAPH 2011 dataset does not cover the area north of the demarcation line.

Sub-Indicator: Watershed Stressors

Overall Assessment
Status: Fair
Trend: Unchanging
Rationale: The status can also be described as MIXED, with GOOD condition found in 19.4% of the watersheds in the Basin, FAIR condition found in 60.1% of the Basin's watersheds, and 20.5% of the Basin in POOR condition, see Tables 1, 2. This sub-indicator reports long term trends at 5-10 year intervals, as data becomes available. The sub-indicator currently reports for the period 2000-2010.

The basin is a globally unique entity subject to moderate or large amounts of development within its watershed. The spatial arrangement of watershed-based stress reflects the basin's geomorphology. Much of the southern part of the basin, which is underlain by rich soils and naturally supports deciduous forest, has been developed for agriculture or dwelling, whereas the northern (Canadian Shield) part of the basin remains largely undeveloped. When the combined stresses of population density, road density, urban development, and agricultural development are considered, two of the five Great Lakes (Erie and Ontario) are individually assessed as having a status of 'Poor', Lake Michigan is assessed as 'Fair', and Lakes Huron and Superior are classified as 'Good' (Table 1a; Figure 1). Consequently, the status of the Great Lakes Basin overall is operationally defined as 'Fair' (Table 1a; Figure 1), since the majority of its watersheds are in fair condition. When the operational definition of condition is based on the percent area, (Table 1b), the majority of the basin's area is in Fair condition.

Across the Basin, roads were ubiquitous and represent the largest source of potential risk of degradation in largely undeveloped areas (Figure 7). Basin wide, condition category shifts were relatively rare with only 81 of 5583 watersheds changing condition categories from 2000 to 2010. Changes from FAIR (generally) to POOR classes were most common (38 watershed transitions), followed by transitions from POOR to FAIR condition (26), and GOOD to FAIR (12). Due to the small number of watershed transitions, which together represent only 1.4% of the total watersheds, and 0.13% percent of the basin area, the trend is listed as UNCHANGING. See author's notes for further explanation of data interpretation issues.

Lake-by-Lake Assessment
Note: impacts from watersheds draining into connecting channels are assigned to the downstream lake.

Lake Superior
Status: Good
Trend: Unchanging
Rationale: Of the 1,534 watersheds in the Lake Superior basin, 595 were classified as GOOD (38.8%), 917 were classified as FAIR (59.8%), and only 22 were classified as POOR (1.4%) (Table 2, Figure 9). The interval from 2000 to 2010 saw a very minor shift in the condition of Lake Superior's watersheds, with a change of 0.6% of total watershed numbers (10 of 1,534) from the GOOD to FAIR category. Five watersheds transitioned from FAIR to GOOD. No watersheds shifted from FAIR to POOR. This suggests that conditions are largely unchanged (Table 2; Figure 8). A portion of the Lake Superior Basin in Canada did not have 2010 era land use data; to derive an estimate of change the assumption was made that there was no change in percent agricultural or developed land. The basin-wide trend is therefore to be regarded as a conservative estimate. Lake Superior has the lowest percentage of agricultural land in the basin, the lowest road density and lowest population density. This basin was second in terms of the number of watersheds in the lowest quintile for percent developed land, behind Lake Huron (Table 3; Figures 2-7).

Lake Michigan
Status: Fair
Trend: Unchanging

Rationale: Lake Michigan's 629 watersheds were classified predominantly as FAIR (83.5%); 16.1% were classified as POOR and less than 1% were scored as GOOD (Table 2; Figure 10). Lake Michigan was unremarkable in terms of the distribution of each of the component stressors with one exception. Few condition transitions were noted for Lake Michigan. Trends for Lake Michigan are based on complete data sets for the basin and therefore represent the best available estimates. It was notable that the Lake Michigan Basin had the lowest number of watersheds in the lowest quintile in terms of road density, suggesting that few roadless areas remain within that basin (Table 3; Figures 2-7).

Lake Huron
Status: Fair
Trend: Unchanging
Rationale: Lake Huron's condition can best be described as FAIR as opposed to GOOD, since in addition to meeting the criterion for GOOD condition, it almost meets the criterion for POOR condition (19.2% of watersheds), and over 50% of its watersheds fall into the FAIR category (Table 2; Figure 11). Six of the nine watershed condition transitions represented conversion from FAIR to the POOR category, and three were the reverse. The proportion of watersheds transition classes was minute relative to the total number of watersheds in the Lake Huron basin (1,646); therefore, the trend is UNCHANGING (Figure 8). A portion of the Lake Huron Basin in Canada did not have 2010 era land use data; therefore, the assumption was made that there was no change in percent agricultural or developed land. These trends are therefore to be regarded as conservative estimates of change. The Lake Huron Basin has the highest number of watersheds in the lowest quintile for percent developed land, and the second lowest in terms of percent agriculture, road density and population density (Table 3; Figures 2-7).

Lake Erie
Status: Poor
Trend: Unchanging
Rationale: Lake Erie's condition is rated as POOR because almost 50% of the watersheds (410 of 854) were classified as being in POOR condition, 47.5% were in FAIR condition, and only 4.4% of watersheds were in GOOD condition (Table 2; Figure 12). Although there were 13 condition transitions into the POOR category, this represents a small proportion (less than 2%) of the watersheds in the Lake Erie Basin (Figure 8). Trends for Lake Ontario are based on complete data sets for the basin and therefore represent the best available estimates. The Lake Erie Basin had the highest number of watersheds in the upper quintile of the distribution for all four stressor components (Table 3; Figure 2-7).

Lake Ontario
Status: Poor
Trend: Unchanging
Rationale: Most (66.2%) of Lake Ontario's watersheds fall into the FAIR category, but approximately 32% fall in the POOR category. The operational definition based on the 20th percentile criteria puts the Lake Ontario basin into the POOR category, but like Lake Huron, the lake could also well be described as MIXED (Figure 13). Condition transitions in Lake Ontario included 13 watersheds moving into the POOR category (1.5% of watersheds) and 15 moving into the FAIR category from POOR (Figure 8). Trends for Lake Ontario are based on complete data sets for the basin and therefore represent the best available estimates. The latter represents the highest number of positive transitions in the overall Basin. The Lake Ontario Basin has the second highest number of watersheds in the upper quintile of the distribution for all four component stressors, behind Lake Erie (Table 3; Figures 2-7).

Other Spatial Scales
The data shown are benchmarked to 2000 era AgDev scores that were derived based on the 20th and 80th percentiles of the AgDev distribution across the entire Great Lakes Basin (Table 1). The same process was applied individually to each lake to determine the relative condition of watersheds within each Lake. Table 3 depicts the 2000 and 2010 era distributions and transitions for individual lakes.

The components of the WSI (AgDev) are tabulated and scored for the land bordering each Lake rather than for the Lakes themselves. However, there is strong evidence that the effects of land-based stress are manifested in habitats most closely associated with each watershed. Niemi et al. (2007), Peterson et al. (2007) and Yurista and Kelly (2009) found that the correlation between land-based stress and waterborne nutrients was highest for tributary streams and coastal wetlands. Although the correlation becomes weaker with increasing distance from shore, the correlation remains statistically significant in water 10 m deep or more. The greater the stress, the greater the risk of degradation of biological features in the lakes themselves. These relationships have recently been qualitatively scored and shown in lakewide and basinwide maps as 'threats' (or risk of degradation) by Allan et al. (2012).

Sub-Indicator Purpose

- Assess the relative degree of stress derived from watersheds on the environmental quality of the Great Lakes;
- Infer potential risk of harm from impacts of human activities in watersheds on water quality, habitat, biota, and natural processes.

Ecosystem Objective

The combined effects of watershed stressors should not result in the impairment of the physical, biological, or chemical integrity of the Great Lakes as reflected in Annexes 2 (Improve quality), 4 (Manage nutrients), and 7 (protect species and their habitats) of the 2012 Water Quality Agreement.

Ecological Condition

The relative amount of stress imposed by four measures of human activity on the land within the 529,679 km^2 area of the Great Lakes Basin was assessed for each of the 5593 watersheds surrounding the Great Lakes (as generated from an ArcHydro GIS analysis (Forsyth et al. *in review*). This sub-indicator will use a combined agriculture + development stress index (AgDev) to calculate scores for individual Great Lakes watersheds using a consistent scale of resolution among reporting periods. This stress score is adapted from a peer-reviewed methodology previously applied to the Great Lakes Basin (Host et al 2011) and revised by Johnson et al. 2015). The index is based on standardized scores of data that represent key manifestations of human activity in the watersheds that are a potential risk to the Great Lakes ecosystem health. Stressors making up the index include **road density, population density, agricultural land cover, and developed land cover** (Host et al. 2011). These stressors together represent the majority of the variation described by five anthropogenic stressors (agricultural/chemical loadings; land use; atmospheric deposition; human population / development; shoreline modification) quantified by Danz et al. (2005).

This revised index differs from the State of the Great Lakes (previously known as SOLEC) 2011 version by eliminating the point source data (which was found to have numerous quality issues), and revising the metric calculation (Johnson et al., 2015). In addition, for 2016, anthropogenic stress was summarized for GLAHF (Wang et al. 2015) watersheds on the U.S. and Canadian sides of the Great Lakes Basin (a binational effort to develop a consistent set of drainage units for the basin; Forsyth et al. *in review)*. An index of agriculture stress (Ag) was based on the areal percentage of land in agricultural estimated from a cross-walked version of the 2011 National Land Cover Dataset (NLCD, and Ontario Land Cover Compilation v.2.0 (see Land Cover sub-indicator). Development was characterized based on the areal percentage of urban land use, human population density (U.S. Census Bureau and Statistics Canada; See Human Population sub-indicator) and road density (TIGER 2000 and 2010, U.S. and NRN 2^{nd} and 7^{th} edition Canada). Each of these variables was scaled to range between values of 0.0 – 1.0 based on the range of data across the Great Lakes Basin (not including the St. Lawrence River watersheds). Following the MaxRel approach used in Host et al. (2005), the maximum of these three normalized (scaled 0-1) values for each watershed was used as the development index (MaxRel Dev). To combine the agriculture and development values for a watershed, we calculated a Euclidean distance from the graph origin (0,0) graph to the x, y coordinates of the Ag and MaxRel Dev Index scores (AgDev; Figure 1). The resulting metric is called AgDev, and supersedes the former Combined Watershed Stress Index (State of the Great Lakes 2011 – previously knowns as SOLEC). To ensure consistency of reporting, we provide the AgDev index calculation based on circa 2000 data, as well as 2010 (Tables 2, 3).

In the absence of biological data against which to calibrate the stressor scores, we have designated the 20th percentile of the distribution of stress scores for each variable and the AgDev index as the criterion for classifying a watershed as ‘Good’ vs. ‘Fair’. We have designated the 80th percentile the distribution as the boundary between ‘Fair’ and ‘Poor’. Watersheds classified as ‘Good’ pose minimal risk of degradation of the biological community in Great Lakes aquatic receiving habitats. Watersheds classified as ‘Poor’ are at greatest risk of having degraded Great Lakes communities. The cutoff values representing the 20th percentile and 80th percentiles for the Great Lakes components and AgDev scores are listed in the legend of Table 1. Status assessments for the 2010 era data are made relative to these values for 2000 era data.

Linkages
Linkages to other sub-indicators in the indicator suite include:

- Aquatic Habitat Connectivity – the number of dams and barriers is an important factor in assessing watershed stress
- Coastal Wetlands: Extent and Composition
- Water Quality in Tributaries
- Human Population

This sub-indicator also links directly to the other indicators in the Watershed Impacts and Climate Trends indicator, particularly Land Cover.

Comments from the Author(s)
The components and total AgDev score have been determined for every Great Lakes sub-watershed based on data from 2000-2010. The locations at greatest risk of significant biological loss (those approaching the boundaries) and those with greatest potential for restoration (sites with stress scores only slightly higher than the boundaries) can be identified using biologically-based thresholds, as well as the quantile approach presented here. These are the locations where investment in protection or restoration should most likely to succeed. Johnson et al. (2015) present a map of risk, based on biologically based thresholds derived from Kovalenko et al. 2014.

This revised version of the Watershed Stressor sub-indicator improves on the 2011 version in two ways: land use data are derived exclusively from data derived from government sources (e.g., land use from NLCD and SOLRIS), and the watershed framework (GLAHF) is based on a binational effort. In contrast, the 2011 version used land use derived from a variety of sources some with known classification flaws. The new Watershed Stressor sub-indicator (AgDev) should, therefore, be a repeatable metric that can be used for tracking trends in the future. Special note should be made regarding assumptions of change; many transitions were found to occur in very small coastal watersheds. These are especially susceptible to changes in area as a result of water level change, and therefore, interpretation of condition transitions should be made with caution. Changes in road network data (e.g., TIGER in the U.S.), for example, caused 34 small watersheds on Isle Royale in Lake Superior to appear to have changed from GOOD to FAIR condition (these were omitted from the calculations of transitions). In addition, land use data derived from remote sensing (e.g., NLCD, SOLRIS) are not 100% accurate, and classifications of bare ground (i.e., exposed bedrock, quarries, sand flats, etc.) are easily confused with spectral signatures of impervious surfaces. Thus, areas along the coast can be subject to misclassification. The cutoff values between good/fair and fair/poor were determined based on the count of watersheds across the entire basin, rather than on area. Because of the very large variation in watershed sizes the cumulative distribution of area precluded the identification of reasonable cutoffs due to large gaps into which particular targets (i.e., 20^{th} and 80^{th} percentiles) were likely to fall.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada				x		
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				
Clarifying Notes: Re: geographic coverage – the SOLRIS land cover dataset is not a complete coverage of the Canadian side of the Great Lakes Basin. It excludes the largely forested northern regions of the Lake Superior and Lake Huron watersheds, north of N 45.88334 and west of W83.10000.						

Acknowledgments
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Contributors: Members of the Great Lakes Environmental Indicators project - Gerald L. Niemi (Senior PI; NRRI, University of Minnesota Duluth), Nicholas P. Danz (University of Wisconsin – Superior), and Thomas Hollenhorst (U.S. EPA, Mid-Continent Ecology Division National Health and Environmental Effects Research Laboratory, Duluth, MN 55804) contributed to formation of the research group that identified the need for this database.

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applied to each lake. Shown are the number and percent of watersheds in the lowest (Good) and highest (Poor) quintiles. Data are summarized for 5584 watersheds delineated by the Great Lakes Aquatic Habitat Framework (GLAHF) project (Wang et al. 2015). Watersheds stress index (AgDev Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673.
Source: T. Brown, NRRI.

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Source: T. Brown, NRRI.
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Figure 9. Condition rankings for Lake Superior. circa ~2010. Classes are based on lower and upper quintiles of the Ag-Dev distribution for the entire Great Lakes Basin and then applied to Lake Superior watersheds. Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673.
Source: T. Brown, NRRI.

Figure 10. Condition rankings for Lake Michigan watersheds, circa ~ 2010. Classes are based on lower and upper quintiles of the Ag-Dev distribution for the entire Great Lakes Basin and then applied to Lake Superior watersheds. Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673. Source: T. Brown, NRRI.

Figure 11. Condition rankings for Lake Huron watersheds, circa ~ 2010. Classes are based on lower and upper quintiles of the Ag-Dev distribution for the entire Great Lakes Basin and then applied to Lake Superior watersheds. Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673.
Source: T. Brown, NRRI.

Figure 12. Condition rankings for Lake Erie watersheds, circa ~ 2010. Classes are based on lower and upper quintiles of the Ag-Dev distribution for the entire Great Lakes Basin and then applied to Lake Superior watersheds. Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673.
Source: T. Brown, NRRI.

Figure 13. Condition rankings for Lake Ontario watersheds, circa ~ 2010. Classes are based on lower and upper quintiles of the Ag-Dev distribution for the entire Great Lakes Basin and then applied to Lake Superior watersheds. Note that watersheds in the St. Lawrence River system were not included in the calculations of the AgDev score, but condition classes are shown for those watersheds. Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673.
Source: T. Brown, NRRI.

Last Updated

State of the Great Lakes 2017 Technical Report

Lake	Number of Watersheds	Number Watersheds 'GOOD'	% Watersheds 'GOOD'	Number Watersheds 'FAIR'	% Watersheds 'FAIR'	Number Watersheds 'POOR'	% Watersheds 'POOR'	Condition Designation 2010
Superior	1,534	595	38.8	917*	59.8	22	1.4	Good
Michigan	629	3	0.5	525	83.5	101	16.1	Fair
Huron	1,646	431	26.2	899	54.6	316	19.2	Fair**
Erie	854	38	4.4	406	47.5	410	48.0	Poor
Ontario	930	18	1.9	616	66.2	296	31.8	Poor

* 34 Isle Royale watersheds not included.

** See Rationale for this designation in Lake-by-Lake Assessment section above.

Table 1a. Summary of the status of each lake for ~2010, based on the basin-wide normalized AgDev score, which is applied to each lake. Shown are the number and percent of watersheds in the lowest (Good) and highest (Poor) quintiles. Data are summarized for 5584 watersheds delineated by the Great Lakes Aquatic Habitat Framework (GLAHF) project (Wang et al. 2015). Watersheds stress index (AgDev Cutoff values of AgDev score for the boundary of good / fair = 0.01228; fair / poor = 0.673.
Source: T. Brown, NRRI.

Lake	Number of Watersheds	Total Area (km^2)	Watershed area 'GOOD'	% Watershed area 'GOOD'	Watershed area 'FAIR'	% Watershed area 'FAIR'	Watershed area 'POOR'	% Watershed area 'POOR'	Condition Designation 2010
Superior	1,534	141,151	85,745	60.7	55,304	39.2	102	0.1	Good
Michigan	629	116,610	2	0.0	112,065	96.1	4,543	3.9	Fair
Huron	1,646	133,294	17,109	12.8	105,800	79.4	10,384	7.8	Fair
Erie	854	76,607	60	0.1	22,585	29.5	53,962	70.4	Poor
Ontario	930	80,268	2	0.0	75,765	94.4	4,501	5.6	Fair

Table 1b. Summary of condition based on % area within each condition class for ~2010 era AgDev scores. These data are shown for contrast only, as cutoff values derived from watershed areas produce spurious results due to large gaps in the cumulative frequency distribution of watershed areas. See author's notes for further information.

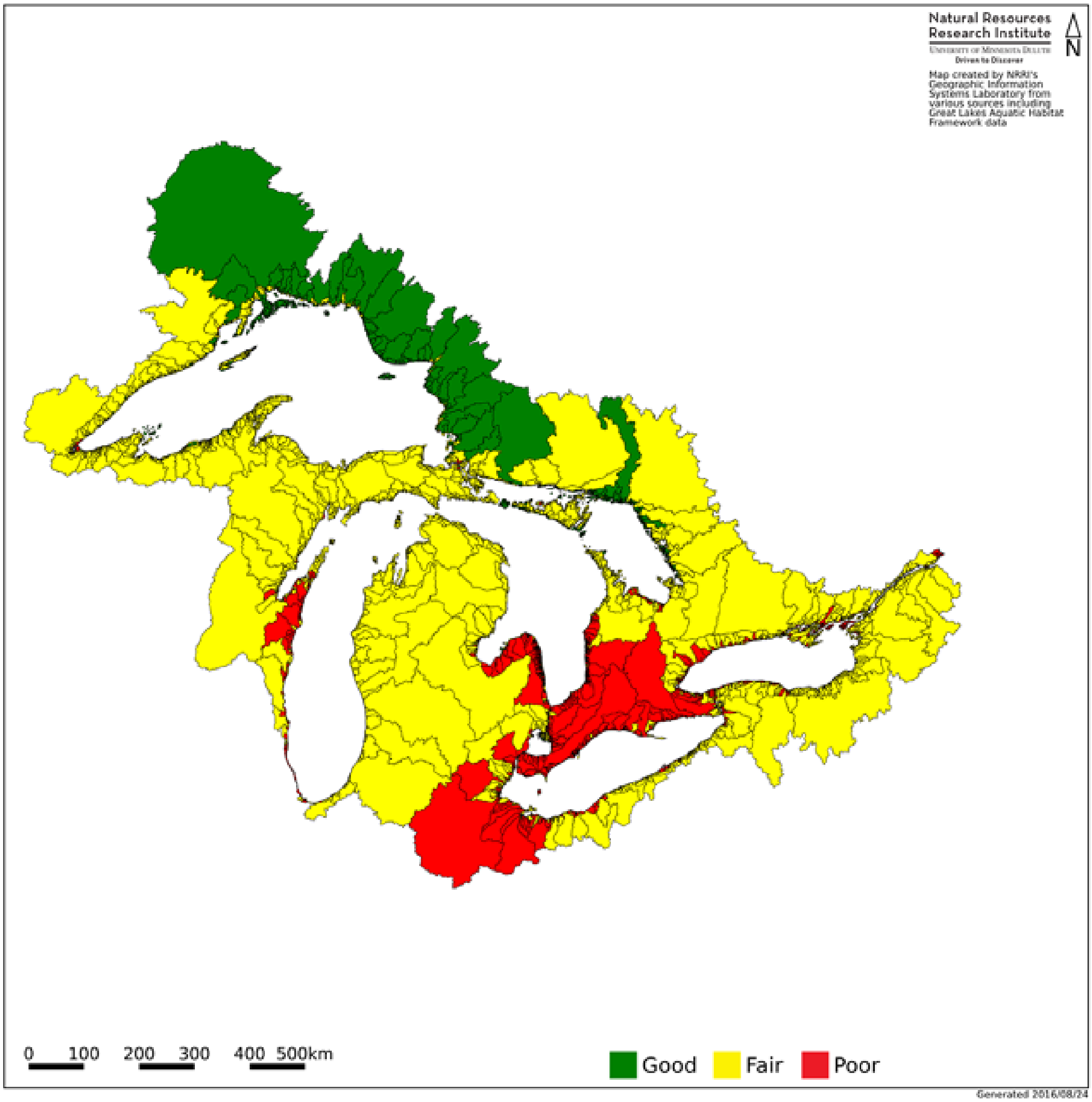
Lake	Condition	Number Watersheds 2000	% Watersheds 2000	Number Watersheds 2010	% Watersheds 2010	Loss 2000-2010	Gain 2000-2010
All Lakes	Good	1092	19.5	1085	19.5	12	5
	Fair	3368	60.2	3363	60.1	43	38
	Poor	1133	20.3	1145	20.5	26	38
Lake Superior	Good	602	39.2	595	38.8	10	3
	Fair	910	59.3	917	59.8	3	10
	Poor	22	1.4	22	1.4	0	0
Lake Michigan	Good	3	0.5	3	0.5	0	0
	Fair	528	83.9	525	83.5	6	3
	Poor	98	15.6	101	16.1	3	6
Lake Huron	Good	431	26.2	431	26.2	0	0
	Fair	902	54.8	899	54.6	6	3
	Poor	313	19	316	19.2	3	6
Lake Erie	Good	40	4.7	38	4.4	2	0
	Fair	412	48.2	406	47.5	13	7
	Poor	402	47.1	410	48.0	5	13
Lake Ontario	Good	16	1.7	18	1.9	0	2
	Fair	616	66.2	616	66.2	15	15
	Poor	298	32	296	31.8	15	13

Table 2. Number and percent of watersheds within each Great Lake basin, and assigned condition category based on the criteria set forth in the sub-indicator description. Transitions from condition categories represent loss or gain of the number of watersheds within a condition category from the period 2000 to 2010. Note that due to lack of SOLRIS land use data from a portion of western Ontario, the transition is believed to be conservative.
Source: T. Brown, NRRI. (See accompanying text and Land Cover sub-indicator for more information.)

Lake	# Wsheds Good 00	# Wsheds Fair 00	# Wsheds Poor 00	# Wsheds Good 10	# Wsheds Fair 10	# Wsheds Poor 10	% Wsheds Good 00	% Wsheds Fair 00	% Wsheds Poor 00	% Wsheds Good 10	% Wsheds Fair 10	% Wsheds Poor 10
Percent Agriculture (cutoff values: good to fair = 0%, fair to poor = 53.942%)												
All	2054	2414	1125	2067	2422	1104	36.7	43.2	20.1	37	43.3	19.7
Superior	1126	407	1	1135	398	1	73.4	26.5	0.1	74	25.9	0.1
Michigan	137	387	105	140	389	100	21.8	61.5	16.7	22.3	61.8	15.9
Huron	595	682	369	597	682	367	36.1	41.4	22.4	36.3	41.4	22.3
Erie	140	376	338	141	380	333	16.4	44	39.6	16.5	44.5	39
Ontario	56	562	312	54	573	303	6	60.4	33.5	5.8	61.6	32.6
Road Density (cutoff values: good to fair = 0.104 km/km2, fair to poor = 7.778 km/km2)												
All	1102	3351	1140	1045	3256	1292	19.7	59.9	20.4	18.7	58.2	23.1
Superior	512	887	135	471	907	156	33.4	57.8	8.8	30.7	59.1	10.2
Michigan	6	431	192	5	400	224	1	68.5	30.5	0.8	63.6	35.6
Huron	441	984	221	437	962	247	26.8	59.8	13.4	26.5	58.4	15
Erie	84	487	283	74	447	333	9.8	57	33.1	8.7	52.3	39
Ontario	59	562	309	58	540	332	6.3	60.4	33.2	6.2	58.1	35.7
Population Density (cutoff values: good to fair = 1.557 people/km2, fair to poor = 62.104 people/km2)												
All	1083	3399	1111	1252	3235	1106	19.4	60.8	19.9	22.4	57.8	19.8
Superior	747	705	82	810	640	84	48.7	46	5.3	52.8	41.7	5.5
Michigan	13	456	160	23	442	164	2.1	72.5	25.4	3.7	70.3	26.1
Huron	311	1221	114	356	1184	106	18.9	74.2	6.9	21.6	71.9	6.4
Erie	4	460	390	53	411	390	0.5	53.9	45.7	6.2	48.1	45.7
Ontario	8	557	365	10	558	362	0.9	59.9	39.2	1.1	60	38.9
Percent Developed (cutoff values: good to fair = 0%, fair to poor = 17.284%)												
All	1395	3065	1133	1391	3045	1157	24.9	54.8	20.3	24.9	54.4	20.7
Superior	564	841	129	564	841	129	36.8	54.8	8.4	36.8	54.8	8.4
Michigan	5	479	145	5	474	150	0.8	76.2	23.1	0.8	75.4	23.8
Huron	698	750	198	697	750	199	42.4	45.6	12	42.3	45.6	12.1
Erie	74	411	369	70	410	374	8.7	48.1	43.2	8.2	48	43.8
Ontario	54	584	292	55	570	305	5.8	62.8	31.4	5.9	61.3	32.8
MaxRel(roads, population, %developed) (cutoff values: good to fair = 0.006, fair to poor = 0.212)												

Lake	# Wsheds Good 00	# Wsheds Fair 00	# Wsheds Poor 00	# Wsheds Good 10	# Wsheds Fair 10	# Wsheds Poor 10	% Wsheds Good 00	% Wsheds Fair 00	% Wsheds Poor 00	% Wsheds Good 10	% Wsheds Fair 10	% Wsheds Poor 10
All	1095	3359	1139	1046	3337	1210	19.6	60.1	20.4	18.7	59.7	21.6
Superior	555	846	133	511	886	137	36.2	55.1	8.7	33.3	57.8	8.9
Michigan	4	470	155	4	454	171	0.6	74.7	24.6	0.6	72.2	27.2
Huron	447	990	209	448	976	222	27.2	60.1	12.7	27.2	59.3	13.5
Erie	53	467	334	46	461	347	6.2	54.7	39.1	5.4	54	40.6
Ontario	36	586	308	37	560	333	3.9	63	33.1	4	60.2	35.8
AgDev (cutoff values: good to fair = 0.012, fair to poor = 0.673)												
All	1091	3367	1135	1050	3398	1145	19.5	60.2	20.3	18.8	60.8	20.5
Superior	601	911	22	560	952	22	39.2	59.4	1.4	36.5	62.1	1.4
Michigan	3	526	100	3	525	101	0.5	83.6	15.9	0.5	83.5	16.1
Huron	431	902	313	431	899	316	26.2	54.8	19	26.2	54.6	19.2
Erie	40	412	402	38	406	410	4.7	48.2	47.1	4.4	47.5	48
Ontario	16	616	298	18	616	296	1.7	66.2	32	1.9	66.2	31.8

Table 3. Summary of component stressors for 2000 and 2010 era AgDev scores, including: road density, population density, percent development, Max-Rel Development (= relative maximum of road density, percent development, population density), and percent agricultural land. Cutoff values for condition classes are derived based on the distribution of each stressor across the entire Great Lakes Basin. Shown below are number and percent of watersheds in Good, Fair and Poor condition during each time period (00 = 2000; 10 = 2010). Boundary cutoffs were derived for each variable. **Note:** very low or zero 'good to fair' transition values reflect the large percentages (sometimes in excess of 20%) of the watersheds in the basin with very low or zero development and / or agriculture levels.



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Source: T. Brown. NRRI.

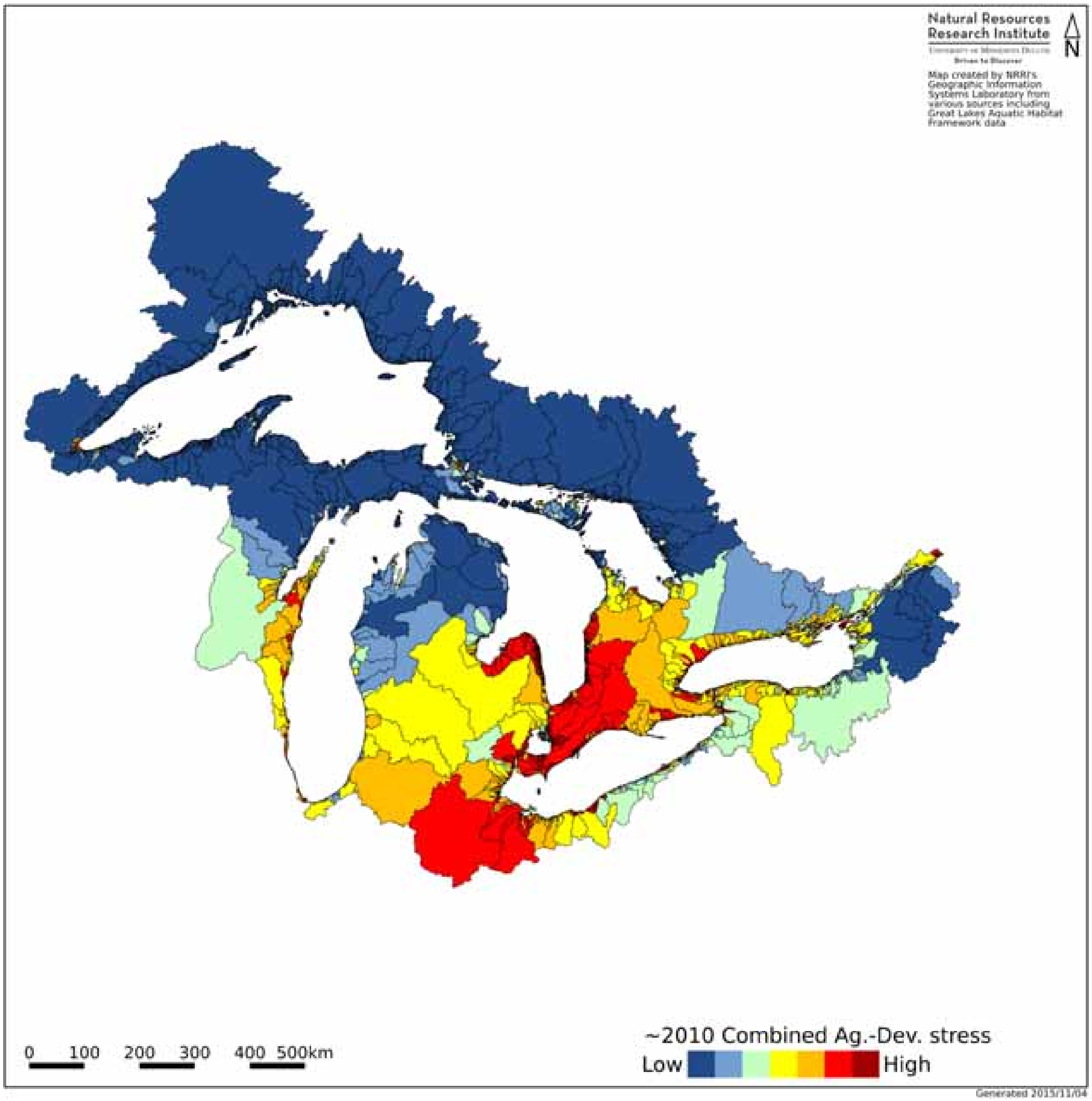

Figure 2. AgDev combined stress score for the Great Lakes Basin based on circa ~2010 era data. Color classes based on even distribution across 7 bins.
Source: T. Brown, NRRI.

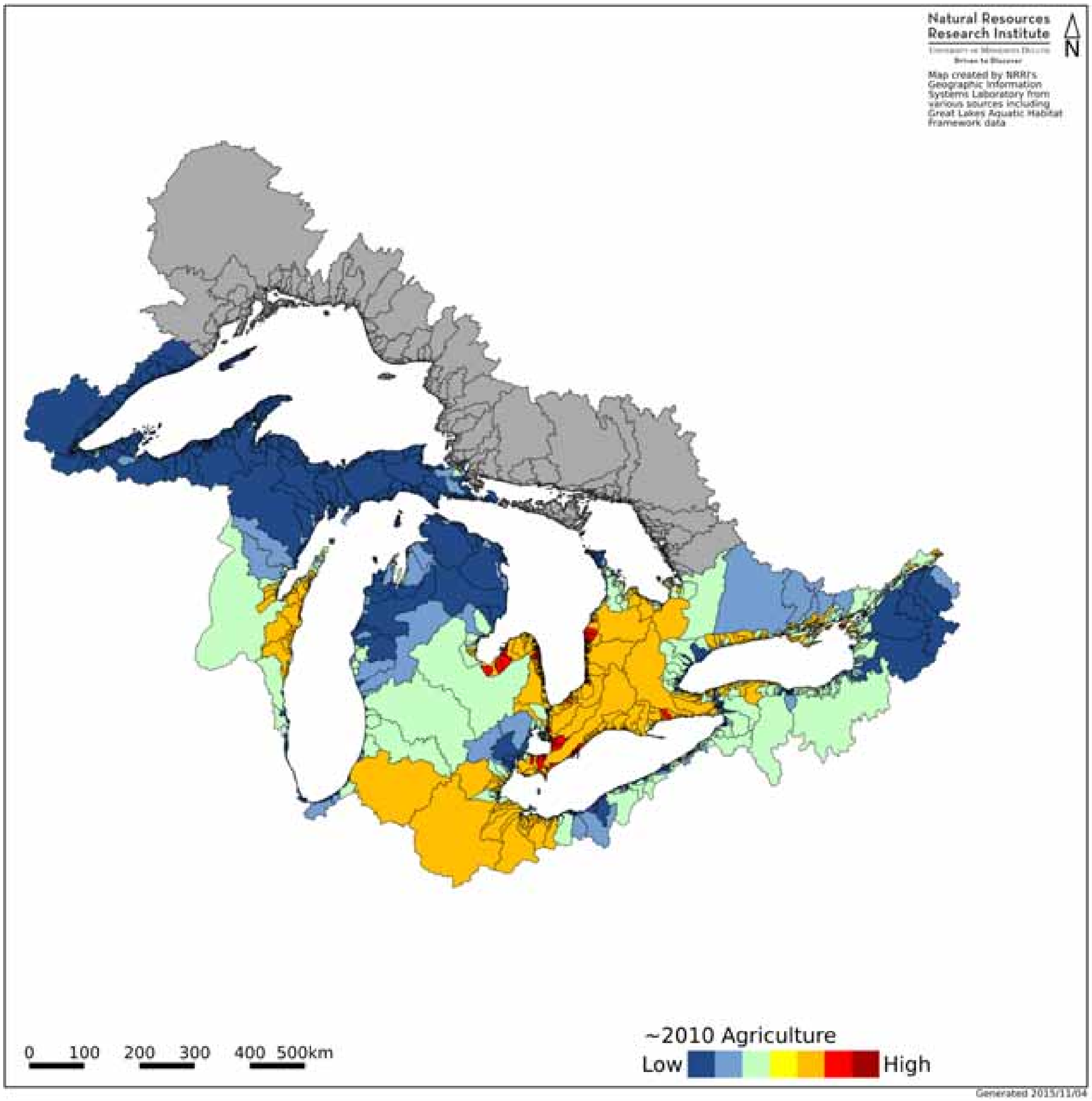

Figure 3. Percent agricultural land for the Great Lakes Basin, 2010. Color classes based on even distribution across 7 bins. Note grey area represents a data gap in the Canadian land use data set for this time period.
Source: T. Brown, NRRI. Unpublished.

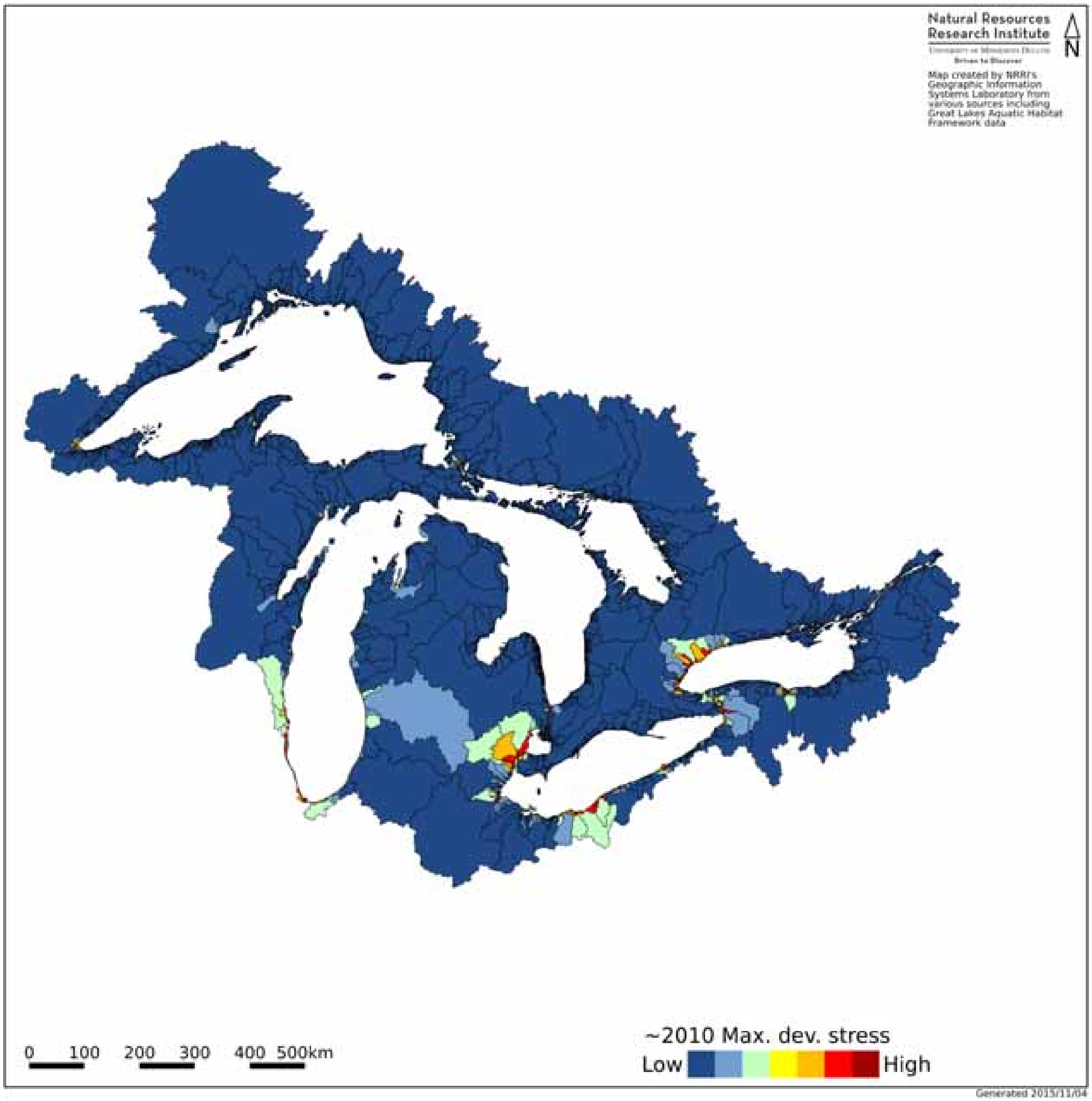

Figure 4. MaxRel Development for the Great Lakes Basin, 2010. Color classes based on even distribution across 7 bins. Note grey area represents a data gap in the Canadian land use data set for this time period.
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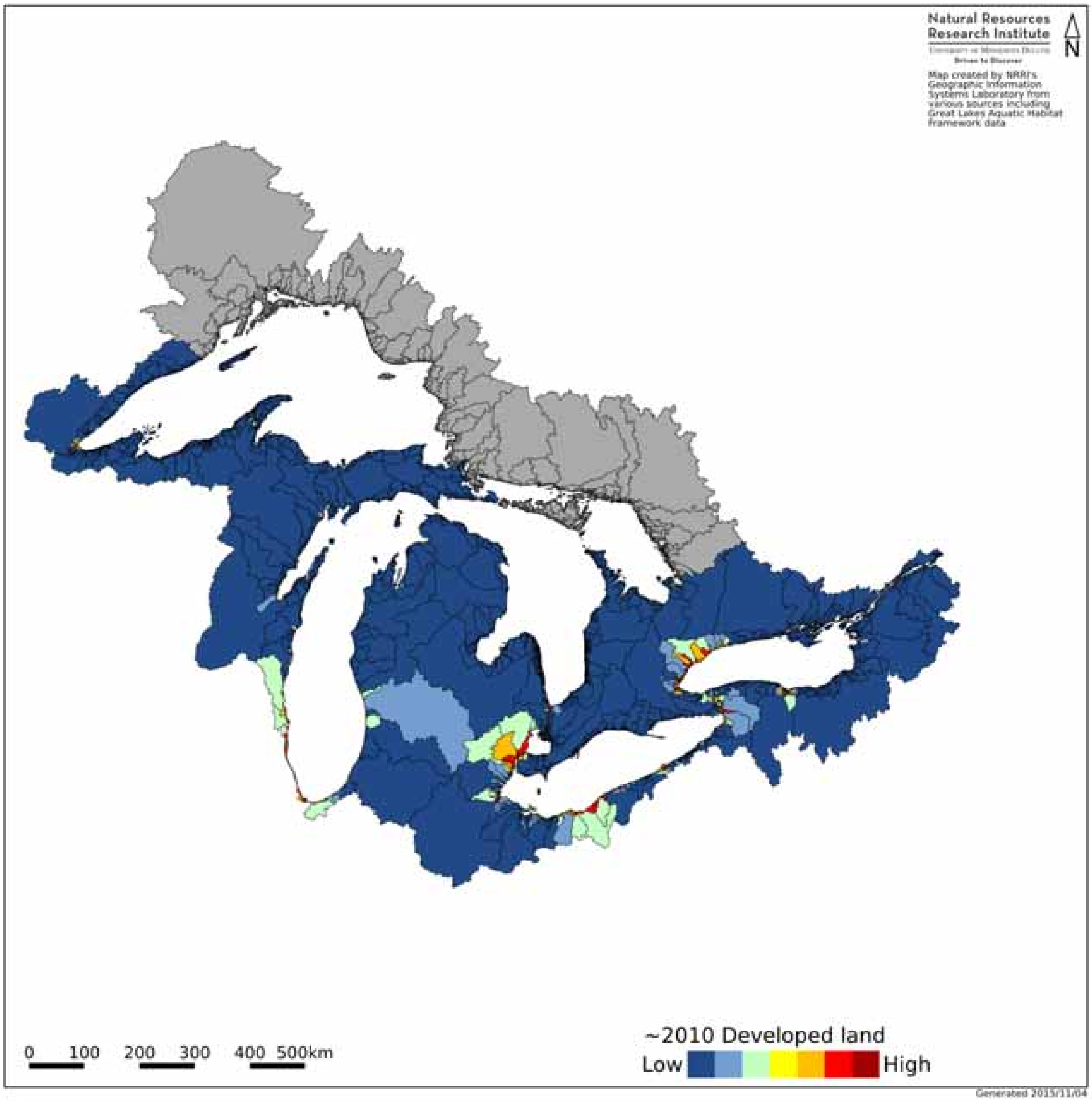


Figure 5. Percent developed land for the Great Lakes Basin, 2010. Note the grey area represents a data gap in the Canadian land use data set for this time period. Color classes based on even distribution across 7 bins. Source: T. Brown, NRRI.

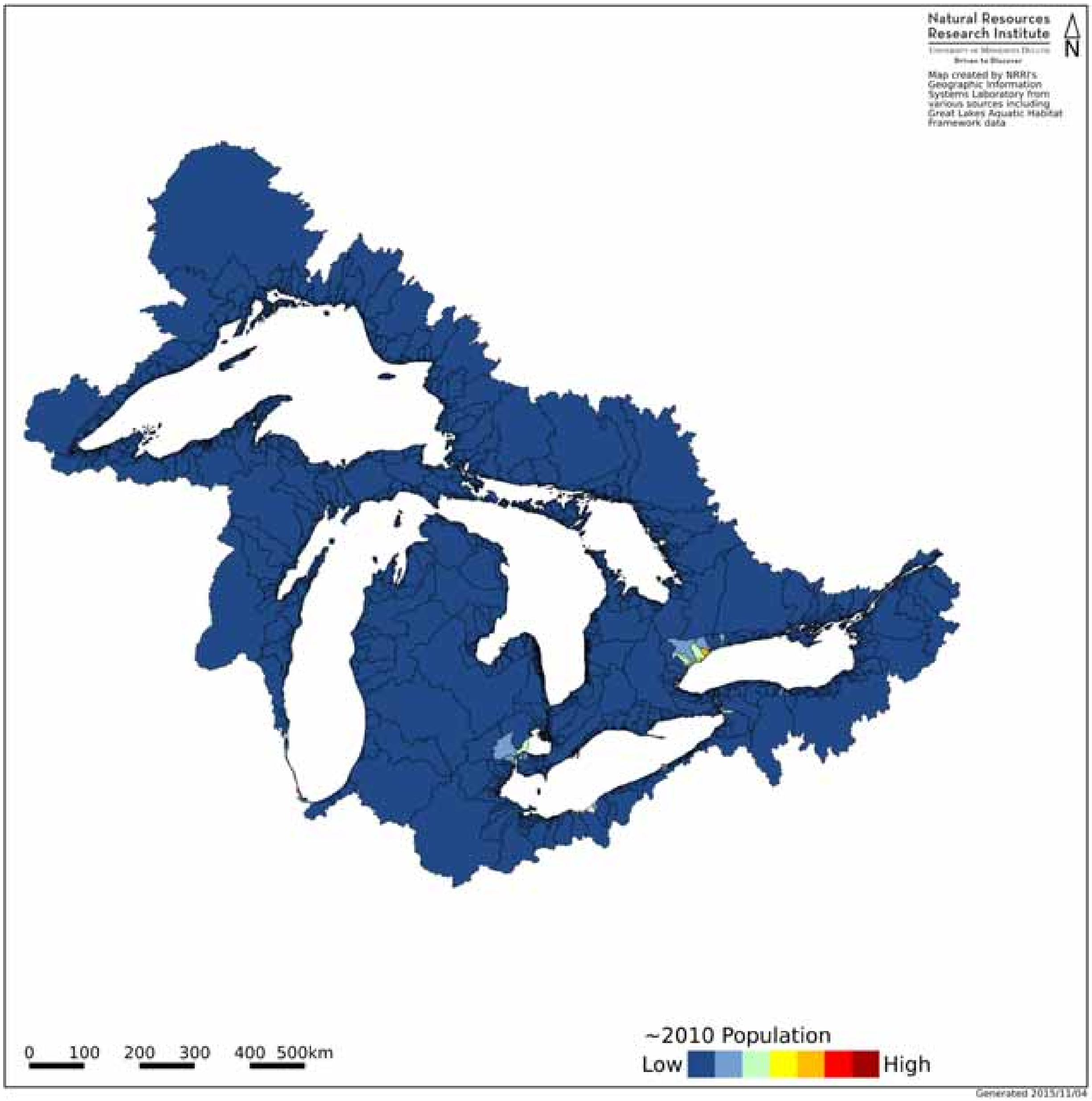


Figure 6. Population density across the Great Lakes Basin, 2010. Color classes based on even distribution across 7 bins.
Source: T. Brown, NRRI.

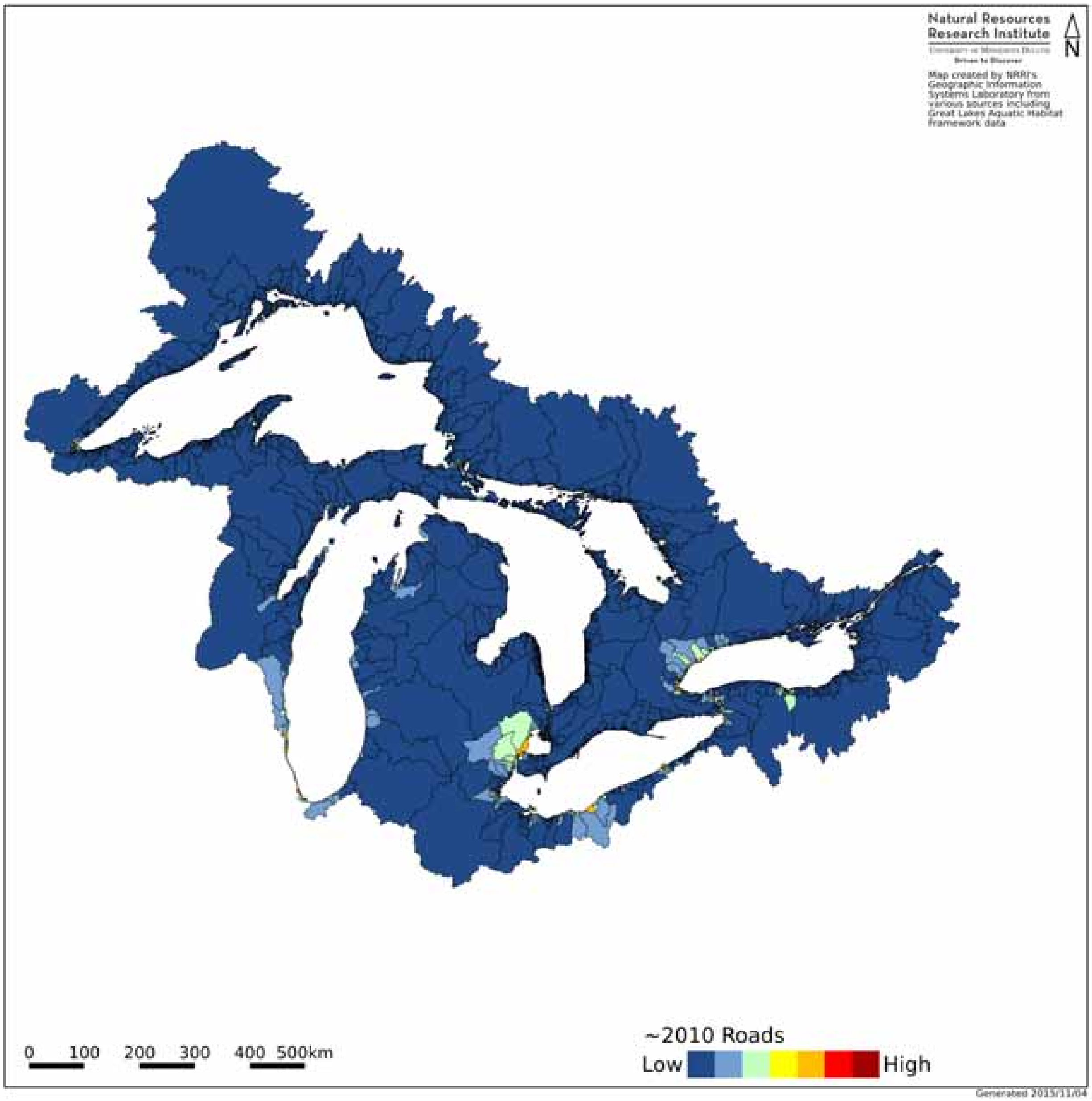
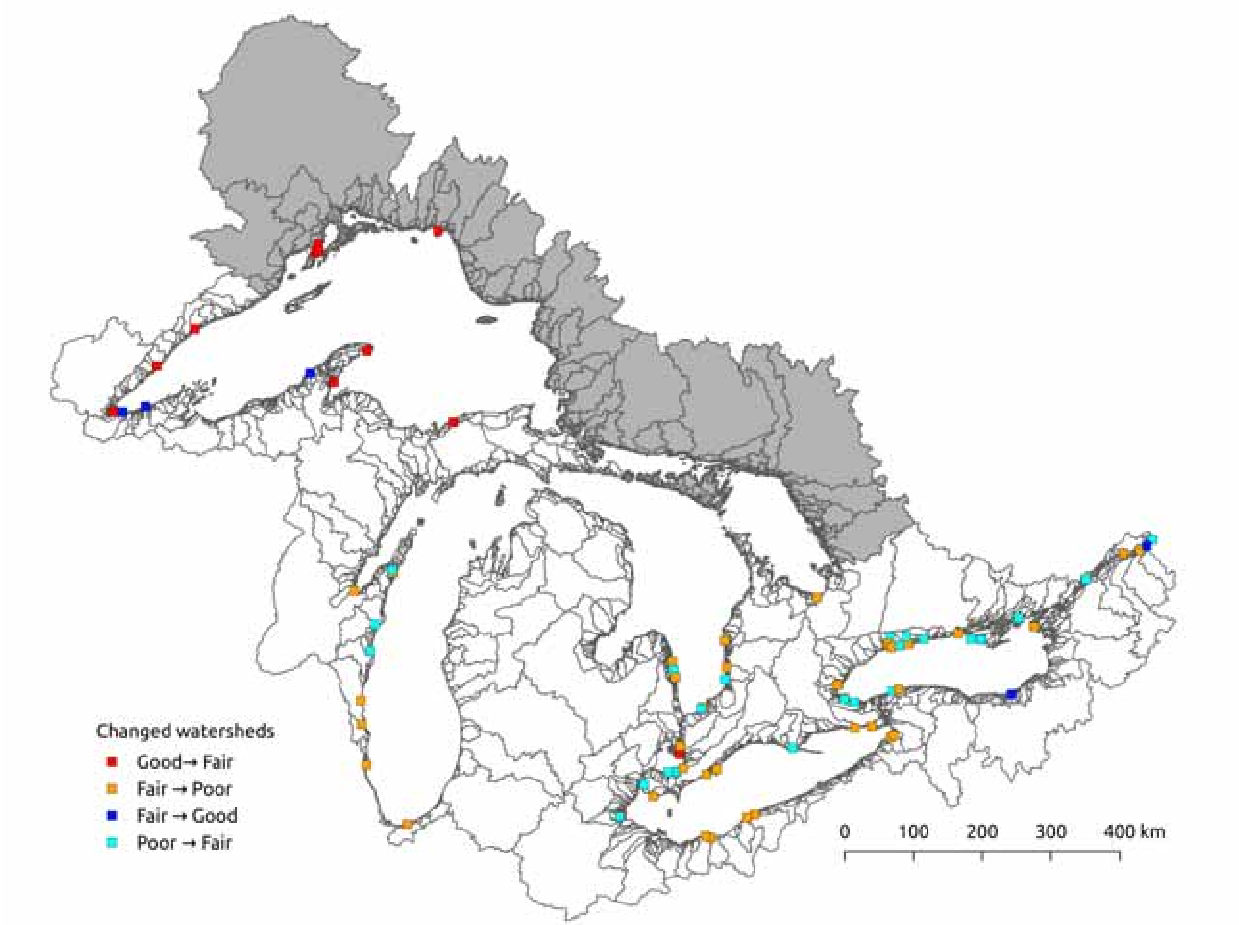


Figure 7. Road density across the Great Lakes Basin, 2010. Color classes based on even distribution across 7 bins. Source: T. Brown, NRRI.



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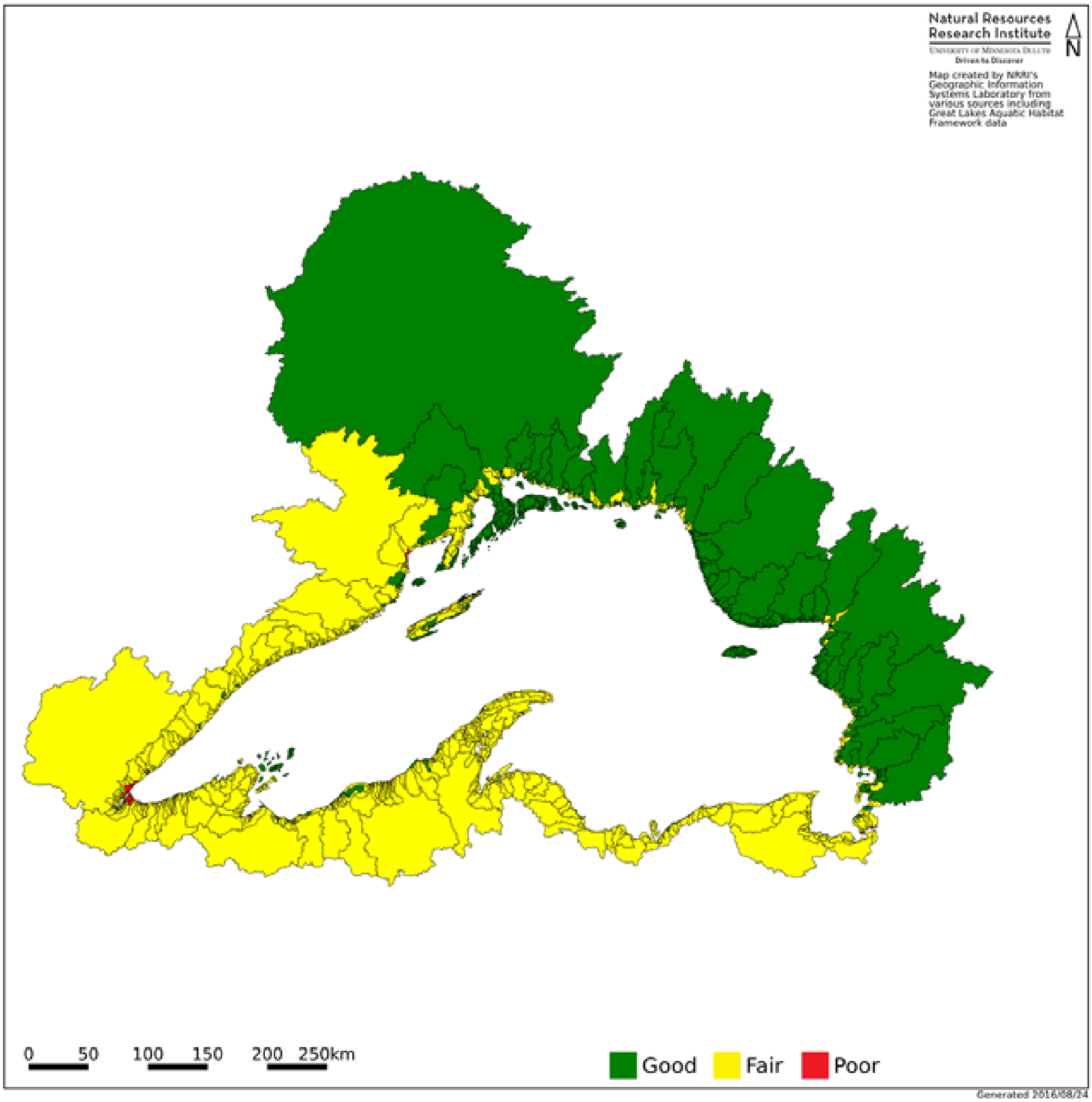

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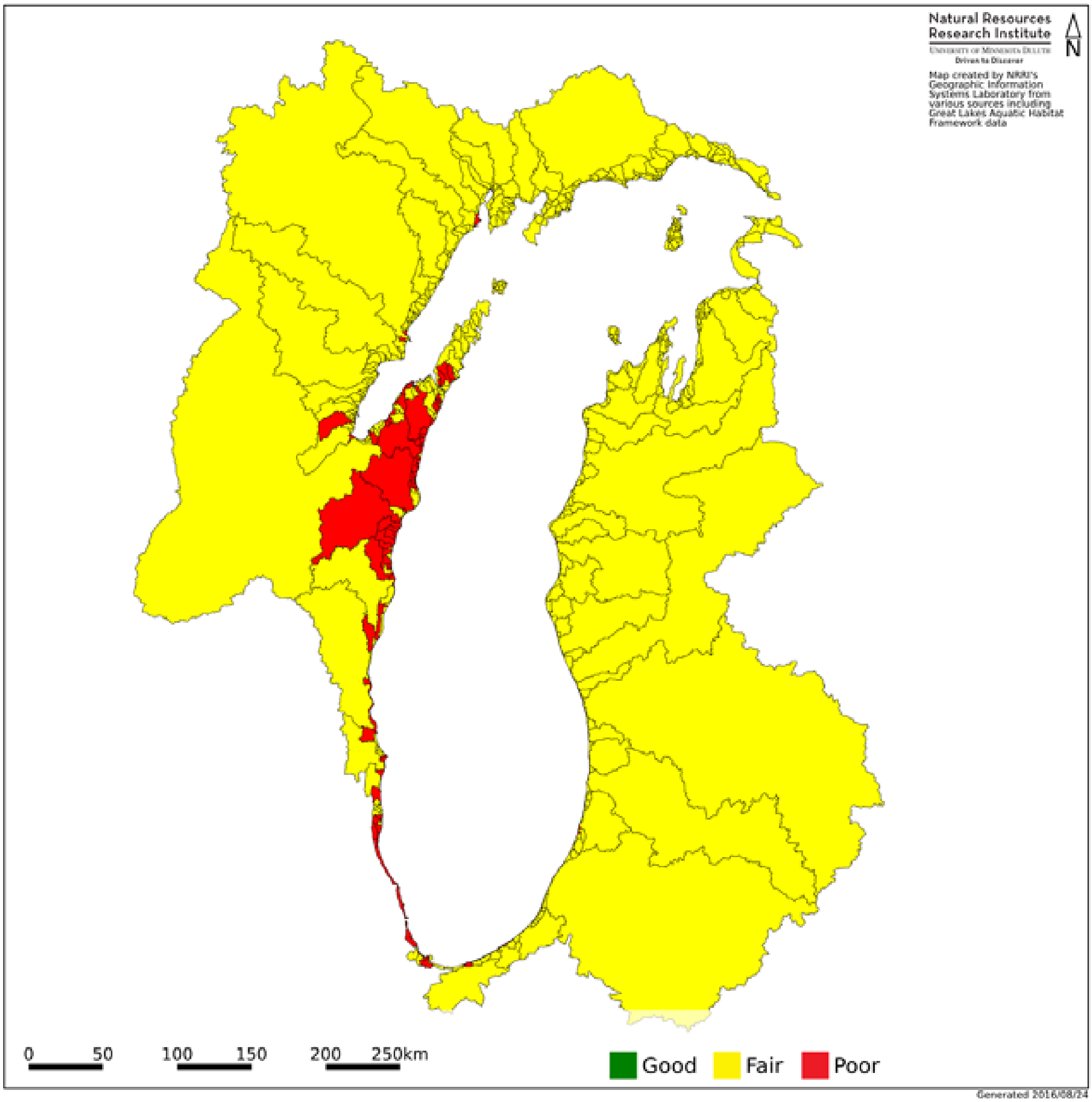
Source: T. Brown, NRRI.



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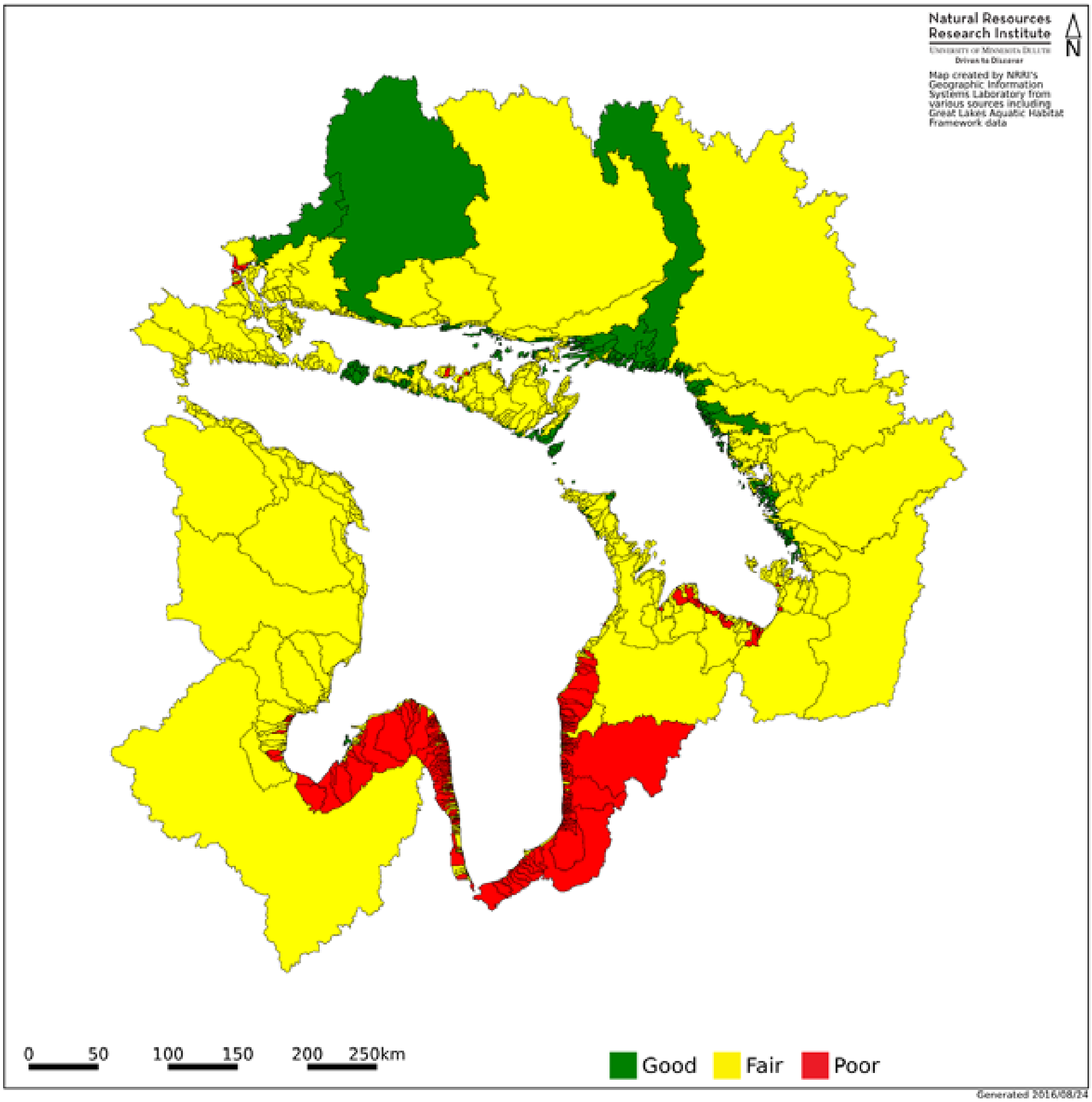
Source: T. Brown, NRRI.



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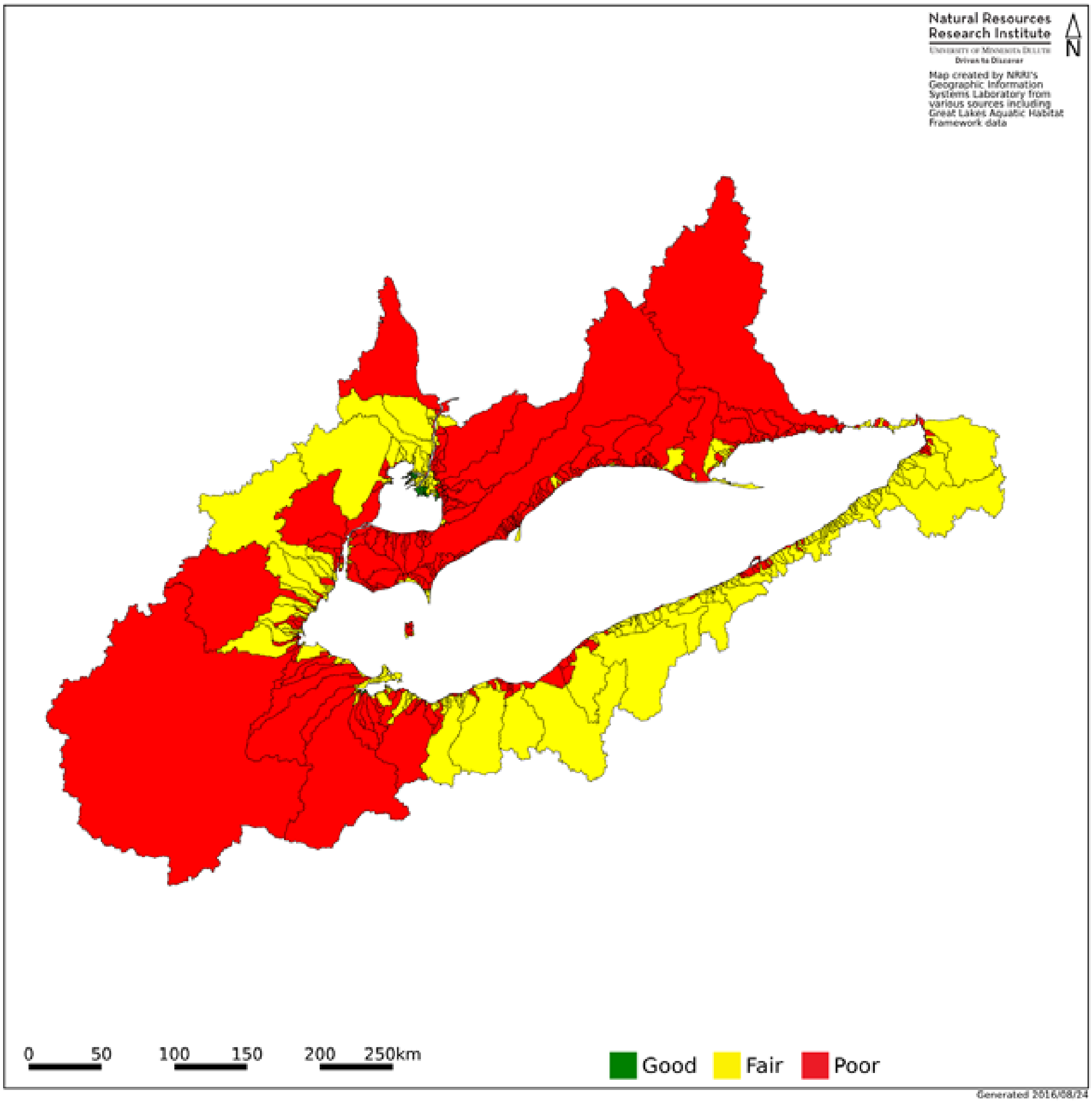
Source: T. Brown, NRRI.



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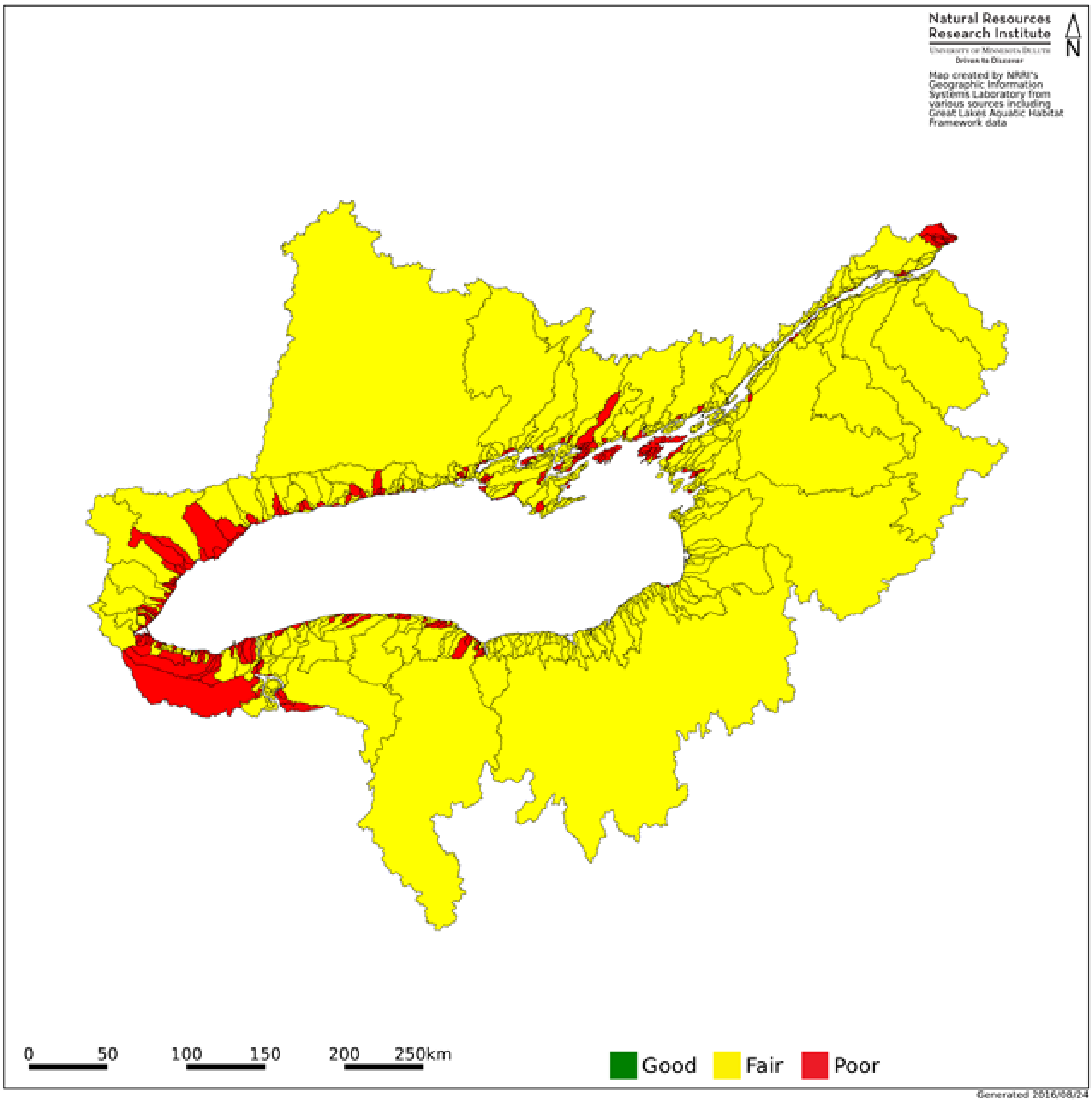
Source: T. Brown, NRRI.



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Source: T. Brown, NRRI.

Sub-Indicator: Hardened Shorelines

Overall Assessment
Status: Undetermined
Trend: Undetermined
Rationale: An overall assessment is not possible as information allowing a direct comparison to previous hardened shoreline indicator status is only available for the Lake Ontario shoreline.

Lake-by-Lake Assessment
Lake Superior
Status: Undetermined
Trend: Undetermined
Rationale: Available information does not allow a direct comparison to previous hardened shoreline indicator status.

Lake Michigan
Status: Undetermined
Trend: Undetermined
Rationale: Available information does not allow a direct comparison to previous hardened shoreline indicator status.

Lake Huron
Status: Undetermined
Trend: Undetermined
Rationale: Available information does not allow a direct comparison to previous hardened shoreline indicator status.

Lake Erie
Status: Undetermined
Trend: Undetermined
Rationale: Available information does not allow a direct comparison to previous hardened shoreline indicator status.

Lake Ontario
Status: Poor
Trend: Deteriorating
Rationale: Updated (2015) shoreline classification datasets for Lake Ontario, not including connecting channels, indicate that approximately 68.5% of the shoreline reaches are in the minor protection or no protection category which is below the poor threshold of 70%. In other words, Lake Ontario has approximately 30% of its shoreline in a heavily or moderately hardened state/condition. The long term trend of Lake Ontario appears to be deteriorating, however, while the short term trend also appears to be deteriorating, there is some uncertainty in the data which could make it more likely that the short term trend is unchanging. While the percent of shoreline in the no protection category was comparable to the previous State of the Great Lakes report update (2001-2002), reductions in the unclassified category were offset by increases in the minor protection, moderate protection, and heavy protection categories suggesting a potential trend towards increased overall shoreline hardening in some areas. However, the redistribution of the proportions of classified shoreline types may be attributed to the increased availability of higher resolution aerial photographs than what were available during the last review of this indicator. This allows for a more detailed delineation of the shoreline to be performed. There is uncertainty in the trend analysis due to

variations in input datasets as discussed further below.

Sub-Indicator Purpose

- To assess the amount of shoreline altered by the construction of shore protections, such as sheet piling, rip rap, and other erosion control shore protection structures.
- To infer the potential harm to aquatic-dependent life, water quality, and natural processes from conditions created by shore protections.

Ecosystem Objective

Shoreline conditions should be healthy to support aquatic and terrestrial plant and animal life, including the rarest species.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes.

Ecological Condition

Measure

The amount (kilometres) of shoreline that has been hardened (or "protected") through construction of sheet piling, rip rap and other erosion control shore protection structures. Shoreline reaches are categorized using descriptions from the 1997 baseline shoreline classification dataset and include highly protected (≥70-100% hardened), moderately protected (>40-<70% hardened), minor protection (≥15-≤40% hardened), no protection (< 15% hardened), non-structural protection, and unclassified.

Note: measure does not include artificial coastal structures that extend out into the waters, such as jetties, groins, breakwaters, piers, etc.

Status Assessment

The reference values for basin wide and lake wide scales are as follows.
Good: ≥80% of the shoreline reaches have minor to no protection
Fair: ≥70 - < 80% of the shoreline reaches have minor to no protection
Poor: < 70% of the shoreline reaches have minor to no protection

Trend Assessment

Improving: Net decrease or no net increase in the percentage of hardened shorelines in the highly protected or moderately protected categories
Unchanging: No change in the amount percentage of hardened shorelines in the highly protected or moderately protected categories
Deteriorating: Net increase in the percentage of hardened shorelines in the highly protected or moderately protected categories

Trend determination will be based on no net increase in the percent of shoreline in the highly protected and moderately protected categories. The defined parameters are intended to support an assessment of relative change over time and represents an initial suggestion for establishing preferred conditions. However, further discussion and refinement of the categories is required to reflect improved understanding of shoreline hardening and ecosystem impacts. The Status Justification section below outlines some of the challenges with attempting to define reference conditions for hardened shorelines.

Status Justification

There is limited documentation on specific shoreline hardening objectives, particularly at the basin wide and lake wide scales. The proposed endpoint values for a hardened shoreline status assessment provide a descriptive point of reference using the baseline Great Lakes (previously known as SOLEC) estimates of the extent and intensity of shoreline hardening. Various environmental services can be impacted by shoreline hardening including changes or reductions in aquatic habitat, alterations in sediment transport, and changes in nearshore groundwater-lake interactions (see Province of Ontario, 2001). There are a variety of challenges in defining appropriate target values regarding shoreline hardening. In particular, a refined assessment should reflect the differing quality and quantity of environmental services being provided (or not provided) by differing shoreline locations (e.g. pollution filtration, fish habitat, etc.) and weight the necessity and amount of the shoreline services required to achieve established ecosystem goals relative to the extent and impact of various shoreline hardening activities. However, the ecological services provided by natural shorelines and the impacts of hardened shorelines are difficult to measure as they often relate to many complex, long-term, and interdependent ecological processes (such as pollution filtration and sediment transport), in addition to more immediate and observable effects such as habitat and habitat loss. There are also variations in the extent to which certain types of shoreline hardening activities actually impact various ecological services based on the age, quality, and design characteristics of the shoreline structures. The current assessment categories only provide a general estimate of the extent and intensity of shoreline hardening and do not reflect an assessment of the relative sensitivity to shoreline hardening on each lake. The selected category ranges account for the fact that some shoreline hardening already exists on the Great Lakes and is likely to be maintained into the future. The trend assessment captures the relative change in the percent of shoreline with >40% hardening.

For the purpose of this report, an overall undetermined reference value has been selected for the basin wide assessment due to the lack of a standardized dataset on many of the lakes that can be directly compared to the baseline conditions established for the State of the Great Lakes (previously known as SOLEC) hardened shoreline sub-indicator. Where updated datasets do exist, they tend to be limited in geographic scope (i.e. they do not cover a full lake basin) or there are issues in matching the existing hardened shoreline assessment categories. The baseline conditions, as represented in the 2009 and 2011 Great Lakes/SOLEC hardened shoreline indicator reports, are provided in Table 1 for reference.

Lake Ontario does have a full dataset that was compared with the baseline conditions identified in previous State of the Great Lakes reporting based on NOAA 1997 data. This dataset was developed in 2001 and 2002 to support the International Joint Commission's (IJC's) International Lake Ontario – St. Lawrence River Regulation Study. A similar methodology was utilized to classify the full U.S. and Canadian Lake Ontario shoreline based on the type and extent of shoreline hardening (see Stewart, 2002) with the results summarized in the Flood and Erosion Prediction System (FEPS) database (see Baird, 2005). The dataset was used to model water level impacts on shoreline structure lifespan and as a result, there are small gaps where direct comparisons to the baseline data set are difficult. In particular, there were some instances where the percent of very low quality shoreline structures was not identified as they were not included in the water level impact modeling. In the case of the Great Lakes comparison, these areas were identified within the unclassified category, even though there was likely some shoreline hardening occurring. It should also be noted that the updated Lake Ontario classification dataset utilized a higher resolution shoreline delineation than was used in the baseline conditions identified in previous State of the Great Lakes reporting. As a result, the classified shoreline extent is greater for the updated dataset. Finally, the updated dataset estimates the percent hardened shoreline using standard 1 km reaches along the full shoreline whereas the baseline dataset categorized reaches of variable (and generally greater) length.

To assess potential changes in the Lake Ontario shoreline since the 2011 State of the Great Lakes report, the U.S. Army Corps of Engineers (USACE) reviewed all existing geospatial data for the Lake Ontario shoreline and determined that while a delineation of the New York State side of Lake Ontario was performed in 2012, there has been no recent delineation of the Canadian side of Lake Ontario since the 2001 and 2005 analysis. Therefore, the USACE developed an updated shoreline dataset of the entire Lake Ontario Shoreline using data from two sources. The United States shoreline was delineated and classified in August 2012 by AECOM in association with the New York State Office of General Services (NYSOGS) and the New York State Department of Environmental Conservation (NYSDEC) for the IJC's Lake Ontario - St. Lawrence River water level study. Each feature within the data layer produced by AECOM represents a reach of shoreline of differing classification. Classification reaches were not defined according to a set unit of measure. The existing NYSOGS/NYSDEC shoreline polyline was modified to most accurately represent the actual shoreline boundary based on 2010-2012 Bing Maps aerial imagery. The shoreline was then split into classifications according to the type of shoreline based on review of 2012 oblique imagery produced by the USACE. The Canadian shoreline was digitized and classified by the USACE-Buffalo District in 2015 using the AECOM classification scheme. Specifically, each feature within the data layer was created to represent a reach of shoreline based on predefined categories of shoreline types. Similar to the AECOM data format, the shoreline reaches defined by the USACE were not initially defined by the 1 km reach standard used in the 2002/2005 dataset. Following the AECOM methodology, the USACE delineated the Canadian shoreline of

Lake Ontario to most accurately represent the shoreline based on a review of 2010-2012 imagery depicted on Bing Maps and ESRI world imagery aerial basemaps. Both the Bing Maps and ESRI imagery use photographs from various sources including federal, state and local entities using satellites and aerial photography. The classifications were assigned by shoreline type based on an additional review of imagery that was accessed via Google Earth Pro and oblique imagery from Bing Maps (Pictometry). The imagery found in Google Earth Pro included high resolution aerial photos from multiple sources taken between May 2015 and September 2015, and the Bing Maps oblique imagery was taken from 2007-2015. To create the final contiguous 2015 shoreline dataset, the AECOM delineation of the New York State shoreline was merged with the dataset created by the USACE. The merged dataset was then copied and divided into 1 km reaches. In order to determine the percent of each shoreline type within the 1 km reaches, a statistical analysis (tabulate intersection) was performed using ArcGIS. The analysis compared the predefined 1 km reaches with the classifications that were determined from the AECOM/USACE delineation of the shoreline. The resulting output included shoreline classification, length, and percentage of each type in each of the 1,988 reaches that were included in the 1 km shoreline reach dataset.

Table 2 provides the length of shoreline in the baseline, 2001-2002 datasets, and 2015 datasets, along with the percent of shoreline within the various percent hardening categories for Lake Ontario. The percent of shoreline within the moderately (40 to 70% hardened) and major (>70% hardened) categories increased by 0.9 and 1.0 %, respectively while the percent of the shoreline within the minor (15 to 40% hardened) increased 6.8% and no protection category (<15% hardened) was reduced by 1.3%. The extent of shoreline in the minor and low protection categories is still below the poor threshold established and resulted in the poor status classification. The results suggest that there has been a slight increase in the amount of shoreline hardening since the 2001-2002 dataset was established and a deteriorating trend was identified. However, since the overall length of categorized shoreline decreased due to the refined shoreline delineation, there is uncertainty as to whether the identified change represents a true increase or a difference in dataset methodologies. Figure 1 provides maps of the baseline Lake Ontario shoreline hardening categorization and the 2001-2002 Lake Ontario data, and Figure 2 shows the updated 2015 Lake Ontario data.

The reason we did not include the data for the connecting channels in this assessment is due to a lack of data to compare to on the short term. In the baseline data the connecting channels or rivers were included as separate entities for comparison. In the 2011 classification they were not given a classification nor were they compared. When we classified Lake Ontario we, simply put, started where the 2012 AECOM dataset left off in New York State, which did not include the Niagara River or the St. Lawrence.

Linkages

The hardening of shorelines can result in the loss of habitat, further erosion of unprotected properties adjacent to the structure, water quality degradation and the interruption of natural shoreline processes including reduced sediment transport. The hardened shoreline can be directly linked to other sub-indicators currently used to assess the Great Lakes Basin. Those sub-indicators/indicators are:

Coastal Wetlands sub-indicators- Fish spawning and feeding habitat associated with coastal wetlands can both be accentuated or diminished based on the physical modification to the shoreline and the effects it may have on coastal and nearshore processes, as well as effects on habitat structure along the Great Lakes shoreline. These data will help to assess where both beneficial and unfavorable impacts occur.

Watersheds Impacts- this is directly related to changes in land cover climactic dynamism in areas with increased or increasing amounts of anthropogenic shoreline modification that diminish littoral drift and impact regional sediment management.

Comments from the Author(s)

There is uncertainty when trying to make a direct comparison between the different datasets for Lake Ontario. The shoreline reach categorizations are defined differently in all three datasets. However, the closest comparison can be made between the 2001-2002 data and the 2015 data since these data use the fixed 1 km shoreline reaches. The large increase in the minor protection and decrease in unclassified categories could be the result of the availability of higher resolution aerial imagery. In addition, it is possible that the difference in shoreline length could be due to variation in lake water levels during the period that aerial images are taken and the increased availability of higher resolution aerial photographs than those used in the 2001-2002 data. The most recent Lake Ontario dataset used the 2001-2002 shoreline delineation as a guide marker, but followed the shoreline present in the aerial imagery in order to obtain an accurate depiction of shoreline for comparison. Since the sub-indicator is based on a relative difference in the percent of shoreline within various categories, it is still possible to make some comparisons. However, it should be recognized that direct comparisons between datasets will be highly uncertain without using a common baseline shoreline delineation and comparable reach lengths. Finally, as stated in the 2011 State of the Great Lakes report, the baseline dataset is not clear on the transition between percent protected categories. For example, a shoreline reach that is 70% hardened could fall within either the 40% to 70% category or the 70% to 100% category. More explicit transitions were used for the categorization of the updated datasets.

There are opportunities for future updates to the hardened shorelines sub-indicator. Updated high resolution aerial imagery exists for much of the Great Lakes shoreline and oblique imagery was collected in 2012 for the U.S. shoreline of the Great Lakes. This information will make it possible to duplicate the Lake Ontario effort across the other Great Lakes to create new datasets of the shoreline and update any existing reach delineations, shoreline classifications, and the percent of shoreline hardening. Any efforts to create new or update existing datasets should ensure that classification methodologies are similar to past efforts (e.g. as used for the updated Lake Ontario shoreline classification) and standardized reach delineations are utilized. Consideration should be given to including all anthropogenic features that are not currently included in the dataset in an updated basin wide dataset. If a basin wide dataset is completed in the future following the basic procedures used for the 2015 Lake Ontario dataset, then this new dataset should be used as the baseline moving forward. This would allow for the use of a measure that would compare the ratio of human modified shoreline to the total length of shoreline in the Great Lakes Basin. This would allow for comparison on a lake-by-lake basis, as well as provide an easy to understand overview for the entire basin.

Assessing Data Quality

Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization		X				
2. Data are traceable to original sources		X				
3. The source of the data is a known, reliable and respected generator of data		X				
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin			X			
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report			X			

Clarifying Notes:

1. There is documentation prepared as part of the IJCs International Lake Ontario – St. Lawrence River Study (see Stewart, 2002). The classification itself was undertaken by private contractors with considerable experience in shoreline classification procedures. However, there is no formal validation methodology for undertaking this type of shoreline classification. The 2015 data documentation was prepared by the USACE and includes documentation provided by AECOM
2. The data can be traced to original sources
3. The classification itself was undertaken by private contractors and USACE employees with considerable experience in shoreline classification and aerial photography interpretation procedures
4. The geographic scale for the updated information only covers Lake Ontario and cannot be used for Great Lakes Basin wide assessments
5. The procedure for identifying hardened shorelines was applied consistently on both the Canadian and U.S. shorelines of Lake Ontario. However, the identification and interpretation of hardened shorelines was influenced by the imagery availability and resolution which varied greatly along certain areas of the

Canadian shoreline. The specific age and quality of input imagery used for individual shoreline reaches are not identified.
6. The variation in reach length and detail of shoreline delineation between the baseline dataset ,the 2001-2002 Lake Ontario data, and the 2015 Lake Ontario data result in uncertainty in the overall status and trends analysis regarding hardened shorelines

Acknowledgments

Authors: Anthony Friona, U.S. Army Corps of Engineers, ERDC (2015)
E. Pirschel and T. Crockett, U.S. Army Corps of Engineers, Buffalo District (2015)

Information Sources

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Source: Baseline data from National Oceanic and Atmospheric Administration (1997), 2001-2002 Lake Ontario data from Stewart (2002) and Baird (2005), and the 2015 updated data from AECOM (2012) and the United States Army Corps of Engineers – Buffalo District (2015)

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Figure 2. Map of the 2015 Lake Ontario Hardened shoreline classification update.
Source: New York shoreline data from AECOM (2012) and Canadian shoreline data from the United States Army Corps of Engineers – Buffalo District (2015)

Last Updated

State of the Great Lakes 2017 Technical Report

Baseline Great Lakes hardened shoreline classification

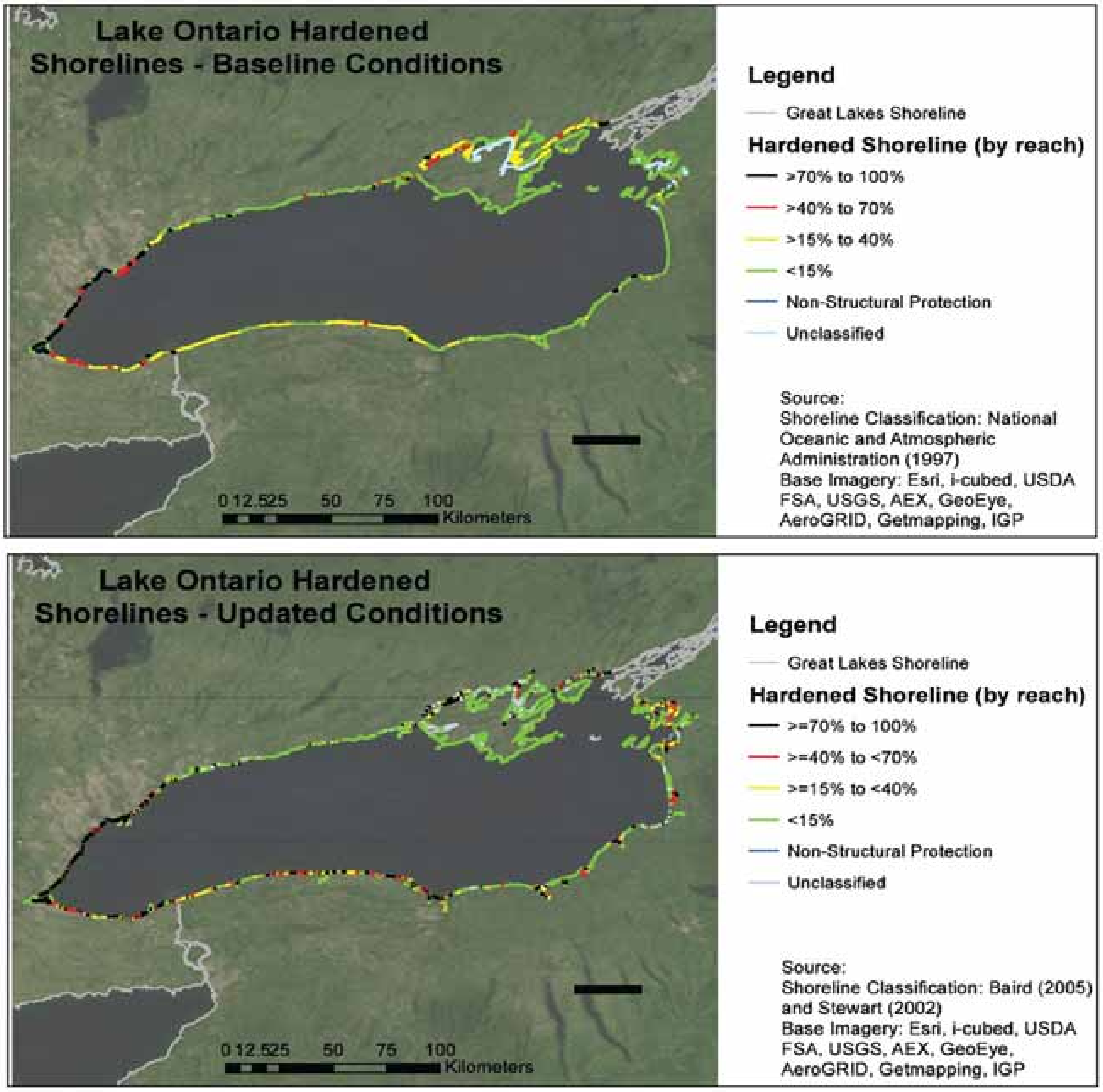
Lake/ Connecting Channel	Heavily Protected (%) (>70%	Moderately Protected (%) (40-70%	Minor Protection (%) (15-40%	No Protection (%) (<15%	Non-structural Protection (%)	Unclassified (%)	Total Shoreline (km)
Lake Superior	3.1	1.1	3	89.4	0.03	3.4	5080
St. Marys River	2.9	1.6	7.5	81.3	1.6	5.1	707
Lake Michigan	8.6	2.9	30.3	57.5	0.1	0.5	2713
Lake Huron	1.5	1.0	4.5	91.6	1.1	0.3	6366
St. Clair River	69.3	24.9	2.1	3.6	0.0	0.0	100
Lake St. Clair	11.3	25.8	11.8	50.7	0.2	0.1	629
Detroit River	47.2	22.6	8.0	22.2	0.0	0.0	244
Lake Erie	20.4	11.3	16.9	49.1	1.9	0.4	1608
Niagara River	44.3	8.8	16.7	29.3	0.0	0.9	184
Lake Ontario	10.2	6.3	18.6	57.2	0.0	6.2	1772
St. Lawrence	12.6	9.3	17.2	54.7	0.0	6.2	2571

Table 1. Baseline Great Lakes hardened shoreline classification used in the 2009 and 2011 State of the Great Lakes Hardened Shoreline indicator report assessments. Original data is from NOAA, 1997.
Source: National Oceanic and Atmospheric Administration (1997)

Comparison of baseline Great Lakes hardened shoreline classification and updated classification

	Baseline Classification	2011 Lake Ontario Classification	2015 Lake Ontario Classification
Length of Shoreline Categorized (km)	1772.0	2444.3	1988.0
1. Heavily Protected (%)(>70% hardened)	10.2	20.0	21.0
2. Moderately Protected (%)(40-70%	6.3	8.0	8.9
3. Minor Protection (%) (15-40% protected	18.6	5.7	12.5
4. No Protection (%) (<15% protected)	57.2	57.3	56.0
5. Non-structural Protection (%)	0.0	0.1	0.0
6. Unclassified (%)	6.2	8.8	1.6

Table 2. Comparison of baseline Great Lakes hardened shoreline classification (using 1997 data), 2011 hardened shoreline classification (using 2002-2005 data), and updated hardened shoreline classification for Lake Ontario using 2015 data.
Source: Baseline data from National Oceanic and Atmospheric Administration (1997), updated Lake Ontario data from Stewart (2002) and Baird (2005), and updated Lake Ontario data from U.S. Army Corps of Engineers (2015).



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Source: Baseline Great Lakes data from National Oceanic and Atmospheric Administration (1997) and updated Lake Ontario data from Stewart (2002) and Baird (2005)

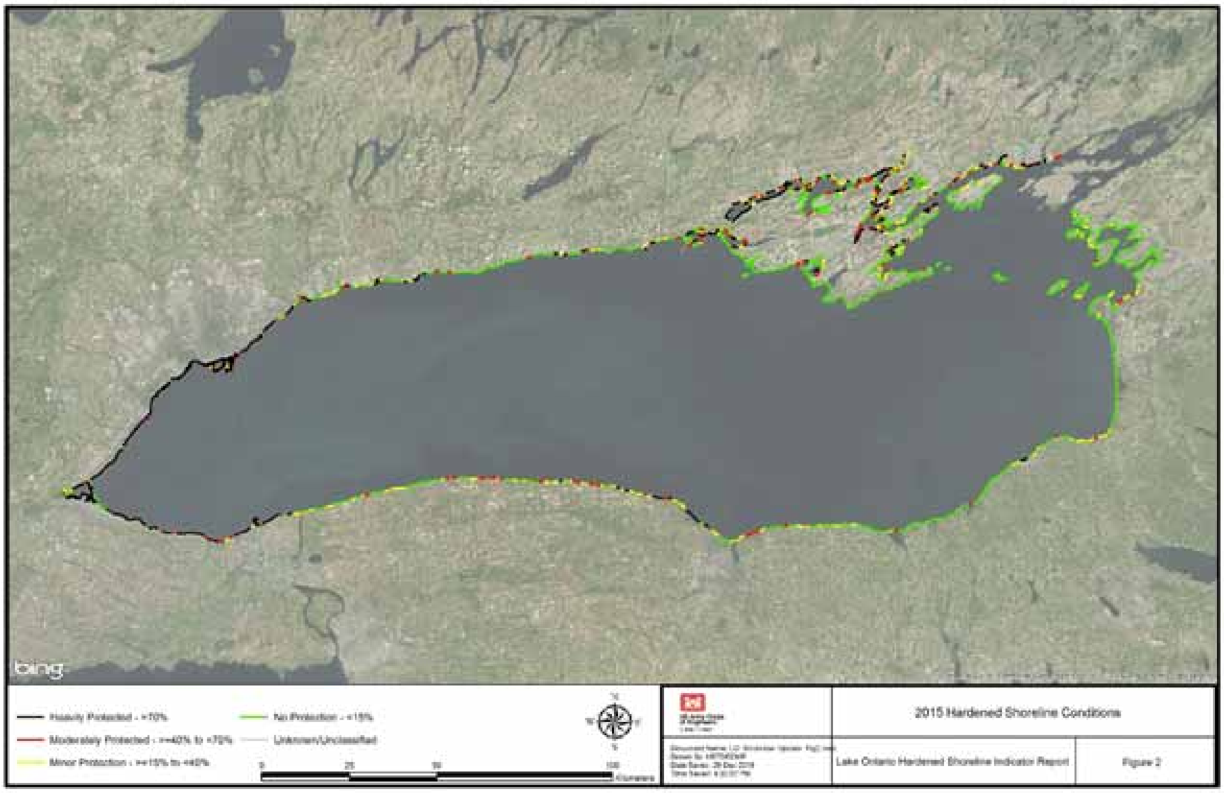

Figure 2. Map of the 2015 Lake Ontario Hardened shoreline classification update.
Source: New York Shoreline data from AECOM (2012) and Canadian shoreline data from the United States Army Corps of Engineers – Buffalo District (2015)

Sub-Indicator: Tributary Flashiness

Overall Assessment
Trend: Unchanging
Rationale: The R-B Index (RBI) for the 27 rivers included in this report was either unchanging or decreasing in most rivers, and had improved or remained unchanged in the short-term. Attention should focus on 3 rivers, in particular, that had deteriorating trends (as defined on page 5) and Lake Ontario which had the highest proportion of rivers with increasing RBI.

Lake-by-Lake Assessment
Individual lake basin assessments were not prepared for this report.

River-by-River Assessment – Lake Superior
Pic River (CAN)
Trend: Unchanging
Rationale: The RBI exhibits no significant trend (p=0.65) and the average RBI increased only slightly from 1995-2004 (0.099) to 2005-2014 (0.102).

Pigeon River (US)
Trend: Unchanging
Rationale: There is no significant trend in RBI (p=0.35) nor has the average RBI changed in the past two decades (both are 0.110).

River-by-River Assessment – Lake Michigan
Fox River (US)
Trend: Unchanging
Rationale: There is no significant long-term trend since 1989 (p=0.22) and the past two decades have an almost identical RBI (0.143 in 1995-2004 vs 0.145 in 2005-2014).

Muskegon River (US)
Trend: Increasing
Rationale: Although the long-term trend is significantly downward (r=-0.64; p<0.001), there is a significant increase since 1996 (r=0.76; p<0.001) and the average RBI increased substantially from 1996-2004 (0.061) to 2005-2014 (0.075).

Manistee River (US)
Trend: Increasing
Rationale: The long-term trend is upward (r=0.52; p<0.001), and the largest increases in average RBI have occurred in the past two decades (0.037 in 1995-2004 and 0.043 in 2005-2014).

Pere Marquette River (US)
Trend: Increasing
Rationale: There is a significant upward long-term trend in RBI (r=0.60; p<0.001), and much of that increase has occurred in the past decade (0.049 in both 1985-1994 and1995-2004 to 0.057 in 2005-2014).

White River (US)
Trend: Increasing
Rationale: The RBI has a significant upward trend (r=0.29; p=0.029), and the average RBI has increased primarily in the past decade from 0.066 in 1995-2004 to 0.075 in 2005-2014.

Escanaba River (US)
Trend: Decreasing
Rationale: The long-term trend is significantly downward (r=-0.75; p<0.001), though the decreases were largely in the late 1960s and the average RBI is similar between 1995-2004 (0.100) and 2005-2014 (0.106).

Grand River (US)
Trend: Decreasing
Rationale: There is a significant downward long-term trend in RBI (r=-0.26; p=0.035), and although there was a slight increase in the mid-1990s, the average RBI has decreased from 1995-2004 (0.077) to 2005-2014 (0.074).

River-by-River Assessment – Lake Huron
French River (CAN)
Trend: Unchanging
Rationale: Neither the long-term trend (p=0.10) nor the average RBI have change substantially from 1995-2004 (0.025) to 2005-2014 (0.026).

Au Sable River (US)
Trend: Unchanging
Rationale: There is no significant trend in RBI starting in 1997 (p=0.15), and though the average RBI increased slightly from 0.046 in 1997-2004 to 0.051 in 2005-2014, much of the decade trends downward.

Magnetawan River (CAN)
Trend: Unchanging
Rationale: There is not a significant long-term trend since 1973 (p=0.63) and the average RBI has been similar across all 4 decades (0.049-0.052).

Maitland River (CAN)
Trend: Unchanging
Rationale: There is no significant long-term trend in RBI (p=0.66), and the average RBI from 1985-1996 was identical to 2003-2014 (0.291). Data were missing for 1997-2002.

Thunder Bay River (US)
Trend: Unchanging
Rationale: The RBI has no significant downward trend (p=0.10). Although there were substantial decreases in the earlier record, since measurements restarted in 2002 the average RBI from 2002-2008 (0.081) was very similar to past 6 years (0.087).

Wanapitei River (CAN)
Trend: Unchanging
Rationale: The long-term data exhibit no significant trend (p=0.59), yet the recent average RBI (2005-2014) was much lower (0.066) than the past decade (0.081 from 1995-2004).

Saginaw River (US)
Trend: Decreasing
Rationale: There is a significant downward long-term trend since 1997 (r=-0.63; p=0.002) and the average RBI has dropped from 0.222 in 1997-2004 to 0.157 in 2005-2014.

Nottawasaga River (CAN)
Trend: Decreasing
Rationale: Although there is no significant long-term trend since 1993 (p=0.10), and average RBI has decreased substantially from 0.074 in 1995-2004 to 0.065 in 2005-2014.

River-by-River Assessment – Lake Erie
River Raisin (US)
Trend: Unchanging
Rationale: There is no significant long-term trend in RBI (p=0.75), and the average RBI was very similar between 1995-2004 (0.162) and 2005-2014 (0.161).

Grand River (OH-US)
Trend: Unchanging
Rationale: There is no significant long-term trend (p=0.10), and the average RBI is similar between 1995-2004 (0.362) and 2005-2014 (0.363).

Maumee River (US)
Trend: Increasing
Rationale: Over the long-term record, there has been a significant increase in RBI (r=0.52; p=0.007), yet the past ten years have trended downward with a higher RBI from 1995-2004 (0.294) compared to 2005-2014 (0.280).

Sandusky River (US)
Trend: Increasing
Rationale: Although the long-term trend is significantly upward (r=0.34; p=0.007), the average RBI decreased from 1995-2004 (0.395) to 2005-2014 (0.375).

Thames River (CAN)
Trend: Increasing
Rationale: There is no significant long-term trend in RBI since 1956 (p=0.11), but there is since 1985 (r=0.59; p<0.001). The average RBI increased over the past two decades from 0.204 in 1994-2004 to 0.221 in 2005-2014.

Cattaraugus River (US)
Trend: Increasing
Rationale: Although the long-term trend is not significant (p=0.16), the RBI has been increasing since the mid-2000s and the average RBI increased from 0.369 in 1995-2004 to 0.396 in 2005-2014.

Portage River (US)
Trend: Increasing
Rationale: There is a significant upward long-term trend in RBI (r=0.26; p=0.038), and the average RBI has increased consistently from 1975-1984 (0.476) to the past decade (0.538).

River-by-River Assessment – Lake Ontario

Humber River (CAN)

Trend: Unchanging

Rationale: The RBI exhibits no significant trend (p=0.57) and though the average RBI decreased from 1995-2003 (0.261) to 2008-2014 (0.241), the recent average is very similar to the long-term average (0.243).

Don River (CAN)

Trend: Increasing

Rationale: The long-term trend is upward (r=0.37; p=0.007), though much of that increase was from 1955 to 1975, there has also been a slight increase in the average RBI from 0.520 in 1985-1994 to 0.530 in 1995-2004 and 0.534 in 2005-2014.

Seneca River (US)

Trend: Increasing

Rationale: The trend in RBI since 1997 is upward, though not significantly so (r=0.46; p=0.056). The average RBI has increased from 0.079 in 1997-2004 to 0.090 in 2005-2014.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to quantify the nebulous concept of flashiness, which is an important aspect of the hydrologic regime as it reflects the frequency and rapidity of short term changes in river flow to which aquatic ecosystems are adapted.
- Increasing or decreasing trends in flashiness may result in increased stress at lake areas that are influenced by river flows and may influence aquatic organisms that use rivers for all or part of their lives.
- The Hydrologic Alteration (R-B Flashiness Index - RBI) is used to quantify the hydrologic responsiveness (i.e. flashiness) of a Great Lakes tributary to temporal changes in precipitation and runoff.

Ecosystem Objective

The ecosystem objective is to avoid hydrologic alteration. Periodic changes in flow rate are characteristic of streams and rivers, and the organisms that live in them are adapted to those changes. Spring floods may be important in opening up spawning areas or nurseries. Higher energies associated with storm runoff flush finer sediment from gravel beds, improving them as habitats for invertebrates and as spawning sites for salmonids. However, changes in the hydrologic regime, either by reduced flashiness such as occurs when a dam is constructed, or by increased flashiness such as occurs with urbanization, require adaptation by the resident organisms; if the changes are great enough, they can lead to the displacement of the native community and its replacement by another, often less desirable community.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes."

Ecological Condition

Tributary flashiness is a measure that reflects the frequency of short-term changes in streamflow; the flow of a flashy stream increases and decreases dramatically in hours or a few days in response to rainfall.

Measure

This sub-indicator measures the flashiness of hydrological response of a stream or river to precipitation (rainfall) and runoff (snowmelt) events. The Richards-Baker Flashiness Index (RBI for short) is calculated from mean daily flows from the U.S. Geological Survey or Environment and Climate Change Canada, usually on an annual basis, by dividing the sum of the absolute values of day-to-day changes in mean daily flow by the total discharge over that time interval (Baker et al. 2004).

$$\frac{\sum_{n=1}^{365} \left| q_n - q_{n-1} \right|}{\sum_{n=1}^{365} q_n}$$

Streams assessed for this sub-indicator are listed in Table 1. Most of these streams cover a range of flashiness and land use, have long flow records, have a large watershed area, and stations are of a great distance (multiple miles/kilometres) from a dam and sufficiently upstream of the Great Lake it feeds.

Endpoints

Desirable outcomes are lack of trend in flashiness, or in most cases of altered ecosystems, reductions in flashiness. To assess endpoints, we used two approaches. For long-term trends, we used a Spearman's rank correlation with statistical significance determined at the □=0.05 level. This non-parametric test does not assume normality or equal variance in the data, nor does it assume a linear trend. It does however, test for monotonic trends. For short-term trends, we examined the 10 year running average in the data over the past two decades (see Figures 1-5) and compared the average RBI from 1995-2004 with 2005-2014, where possible.

Status

Overall, the long-term and short-term trends in RBI varied by river. Over the short-term (past two decades), 9 of the 27 rivers had increasing RBI, 6 had decreasing trends, and 12 had unchanging trends (Table 1, Figures 1-5). Together, this suggests that 18 of the rivers, or 67%, were at or approaching desirable outcomes for flashiness. Furthermore, of the 7 rivers in the previous Great Lakes Indicator (previously known as SOLEC) report that are also included in this update, 5 have the exact same or similar status and 2 of the rivers had trends that have improved (changed from increasing to unchanging or decreasing). This data implies that flashiness has been improving over time as well.

However, it is also important to compare the short-term and long-term trends to see if there have been declines in the RBIs (Table 1). Most of the rivers exhibited similar trends in the long- (since 1950) and short- (since 1995) term– 18 of the 24 rivers with long-term data either didn't change or went from decreasing to unchanging. Three rivers (Maumee, Sandusky, Wanapitei) improved in the recent decade over the long-term trends (i.e., changed from unchanging to decreasing, or increasing to decreasing). Yet, 9 rivers had increasing trends with 3 of the 9 in particular, showing a deteriorating trend, i.e. RBI changed from decreasing or unchanging to increasing. These included the Muskegon (Michigan), Thames (Erie), and Cattaraugus (Erie) Rivers. In summary, most rivers are showing either stable or improving long-term trends, however; three rivers should be closely monitored for continued deteriorating trends.

Collated by lake, Lake Superior and Lake Huron were the only lakes with no rivers with increasing flashiness. Lake Erie and Ontario, in contrast, has the most number of rivers with increasing flashiness. However, in Lake Erie the two largest rivers that together made up 25% of the watershed area were exhibiting decreasing trends. Lake Michigan had 4 rivers with increasing flashiness, but the rivers with decreasing or unchanging flashiness made up a greater proportion of the watershed (27% vs 9%). Yet, any of the lakes with a substantial number of smaller rivers exhibiting increasing trends (i.e., Michigan and Erie) should be closely monitored in case these smaller rivers are showing changes that would take longer to detect in larger watersheds. In Lake Ontario two of the three rivers assessed exhibited increasing flashiness, which may suggest this lake should be monitored more closely for affects such as increased erosion and fine sediment export, decreased habitat, and displacement of native biological communities.

Some of the rivers assessed (i.e., the Maumee and Sandusky Rivers) are known to have increasing discharge. It is important to note that the RBI may not reflect the influence of increasing discharge if storm events have changed in character to become more dispersed and cover more days. The influence of higher discharges may be quite similar to higher flashiness, hence some rivers may have negative impacts, such as high fine sediment export and erosion, even with declining flashiness trends.

Linkages

Linkages to other sub- indicators in the indicator suite include:

- Precipitation Amounts in the Great Lakes Basin
- Water Quality in Tributaries
- Baseflow due to Groundwater

This sub- indicator also links directly to the other sub-indicators in the Watershed Impacts category, particularly Land Cover.

Comments from the Author(s)

This index offers an integrated perspective on changing hydrology in selected, and hopefully representative, major Great Lakes tributaries. It can be used to track the effects of, and guide decisions about, land use changes as they affect hydrology and its impact on riverine ecosystems. It utilizes basic flow data from the U.S. Geological Survey and Environment and Climate Change Canada, however, a number of rivers have patchy or incomplete data sets.

The R-B Index is easy to calculate from widely available data, and has come into widespread use. Possible range of values is from 0 to 2. Typical values are from 0.05 (very stable) to about 1.2 (very flashy). The RBI integrates all flow data, rather than picking a given percentile. It is believed to be the only flashiness index or index of hydrologic alteration which incorporates the temporal sequence of flows, a very important part of the concept of flashiness. The RBI is relatively stable from year-to-year (i.e. insensitive to weather effects), consequently it is relatively sensitive to longer-term trends.

For small streams, the hydrologic response is too rapid to be adequately resolved by daily flow data. For such systems, a version of the R-B Index based on hourly flow data can be used. However, index values derived from hourly data cannot be directly compared with those derived from daily data. Since the best use of the RBI is to track the hydrologic response of a stream through time, the index based on daily data is still useful for small streams, even if it under-represents the true flashiness. Most of the watersheds selected for this sub-indicator are large, and flows change relatively slowly, so daily data are adequate for calculating the RBI. Most of these streams cover a range of flashiness and land use, have long flow records, have a large watershed area, and stations are of a great distance (over 3 miles) from a dam and sufficiently upstream of the Great Lake it feeds. More information about the RBI, and some applications in the Midwestern United States, can be found in the paper cited below.

Given the observed increases in discharge in some of the rivers, this metric may be improved by further examining potential increases in long-term and short-term trends in discharge along with RBI across all rivers. This would further flush out potential reasons for trends in RBI as well as serve as a linkage to the effects of other sub-indicators such as precipitation and the watershed stressor index.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada	X					

6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

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Information Sources
Literature Citation:

Baker, D.B., R.P. Richards, T.T. Loftus, and J.K. Kramer. 2004. A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association 40(2): 503-522.
Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/ See Table 1 for station identification codes.

List of Tables

List of Figures

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Lake	River	Country	Latitude	Longitude	USGS or EC ID	HUC	Drainage Area (mi^2)	Drainage Area (km^2)	Any dams present?	Short term trend	Long term trend
Superior											
	Pic	Canada	48°46'26"	86°17'47"	02BB003		1649	4271	No	–	–
	Pigeon	Canada	48°00'44"	89°36'58"	4010500 02AA001	4010101	235	609	Yes	–	–
Michigan											
	Fox	US	44°31'43"	88°00'36"	40851385	4030204	6330	16395	No	–	–
	Muskegon	US	43°26'05"	85°39'55"	4122000/ 4121970	4060102	2313	5991	Yes	↑	↓
	Grand	US	42°57'52"	85°40'35"	4119000	4050006	4900	12691	Yes	↓	↓
	Escanaba	US	45°54'31"	87°12'49"	4059000	4030110	870	2253	Yes	–	↓
	Manistee	US	44°26'11"	85°41'55"	4124000	4060103	857	2220	Yes	↑	↑
	Pere Marquette	US	43°56'42"	86°16'43"	4122500	4060101	681	1764	No	↑	↑
	White	US	43°27'51"	86°13'57"	4122200	4060101	406	1052	No	↑	↑
Huron											
	Saginaw	US	43°25'19"	83°57'07"	4157005	4080206	6060	15695	No	↓	n/a
	French	Canada	46°04'6"	80°36'41"	02DD010		5367	13900	Yes	–	–
	Au Sable	US	44°36'46"	83°50'16"	4136900	4070007	1513	3919	Yes	–	–
	Wanapitei	Canada	46°20'44"	80°50'22"	02DB005		1218	3154	Yes	↓	–
	Magnetawan	Canada	45°46'23"	80°28'56"	02EA011		1096	2839	Yes	–	–
	Nottawasaga	Canada	44°29'6"	79°57'57"	02ED027		1037	2686	Yes	↓	n/a
	Maitland	Canada	43°53'12"	81°19'35"	02FE002		635	1644	Yes	–	–
	Thunder Bay	US	45°07'27"	83°38'08"	4133501	4070006	586	1518	Yes	–	↓
Erie											
	Maumee	US	41°30'00"	83°42'46"	4100009	4100009	6330	16395	Yes	↓	↑
	Thames	Canada	42°32'41"	81°58'2"	02GE003		1660	4299	Yes	↑	–
	Sandusky	US	41°18'28"	83°09'32"	4198000	4100011	1251	3240	Yes	↓	↑
	Raisin	US	41°57'38"	83°31'52"	4176500	4100002	1042	2699	Yes	–	–
	Grand (OH)	US	41°43'08"	81°13'41"	4212100	4110004	685	1774	No	–	–
	Cattaraugus	US	42°27'48"	78°56'03"	4213500	4120102	436	1129	Yes	↑	–
	Portage	US	41°26'58"	83°21'41"	4195500	4100010	428	1109	Yes	↑	↑
Ontario											
	Humber	Canada	43°48'40"	79°37'39"	02HC025		114	296	Yes	–	–
	Seneca	US	43°04'43"	76°38'44"	4235600	4140201	2815	7291	Yes	↑	↑
	Don	Canada	43°41'9"	79°21'41"	02HC024		123	319	Yes	↑	n/a

Table 1. Rivers used for the Tributary Flashiness sub-indicator. Short-term (two decades or less) and long-term (over two decades) trends are denoted as unchanging in green (-), increasing in red (↑), or decreasing in blue (↓). When a stream includes several HUC8s but does not comprise a complete HUC6, the HUC8 is listed that includes the gaging station from which the flow data are derived.

Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/

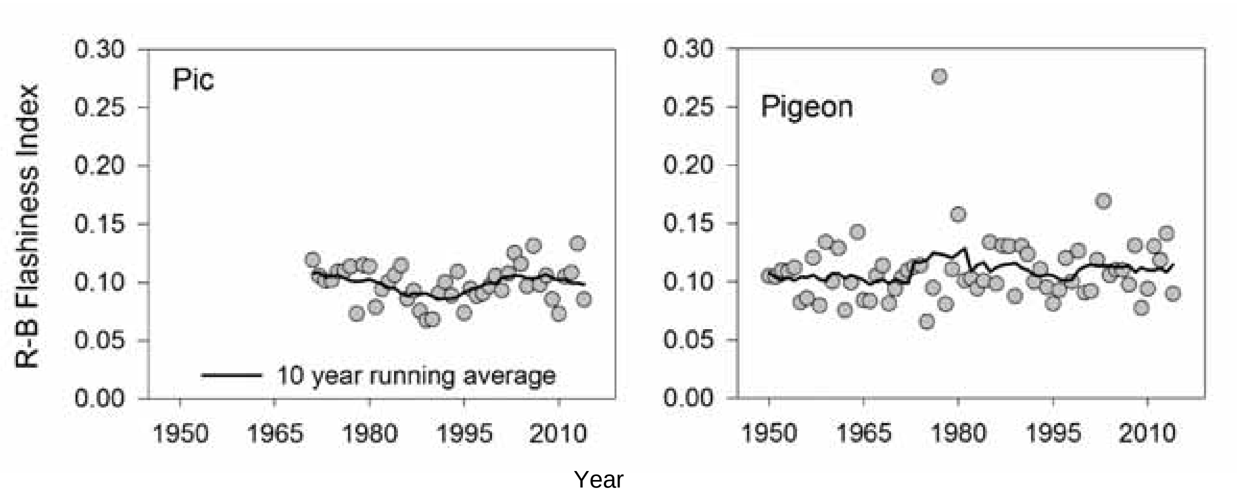

Figure 1. The R-B flashiness index for tributaries to Lake Superior. Note differences in y-axis scales. Solid lines indicate the 10 year running average.
Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/

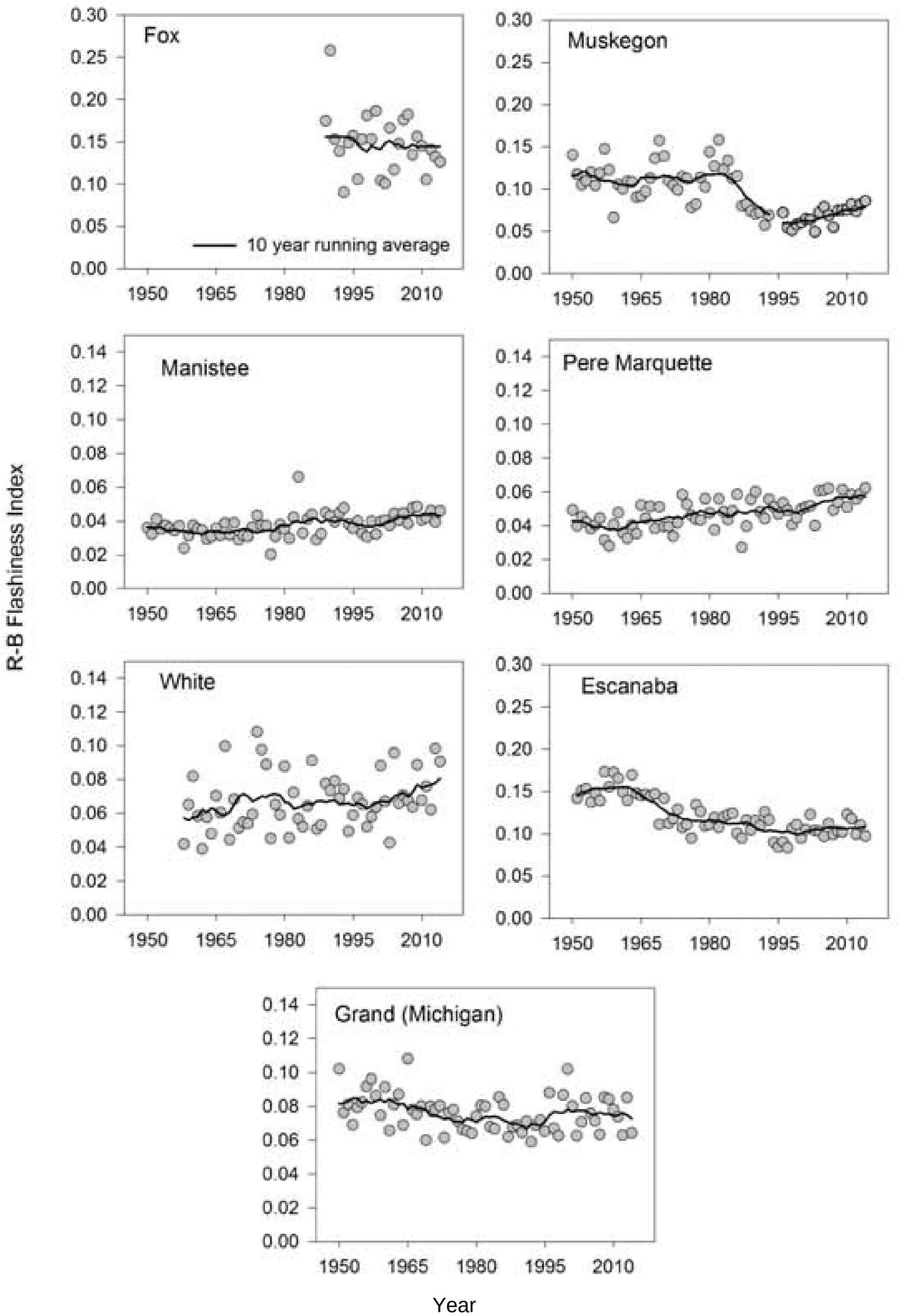

Figure 2. The R-B flashiness index for tributaries to Lake Michigan. Note differences in y-axis scales. Solid lines indicate the 10 year running average.
Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/

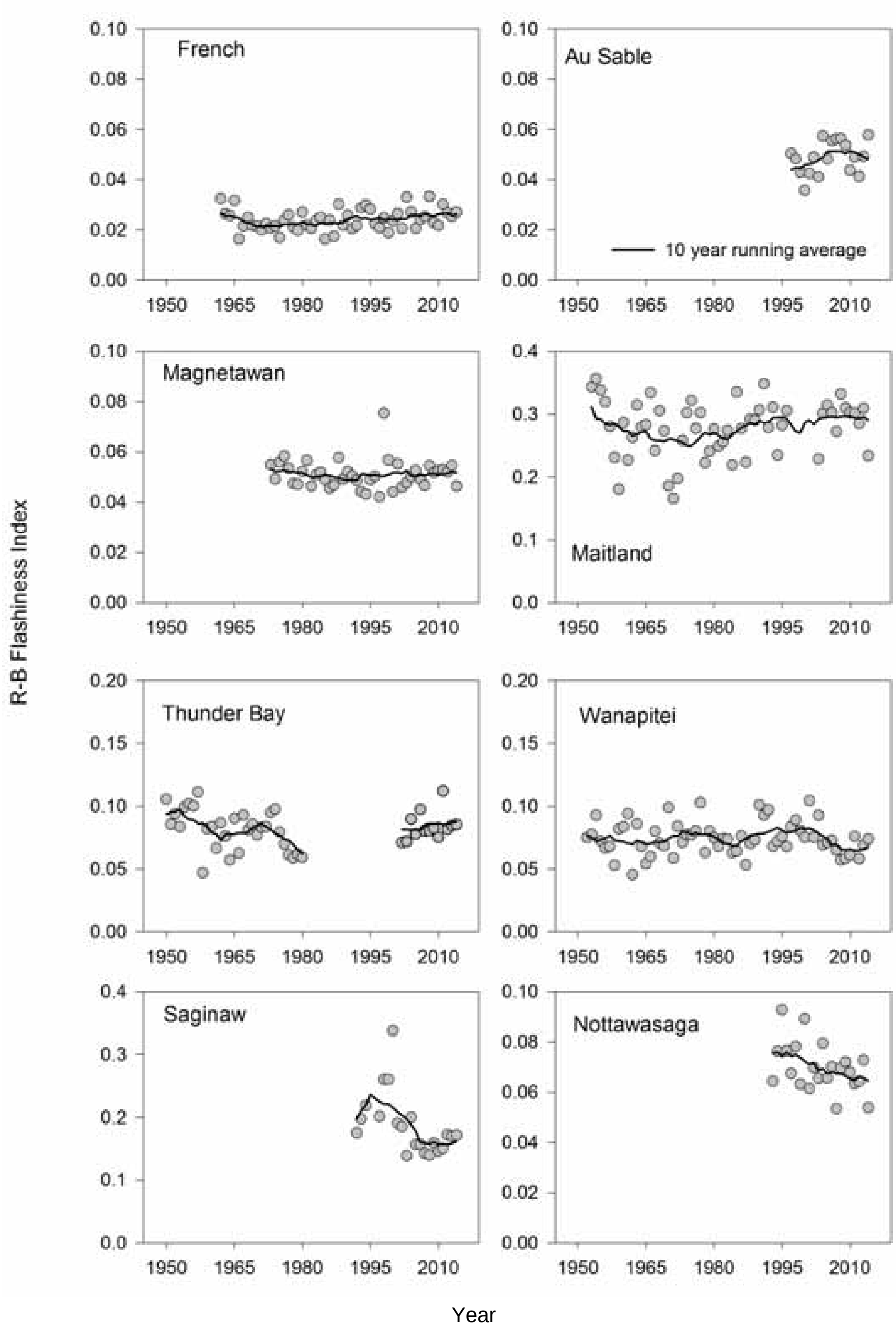

Figure 3. The R-B flashiness index for tributaries to Lake Huron. Note differences in y-axis scales. Solid lines indicate the 10 year running average.
Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/

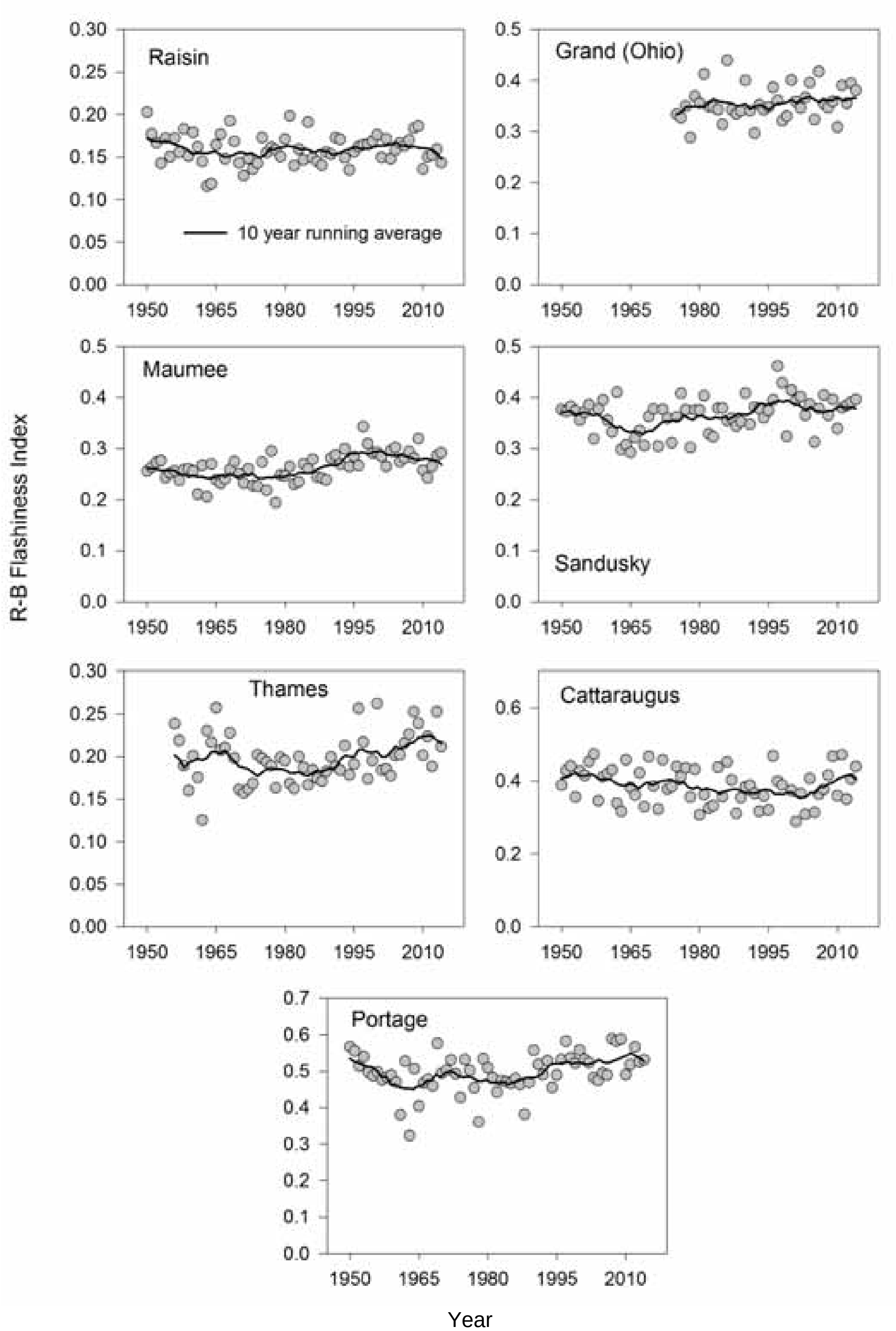

Figure 4. The R-B flashiness index for tributaries to Lake Erie. Note differences in y-axis scales. Solid lines indicate the 10 year running average.
Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/

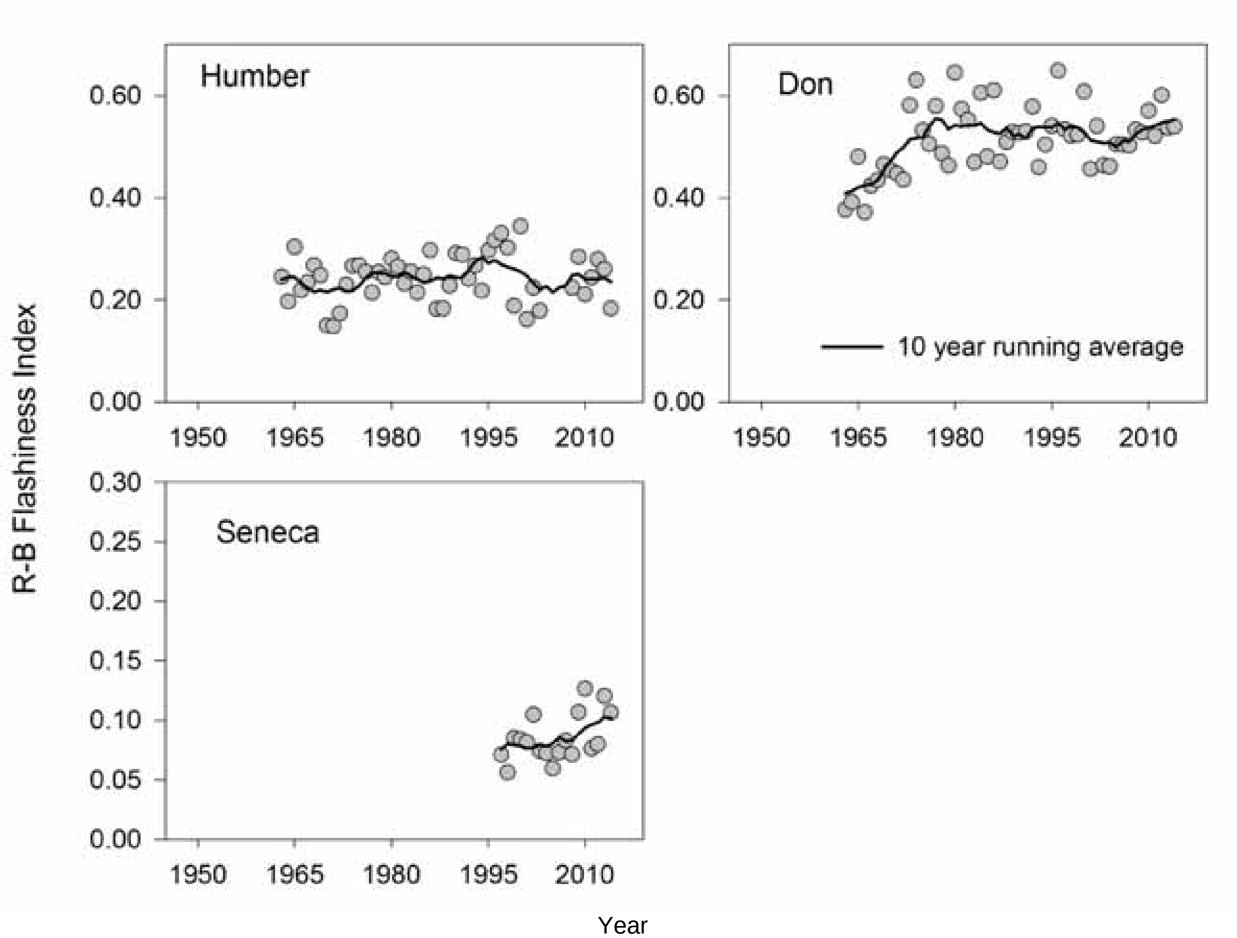

Figure 5. The R-B flashiness index for tributaries to Lake Ontario. Note differences in y-axis scales. Solid lines indicate the 10 year running average.
Data sources: http://waterdata.usgs.gov/nwis/rt or http://wateroffice.ec.gc.ca/

Sub-Indicator: Human Population

Overall Assessment
Trend: Increasing
Rationale: The long-term trend of the total population in the Great Lakes is increasing. The region has experienced 19.3% growth in population from 1971 to 2011. In the short term, there has been a 1.5% increase in total population from 2006 to 2011.

Lake-by-Lake Assessment

Lake Superior
Trend: Decreasing
Rationale: Over the long term, the Lake Superior basin has experienced a 3.7% decrease in population. The short-term trend indicates a 0.1% decrease in population from 2006 to 2011.

Lake Michigan
Trend: Increasing
Rationale: Population in the Lake Michigan basin has increased by 15.9% over the long term. In the short term, there has been a 0.9% increase in population.

Lake Huron
Trend: Increasing
Rationale: From 1971 to 2011, the population has increased by 34.1% in the Lake Huron basin with the Canadian side of the basin having over a 60% increase in population over the same time period. Short term growth has been significantly lower with the population increasing by 0.2% from 2006 to 2011.

Lake Erie
Trend: Increasing
Rationale: The long-term trend indicates a 2.7% increase in population from 1971 to 2011. Over the short term, there has been a 0.7% decrease in population.

Lake Ontario
Trend: Increasing
Rationale: From 1971 to 2011, the population has increased by 51.7% in the Lake Ontario basin. Over the short term, the population has increased by 5.7%. The population of the province of Ontario has also grown the most over the long term; the population increased 70% over the same 40-year period.

Sub-Indicator Purpose

- To assess the current human population trends in the Great Lakes region.

Ecosystem Objective

Humans are a key driving force in the overall impact on the environment in the Great Lakes Basin, and emphasis should be placed on ensuring humans are working, playing and living sustainably.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be from other substances, materials, or conditions that may negatively impact the chemical physical or biological integrity of the Waters of the Great Lakes." However, the human population has an impact on achieving all General Objectives of the Great Lakes Water Quality Agreement.

Ecological Condition

In this report, the Great Lakes Basin is defined as the watershed of the Great Lakes.

Measures

There are numerous approaches to determining population distribution in the Great Lakes Basin (Table 1). In the United States, population figures are not available by watershed as they are in Canada. The U.S. County Adjusted Ratio Approach was developed, which uses two levels of adjustment to U.S. county census data to determine the population in the Great Lakes Basin. A geographic information system was used to calculate the proportion of a county within the Great Lakes Basin. The first level of adjustment multiplies the county population by the proportion of the county within the Great Lakes Basin. This step assumes that population distribution across counties is uniform, which is not necessarily the case. To ensure a higher level of accuracy, a second level of adjustment is completed for counties with populations close to 40 000 people in the Lake Superior basin, and counties of 100 000 people in the four other lake basins. This second level adjustment involves examining the county to ensure that major population centres have been accurately represented in the population calculations. Adjustments were also necessary in the Chicago Metropolitan Area (Cook, DuPage, Lake and Will counties) to reflect the 6.4 million that draw drinking water from Lake Michigan. Only 4.2% of Cook County is located within the Lake Michigan basin, which would result in a first level adjusted population of approximately 220 000 people. However, the second level adjusted population of 4.9 million people in Cook County more accurately reflects the county's impact on the basin. In total, 21 counties of 653 had ratios adjusted to more accurately reflect their population calculations (Table 2).

Adjustments since 2011 Reporting Cycle

A few adjustments have been made to the methodology since the 2011 reporting cycle. In previous reports, U.S. intercensal data was used as it would align with Canadian census years. In this report, U.S. census data has been used to improve accuracy of population figures. However, this results in an imperfect alignment of census data since U.S. census data is collected a year before Canadian census data. The lengths of the census cycles are also different; U.S. census data is collected every 10 years, while Canadian census data is collected every 5 years. This report follows the shorter Canadian census cycle; data from 1971 represents 1970 U.S. census data and 1971 Canadian census data (Table 3). Also, a larger number of counties were reviewed in preparation for this report to determine if a second level of adjustment was warranted to ensure greater accuracy of population values. Previously, only counties that reached a population threshold of 100 000 people or greater in the Lake Erie, Huron, Michigan and Ontario basins, or 40 000 or greater in the Lake Superior basin in 1971 would be reviewed for a second level of adjustment. In this report, any county that reached a population of 100 000 people or greater from 1971 to 2011, or 40 000 or greater in the Lake Superior basin, was reviewed for a second level of adjustment. As a result, 34 more counties were reviewed in this report than in the previous indicator report. Of these 34, nine counties had ratios adjusted to better reflect the amount of their population residing in the Great Lakes Basin.

Total Populations in the Great Lakes Region (Ontario and Eight Great Lakes States)

In 2011, the Great Lakes region was home to about 39 385 438 people (Table 4); 25.8% reside in Canada while 74.2% reside in the United States. The Lake Ontario basin continued to experience the largest growth. Population in the Lake Michigan and Lake Huron basins stayed relatively static in the short term (2006-2011) while population in Lake Superior and Lake Erie experienced a slight decline. Of the Great Lakes region, the Province of Ontario continued to exhibit the largest amounts of growth with a 6.0% increase in population from 2006 to 2011. From 1971 to 2011, the population has increased by 51.7% in the Lake Ontario basin. The population of the Province of Ontario has also grown the most over the long term; the population increased 70.1% from 1971 to 2011. Furthermore, 87% of Ontario's population resides in the Great Lakes Basin (Figure 1).

Lake Basins

The total population in the Great Lakes Basin has increased since 1971 (Figure 2), though population growth rates have varied across the years (Figure 3).

The population in the Lake Superior basin is significantly smaller than in the other basins; 1.5% of the total population in the Great Lakes Region live in the Lake Superior basin. Furthermore, it is the only basin in the Great Lakes where both the short and long term trends indicate a decline in population (Figure 3).
The Lake Michigan basin is home to 33.8% of the total Great Lakes population, the most populated basin of all the Great Lakes. The population in this basin reflects population adjustments as well as the 6.4 million people in Cook, DuPage, Lake and Will counties that draw drinking water from Lake Michigan. This basin is completely contained within the United States (Figure 4); more specifically, the states of Illinois, Indiana, Michigan and Wisconsin are located in the Lake Michigan basin.

Lake Huron's population has remained relatively static as population growth from 2006 was 0.2%. On average, the population in the Lake Huron basin has made up roughly 7.7% of the total population in the Great Lakes Basin (Figure 4). Over time, the proportion of the population living on the Canadian side of the basin has increased. A 40-year span yielded an 8.1% increase in the proportion of Canadians living in the Lake Huron basin.

In the Lake Erie basin, population has remained fairly stable and is the second most populated of the Great Lakes basins. The greatest population change occurred from 1991 to 1996 with a population increase of 3.0%. Nearly 30.9% of the Great Lakes population resides in the basin (Figure 4) – 25.3% of Lake Erie's population lived in the U.S. basin and 5.6% lived in the Canadian basin (Figure 5).

The Lake Ontario basin has consistently experienced the greatest amount of growth in the Great Lakes region. The population change in the Lake Ontario basin since 1971 has exhibited an average growth of 5.3% (per 5-year period) This lake basin has been home to the greatest proportion of Canadians living in the Great Lakes region from 1971-2011; 18.8% of the total population in the Great Lakes region are Canadians that live in the Lake Ontario basin (Figure 4).

Linkages

Humans are a key driving force in the overall impact on the environment. Emphasis should be placed on ensuring humans are working, playing and living sustainably. Further analysis in population trends, urban sprawl and consumption rates can help understand and calculate the different impacts humans can have on the environment. As human population continues to grow, cities will expand outwards, resulting in the loss of agricultural and natural lands. Associated impacts of urban growth include an increase in air pollution through gridlock, fragmentation of habitats and greater strains on water systems for drinking water. This sub-indicator is essential in identifying areas within the Great Lakes Basin that may be facing increased environmental pressures as a result of large amounts of population growth. In the Greater Toronto Area, located on the northwestern shores of Lake Ontario, urban areas have grown roughly 20% from 1985 to 1995 and roughly 15% from 1995 to 2005 (Furberg & Ban, 2012). Areas of high population can be identified on the northwestern shores of Lake Ontario, the southwestern tip of Lake Michigan and along the northern and western shores of Lake Erie/St. Clair-Detroit River Ecosystem (Figure 6). This is contrasted by the Lake Huron and Lake Superior basins that have very few large population centres. Rapid population growth can result in a great amount of stress exerted on the environment due to inadequate transportation systems and demands for infrastructure (Mikovits, Rauch & Kleidorfer, 2014; Addie, 2013).

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada		X				
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Acknowledgments

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Source: Government of Ontario, Statistics Canada, U.S. Census Bureau

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Approach	Population Estimates (2011)			
	Ontario	**Quebec**	**Eight Great Lakes States**	**Total**
Great Lakes and St. Lawrence River Region – All of Ontario, Quebec and Eight Great Lakes States	12,851,821	7,903,001	83,805,970	104,560,792
Great Lakes Region – All of Ontario and All Eight Great Lakes States	12,851,821	-	83,805,970	96,657,791
Great Lakes Basin – Canadian population in Great Lakes Basin and population in U.S. Counties partially or wholly contained within basin	11,234,177	-	37,681,537	48,915,714
Great Lakes Basin – Canadian population in Great Lakes Basin and population in U.S. using County Adjusted Ratio Approach (without Chicago Metropolitan Area)	11,234,177	-	21,785,962	33,020,139
Great Lakes Basin – Canadian population in Great Lakes Basin and population in U.S. using County Adjusted Ratio Approach (with Chicago Metropolitan Area), used in this report	**11,234,177**	-	**28,151,261**	**39,385,438**

Table 1. Population Estimate Approaches (2011)
Source: Statistics Canada, U.S. Census Bureau

County	Basin – Original Ratio	Basin – Adjusted Ratio	Rationale
Cook, IL	Lake Michigan – 4.24%	Lake Michigan – 95%	Population extracts drinking water from Lake Michigan
DuPage, IL	Lake Michigan – 0%	Lake Michigan – 50%	
Lake, IL	Lake Michigan - 11.51%	Lake Michigan – 90%	
Will, IL	Lake Michigan – 0%	Lake Michigan – 50%	
LaPorte, IN	Lake Michigan 24.09%	Lake Michigan – 35%	Accounting for Michigan City
St. Joseph, IN	Lake Michigan – 39.68%	Lake Michigan – 70%	Accounting for South Bend and Mishawaka
Jackson, MI	Lake Erie – 16.24% Lake Michigan – 83.76%	Lake Erie – 7% Lake Michigan – 93%	Larger population centres in Michigan basin than Erie
Marquette, MI	Lake Michigan – 55.97% Lake Superior – 44.03%	Lake Michigan – 45% Lake Superior – 55%	Larger population centres in Superior basin than Michigan
Oakland, MI	Lake Erie – 79.65% Lake Huron – 20.35%	Lake Erie – 90% Lake Huron – 10%	Larger population centres in Erie basin than Huron
Saginaw, MI	Lake Huron – 97.81% Lake Michigan – 2.19%	Lake Huron – 99% Lake Michigan – 1%	Larger population centres in Huron basin than Michigan
St. Louis, MN	Lake Superior – 49.27%	Lake Superior – 90%	Accounting for Duluth
Chemung, NY	Lake Ontario – 9.10%	Lake Ontario – 3%	Few population centres in basin
Jefferson, NY	Lake Ontario – 57.8%	Lake Ontario – 75%	Numerous population centres in basin
Onondaga, NY	Lake Ontario – 93.07%	Lake Ontario – 98%	Numerous population centres in basin
Steuben, NY	Lake Ontario – 12.75%	Lake Ontario – 5%	Few population centres in basin
Tompkins, NY	Lake Ontario – 81.70%	Lake Ontario – 92%	Numerous population centres in basin
Erie, PA	Lake Erie – 52.89%	Lake Erie – 80%	Accounting for Erie
Douglas, WI	Lake Superior – 57%	Lake Superior – 80%	Accounting for Superior
Kenosha, WI	Lake Michigan – 22.8%	Lake Michigan – 75%	Accounting for Kenosha
Racine, WI	Lake Michigan – 47.77%	Lake Michigan – 75%	Accounting for Racine
Waukesha, WI	Lake Michigan – 7.72%	Lake Michigan – 15%	Accounting for Menomonee Falls

Table 2. Counties requiring second level ratio adjustment to better reflect population numbers in basin
Source: Government of Ontario, U.S. Census Bureau

Population Data (1970/1971 – 2010/2011)

Canada	1971	1976	1981	1986	1991	1996	2001	2006	2011
U.S.	1970	1976*	1980	1986*	1990	1996*	2000	2006*	2010

*Intercensal population estimates

Table 3. Years of Intercensal and Census Data
Source: Statistics Canada, U.S Census Bureau

Lake Basin	1971	1976	1981	1986	1991	1996	2001	2006	2011
Superior	603,507	621,886	618,958	585,591	586,389	584,622	585,630	581,722	581,093
Michigan	11,497,315	11,718,373	11,796,578	11,857,716	12,042,678	12,561,047	13,101,190	13,211,346	13,325,057
Huron	2,332,911	2,519,332	2,612,775	2,617,271	2,776,130	2,917,142	3,018,271	3,123,897	3,129,153
Erie	11,863,069	11,829,173	11,784,483	11,559,464	11,741,188	12,098,730	12,258,143	12,266,000	12,180,736
Ontario	6,703,266	7,036,916	7,241,352	7,570,122	8,213,685	8,653,646	9,121,919	9,621,761	10,169,399
Total	**33,000,068**	**33,725,680**	**34,054,145**	**34,190,163**	**35,360,070**	**36,815,187**	**38,085,152**	**38,804,726**	**39,385,438**

Table 4. Total Population in each Great Lakes Basin
Source: Statistics Canada, U.S. Census Bureau

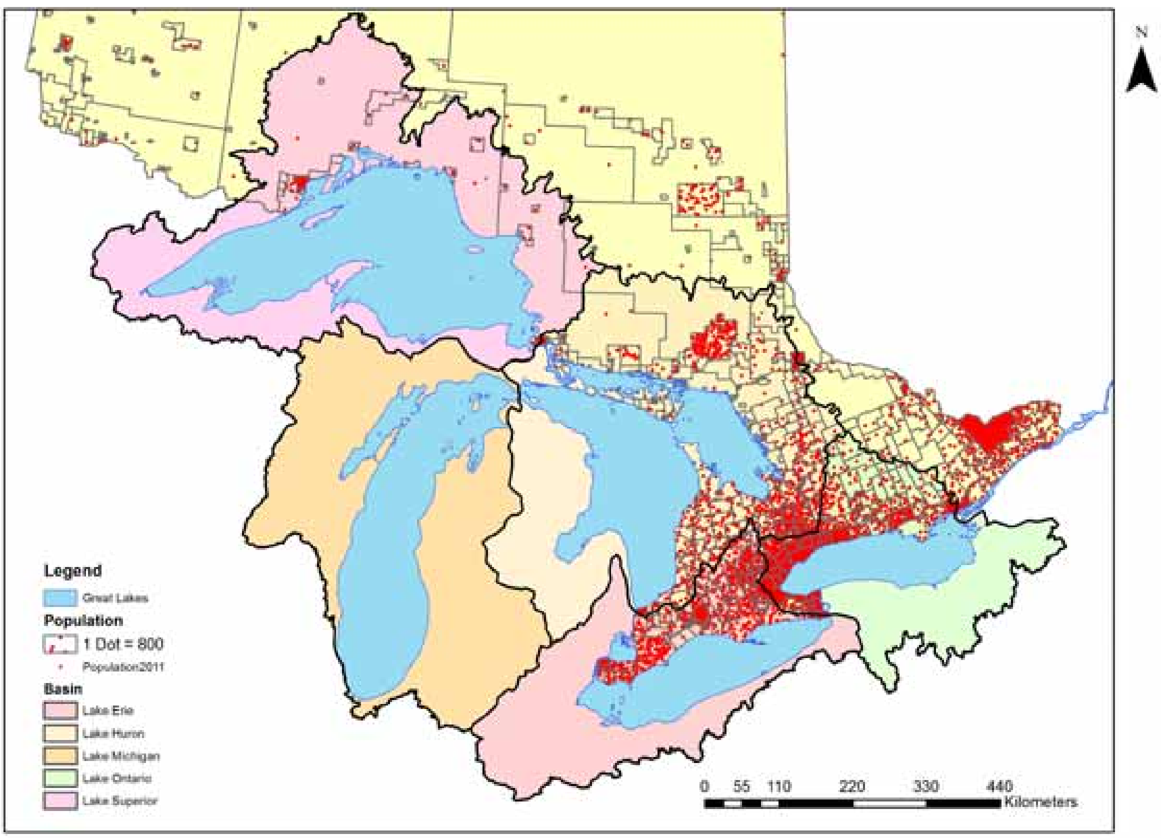

Figure 1. Population in Ontario by Census Subdivision (2011)
Source: Government of Ontario, Statistics Canada

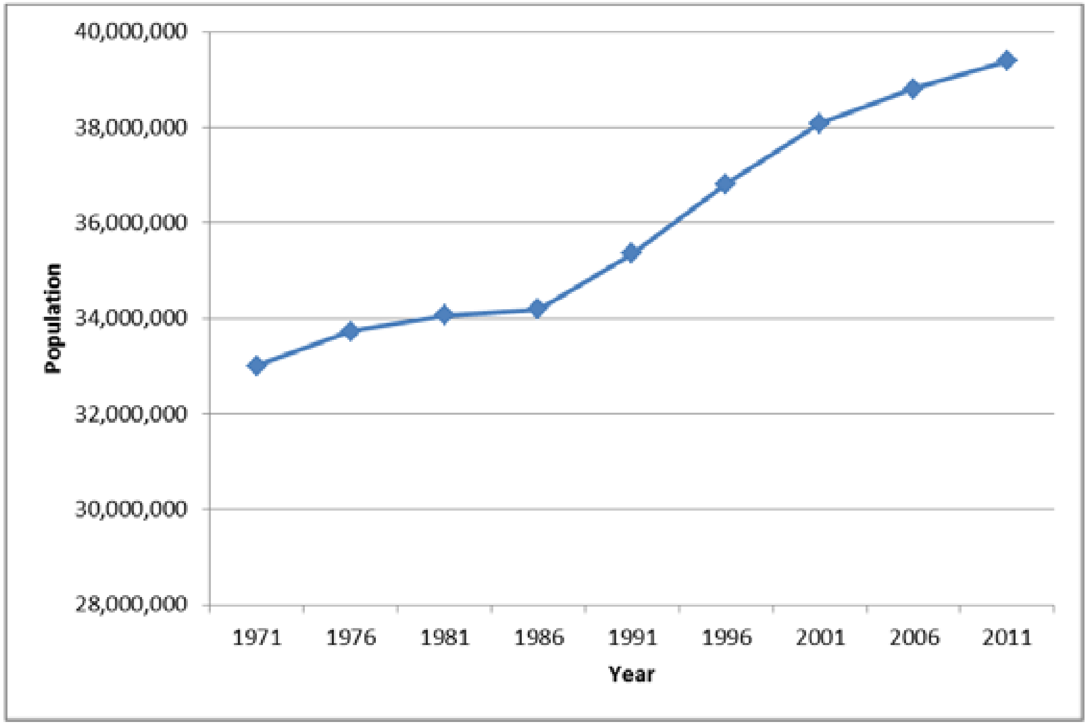

Figure 2. Total Population in the Great Lakes Region (1971-2011)
Source: Statistics Canada, U.S. Census Bureau

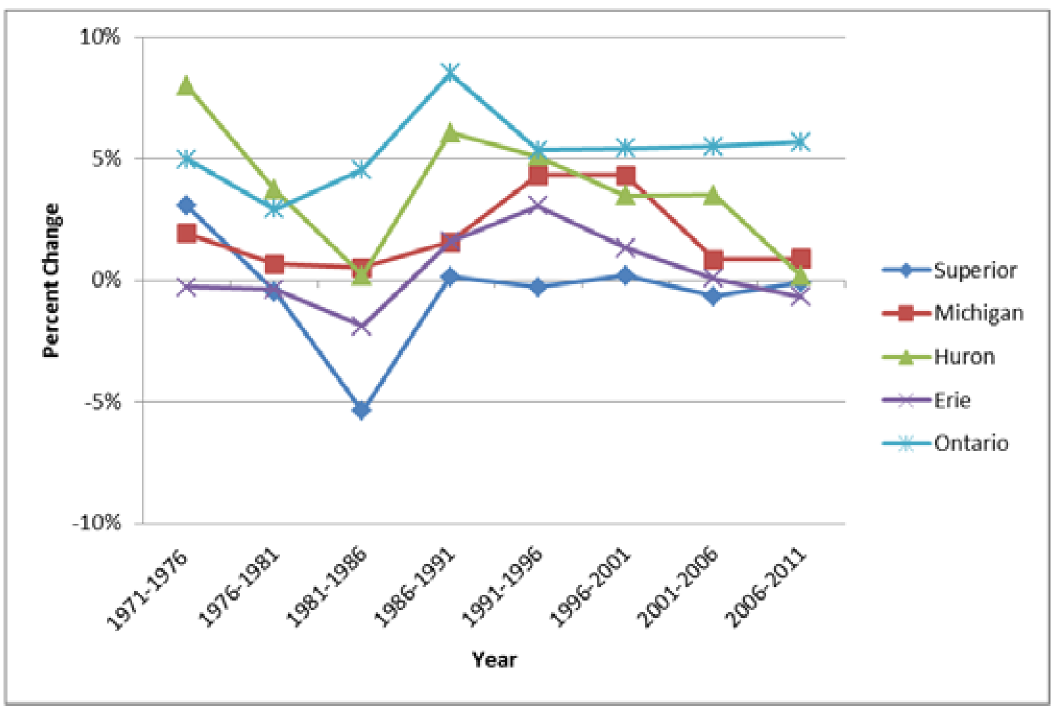

Figure 3. Population Change (%) in each Great Lakes Basin from 1971-2011
Source: Statistics Canada, U.S. Census Bureau

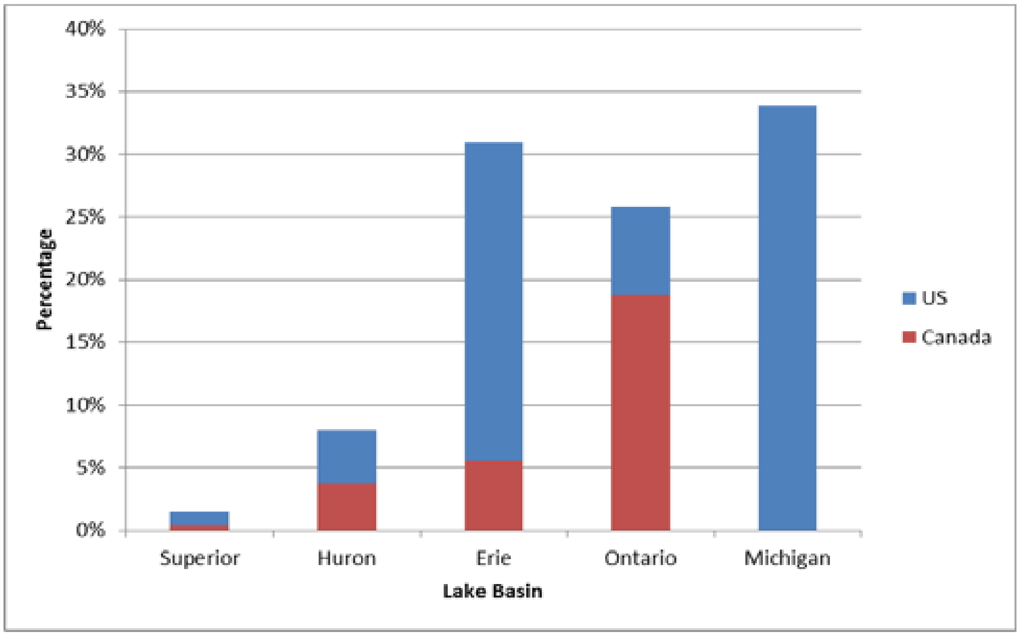

Figure 4. Proportion of Total Great Lakes Population by Canadian and U.S. Lake Basin (2011)
Source: Statistics Canada, U.S. Census Bureau

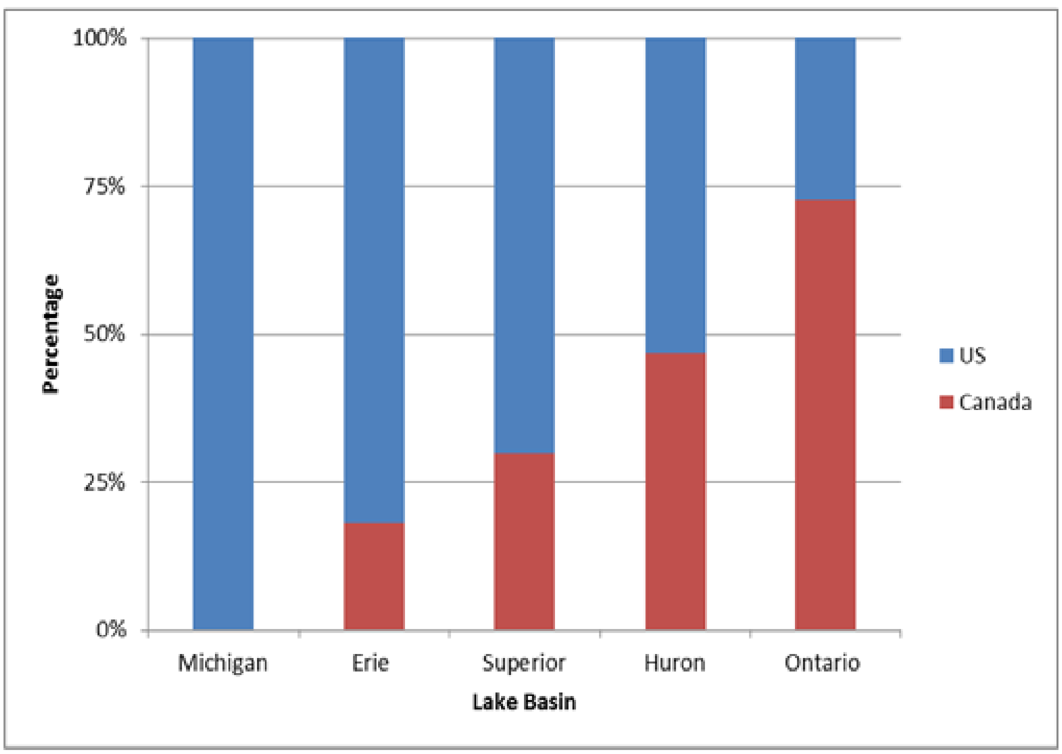

Figure 5. Proportion of Canadian and U.S. Population Located in each Great Lakes Basin (2011)
Source: Statistics Canada, U.S. Census Bureau

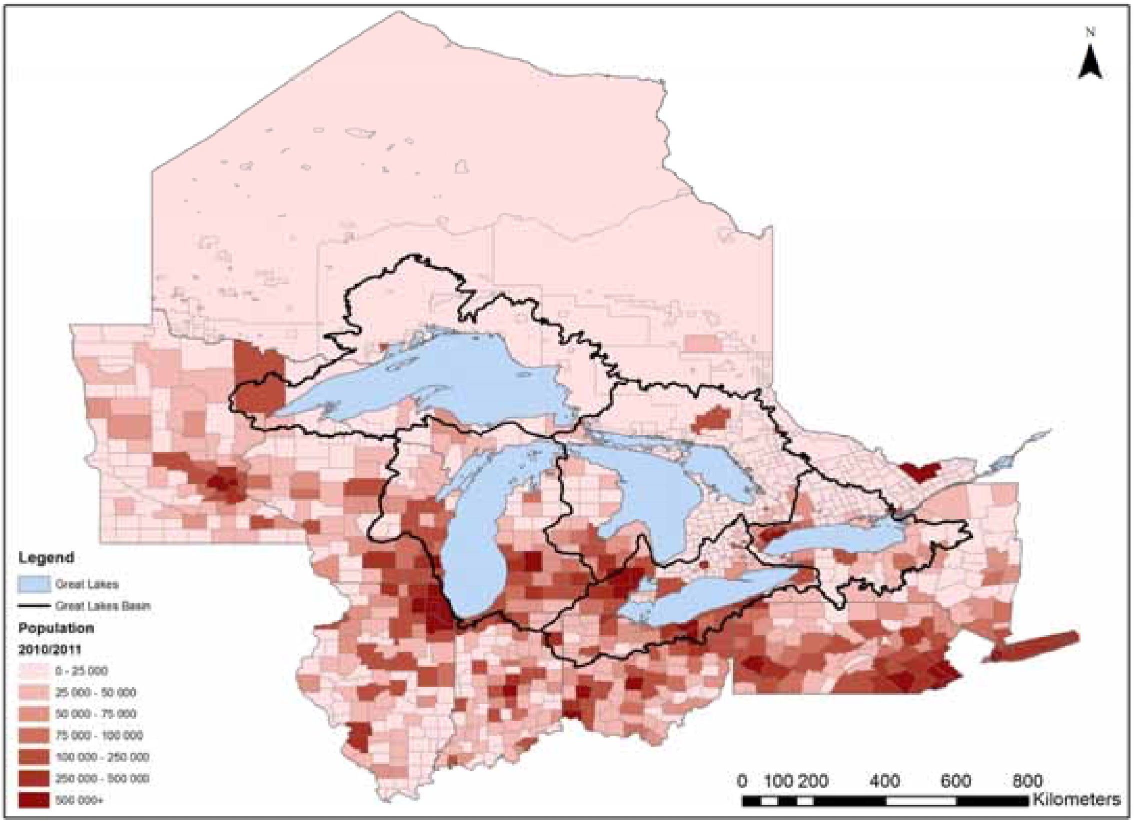

Figure 6. Population by County or Census Subdivision in the Great Lakes Basin (2010/2011)
Source: Government of Ontario, Statistics Canada, U.S. Census Bureau

Sub-Indicator: Precipitation Amounts in the Great Lakes Basin

Overall Assessment
Trend: Increasing
Rationale: The annual precipitation anomaly (the departure from the 1961–1990 base-period average) for the period of study (1948–2015) for Canadian stations within the Great Lakes Basin displays a statistically significant (at the 0.05 level) increasing trend of 10.9% over the study period. While the 2015 anomaly is only 0.13% (above the 1961–1990 base-period average), a better measurement of the "current status" of the sub-indicator (due to the interannual variability of precipitation amounts is the average of the 5 previous years (2011–2015) which is 6.5% above the base-period average. In summary: the annual amount of precipitation in the Great Lakes Basin is above the long-term average and displays an increasing trend.

Lake-by-Lake Assessment
Individual lake basin assessments were not prepared for this report.

Sub-Indicator Purpose
The purpose of this sub-indicator is to assess the amount of precipitation falling within the Great Lakes Basin, both annually and seasonally, and to infer the potential impact on ecological components of the Great Lakes Basin that varying precipitation amounts due to climate change will have.

Ecosystem Objective
- To maintain the ecosystem of the Great Lakes and surrounding region by allowing the hydrologic system of the Great Lakes Basin to continue to follow historic patterns. Changes to the frequency, seasonal distribution, or magnitude of precipitation will impact the hydrological system of the entire Great Lakes Basin, having effects such as altering water levels or changing the rates and patterns of storm runoff – directly influencing the distribution of pollutants, nutrients that support algae/bacteria growth, and invasive species.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes." This sub-indicator also relates to all of the General Objectives in the Agreement as this sub-indicator directly applies to them all.

Ecological Condition
The annual precipitation anomaly for 1948–2015 is shown in Figure 1. It displays a statistically significant (at the 0.05 level) increasing trend of 10.9% over the period. An increasing trend of 6.2% was found for the 30-year period from 1986–2015; however, this trend was found to be statistically insignificant which means the trend cannot be confidently discerned from the variability in the data signal over this time period. While no conclusions can be made over the 30-year period alone, this sub-indicator shows an increasing trend over the longer period (1948–2015).

The precipitation anomaly can also be analyzed on a seasonal basis with seasons being defined as winter (December, January, February); spring (March, April, May); summer (June, July, August); and autumn (September, October, November). The 9-year running means of the seasonal precipitation anomalies for the Great Lakes Basin over the period of record (1948–2015) are shown in Figure 2. Autumn was found to have a statistically significant increasing trend of 15.2% over the study period while winter, spring, and summer each displayed statistically insignificant but increasing trends of 7.8%, 11.7%, and 8.9%, respectively.

While 2015 showed only a slight positive anomaly, the number and magnitude of positive anomalies is generally larger towards the end of the period (1948–2015). Five of the 10 years showing the most total annual precipitation during the entire study period, shown in Table 1, have occurred since 2000 with all 10 occurring in the later-half of the period. The largest positive precipitation anomaly (21.5%) was recorded in 2008 and the largest negative (-18.3%) in 1963.

In the next century, annual precipitation is expected to increase by up to 20% across the Great Lakes Basin with greater annual precipitation projected for Lake Superior (Logfren et al. 2002; McKenney et al. 2011). Lake-effect precipitation continues to be observed in future projections and is expected to increase due to decreasing ice cover on lakes (Burnett et al. 2003; Notaro et al. 2014). The form of precipitation is also expected to change, with more precipitation falling as rain and freezing rain and less as snow. Shifts in the timing of precipitation are expected, where rainfall will increase in the spring but decrease in the summer (Kling et al. 2003; Hayhoe et al. 2010).

Linkages

An increase in global temperature will enhance the ability of the atmosphere to store and transport water vapour which will affect storm evolution and geographical distribution. In any one region, this may result in both the amount and type of precipitation varying at rates greater than those predicted by local climate change alone. This could result in significant changes in both precipitation event frequency and magnitude in the Great Lakes Basin, which will affect the hydrological system of the entire basin. The impacts of such changes would be numerous; some examples specific to an increase in precipitation event magnitude include crop loss due to storm-damage, erosion, and flooding.

Precipitation Amounts in the Great Lakes Basin links directly to almost all other sub-indicators in the suite as precipitation events are a driving force in hydrology, nutrient and toxin distribution, and shoreline and wetland health. Some specific examples include:

- Beach Advisories—Runoff following precipitation events and related bacteria loading is a major concern to beach safety
- Coastal Wetland Sub-indicators (Coastal Wetland Amphibians, Coastal Wetland Birds, Coastal Wetland Fish, Coastal Wetland Invertebrates, Coastal Wetland Plants, Coastal Wetland: Extent and Composition)—Change in precipitation event frequency or intensity will have a direct impact on coastal wetlands
- Tributary Flashiness—Precipitation events, especially extreme ones, lead to tributary flashiness

This sub-indicator also links directly to the other sub-indicators in the Watershed Impacts and Climate Trends category.

- Precipitation Amounts in the Great Lakes Basin directly contributes to all 14 Beneficial Use Impairments laid out in Annex 1 of the 2012 Great Lakes Water Quality Agreement:
- Restrictions on fish and wildlife consumption
- Tainting of fish and wildlife flavour
- Degradation of fish and wildlife populations
- Fish tumours or other deformities
- Bird or animal deformities or reproduction problems
- Degradation of benthos
- Restrictions on dredging activities
- Eutrophication or undesirable algae
- Restrictions on drinking water consumption, or taste and odour problems
- Beach closings
- Degradation of aesthetics
- Added costs to agriculture or industry
- Degradation of phytoplankton and zooplankton populations
- Loss of fish and wildlife habitat

Comments from the Author(s)

Analysis was performed using the 147 grid-points of the Canadian Gridded Temperature and Precipitation Anomalies Dataset (CANGRD) that fell within the definition of the Great Lakes Basin. The CANGRD is based on the Adjusted and Homogenized Canadian Climate Data (AHCCD) dataset. More information about the precipitation data used in CANGRD can be found in Mekis and Vincent (2011). Also, see the Canadian Environmental Sustainability Indicators (CESI) – Precipitation Change in Canada indicator.

Trend values were estimated using the method of Sen (1968). For a computed trend to be deemed statistically significant it must be large enough to stand out from the variability of the data. Statistical significance was computed using Kendall's test (Kendall 1955) at the 0.05 level. While trends deemed statistically insignificant may still be true, there is also a tangible chance that they instead represent cyclic variations in the data.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin		x				
5. Data obtained from sources within the U.S. are comparable to those from Canada						x
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					
Clarifying Notes: No US data were available for this reporting cycle.						

Acknowledgments

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Contributors:
Lucie Vincent, Environment and Climate Change Canada

Information Sources

The Canadian Gridded Temperature and Precipitation Anomalies Dataset (CANGRD):
http://open.canada.ca/data/en/dataset/3d4b68a5-13bc-48bb-ad10-801128aa6604

The Adjusted and Homogenized Canadian Climate Data (AHCCD) dataset:
http://open.canada.ca/data/en/dataset/9c4ebc00-3ea4-4fe0-8bf2-66cfe1cddd1d

The Canadian Environmental Sustainability Indicators (CESI) – Precipitation Change in Canada:
https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=En&n=ACD78526-1

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Rank	Year	% Anomaly
1	2008	21.5
2	1985	18.1
3	2013	17.9
4	2014	16.0
5	1996	15.3
6	1977	11.2
7	2004	10.2
8	1995	10.0
9	1988	9.9
10	2001	9.3

Table 1. The 10 years showing the most annual precipitation (in % anomaly above the 1961–1990 mean) in the Great Lakes Basin.
Source: Environment and Climate Change Canada

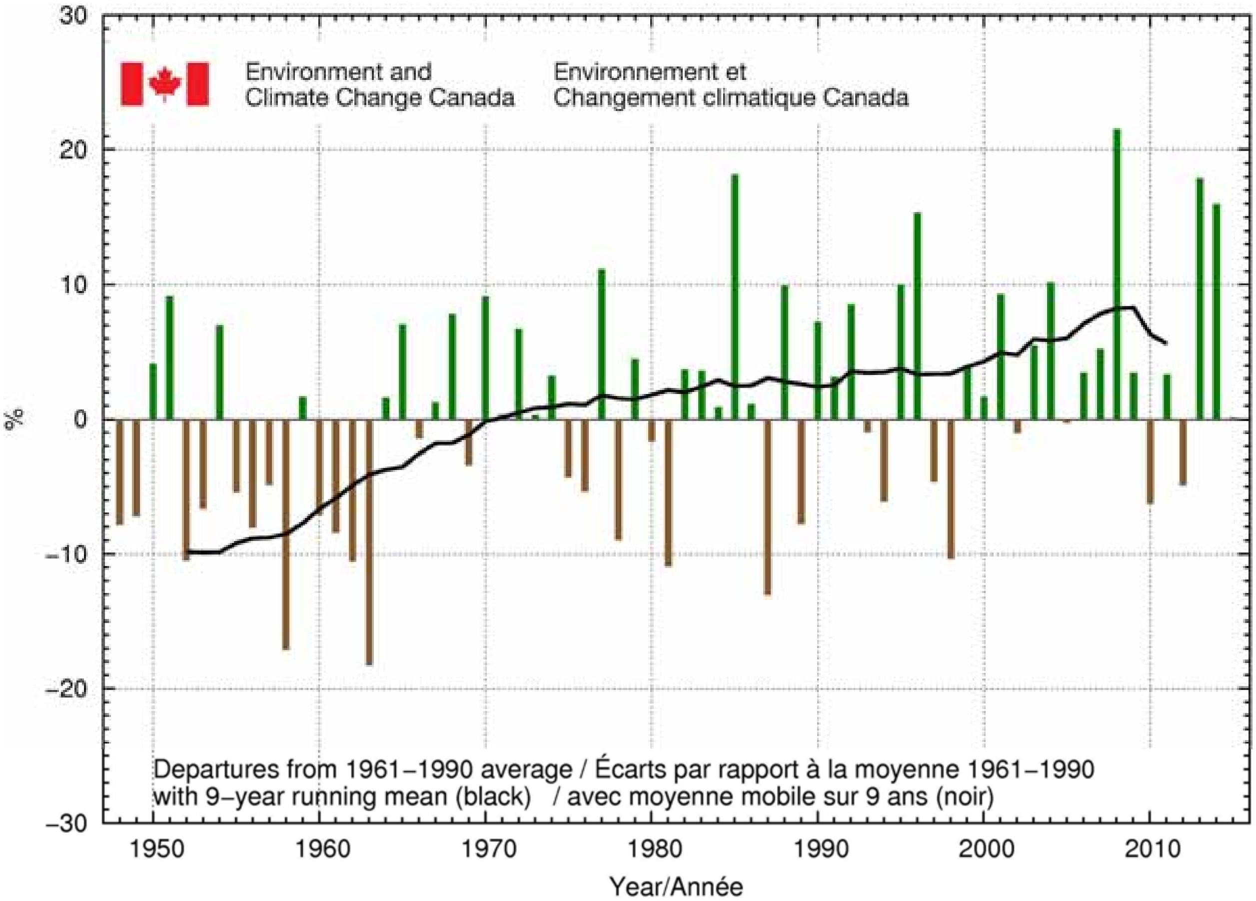

Figure 1. Annual precipitation anomaly (departure from the 1961–1990 mean) for the Great Lakes Basin over the period 1948–2015. Note that the mean for a particular 9-year interval is centred on the middle year, meaning the first year for which the running mean can be defined is 1952 and the last is 2011.
Source: Environment and Climate Change Canada

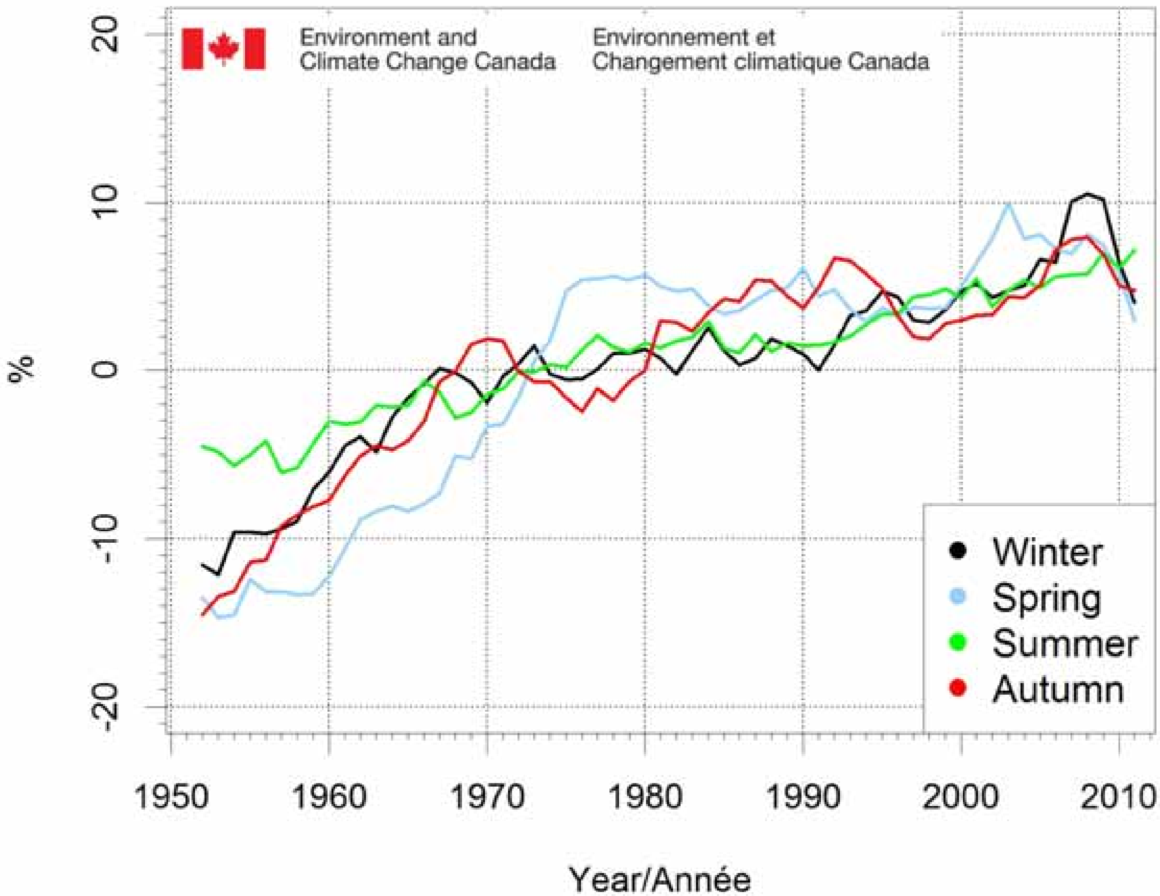

Figure 2. 9-year running means of seasonal precipitation anomalies (from the 1961-1990 seasonal means) for the Great Lakes Basin over the period of record (1948–2015). Note that the mean for a particular 9-year interval is centred on the middle year, meaning the first year for which the running mean can be defined is 1952 and the last is 2011.
Source: Environment and Climate Change Canada

Sub-Indicator: Surface Water Temperature

Overall Assessment
Trend: Increasing
Rationale: Based on open-lake surface water temperature measurements, summer (July-September) water temperatures are increasing at statistically significant rates in most of the Great Lakes. The rate on Lake Erie is increasing but not at a statistically significant rate. Insufficient data exists to make a determination regarding Lake Ontario. Additionally, based on the date of the onset of summer stratification from NDBC data, all of the upper lakes (Superior, Michigan, and Huron) are stratifying earlier and are thus classified as increasing. There is insufficient data from US and Canadian sources to evaluate onset of stratification dates in Lake Erie because buoys are deployed later than the onset of stratification in most years. Data from the National Data Buoy Center (NDBC), which is part of the National Oceanic and Atmospheric Administration, and Environment and Climate Change Canada (ECCC) is used in this report (Figure 1). These data are available for most lakes since 1980 (excepting Lake Ontario) and no other reliable, consistent datasets are available for evaluating these trends over a longer period. Verified data from 2015 were not available at the time of preparation of this report. All of the data are from open-water buoys, so trends noted here do not necessarily reflect trends in coastal waters or interconnecting channels.

Lake-by-Lake Assessment
Lake Superior
Trend: Increasing
Rationale: Linear regression of data from 1979-2014 suggest that the summer surface water temperature on Lake Superior has increased at a rate of approximately 0.8±0.4C/decade over the period of interest. Warming rates measured at three separate buoys are statistically consistent with each other, though the rates appear slightly elevated in the eastern part of the lake. Linear regression of data from 1979-2014 suggest that the onset of summer stratification in Lake Superior has become earlier over the period of interest at a rate of approximately 4±2 days per decade. The moorings in the western and central parts of the lake show somewhat reduced rates.

Lake Michigan
Trend: Increasing
Rationale: Linear regression of data from 1980-2014 suggest that the summer surface water temperature on Lake Michigan has increased at a rate of approximately 0.5±0.2C/decade over the period of interest. Warming rates measured at two separate buoys are statistically consistent with each other.
Linear regression of data from 1980-2014 suggest that the onset of summer stratification in Lake Michigan has become earlier over the period of interest at a rate of approximately 5±2 days per decade. The rate is consistent between two NOAA NDBC buoys.

Lake Huron
Trend: Increasing
Rationale: Linear regression of data from 1980-2014 suggest that the summer surface water temperature on Lake Huron has increased at a rate of approximately 0.7±0.3C/decade over the period of interest. Warming rates measured at two separate buoys are statistically consistent with each other. Linear regression of data from 1980-2014 suggest that the onset of summer stratification in Lake Huron has become earlier over the period of interest at a rate of approximately 5±2 days per decade. The moorings in the southern portion of the lake shows a somewhat reduced rate.

Lake Erie
Trend: Undetermined
Rationale: Linear regression of data from a single NDBC buoy (45005) from 1980-2014 suggest that the summer surface water temperature on Lake Erie has increased at a rate of approximately 0.1±0.1C/decade over the period of interest, so that the warming trend there is not statistically significant. Data from ECCC

buoys also show a positive trend, but over a shorter time span. This trend is also not statistically significant. Temperatures at the ECCC buoys are lower than at the NDBC buoy, which is located in the shallow western basin of the lake. Due to its shallow depth, Lake Erie stratifies significantly earlier than the other Great Lakes. There are few years where the buoys are deployed before the onset of stratification.

Lake Ontario
Trend: Undetermined
Rationale: While the interannual variability at different buoys in Lake Ontario is correlated, insufficient temperature data exists to make reliable estimates of trends. NDBC data collection in Lake Ontario started in 2002, too recently to make a determination of significant trends. Not enough ECCC data exists early enough in the year to identify the date of onset of stratification.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to assess trends in surface water temperature for each of the five Great Lakes by measuring changes in duration and spatial extent of water temperature using long-term data, and to infer the impact of climate change on the Great Lakes Region. This sub- indicator measures the thermal properties of the Great Lakes that affects the ecosystems' function and influences water evaporation from the lakes that affects lake's water level (if higher surface water temperatures persists, this may lead to reduced winter ice cover and increased water evaporation from the lakes resulting in lower water levels).

Ecosystem Objective
There should be no change in temperature that would adversely affect any local or general use of the waters.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes."

Ecological Condition
Surface water temperature is directly dependent on regional air temperatures and hence regional climate. Upward trends in surface water temperatures have been documented on the Laurentian Great Lakes (e.g. Austin and Colman 2007, Huang et al. 2012) as well as on lakes around the world (O'Reilly et al. 2015). Water temperature is a primary ecosystem driver, affecting a wide range of processes including nutrient uptake, metabolism rates, and defines fish habitat. Surface heat and moisture fluxes (evaporation) are also a strong function of surface water temperature. Summer surface water temperatures are a reflection of not only summer air temperatures, but ice conditions the previous winter (Austin and Colman 2007). In addition, the onset of summer stratification (the date on which the lake stays above the temperature of maximum density, or about 4°C) provides a robust, integrated measure of winter conditions, in which higher-ice winters tend to result in a later onset of stratification and low-ice winters result in earlier onset of stratification. In lakes without significant ice formation (e.g. Michigan, Ontario), the onset of stratification is a reflection more of the winter thermal storage of the lake, again with colder years resulting in a later onset of stratification. The date of the onset of stratification is a strong predictor of the summer surface water temperature, and the results in this report are consistent with each other: the date of the onset of stratification is getting earlier, and summer surface water temperatures are increasing. While the date of the onset of winter conditions would also be a useful metric, it is a more difficult date to determine, and most buoys are not left in late enough into the season to make consistent observations of it.

There is a great deal of natural inter-annual variability that sits on top of the warming trend. Several features are consistent across the lakes. First and perhaps most importantly, a significant jump occurs between 1997 and 1998, a strong El Niño year. It has been pointed out (van Cleave et al. 2014) that taken separately, summer water temperature prior to 1998 and from 1998 to the present have no significant trends, but a strong discontinuity between the average water temperature between these two time periods. The offset between these two time periods for the upper lakes is on the order of 2C.

In addition, there have been two “extreme” years since the last report. 2012 was an anomalously warm year, following a very warm winter of 2011-2012 (Bai et al. 2014), in which very little ice formed on the lakes (including, remarkably, Lake Erie), resulting in an (in many cases) record-setting early onset of stratification and consequent warm summer. Conversely, in 2014, the “polar vortex” resulted in extreme cold conditions across the Great Lakes region (Clites et al. 2014, Gronewold 2015), during which ice cover was extremely heavy across the lakes, resulting in very late overturn dates and relatively low summer water temperatures. The effect of these two extreme events to a certain extent offset each other, so that the trends observed in this report are to first order consistent with those of the 2011 report.

Linkages

There is a clear link between the onset of summer stratification and average summer water temperatures. Further, the onset of summer stratification is closely tied to ice cover in lakes that form ice cover (Austin and Colman 2007). Taking this a step further, recent (unpublished) work has shown a strong link between average winter air temperatures and the amount of ice cover, suggesting a series of statistically significant linkages (winter air temperatures → ice cover → onset of stratification → summer water temperatures) which may prove useful to resource managers.

Trends towards earlier stratification onset (and later breakdown) imply that the period of stratification is increasing. Separate research (Austin and Colman 2008) suggest that over the period 1906-2006, the length of the period of summer stratification has increased from roughly 145 days to 170 days, an increase of about 20%. This is going to have significant implications for primary productivity in the lakes, as well as oxygen depletion in shallower, more productive parts of the Great Lakes.

Comments from the Author(s)

The observed trends towards earlier stratification and higher summer water temperatures are driven by long-term changes in atmospheric conditions, primarily air temperature, which is widely acknowledged to be a consequence of changing atmospheric chemistry, specifically the addition of carbon dioxide (and to a lesser extent methane) from the burning of fossil fuels. It is important, however, that the Great Lakes community continue to develop a better understanding of the impacts of warming on lake ecosystems, as well as to continue to carefully document these trends.

While there are some groups that periodically deploy equipment over the winter, there are no structures in place to guarantee funding for systematic, year-round measurements of temperature in the Great Lakes during the winter months. As these systems have strong seasonal connectivity, developing a long-term program for year-round measurements should be a priority. Likewise, there are very few long-term measurements of thermal structure (temperature throughout the water column) so little if anything is known about trends in features like thermocline depth.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
Data are documented, validated, or quality-assured by a recognized agency or organization	X					
Data are traceable to original sources	X					
The source of data is a known, reliable, and respectable generator of data	X					
Geographic coverage and		X				

scale of data are appropriate to the Great Lakes Basin						
Data obtained from sources within the US are comparable to those from Canada		X				
Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X					

Acknowledgments
Authors:
Jay Austin, University of Minnesota Duluth
Ram Yerubandi, Environment and Climate Change Canada

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Figure 1. Location of surface buoys used in this report.
Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)
Figure 2. Dates of onset of stratification on the three upper Great Lakes. The onset of stratification date is the first date after which the surface water temperature stays above the temperature of maximum density. Trends are in units of days per decade and negative trends indicate the date of onset is becoming earlier. Note that the ranges on the y-axes differ.
Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)
Figure 3. Summer (July-September) surface water temperature trends for the upper Great Lakes.
Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)

Figure 4. Summer surface water temperature trends for the lower Great Lakes
Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)

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Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)

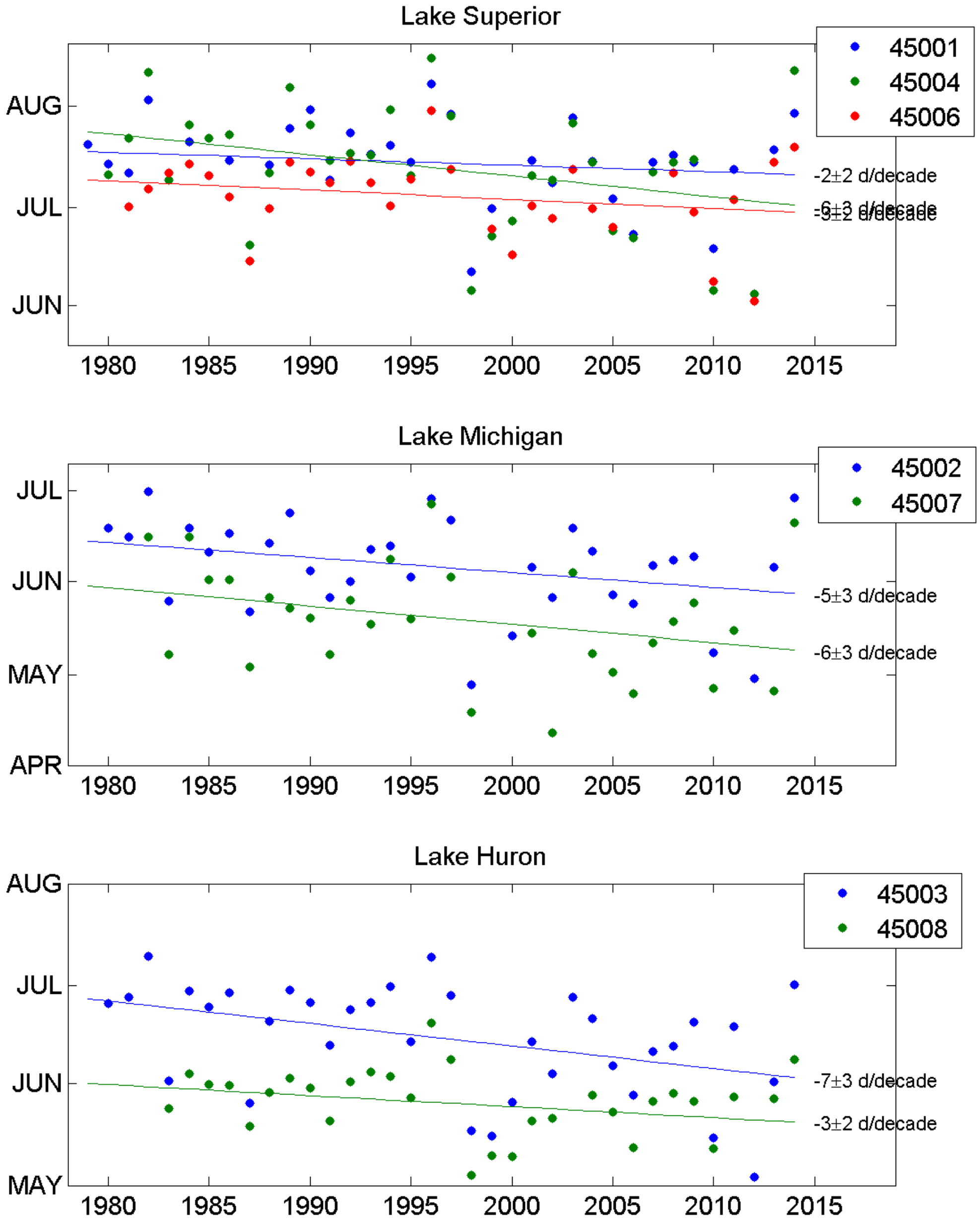

Figure 2. Dates of onset of stratification on the three upper Great Lakes. The onset of stratification date is the first date after which the surface water temperature stays above the temperature of maximum density. Trends are in units of days per decade and negative trends indicate the date of onset is becoming earlier. Note that the ranges on the y-axes differ.
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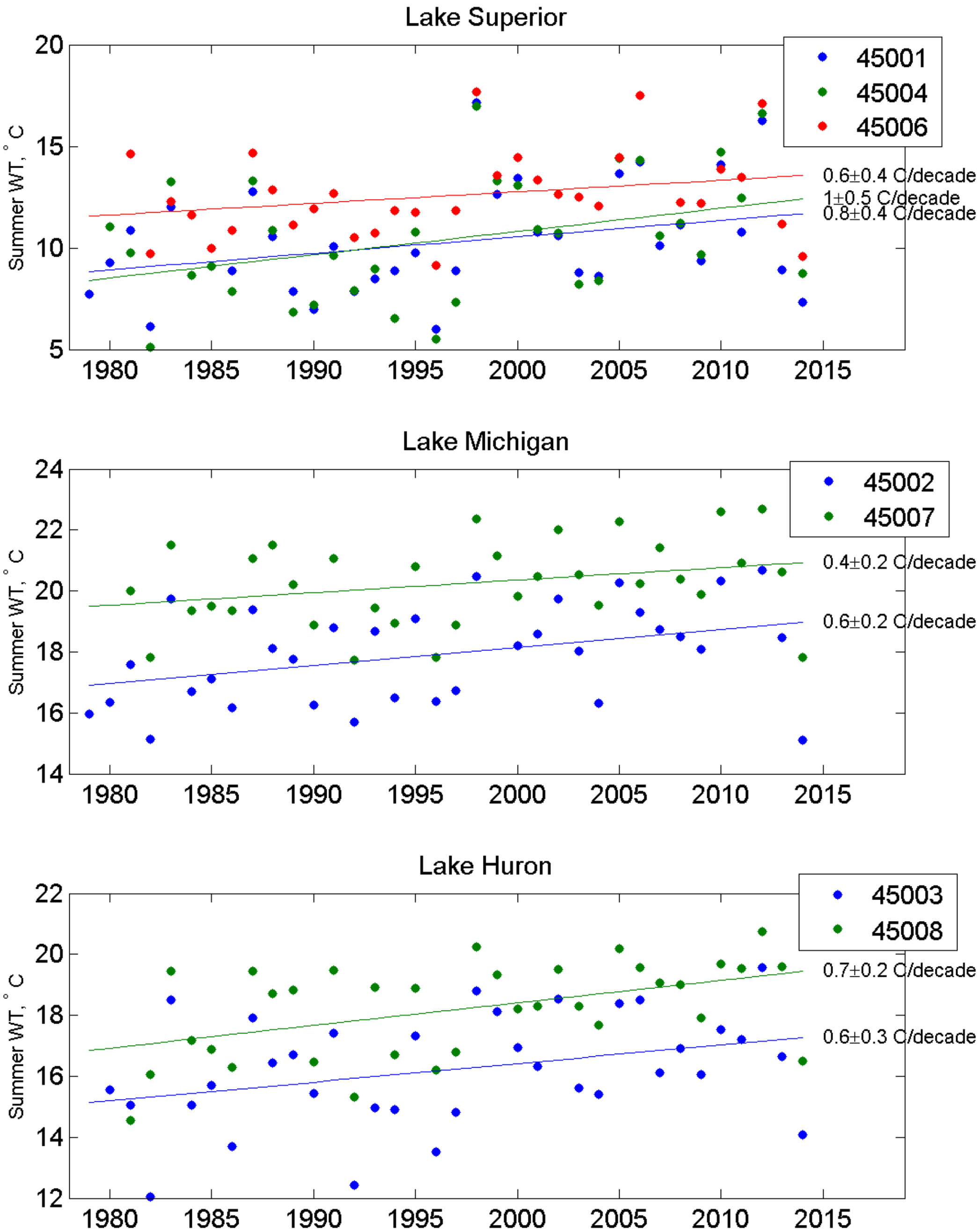

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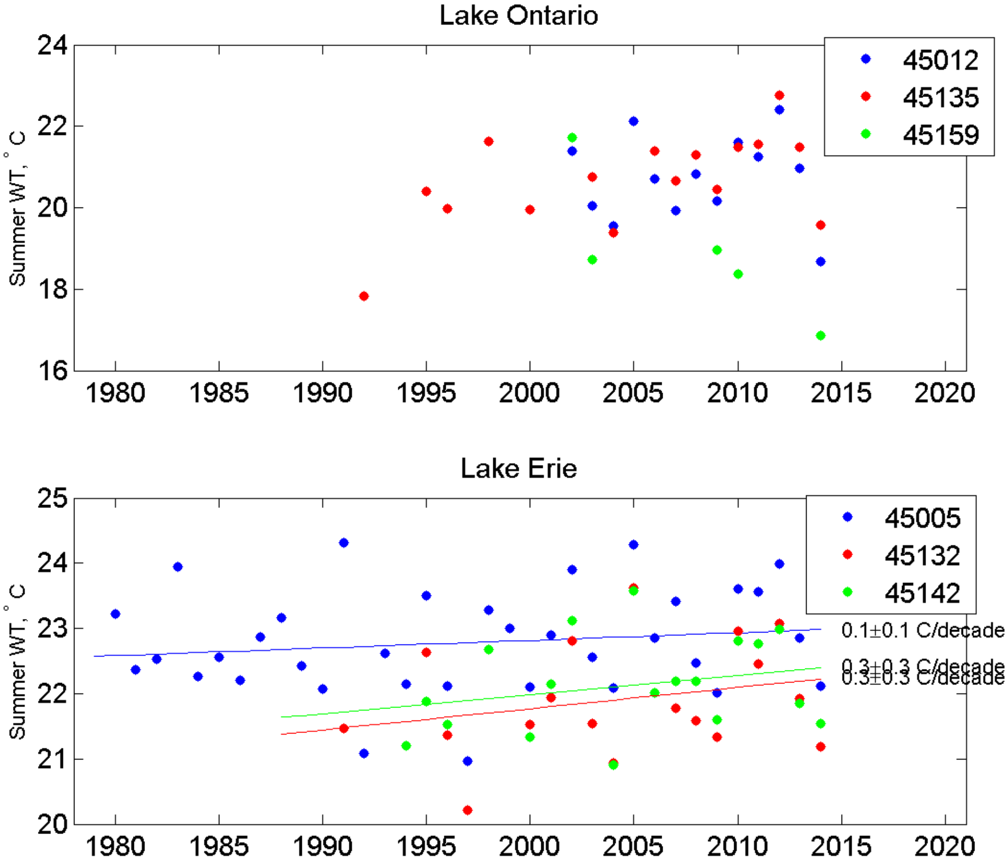

Figure 4. Summer surface water temperature trends for the lower Great Lakes.
Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)

Sub-Indicator: Ice Cover

Overall Assessment
Trend: Decreasing
Rationale: The basin-wide loss of ice cover from 1973 to 2015 is 26%, i.e., the annual trend is -0.6% per year. The annual trend for the period 1973-2013 is -0.79% per year. The interannual (year-to-year) change of Annual Maximum Ice Coverage (AMIC) is due to the interannual variability of North Atlantic Oscillation (NAO) and El Nino and Southern Oscillation (ENSO). Lake ice cover is a sensitive indicator of regional climate and climate change. Seasonal ice cover repeats each year with large interannual variability. For example, the maximum ice coverage over all of the Great Lakes was 95% in 1979 and only 11% in 2002. Possible contributors include interannual and interdecadal climate variability, and long-term trends, possibly related to global climate warming. Even in response to the same climate forcing, Great Lakes ice cover may experience different spatial and temporal variability due to an individual lake's orientation, depth (i.e., water heat storage), and turbidity (i.e., albedo due to sedimentation). Since the last update to the Great Lakes ice cover database (Wang et al. 2012a), there has been significant change in ice cover on the Great Lakes, in particular in the last two winters (93% and 89% coverage for 2013/14 and 2014/15, respectively), which was considerably above the long-term average of 53.2%.

Lake-by-Lake Assessment
Lake Superior
Trend: Decreasing
Rationale: Lake Superior ice cover is highly controlled by the atmospheric teleconnection patterns such as NAO, ENSO, AMO (Atlantic Multi-decadal Oscillation), and PDO (Pacific Decadal Oscillation). Lake Superior has the highest total loss of ice area among the lakes at -39% since 1973 (see Tables 1 and 2; Figure 2a). The annual (decadal) trend was estimated to be -0.9% (-9%).In addition to that the ice cover is controlled by the atmospheric teleconnection patterns such as NAO, ENSO, AMO, and PDO. The other mechanism is partially due to the warming caused by the ice/water albedo feedback (Wang et al. 2005; Austin and Colman 2007), because Lake Superior has the deepest depth and largest volume of water of all five lakes. AMIC was above Long-Term Average during winters of 2013/14, 2014/15.

Lake Michigan
Trend: Decreasing
Rationale: Lake Michigan ice cover is controlled by the atmospheric teleconnection patterns such as NAO, ENSO, AMO, and PDO. Lake Michigan has the second lowest ice loss at -17% since 1973. The annual (decadal) trend was estimated to be -0.39% (-3.9%) (see Tables 1 and 2; Figure 2b). AMIC was above Long-Term Average during winters of 2013/14, 2014/15.

Lake Huron
Trend: Decreasing
Rationale: Lake Huron has the second highest total loss among the lakes at -22% since 1973. The annual (decadal) trend was estimated to be -0.51% (-5.1%). Lake Huron ice cover is controlled by the atmospheric teleconnection patterns such as NAO, ENSO, AMO, and PDO. AMIC was above Long-Term Average during winters of 2013/14, 2014/15.

Lake Erie
Trend: Decreasing
Rationale: Lake Erie has the second lowest ice loss at -17% since 1973. The annual (decadal) trend was estimated to be -0.48% (-4.8%). Lake Erie ice cover is controlled by the atmospheric teleconnection patterns such as NAO, ENSO, AMO, and PDO. Another important factor is that Lake Erie is the shallowest lake and its heat content is the smallest. Although located in the southern part of the basin with warmer air and water temperatures, on average, most winters, Lake Erie is almost completely ice covered. AMIC was above Long-Term Average during winters of 2013/14, 2014/15

Lake Ontario

Trend: Decreasing

Rationale: The annual (decadal) trend was estimated to be -0.36% (-3.6%). Lake Ontario ice cover is controlled by the atmospheric teleconnection patterns such as NAO, ENSO, AMO, and PDO. Lake Ontario has the smallest mean ice cover of all lakes. AMIC was above Long-Term Average during winters of 2013/14, 2014/15.

Sub-Indicator Purpose

The overall purpose of this sub-indicator is to assess winter ice cover and its impacts on seasonal and interannual lake temperature and accompanying physical changes to each lake over time by measuring the thermal properties of the Great Lakes that affect the ecosystems' function and influence water evaporation from the lakes that affects water levels. This sub-indicator tracks the extent of winter ice cover for each of the five Great Lakes by measuring changes in duration and spatial extent of water temperature and ice cover using long term data. This sub-indicator is also used to infer potential impact of climate change on wetlands since ice cover affects water levels and protects the shorelines including wetlands from erosion by waves and storms.

Ecosystem Objective

Change in lake ice cover during the winter due to climate change will affect water temperature on the Lakes in the following spring and summer and, in turn, affect lake ecosystems. Awareness of occurrence will encourage human response to reduce the stressor towards minimizing biological disruption.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes."

Ecological Condition

This sub-indicator is used as a potential assessment of climate change, particularly within the Great Lakes Basin. Changes in water and air temperatures will influence ice development on the lakes and, in turn, affect coastal wetlands, nearshore aquatic environments, and inland environments. More importantly, ice cover directly controls the lake water temperature change, duration of stratification, and fish behaviours. Based on the observations (Figure 1), the highest maximum ice cover for each Great Lake occurred in 1977-1979, 1994, and 2014-2015. For Lakes Michigan, Erie and Ontario, the highest maximum ice over took place in 1977, 1978 and 1979 respectively.

This sub-indicator will measure annual maximum and average ice concentrations of the Great Lakes area. According to Assel (2005), the daily spatial average ice cover for each of the Great Lakes was calculated from daily grids. Daily grids were generated by linear interpolation of observed ice cover grids between adjacent dates for a given winter season from the date of first ice chart to date of last ice chart (Assel 2005). Lake-averaged ice cover prior to date of first ice chart and after date of last ice chart was assumed to be zero. The daily lake-averaged ice cover on each of the Great Lakes is used to calculate the seasonal average ice cover. The seasonal average ice cover is the sum of the daily lake-averaged ice cover over a winter divided by 182 (the number of days between 1 December to the following 31 May). The seasonal average ice cover is calculated for days when the lake-averaged ice cover was greater than or equal to 5%.

The seasonal average ice cover is an index of the severity of an annual ice cycle. Ancillary ice cycle variables calculated for each winter are the Julian dates that the first and last observed lake- averaged ice cover was greater than or equal to 5% and the duration of the ice cover, that is, the difference between dates of last and first ice.

Annual maximum ice cover (AMIC) is defined as a maximum percentage of ice cover in one day during an ice season (winter). This snapshot of the ice season is a realization that can be measured, which reflects the overall atmospheric cumulative effects on lake ice. Furthermore, its seasonal and interannual variability can be accurately recorded and analyzed (Bai et al. 2012). The trend of AMIC for a specified period can be calculated (Wang et al. 2012a,b). However, the trend varies with different length of the time series included, because there is multidecadal variability in lake ice that is caused by multidecadal atmospheric (Wang et al. 2016, submitted) and water thermal forcings.

There is spatial variability in AMIC trend. The highest trend is located along heavy ice-covered coasts in Lake Superior, Georgian Bay, northern Lake Huron, and northern Lake Michigan. Offshore ice cover has smaller trend, since ice cover is not continuous. Research is needed to map the grid points of a lake using GIS to calculate each grid point trend. This on-going research will reveal spatial trend distribution over the Great Lakes (Mason et al. 2016).

During the 2015/16 winter, Great Lakes annual maximum ice coverage (AMIC) was observed to be 33%, significantly below the long-term average, mainly due to the simultaneous occurrence of a strong El Nino, positive North Atlantic Oscillation (NAO), warm phase of Atlantic Multi-decadal Oscillation (AMO), and warm phase of Pacific Decadal Oscillation (PDO).

Air temperatures over a lake are one of the few factors that control the formation of ice on that surface. Colder winter temperatures increase the rate of heat released by the lake, thereby increasing the freezing rate of the water. Milder winter temperatures have a similar controlling effect, only the rate of heat released is slowed and the ice forms more slowly. Globally, some inland lakes appear to be freezing up at later dates, and breaking-up earlier, than the historical average, based on a study of 150 years of data (Magnuson et al. 2000). These trends add to the evidence that the earth has been in a period of global warming for at least the last 150 years.

The freezing and thawing of lakes is a very important aspect to many aquatic and terrestrial ecosystems. Many fish species rely on the ice to give their eggs protection against predators during the late part of the ice season. Nearshore ice has the ability to change the shoreline as it can encroach upon the land during winter freeze-up times. Even inland systems are affected by the amount of ice that forms, especially within the Great Lakes basin. Less ice on the Great Lakes allows for more water to evaporate and be spread across the basin in the form of snow. This can have an effect on the foraging animals (such as deer) that need to dig through snow during the winter in order to obtain food.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Coastal Wetlands: Extent and Composition
- Hardened Shorelines – less ice cover exposes the shoreline to waves generated by winter storms that accelerates erosion
- Dreissenid Mussels
- Harmful Algal Blooms – higher water temperatures and less ice cover may be related to more and earlier algal blooms
- Toxic Chemicals in Great Lakes Herring Gull Eggs – a link has been shown between contaminant levels in Herring Gull eggs and Ice Cover

This sub-indicator also links directly to the other sub-indicators in the Watershed Impacts and Climate Trends indicator. It is indirectly linked to other sub-indicators that track trends in wetland area and habitat change.

Comments from the Author(s)

This report is based on previous and on-going research. This indicates that research is the base to accurate lake ice analysis, prediction, projection, and application. Therefore, long-term investment in research is the key for our better understanding the lake ice and related climate changes, as well as its implications to ecosystem in the Great Lakes (Bai et al. 2015). Research can guarantee to deliver physical sound knowledge to the forecast and application to serve the Great Lakes community.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					

4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		x				

Acknowledgments
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Jia Wang, Ph.D., Ice Climatologist, NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan
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All data analyzed and charts created by the authors.

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	a	b/annual trend	Decadal trend	Total loss up to 2015
Superior	77.00	-0.90	-9.0	-38.70
Michigan	39.04	-0.39	-3.9	-16.77
Huron	66.87	-0.51	-5.1	-21.93
Erie	90.86	-0.48	-4.8	-20.64
Ontario	26.00	-0.36	-3.6	-15.48
Basin	62.00	-0.60	-6.0	-25.80

Table 1. Regression linear trend of AMIC, $x=a+bt$ in percentage (t in years starting with 0 at 1973, a is constant, and b is the trend/slope).

	a	b/annual trend	Decadal trend	Total loss up to 2013
Superior	79.73	-1.09	-10.9	-44.69
Michigan	50.57	-0.61	-6.1	-25.01
Huron	80.92	-0.66	-6.6	-27.06
Erie	97.82	-0.56	-5.6	-22.96
Ontario	43.80	-0.50	-5.0	-20.50
Basin	62.43	-0.79	-7.9	-32.39

Table 2. The same as Table 1, except excluding 2014 and 2015 ice seasons.

From 1973 to 2015	Superior	Michigan	Huron	Erie	Ontario	Basin
mean	63.05	40.69	64.74	83.92	29.03	53.20
standard deviation	30.55	22.62	24.08	26.13	21.50	24.03

Table 3. Statistic parameters (mean and standard deviation) of AMIC five individual lakes using data from 1973-2015.

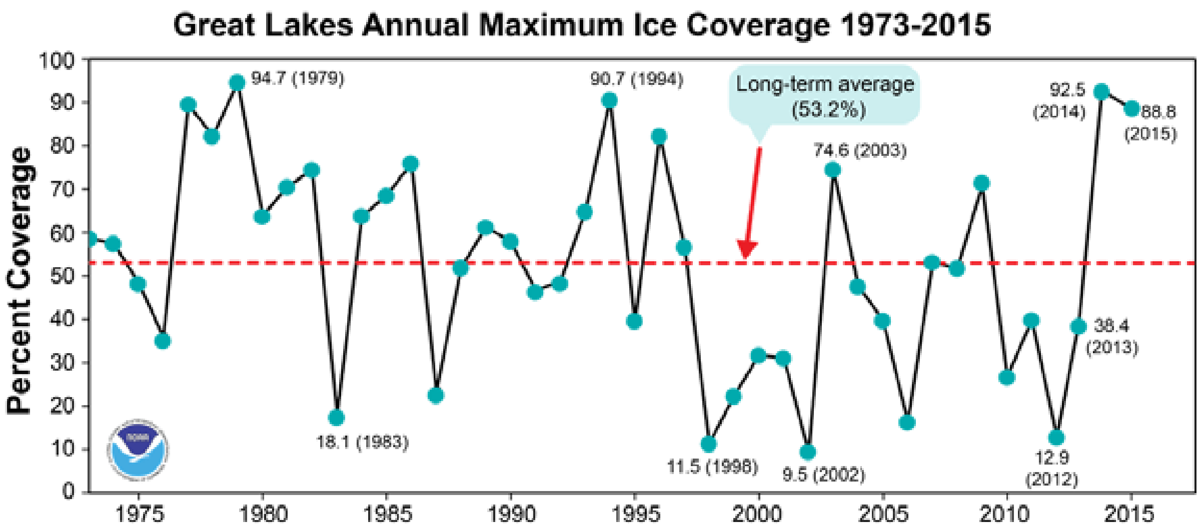


Figure 1. Time series of five Great Lakes' AMIC for the period 1979-2015, which is based on the binational NIC and CIS dataset.
Source: NOAA Great Lakes Environmental Research Laboratory (GLERL) and National Ice Service (NIC)

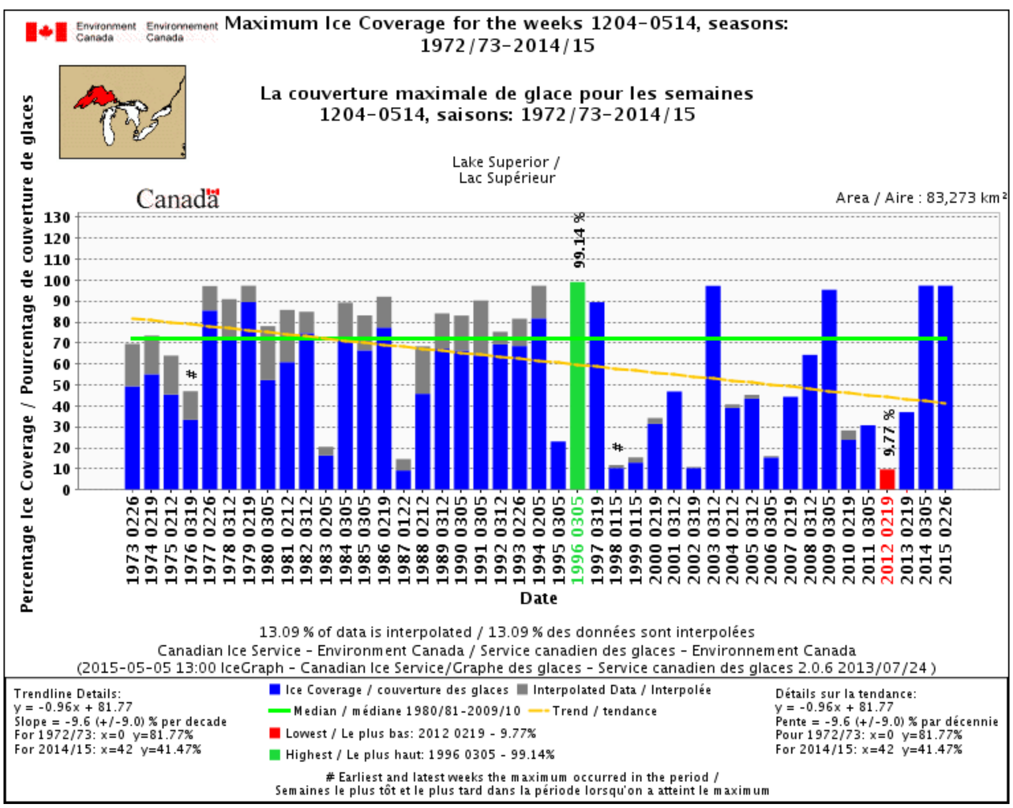


Figure 2a.

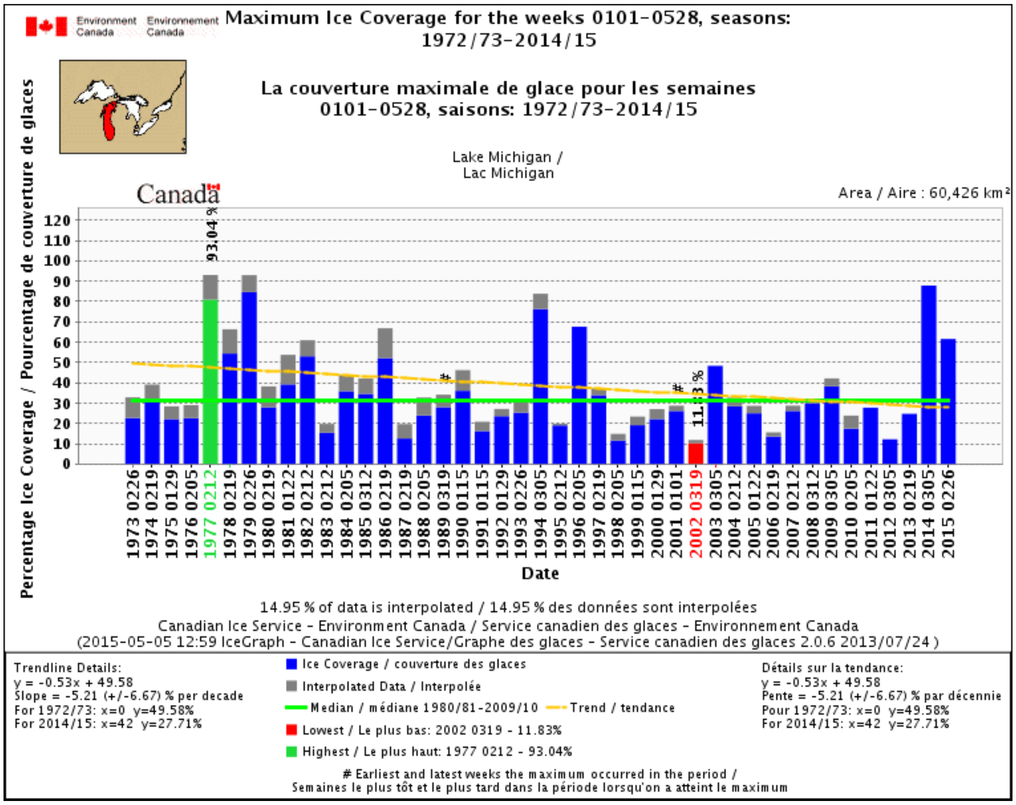
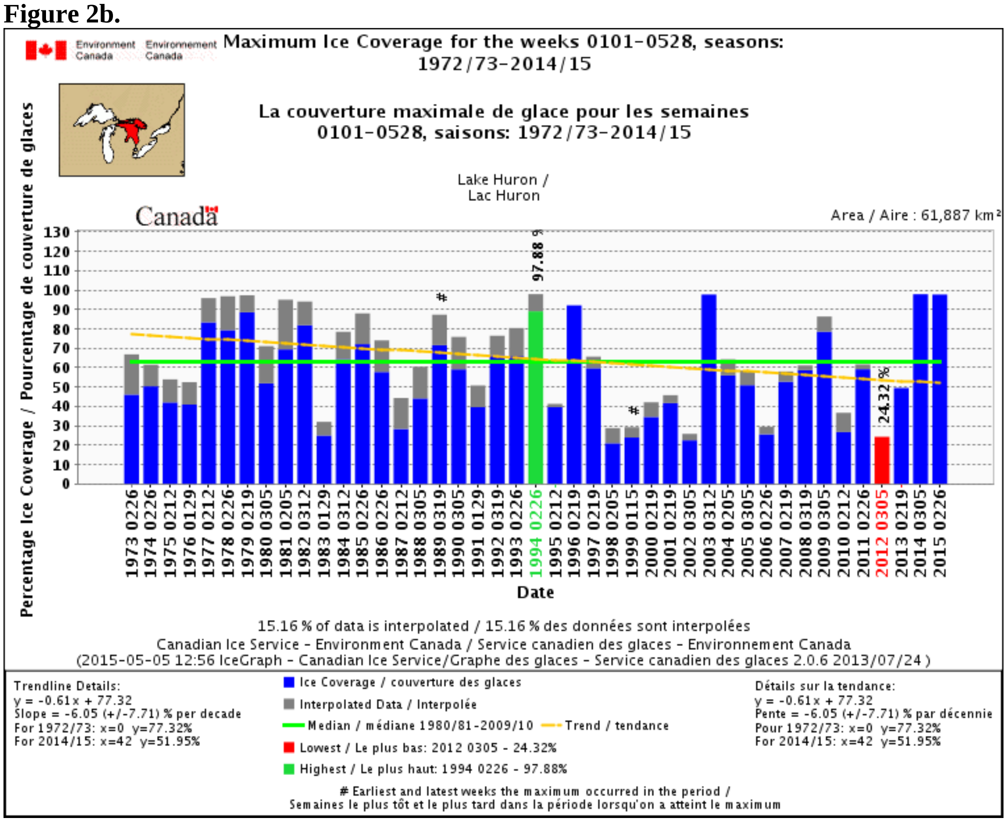


Figure 2b.



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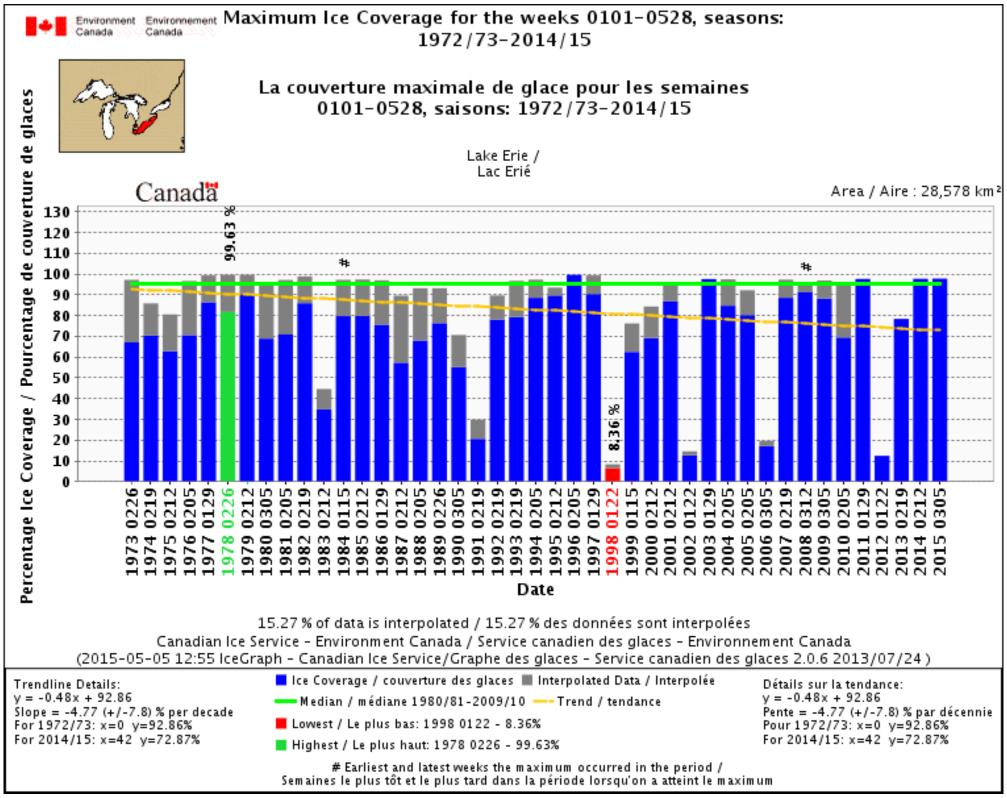

Figure 2d.

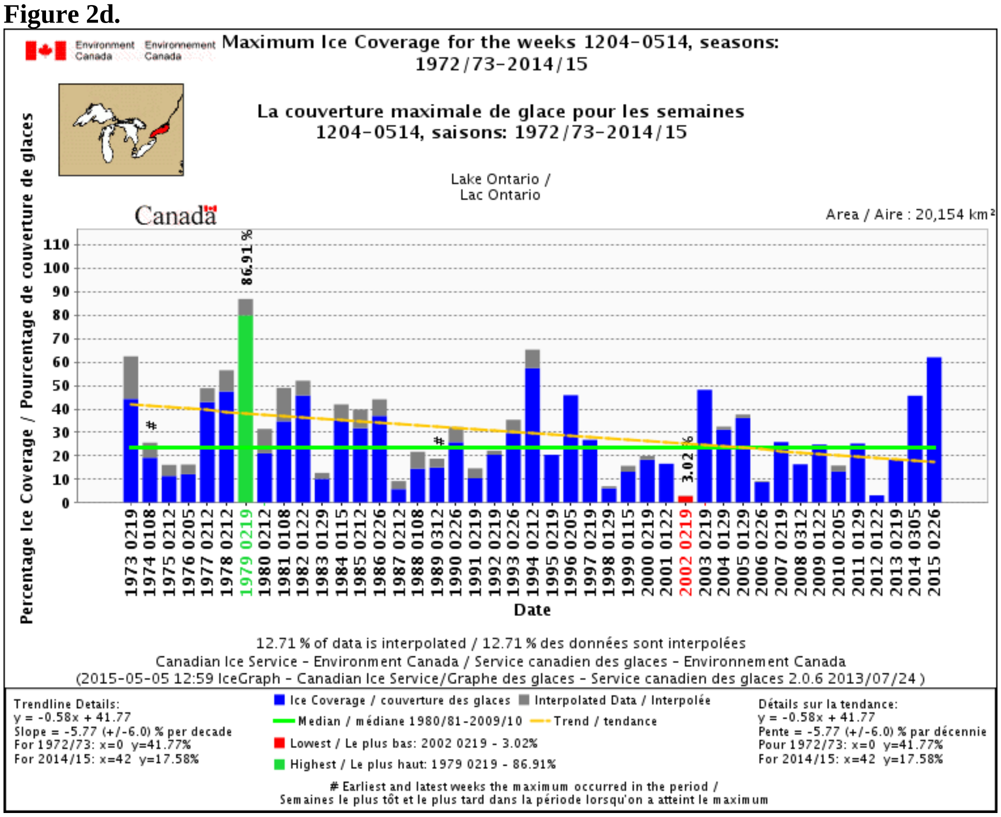

Figure 2e

Figures 2a-e. AMIC (in %) of all five individual lakes for the period 1973-2015. The linear lines are the trend in AMIC calculated from the least square fit method. Units for the vertical axes are in %. Other parameters are given in each lake.

Source: ECCC Ice Service

Sub-Indicator: Water Levels

Overall Assessment
Trend: Decreasing (30-year trend, 1985-2015)
Rationale: Water level conditions have historically varied, and continue to vary considerably across each of the Great Lakes (Quinn and Edstrom 2000) (Lenters 2004). For all the Great Lakes, it is difficult to say whether there is a discernable trend over the past 100 years. However, notable basin-scale water level dynamics over the past 30 years include a significant decline in the late 1990s (Assel, Quinn, and Sellinger 2004), persistent and record-low monthly mean levels (Gronewold and Stow 2014) on Superior (August and September 2007) and Michigan-Huron (December 2012 and January 2013), and a record setting rise on both Superior and Michigan-Huron between January 2013 and December 2014 (Gronewold, et al. 2015). At the end of calendar year 2015, monthly and annual mean water levels on all of the Great Lakes were at or above their long-term averages. It is informative to note that water level data on the Great Lakes dates back to the 1800s and any assessment of temporal trends in water levels depends on the period selected from this historical record. For the purposes of this report, trends have been identified in annual water levels across the most recent 5, 30, and 100 year periods. It is understood and recognized that additional periods could be used in the assessment as well and that the trends could be different than what is presented in this assessment report.

Lake-by-Lake Assessment
Lake Superior
Trend: 5-year: Increasing
30-year: Decreasing
100-year: Decreasing
Rationale: Lake Superior annual mean and monthly mean water levels were predominantly below long-term average values between the late 1990s and 2013. In 2013 and 2014, however, Lake Superior water levels rose at a very high rate and are currently above long-term average values. Although water levels on Lake Superior are higher than they were at the time of the previous State of the Great Lakes (SOGL) report, the potentially high-rate of interannual variability in climate conditions and the regional hydrologic cycles makes it difficult to determine whether these changes are expected to persist in the future.

Lake Michigan and Lake Huron
Trend: 5-year: No significant trend
30-year: Decreasing
100-year: No significant change
Rationale: Note: Lake Michigan and Lake Huron are commonly considered one lake system from a long-term hydrological perspective and therefore are referenced collectively as Lake Michigan-Huron.
Lake Michigan-Huron annual mean and monthly mean water levels were predominantly below long-term average values between the late 1990s and late 2014. In late 2014 and 2015, however (as part of a rise that began in early 2013) water levels rose above long-term average values. Although water levels on Lake Michigan-Huron are higher than they were at the time of the previous State of the Great Lakes (SOGL) report, the potentially high-rate of interannual variability in climate conditions and the regional hydrologic cycles makes it difficult to determine whether these changes will persist.

Lake Erie
Trend: 5-year: No significant change
30-year: Decreasing
100-year: Increasing
Rationale: Monthly mean and annual mean water levels on Lake Erie have oscillated above and below long-term

average values for the past decade, including from 2011 through 2015. However, water level conditions on Lake Erie (unlike conditions on Lakes Superior and Michigan-Huron) did not approach record annual and monthly lows during this period. It is informative to note, however, that water levels on Lake Erie rose dramatically in 2011 (in response to widespread increased annual precipitation) and then declined (starting in November 2011) for 10 straight months – the longest continuous period of monthly mean water level decline in Lake Erie's history (Gronewold and Stow 2013).

Lake Ontario

Trend: 5-year: No significant change
30-year: No significant trend
100-year: Increasing

Rationale: Water levels have been oscillating above and below long-term annual and monthly average values for the past 30 years. Water level variability on Lake Ontario is impacted by regulation of its outflows and, in general, has been reduced for the past 50 years (relative to the pre-regulation period). The International Joint Commission (IJC) periodically investigates alternative approaches to managing Lake Ontario outflows to help restore Lake Ontario's coastal wetlands while balancing other water resource management planning considerations. Most recently, the IJC announced the adoption of ``Plan 2014".

Other Spatial Scales

Water level fluctuations at finer spatial scales (including the fluctuations on Lake St. Clair) are not considered in this report.

Sub-Indicator Purpose

- The purpose of this sub-indicator is to track seasonal, inter-annual, and long-term (i.e. decadal) trends in lakewide-average water levels across each of the Great Lakes.
- The water levels sub-indicator is used in support of the climate change category, as well as general objective #9 of the Great Lakes Water Quality Agreement (GLWQA) and the climate change, lakewide management, and habitat and species annexes of the GLWQA.

Ecosystem Objective

Water level fluctuations have strong influences on Great Lakes habitats and the biological communities associated with them. Impacts of alterations in water level fluctuations on shoreline ecosystems (particularly coastal wetlands) are widely-documented, and underscore important additional (but less apparent) relationships between ecosystem response, human intervention, and climate change.

Ecological Condition

Changes in Great Lakes water levels take place over a variety of time scales ranging from hourly fluctuations to those taking place over hundreds and even thousands of years. Most of the monthly and interannual changes documented over the past 150 years are the result of changes in the Great Lakes hydrologic cycle. These are influenced by natural and anthropogenic factors, and long-term climate trends (Baedke and Thompson 2000; Booth and Jackson 2003). Fluctuating water levels and changing connecting channel flows on the Great Lakes pose significant risks to the economic, social, and environmental well-being of the Great Lakes region. High water levels can cause significant damage due to flooding, erosion, overtopping of shore protection structures, loss of beaches and recreational lands and their economic and social benefits, and loss of wetlands. High channel flows can impede navigation, and there can be a greater susceptibility to storm damage from wind and waves. Low water can lead to increased dredging, encroachment of development in the nearshore, exposure of mudflats, undercutting of shore protection, loss of marina services and access to boat launch facilities, risks to water supply infrastructure, nearshore water quality issues, and ecosystem effects (e.g. isolating fish from their spawning habitats, or stranding wetlands). From an ecological perspective, short and long-term lake level fluctuations are critical to maintain healthy coastal habitats, especially coastal wetlands. However, dramatic or sustained long-term changes can degrade coastal habitats.

The summary below is an account of the overall factors affecting the Great Lakes water balance (Neff and Killian 2003), and ultimately the water levels, and a limited discussion on water level history and variability.

The natural factors associated with long-term water level changes in the Great Lakes include environmental processes that contribute to inflow to, outflow from, and storage in the system. Within broad scales, water inflow and outflow are dictated by climatically-induced changes that affect the components of the hydrologic cycle. These components include over-lake precipitation, runoff, over-lake evaporation, and connecting channel flows (i.e. the flow of water into and out of each lake through the upstream and downstream connecting channel). Groundwater flows, while an important contribution to the water cycle, do not represent a significant contribution to water level variability relative to over-lake precipitation, runoff, and evaporation (Piggott et al. 2007).

An additional natural factor that affects water levels is glacial isostatic adjustment (GIA), which is the response of the earth's crust to removal of the weight of the last glacial ice sheets that crossed the area (Wilcox et al.,2007; IUGLS 2009). Unlike hydrologic factors, GIA impacts on water levels vary from one location to another around a lake. At some locations, water levels appear to be rising as a result of GIA, while levels appear to be falling at other locations on the same lake. This has an implication for the analysis of historic water level data at a specific location.

Regulation of the outflows from Lake Superior and Lake Ontario seeks to lessen high and low levels (Wilcox et al. 2007). Lake Superior water levels have been regulated since 1916. In its 1914 Order of Approval, the International Joint Commission (IJC) established the International Lake Superior Board of Control and delegated to it responsibility for setting Lake Superior outflows. The Board of Control established a regulation plan that has undergone several revisions. The regulation plan currently in place incorporates the concept of balancing Lake Superior and Lake Michigan-Huron levels.

With the approval by the IJC of the hydropower project at Cornwall, Ontario and Massena, New York under the Order of Approval of 1952, Lake Ontario's outflow became subject to regulation. The first regulation plan became operational in 1960. The subsequent reduction of the variability in Lake Ontario water levels has been shown to diminish wetland plant diversity and the habitats they support (LOSLR Study Board, 2006).

Water levels are measured at several locations along the shore of the Great Lakes and their connecting channels by the National Oceanic and Atmospheric Administration (NOAA) in the United States and by the Canadian Hydrographic Service (CHS) in Canada (CHS, 2008). Several gauges in the current network of multiple gauges have been in operation only since 1918, while others have gauge records (some less reliable) extending back to the 1840s.

<u>Status and Trends in Lake Levels</u>
Hydrographs in Figures 1 of recorded lake levels show some similarities of interest (Wilcox et al.2007). Generally, periods of higher levels occurred in the late 1920s, the mid-1950s, and from the early 1970s to mid-1990s. Pronounced low lake level periods occurred in the mid-1920s, the mid-1930s and the mid-1960s (Wilcox et al. 2007). Though, less well documented, low levels also occurred in the late 1890s, following a long period of high lake levels.

Based on the historical record as shown in Figure 1, there appears to be a range within which the lake levels remain, but paleo records indicate a range that may have been greater *(*Brown et al. 2012).

There is considerable uncertainty in how climate change, particularly changes in precipitation and evaporation, may impact net basin water supplies and water levels and flows in the Great Lakes-St. Lawrence River region. The current state-of-the-art in climate models indicates that water levels are likely to be above and below their long-term averages in the future, but that there is not strong evidence for a pronounced shift in the long-term mean.

Linkages

- Coastal Wetland sub-indicators (Coastal Wetland Invertebrates, Coastal Wetland Fish, Coastal Wetland Birds, Coastal Wetland Amphibians, Coastal Wetland Plants, and Coastal Wetlands: Extent and Composition) – water levels have a major influence on undiked coastal wetlands and are basic to any analysis of wetland change trends
- Phytoplankton, Zooplankton, Benthos, *Diporeia*, Preyfish, Lake Trout, Walleye, Lake Sturgeon, and Fish Eating and Colonial Nesting Waterbirds
- Ice Cover
- Surface Water Temperature

Comments from the Author(s)

The authors concur with previous State of the Great Lakes (previously known as SOLEC) reports that additional future reporting cycles may want to focus on explicit connections between water level variability and ecosystem response. Given the water level patterns over the past 10 years, it seems that there might be a significant opportunity to improving that understanding if and when ecological data becomes available.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	x					
2. Data are traceable to original sources	x					
3. The source of the data is a known, reliable and respected generator of data	x					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin	x					
5. Data obtained from sources within the U.S. are comparable to those from Canada	x					
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	x					

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Figure 1. Water Levels in the Great Lakes. Red represents a 5-year trend, green represents a 30-year trend and blue represents a 100-year trend.
Source: NOAA-GLERL

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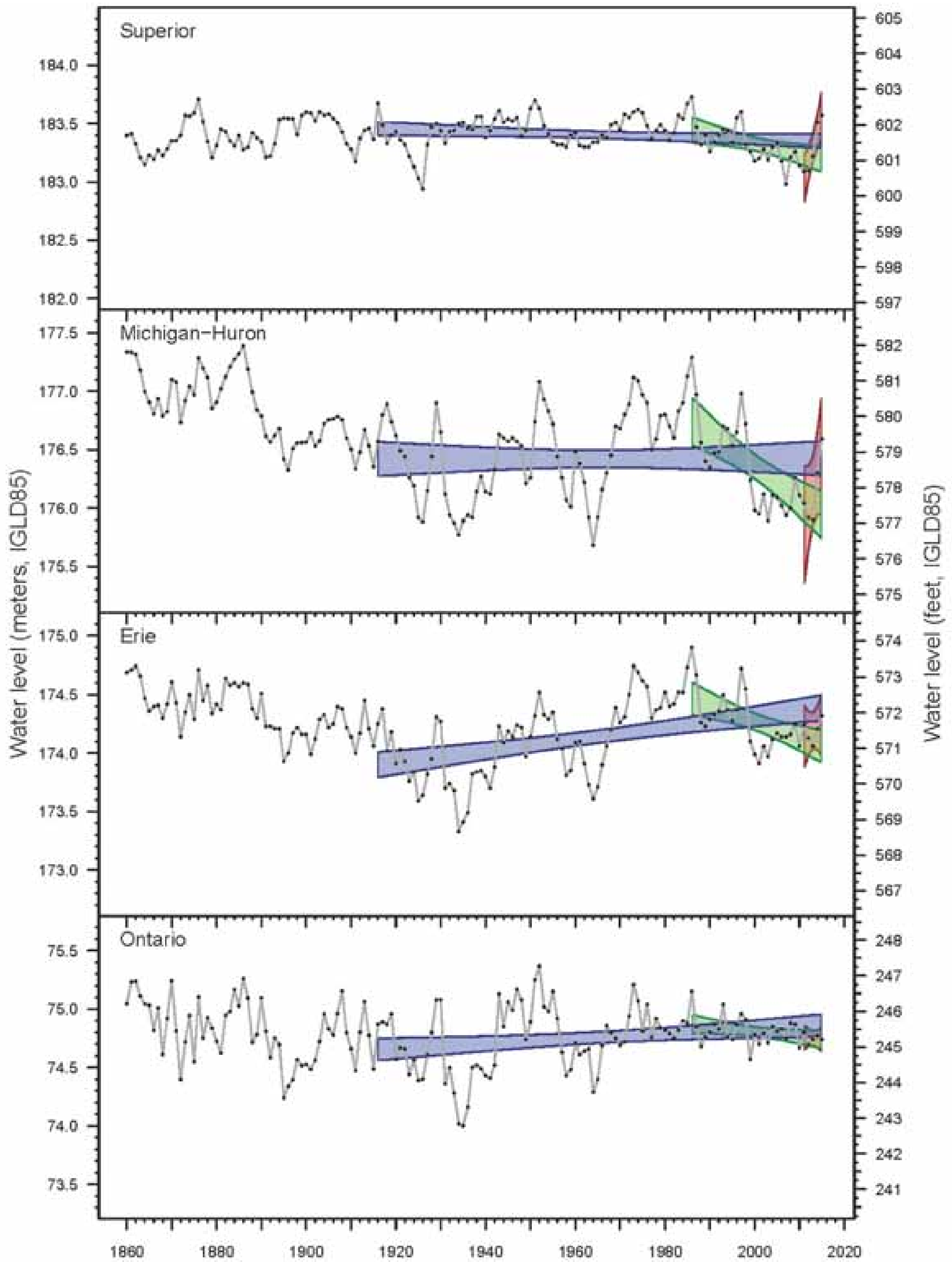

Figure 1. Water Levels in the Great Lakes. Red represents a 5-year trend, green represents a 30-year trend and blue represents a 100-year trend.
Source: NOAA-GLERL

Sub-Indicator: Base Flow Due to Groundwater

Overall Assessment
Trend: Undetermined
Rationale: For stream gages in the U.S. portion of the Great Lakes Basin, the Base Flow Index is near the long-term average. Although base flow appears to be increasing in the western part of the basin and decreasing in the central and eastern part of the Great Lakes Basin, the changes in Base Flow Index (ratio of base flow to overall streamflow) are small, indicating that climatic variation during the time periods analyzed may be driving the overall base flow values. Specific subwatershed trends have not been determined for each stream gage in the Great Lakes Basin, and examination of local trends may indicate impacts on base flow not apparent at the lake-basin scale. The stream gage data used in this analysis were only from the U.S. portion of the basin and the time period from 2005-2013 was compared to records prior to 2005. Other analysis of trends such as annual evaluations may reveal more subtle patterns.

Lake-by-Lake Assessment
Individual lake basin assessments were not prepared for this report.

Sub-Indicator Purpose
- This sub-indicator estimates the contribution of base flow to total stream flow by subwatershed (lake-scale)
- To detect changes in the source of water (base flow versus direct runoff) to total streamflow. Large changes in base flow or base flow-index would indicate potential changes in the groundwater contribution to streamflow that could affect the ecological function of the stream or riparian users.

Ecosystem Objective
The capacity of base flow to maintain in-stream flow conditions and aquatic habitat at, or near potential is not compromised by anthropogenic factors.

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes."

Ecological Condition
Measure
Aquatic ecosystems in the streams of the Great Lakes Basin have developed in response to natural variations in flow including low-flow conditions. Because base flow maintains streamflow volume and helps regulate stream temperature, it is considered important in maintenance of aquatic ecosystems. Long term average base flow relative to streamflow is referred to as a Base Flow Index. The Base Flow Index is a dimensionless value between 0 and 1 where increasing values of the index indicate increasing groundwater discharge and base flow. Significant extents of sand and gravel within a watershed often result in relatively large values of base flow index while significant extents of clay often result in relatively small values. Human impacts on base flow can potentially be detected using trend analysis of base flow, however, climatic factors can also result in Base Flow Index changes over time.

Endpoint
Anthropogenic factors are not responsible for deviations in the base flow characteristics of subwatersheds. No quantifiable endpoint or reference value is available at this time.

Background
Base flow provides a relatively stable supply of usually high quality water with stable temperatures. The Base Flow Index indicates how much of a stream's flow comes from base flow compared to total streamflow. A high Base Flow Index indicates that direct runoff contributes little to overall streamflow. Changes in the Base Flow Index through time indicate variability in the relative contribution of base flow and runoff to streamflow, and these chang-

es may have implications for the health of stream ecosystems. Changes in the Base Flow Index through time may result from climate variability and (or) anthropogenic influences.

A significant portion of precipitation over the inland areas of the Great Lakes Basin returns to the atmosphere by evapotranspiration. Water that does not return to the atmosphere either flows across the ground surface or infiltrates into the subsurface and recharges groundwater. Water that flows across the ground surface discharges into surface water features (rivers, lakes, and wetlands) and then flows toward and eventually into the Great Lakes. Water that infiltrates into the subsurface and recharges groundwater also results in flow toward the Great Lakes. Groundwater contributes more than 50 percent of the flow in streams that discharge into the Great Lakes (Grannemann et al. 2000). Accordingly, groundwater is a critical factor in the establishment and maintenance of aquatic habitat (Mortsch et al. 2003) because groundwater discharge often provides thermal refuges for fish in summer when temperatures are high. Most recharged groundwater flows at relatively shallow depths at local scales and discharges into adjacent surface water features as base flow. However, groundwater also flows at greater depths at regional scales and discharges either directly into the Great Lakes or into distant surface water features. The quantities of groundwater flowing at these greater depths can be significant locally but are generally believed to be modest relative to the quantities flowing at shallower depths.

The component of stream flow due to runoff from the ground surface is rapidly varying and transient, and results in the peak discharges of a stream. Groundwater discharge to surface water features in response to precipitation is greatly delayed relative to surface runoff. The stream flow resulting from groundwater discharge is, therefore, more uniform. In the Great Lakes region, groundwater discharge is often the dominant component of base flow. Base flow is the less variable and more persistent component of total streamflow (example hydrograph in figure 1).

For this report, base flow represents the consistent part of streamflow that is not surface-runoff. In the Great Lakes region, groundwater discharge is often the dominant component of base flow.   However, anthropogenic activities such as flow regulation, the storage and delayed release of water using dams and reservoirs, creates a steady streamflow signature that is similar to that of groundwater discharge. This analysis does not distinguish between base flow from groundwater discharge and base flow-type streamflow patterns resulting from anthropogenic activities.

Status of Base Flow

Base flow is frequently determined using hydrograph separation. This process uses streamflow monitoring information as input and partitions the observed flow into rapidly and slowly varying components, i.e., surface runoff and base flow, respectively. Figure 1 illustrates the daily streamflow monitoring information and the results of hydrograph separation for the Nith River at New Hamburg, Ontario, for January 1 to December 31, 1993. The rapidly varying response of streamflow to precipitation and snow melt are in contrast to the more slowly varying base flow.

Application of hydrograph separation to daily streamflow monitoring information results in lengthy time series of output. Various measures are used to summarize this output. For example, the Base Flow Index is a simplified summary of the relative contribution of base flow to streamflow that is appropriate for use in regional scale studies (Neff et al., 2005). Base Flow Index is defined as the average rate of base flow relative to the average rate of total streamflow, has no units, and varies from zero to one where increasing values indicate an increasing contribution of base flow to streamflow. The value of Base Flow Index for the data shown in Figure 1 is 0.28, which implies that 28% of the observed flow is estimated to be base flow

For this sub-indicator, five base flow separation techniques were applied to daily mean streamflow data from 227 gages operated by the U.S. Geological Survey (USGS) in the U.S. portion of the Great Lakes Basin. The five techniques were: BFI (Base Flow Index method or the UKIH method, Wahl and Wahl, 2003), HYSEP local minimum, HYSEP fixed interval, and HYSEP sliding interval (Sloto and Crouse, 1996), and PART (Rutledge, 1998). The 227 gages were selected according to the following criteria; the gages: (1) had data available in the USGS NWIS database, (2) were included in the Neff et al. (2005) report, and (3) had at least 3 continuous years of complete daily streamflow data for each time period (pre-2005 and 2005-2013). The Base Flow Index in each time period for each basin is the mean of five base flow separation techniques. The gages are a subset of the 959 gages that Neff et al. (2005) used to develop a regression model to predict base flow in ungagged basins (Figure 2). The pre-2005 values presented in this report are not taken directly from Neff et al. (2005), but were re-calculated using the same 5 base flow separation methods as applied to the 2005-2013 data. The base flow indices in this report may therefore be slightly different from the Neff et al (2005) report, but are well-suited for a direct comparison between pre-2005 and 2005-2013 (Figure 3 and Table 1).

When the base flow indices for all 227 gages are aggregated together, there is very little change in the overall mean Base Flow Index, suggesting there was not a consistent shift in Base Flow Index for the entire U.S. portion of the Great Lakes Basin (table 1). The change in the mean and maximum Base Flow Index values using any of the analysis methods are generally less than one percent. The estimated minimum Base Flow Index value is sensitive to small changes and has a higher percent change. Overall, this simple comparison does not indicate significant trend in the sub-indicator. However, many individual gages show differences in the Base Flow Index between the two time periods (Table 2). Of the 227 gages, 142 had increases or decreases in all 5 base flow separate techniques. This change was considered a "strong" signal and these basins are shown as red or blue points in Figure 3 and are summarized in Table 2. The largest within-basin negative change was -0.15 and the largest positive change was 0.15. This value represents a large change in Base Flow Index (recalling that the scale goes from 0 to 1). The positive and negative responses show some spatial clustering (Figure 3) suggesting that regional climatic patterns and (or) regional land use changes are driving at least part of the change in Base Flow Index. However, this entire analysis is very coarse and a more rigorous analysis of individual streamflow records at a more refined time interval may be necessary to identify trends.

Additional information is also required to determine the extent to which human activities have impaired groundwater discharge. Change in base flow over time may be subtle and difficult to quantify (e.g., variations in the relation of base flow to climate) and may be continuous (e.g., a uniform increase in base flow due to aging water supply infrastructure and increasing conveyance losses) or discrete (e.g., an abrupt reduction in base flow due to a new consumptive water use). Change may also be the result of cumulative impacts due to a range of historical and ongoing human activities, and may be more pronounced and readily detected at local scales than at the scales that are typical of continuous stream flow monitoring.

The discharge of groundwater to surface water features is the end-point of the process of groundwater recharge, flow, and discharge. Human activities impact groundwater discharge by modifying the components of this process where the time, scale, and to some extent the severity, of these impacts is a function of hydrogeological factors and the proximity of surface water features. Increasing the extent of impervious surfaces during residential and commercial development and installation of drainage to increase agricultural productivity are examples of activities that may reduce groundwater recharge and ultimately groundwater discharge.

Withdrawals of groundwater as a water supply and during dewatering (pumping groundwater to lower the water table during construction, mining, etc.) remove groundwater from the flow regime and may also reduce groundwater discharge. Groundwater discharge may be impacted by activities such as the channelization of water courses that restrict the motion of water across the groundwater and surface water interface. Human activities also have the capacity to intentionally, or unintentionally, increase groundwater discharge. Induced storm water infiltration, conveyance losses within municipal water and wastewater systems, and closure of local water supplies derived from groundwater are examples of factors that may increase groundwater discharge. Climate variability and change may compound the implications of human activities relative to groundwater recharge, flow, and discharge.

Linkages

Base flow due to the discharge of groundwater to the rivers, inland lakes and wetlands of the Great Lakes Basin is a significant and often major component of stream flow, particularly during low-flow periods. Base flow frequently satisfies flow, level, quality and temperature requirements for aquatic species and habitat. Water supplies and the capacity of surface water to assimilate wastewater discharge are also dependent on base flow. Base flow due to groundwater discharge is therefore critical to the maintenance of water quantity, quality, and integrity of aquatic species and habitat. Natural factors such as climate variability modify both average rates of base flow and the annual distribution of flow. Pressures such as urban development and water use, in combination with the potential for climate change impacts, may alter base flow. Reductions in base flow may compromise the assimilative capacity of surface water for wastewater discharge during periods of otherwise low flow and result in reduced water quality.

The higher the Base Flow Index value, the more sensitive the watershed is to climate change based on the Sensitivity Mapping and Local Watershed Assessments for Climate Change Detection and Adaptation Monitoring report."

Comments from the Author(s)

Groundwater has important societal and ecological functions across the Great Lakes Basin. Groundwater is typically a high quality water supply that is used by a significant portion of the population, particularly in rural areas where it is often the only available source of water. Groundwater discharge to rivers, lakes, and wetlands is also critical to aquatic species and habitat and to in-stream water quantity and quality. These functions are concurrent and occasionally conflicting.

Pressures such as urban development and water use, in combination with the potential for climate impacts and further contamination of the resource, may increase the frequency and severity of these conflicts. In the absence of systematic accounting of groundwater supplies, use, and dependencies, it is the ecological function of groundwater that is most likely to be compromised.

Managing the water quality of the Great Lakes requires an understanding of water quantity and quality within the inland portion of the basin, and this understanding requires recognition of the relative contributions of surface runoff and groundwater discharge to stream flow. The results described in this report indicate the significant contribution of groundwater discharge to flow within the tributaries of the Great Lakes.

The dynamics of groundwater flow and transport are different than those of surface-water flow. Groundwater discharge responds more slowly to climate and maintains stream flow during periods of reduced water availability, but this capacity is known to be both variable and finite. Contaminants that are transported by groundwater may be in contact with geologic materials for years, decades, and perhaps even centuries or millennia. As a result, there may be considerable opportunity for attenuation of contamination prior to discharge. However, the lengthy residence times of groundwater flow also limit opportunities for the removal of contaminants, in general, and non-point source contaminants, in particular.

Further research and analysis is required to determine if the changes in base flow noted are due to human causes and to determine conditions on a lake-by-lake basis.

Recent investigations on trends in streamflow characteristics (Hodgkins et al. 2007) could be expanded to the Canadian part of the basin. Similarly, analyses of trends in groundwater recharge (Rivard et al. 2009) could be completed in greater detail across both the Canadian and U.S. portions of the basin.

Assessing Data Quality

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes Basin			X			
5. Data obtained from sources within the U.S. are comparable to those from Canada			X			
6. Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report		X				

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the

U.S. Government.

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Table 1. Comparison of Base Flow Index for 227 gages with at least 3 continuous years of daily streamflow data in two time periods: pre-2005 and 2005 to 2013. The gages are all in the U.S. portion of the Great Lakes Basin and were included in the Neff et al. (2005) analysis of base flow.
Source: unpublished data from J. Trost, U.S. Geological Survey

Table 2. Number of gages (grouped by the magnitude of the change) in which all 5 base flow separation methods indicated either an increase or decrease in Base Flow Index from pre-2005 to 2005-2013. These correspond to the red and blue points in figure 3.
Source: unpublished data from J. Trost, U.S. Geological Survey

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Figure 1. Hydrograph of observed total stream flow (black) and calculated base flow (red) for the Nith River at New Hamburg during 1993.
Source: Environment Canada and the U.S. Geological Survey.

Figure 2. Location of gages with streamflow records used in Neff et al. (2005) to predict base flow in ungagged basins.
Source: Environment Canada and the U.S. Geological Survey (Neff et al., 2005).

Figure 3. Difference in Base Flow Index for selected stream gages on the U.S. part of the Great Lakes Basin for the period 2005-2013 and data prior to 2005.
Source: unpublished analysis from J. Trost, U.S. Geological Survey

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Method	Pre-2005			2005-2013		
	minimum	**mean**	**maximum**	**minimum**	**mean**	**maximum**
BFI	0.071	0.575	0.955	0.120	0.578	0.958
HYSEP fixed interval	0.257	0.708	0.957	0.241	0.702	0.960
HYSEP local minimum	0.226	0.642	0.955	0.196	0.633	0.954
HYSEP sliding	0.259	0.708	0.957	0.231	0.702	0.959
PART	0.064	0.711	0.965	0.058	0.710	0.966

Table 1. Comparison of Base Flow Index for 227 gages with at least 3 continuous years of daily streamflow data in two time periods: pre-2005 and 2005-2013. The gages are all in the U.S. portion of the Great Lakes Basin and were included in the Neff et al. (2005) analysis of base flow.
Source: Neff et al. (2005) and U.S. Geological Survey

Magnitude of change between time periods	Increase	Decrease
	Number of gages	
0 to 0.05 change	42	74
0.05 to 0.10 change	7	14
more than 0.10 change	4	1
Total	53	89

Table 2. Number of gages (grouped by the magnitude of the change) in which all 5 base flow separation methods indicated either an increase or decrease in Base Flow Index from pre-2005 to 2005-2013. These correspond to the red and blue points in figure 3.
Source: U.S. Geological Survey

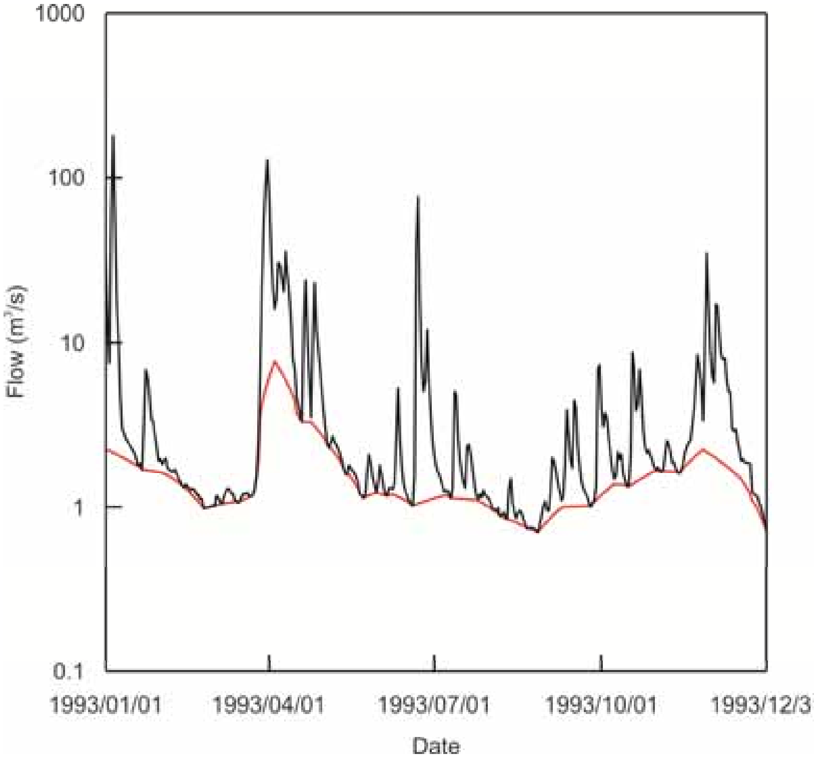

Figure 1. Hydrograph of observed total stream flow (black) and calculated base flow (red) for the Nith River at New Hamburg during 1993.
Source: Environment Canada and the U.S. Geological Survey.

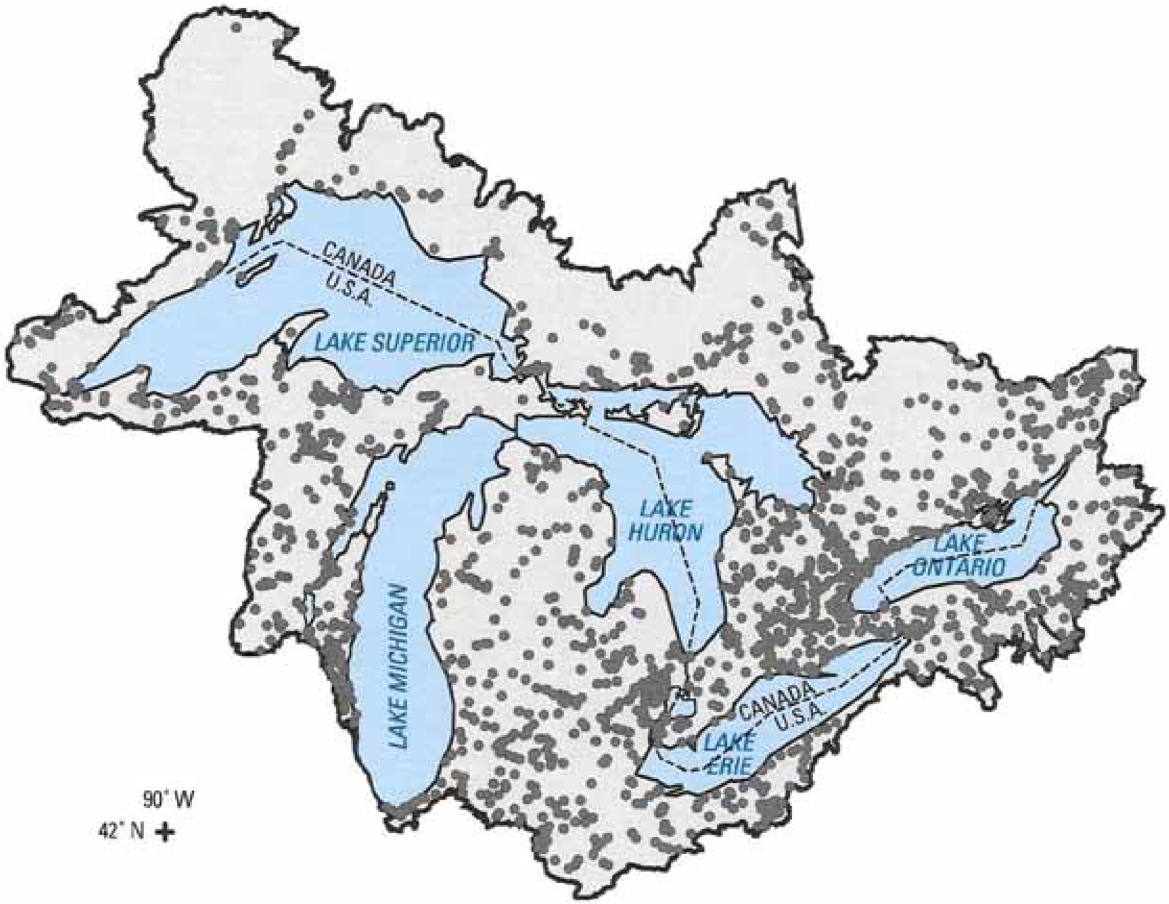

Figure 2. Location of gages with streamflow records used in Neff et al. (2005) to predict base flow in ungagged basins.
Source: Environment Canada and the U.S. Geological Survey (Neff et al., 2005).

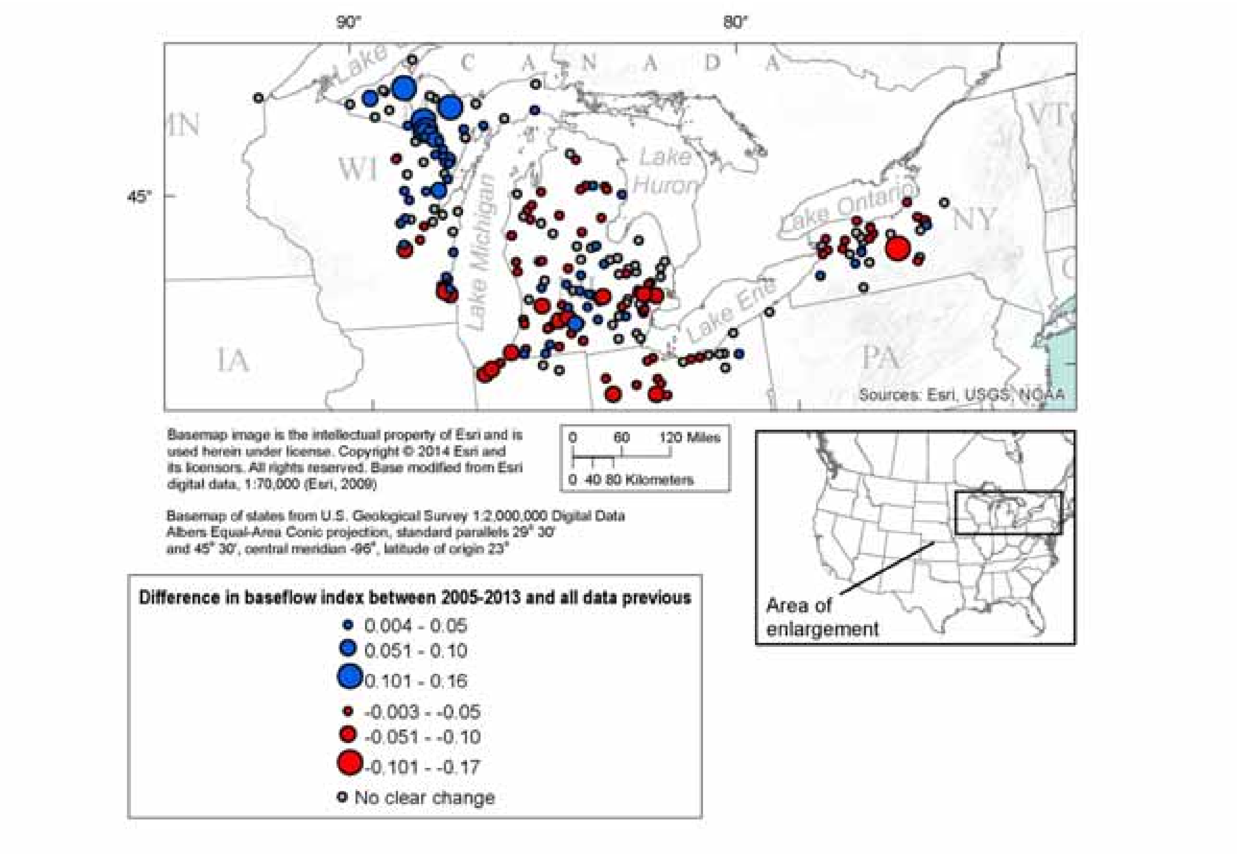

Figure 3. Difference in Base Flow Index for selected stream gages on the U.S. portion of the Great Lakes Basin for the period 2005-2013 and data prior to 2005.
Blue = higher in 2005-2013 than previous
Red = lower BFI in 2005-2013 compared to previous.
Source: unpublished analysis from J. Trost, U.S. Geological Survey

6. Conclusion & Overall Assessment Summary Table

The overall assessment for ecosystem conditions in the Great Lakes is **Fair** and the trend is **Unchanging** since the last assessment in 2011. Significant progress has been made to reduce toxic chemicals in the Great Lakes over the past 40 years. However, challenges exist including, excessive nutrient loadings to Lake Erie and other nearshore areas of the Great Lakes which are contributing to harmful and nuisance algae. And while the number of new invasive species entering the Great Lakes has been dramatically reduced, the impact and spread of existing invaders in the basin are posing significant consequences for the ecosystem. This overall assessment is based on the nine science-based indicators that assess water quality and ecosystem health. The assessment also takes into consideration climate trends (see table below). There are 44 sub-indicators that support the nine high-level indicators used for state of the Great Lakes reporting and are used to measure progress against the nine General Objectives of the Agreement.

Indicator	Sub-Indicator	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario	Overall Assessment
Drinking Water	Treated Drinking Water	No lake was assessed separately Great Lakes Basin assessment is **Good** and **Unchanging**					Good and Unchanging
Beaches	Beach Advisories	Unchanging	Unchanging	Unchanging	Deteriorating	Unchanging	Fair to Good and Unchanging
Fish Consumption	Contaminants in Edible Fish	Unchanging	Improving	Unchanging	Deteriorating	Improving	Fair and Unchanging
Toxic Chemicals	Toxic Chemical Concentrations	Improving	Unchanging	Unchanging	Unchanging	Unchanging	Fair and Unchanging to Improving
	Toxic Chemicals in Sediments	Unchanging	Unchanging	Unchanging	Improving	Improving	
	Toxic Chemicals in Great Lakes Whole Fish	Unchanging	Improving	Unchanging	Unchanging	Improving	
	Toxic Chemicals in Great Lakes Herring Gull Eggs	Improving	Improving	Improving	Unchanging	Unchanging	
	Atmospheric Deposition of Toxic Chemicals	No lake was assessed separately Great Lakes Basin assessment is **Fair** and **Improving**					
Habitat and Species	Coastal Wetland Amphibians	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging	Fair and Unchanging
	Coastal Wetland Birds	Unchanging	Unchanging	Unchanging	Deteriorating	Improving	
	Coastal Wetland Fish	No lake was assessed separately Great Lakes Basin assessment is **Fair** and **Improving**					
	Coastal Wetland Invertebrates	No lake was assessed separately Great Lakes Basin assessment is **Fair** and **Deteriorating**					
	Coastal Wetland Plants	Undetermined	Undetermined	Deteriorating	Deteriorating	Unchanging	
	Coastal Wetlands: Extent and Composition	No lake was assessed separately Great Lakes Basin assessment is **Undetermined**					
	Aquatic Habitat Connectivity	Improving	Improving	Improving	Improving	Improving	
	Phytoplankton	Unchanging	Deteriorating	Deteriorating	Deteriorating	Unchanging	
	Zooplankton	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging	
	Benthos	Unchanging	Unchanging	Unchanging	Deteriorating	Unchanging	
	Diporeia	Unchanging	Deteriorating	Deteriorating	Deteriorating	Deteriorating	
	Prey Fish	Unchanging	Deteriorating	Undetermined	Improving	Deteriorating	
	Lake Sturgeon	Improving	Improving	Improving	Improving	Improving	
	Walleye	Unchanging	Unchanging	Unchanging	Improving	Unchanging	
	Lake Trout	Unchanging	Improving	Improving	Improving	Improving	
	Fish Eating and Colonial Nesting Waterbirds	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging	
Nutrients and Algae	Nutrients in Lakes	Unchanging	Deteriorating	Deteriorating	Deteriorating	Deteriorating	Fair and Unchanging to Deteriorating
	Cladophora	Unchanging	Undetermined	Undetermined	Undetermined	Undetermined	
	Harmful Algal Blooms	Undetermined	Undetermined	Undetermined	Deteriorating	Deteriorating	
	Water Quality in Tributaries	Unchanging	Undetermined	Unchanging	Unchanging	Unchanging	
Invasive Species	Impacts of Aquatic Invasive Species	Deteriorating	Deteriorating	Deteriorating	Deteriorating	Deteriorating	Poor and Deteriorating
	Dreissenid Mussels	Unchanging	Deteriorating	Deteriorating	Improving	Deteriorating	
	Sea Lamprey	Improving	Improving	Improving	Improving	Unchanging	
	Terrestrial Invasive Species	Deteriorating	Deteriorating	Deteriorating	Deteriorating	Deteriorating	
Groundwater	Groundwater Quality	Undetermined	Undetermined	Undetermined	Undetermined	Undetermined	Fair and Undetermined
Watershed Impacts and Climate Trends	Forest Cover	Unchanging	Unchanging	Unchanging	Improving	Deteriorating	Fair and Unchanging
	Land Cover	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging	
	Watershed Stressors	Unchanging	Unchanging	Unchanging	Unchanging	Unchanging	
	Hardened Shorelines	Undetermined	Undetermined	Undetermined	Undetermined	Deteriorating	
	Tributary Flashiness	No lake was assessed separately Great Lakes Basin trend is **Unchanging**					
	Human Population	Decreasing	Increasing	Increasing	Increasing	Increasing	
Watershed Impacts and Climate Trends	Precipitation Amounts (1948-2015)	No lake was assessed separately Great Lakes Basin trend is ↑					No Overall Assessment
	Surface Water Temperature (1979/1980-2014)	↑	↑	↑	Undetermined	Undetermined	
	Ice Cover (1973-2015)	↓	↓	↓	↓	↓	
	Water Levels (1985-2015)	↓	↓	↓	↓	No significant change	
	Baseflow Due to Groundwater	No lake was assessed separately Great Lakes Basin trend is **Undetermined**					

Status: GOOD | FAIR | POOR | UNDETERMINED

7. Acknowledgements

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The ***State of the Great Lakes 2017*** preparation team included:

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Individual authors and contributors are recognized at the end of their respective report component.
We recognize the participation of the following organizations as authors and members of the Ecosystem Indicators and Reporting Task Team who have contributed invaluable advice and support in the development of the State of the Great Lakes 2017 products.

Appendix 1 – Data Quality

Environment and Climate Change Canada and U.S. Environmental Protection Agency staff seek to disseminate the highest quality information available to a wide variety of environmental managers, policy officials, scientists and other interested public. The importance of the availability of reliable and useful data is implicit in the State of the Great Lakes reporting process.

To ensure that data and information made available to the public by federal agencies adhere to a basic standard of objectivity, utility, and integrity, the U.S. Office of Management and Budget issued a set of Guidelines in 2002 (OMB 2002). Subsequently, other U.S. federal agencies have issued their own guidelines for implementing the OMB policies. According to the Guidelines issued by the U.S. Environmental Protection Agency (U.S. EPA 2002), information must be accurate, reliable, unbiased, useful and uncompromised though corruption or falsification.

Other assessment factors (U.S. EPA 2003) that are typically taken into account when evaluating the quality and relevance of scientific and technical information include:

• **Soundness** - the extent to which the scientific and technical procedures, measures, methods or models employed to generate the information are reasonable for, and consistent with, the intended application
• **Applicability and Utility** - the extent to which the information is relevant for the intended use
• **Clarity and Completeness** - the degree of clarity and completeness with which the data, assumptions, methods, quality assurance, sponsoring organizations and analyses employed to generate the information are documented
• **Uncertainty and Variability** - the extent to which the variability and uncertainty (quantitative and qualitative) in the information or in the procedures, measures, methods or models are evaluated and characterized
• **Evaluation and Review** - the extent of independent verification, validation and peer review of the information or of the procedures, measures, methods or models

Recognizing the need to more formally integrate concerns about data quality into the State of the Great Lakes reporting process, organizers developed a Quality Assurance Project Plan (QAPP). The QAPP recognizes that, as an entity, does not directly measure any environmental or socioeconomic parameters.

Existing data are contributed by cooperating federal, state and provincial environmental and natural resource agencies, non-governmental environmental agencies or other organizations engaged in Great Lakes monitoring. Additional data sources may include local governments, planning agencies, and the published scientific literature. Therefore, State of the Great Lakes reporting relies on the quality of datasets reported by others.

Characteristics of datasets that would be acceptable for indicator reporting include:
• Data are documented, validated, or quality-assured by a recognized agency or organization.
• Data are traceable to original sources.
• The source of the data is a known, reliable and respected generator of data.
• Geographic coverage and scale of data are appropriate to the Great Lakes Basin.
• Data obtained from sources within the United States are comparable with those from Canada.

Additional considerations include:
• Gaps in data availability should be identified if datasets are unavailable for certain geographic regions and/or contain a level of detail insufficient to be useful in the evaluation of a particular sub-indicator.
• Data should be evaluated for feasibility of being incorporated into sub-indicator reports. Attention should be given to budgetary constraints in acquiring data, type and format of data, time required to convert data to usable form, and the collection frequency for particular types of data.

State of the Great Lakes reporting relies on a distributed system of information in which the data reside with the original providers. Although data reported through this process are not centralized, clear links for accessibility of the data and/or the sub- indicator authors are provided. The authors hold the primary responsibility for ensuring that the data used are adequate for sub-indicator reporting. *Users of the sub-indicator information, however, are obliged to evaluate the usefulness and appropriateness of the data for their own application, and they are encouraged to contact the authors with any concerns or questions.*

Appendix 2 – Status and Trend Definitions for State of the Great Lake Reporting

Status and Trend Definitions for State of the Great Lakes 2017 Reports

Below are generic definitions for the terms used to assess the sub-indicators and indicators in the suite. Specific language for these terms is included in each complete sub-indicator report included in Chapter 5 of this document.

STATUS Terms	
GOOD	Most or all ecosystem components are in acceptable condition.
FAIR	Some ecosystem components are in acceptable condition.
POOR	Very few or no ecosystem components are in acceptable condition.
UNDETERMINED	Data are not available or are insufficient to assess condition of the ecosystem components.

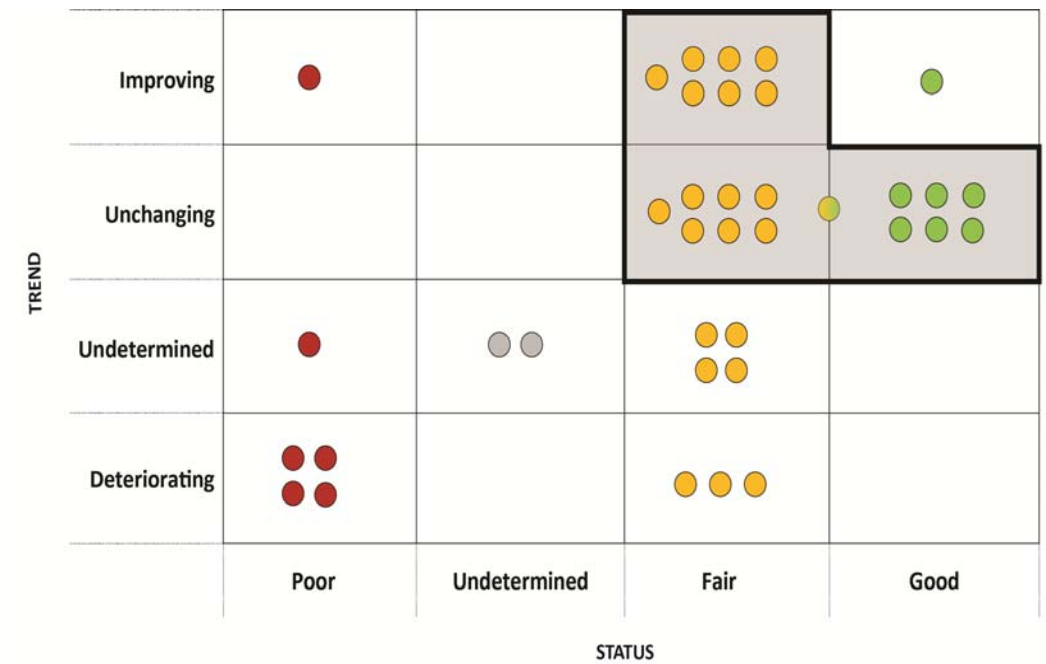
TREND Terms	
IMPROVING	Metrics show a change toward more acceptable condition.
UNCHANGING	Metrics generally show no overall change in condition.
DETERIORATING	Metrics show a change away from acceptable condition.
UNDETERMINED	Metrics do not indicate a clear overall trend, or data are not available to report on a trend.

Climate information is not assessed in the same manner as other indicators in this report. For example, the ecosystem has adapted to and needs both high and low water levels and neither condition can be assessed as Good or Poor. However, prolonged periods of high or low water levels may cause stress to the ecosystem. Therefore, climate trends are simply assessed as Increasing, Unchanging or Decreasing over a defined period of time. In addition to the climate trends sub-indicators, there are two additional sub-indicators that are assessed using the trend analysis noted here, i.e. Tributary Flashiness and Human Population, for a similar explanation as noted above, that increasing or decreasing flashiness or population cannot be assessed as Good or Poor.

INCREASING	Indicator metric is increasing.
DECREASING	Indicator metric is decreasing.
UNCHANGING	Indicator metric has not changed over time.
UNDETERMINED	Data are not available to report on a trend.

Appendix 3 – Tracking Progress: Another Perspective

The overall assessment for the Great Lakes is **Fair** and **Unchanging**, however, the assessments of the sub-indicators can also be plotted individually to show that most of the results fall within the shaded zone of Fair and Improving, Fair and Unchanging, and Good and Unchanging. Summarizing the information in this manner shows an alternate way to track progress. The goal is to see more sub-indicators assessed in the upper right zone of the chart. Note that the figure includes 37 sub-indicator assessments as the remaining 7 sub-indicators are not assessed in this same manner.



Appendix 4 – Acronyms and Abbreviations

Agencies and Organizations
ATSDR – Agency for Toxic Substances and Disease Registry
CAMNet – Canadian Atmospheric Mercury Network
CCFM – Canadian Council of Forest Ministers
CCME – Canadian Council of Ministers of the Environment
CDC – Center for Disease Control (U.S.)
CHS – Canadian Hydrographic Service
CIS – Canadian Ice Service
CMI-CWF – Clean Michigan Initiative-Clean Water Fund
CORA – Chippewa Ottawa Resource Authority
CWS – Canadian Wildlife Service
DFO – Department of Fisheries and Oceans Canada
EC – Environment Canada
ECCC – Environment and Climate Change Canada
ECO – Environmental Careers Organization
EDDMapS – Early Detection & Distribution Mapping System
EIA – Energy Information Administration (U.S.)
EMAN – Ecological Monitoring and Assessment Network
GLBET – Great Lakes Basin Ecosystem Team (USFWS)
GLC – Great Lakes Commission
GLCWC – Great Lakes Coastal Wetlands Consortium
GLFC – Great Lakes Fishery Commission
GLNPO – Great Lakes National Program Office (U.S. EPA)
IJC – International Joint Commission
IUCN – International Union for the Conservation of Nature
LEC – Great Lakes Fishery Commission's Lake Erie Committee
LEPMAG – Lake Erie Percid Management Advisory Group
LSSU – Lake Superior State University
MDEQ – Michigan Department of Environmental Quality
MDNR – Michigan Department of Natural Resources
NAPS – National Air Pollution Surveillance (EC)
NDBC – National Data Buoy Centre
NHEERL – National Health & Environmental Effects Research Laboratory (U.S. EPA)
NISC – National Invasive Species Council
NOAA – National Oceanic and Atmospheric Administration
NOS – National Ocean Service
NRCan – Natural Resources Canada
NRCS – Natural Resources Conservation Service (USDA)
NRRI – Natural Resources Research Institute (University of Minnesota – Duluth)
NYSDEC – New York State Department of Environmental Conservation
NYSOGS – New York State Office of General services
ODNR – Ohio Department of Natural Resources
ODW – Ohio Division of Wildlife
OGS – Ontario Geological Survey
OIPIS – Ontario Invasive Plant Information System
OMAF – Ontario Ministry of Agriculture and Food (now OMAFRA, see below)
OMAFRA – Ontario Ministry of Agriculture, Food and Rural Affairs

OMOE – Ontario Ministry of Environment
OMOECC – Ontario Ministry of the Environment and Climate Change
OMNRF – Ontario Ministry of Natural Resources and Forestry
OSCIA – Ontario Soil and Crop Improvement Association
ORISE – Oak Ridge Institute for Science and Education
PDEP – Pennsylvania Department of Environmental Protection
REMAP – Regional Environmental Monitoring and Assessment Program (U.S.)
STC – Standing Technical Committee
TNC – The Nature Conservancy
UKIH – United Kingdom Institute of Hydrology
USACE – United States Army Corp of Engineers
USDA – U.S. Department of Agriculture
USEPA – U.S. Environmental Protection Agency
USFDA – U.S. Food and Drug Administration
USFWS – U.S. Fish and Wildlife Service
USFS – U.S. Forest Service
USGS – U.S. Geological Survey
WBCSD – World Business Council for Sustainable Development
WDNR – Wisconsin Department of Natural Resources
WiDPH – Wisconsin Department of Public Health
WWF – World Wildlife Fund (Canada)

Units of Measure
C – Celsius
Cfu – colony forming units
cm – centimeter (centimetre), 10^{-2} meters (metres)
Chl a – chlorophyll a, a measure of phytoplankton biomass
F – Fahrenheit
Fg – femptogram, 10^{-15} gram
ft – feet (British system)
g Dw m-2 – grams dry weight per meter (metre) squared
g m-2 – grams per meter (metre) squared (areal biomass)
ha – hectare, 10,000 square meters (metres)
lbs – pounds (British system)
kg – kilogram, 1000 grams
km – kilometer (kilometre)
kt – British kiloton: $2x10^6$ pounds; metric kilotonne: 10^6 kg or $2.2x10^6$ pounds
kWh – kilowatt-hour
m – meter (metre)
mg – milligram, 10^{-3} gram
MGD – Million Gallons per Day (3785.4 m^3 per day)
mg m^{-3} – milligram per cubic meter (metre), volumetric biomass
mg/kg – milligram per kilogram, part per million
mg/l – milligram per liter (litre)
ml – milliliter (millilitre), 10^{-3} liter (litre)
MLD – Million Liters (Litres) per Day (1000 m^3 per day)
mm – millimeter (millimetre), 10^{-3} meter (metre)
MWh – megawatt-hour
ng – nanogram, 10^{-9} gram

ng/g – nanogram per gram, part per billion
ng /g dw – nanogram per gram, dry weight
ng/l – nanogram per liter (litre)
pg – picogram, 10^{-12} gram
pg/m3 – picogram per cubic meter (metre)
pH – per Hydrogen (a unit of acidity)
ppb – part per billion
ppm – part per million
ton – British ton, 2000 lb
tonne – metric tonne, 1000 kg
µg – microgram, 10^{-6} gram
µg/g – microgram per gram, part per million
µg/l – microgram per liter (litre)
µg/m3 – microgram per cubic meter (metre)
µm – micrometer (micrometre), micron, 10^{-6} meter (metre)
ww – wet weight

Imperial to Metric conversion chart

Imperial → Metric
1 inch = 2.54 centimeters (centimetres)
1 gallon = 3.8 liters (litres)
1 ounce = 28.35 grams
1 fluid ounce = 29.57 milliliters (millilitres)
1 mile = 1.6 kilometers (kilometres)
1 pound = 0.45 kilogram (450 grams)
1 Fahrenheit= -17.21 Celsius

Chemicals, Nutrients & Bacteria
2,4-D – 2,4-dichlorophenoxyacetic acid
2,4,5-T – 2,4,5-trichlorophenoxyacetic acid
AFFF – Aqueous film forming foam
ALA – a-linolenic acid
ATE—ally-2,4,6-tribromophenyl ether
BaP – Benzo[α]pyrene
BDE – Brominated diphenyl ethers
BFR – Brominated flame retardants
cHAB – cyanobacteria-based harmful algal blooms
CO – Carbon monoxide
DBDPE – decabromodiphenylethane
DDC – syn-Dechlorane Plus
DDT – 1,1,1-trichloro-2,2-bis(p-chlorophenyl) ethane or dichlorodiphenyl-trichloroethane
DDD – 1,1-dichloro-2,2-bis(p-chlorophenyl) ethane
DDE – 1,1-dichloro-2,2-bis(chlorophenyl) ethylene or dichlorodiphenyl-dichloroethene
DHA – Docosahexaenoic acid
DOC – Dissolved organic carbon
anti-DP – anti-Dechlorane Plus

syn-DP – syn-Dechlorane Plus
EPA – Eicosapentaenoic acid
HABs – Harmful Algal Blooms
HBB –Hexabromobenzene
HBCDD – Hexabromocyclododecane
HCB – Hexachlorobenzene
α-HCH – Hexachlorocyclohexane
γ-HCH – Lindane
HE – Heptachlor epoxide
Hg – Mercury
HxBDE – Sum-hexabrominated diphenyl ethers
NAB – Nuisence Algal Blooms
MCs – Microcystins
MCPCAs – Medium chain polychlorinated alkanes
MeHg – Methylmercury
MIB – 2-methylisoborneol
NAPH – Naphthalene
NO2 – Nitrogen dioxide
NO_3:TP – Nitrogen trioxide
NO_X – Nitrogen oxides
NPE – Polychlorinated alkanes
O_3 – Ozone
OC – Organochlorine
OCS – Octachlorostyrene
OCPs – Organochlorine pesticides
PAH – Polynuclear aromatic hydrocarbons
PBDE – Polybrominated diphenyl ether
PBEB – [pentabromoethyl benzene
PCA – Polychlorinated alkanes
PCB – Polychlorinated biphenyls
PCDD – Polychlorinated dibenzo-p-dioxin
PCDDF – Polychlorinated dibenzo furan
PCN – Polychlorinated naphthalenes
PeBDE – Sum-pentabrominated diphenyl ethers
PFAA – Perfluoroalkyl acids
PFBA – Perfluorobutanoic acid
PFBS – Perfluorobutane sulfonate
PFC – Perfluoroalkyl Compounds
PFDA – Polychlorinated alkanes
PFDoA – Polychlorinated alkanes
PFDS – Polychlorinated alkanes
PFOA – Perfluorooctanoic acid
PFOS – Perfluorooctanyl sulfonate
PFSA – Perfluoroalkyl sulfonate acids
PFTrA – Perfluorotridecanoic acid
PFUnA – Perfluoroundecanoic acid
PHC – Polyhalogenated carbazoles
POP- Persistent organic pollutants
PM_{10} – Atmospheric particulate matter of diameter 10 microns or smaller

$PM_{2.5}$ – Atmospheric particulate matter of diameter 2.5 microns or smaller
PPCP – Pharmaceuticals and personal care products
PUFA – Polyunsaturated fatty acid
SCPCA – Short chain polychlorinated alkanes
SO2 – Sulfur dioxide
SPCB – Suite of PCB congeners that include most of PCB mass in the environment
SRP:TP – Soluble Reactive Phosphorus: Total Phosphorous
TBB – 2-ethylhexyl-2,3,4,5-tetrabromobenzoate
TBE – 1,2-bis(2,4,6-tribromophenoxy)ethane
TBPH – bis(2-ethylhexyl)-tetrabromophthalate
TCDD – Tetrachlorodibenzo-p-dioxin
TCE – Trichloroethylene
TDS – Total dissolved solids
TDP –Total Dissolved Phosphorous
TeBDE – Sum-tetrabrominated diphenyl ethers
TFN – 3-trifluoromethyl-4'-nitrophenol
TGM – Total gaseous mercury
TOC – Total organic carbon
TON – Total Oxidized Nitrogen
TRS – Total reduced sulfur
VOC – Volatile organic compound

Reports, Programs, Policies and Guidelines
APF – Agricultural Policy Framework (Canada)
ARET – Accelerated Reduction/Elimination of Toxics program (Canada)
BOB – Ballast On Board (also Upbound Transoceanic Ballasted vessels)
BEACH – Beaches Environmental Assessment and Coastal Health (U.S. Act of 2000)
BEACON – Beach Advisory and Closing On-line Notification
CEPA – Canadian Environmental Protection Act, 1999
CHT – Contaminants in Human Tissue program (part of EAGLE)
CSMI – Cooperative Science Monitoring Initiative
CWM – Coastal Wetland Monitoring Program
DWSP – Drinking Water Surveillance Program (Canada)
EFP – Environmental Farm Plan (Ontario)
FEQG – Federal Environmental Quality Guidelines (Canada)
GAP – Gap Analysis Program (land cover assessment)
GLAHF – Great Lakes Aquatic Habitat Framework
GLANSIS – Great Lakes Aquatic Nonindigenous Species Information
GLHGMP – Great Lakes Herring Gull Monitoring Program
GLRI – Great Lakes Restoration Initiative (USEPA)
GLMMP – Great Lakes Marsh Monitoring Program
GLWQA – Great Lakes Water Quality Agreement
GRDI – Genomic Research and Development Initiative
HGEMP – Herring Gull Egg Monitoring Program
IADN – Integrated Atmospheric Deposition Network
LAMP – Lakewide Action and Management Plan
LHBP – Lake Huron Binational Program
MMP – Marsh Monitoring Program
NAFTA – North America Free Trade Agreement

NATA – National Air Toxics Assessment (U.S.)
NEEAR – National Epidemiological and Environmental Assessment of Recreational [Water Study]
NMAN – Nutrient Management Planning software (Ontario)
NISA – National Invasive Species Act (U.S.)
NMP – Nutrient Management Plan (Ontario)
NPRI – National Pollutant Release Inventory (Canada)
NRVIS – Natural Resources and Values Information System (OMNRF)
ODWQS – Ontario Drinking Water Quality Standard
PGMN – Provincial Groundwater-Monitoring Network (Ontario)
PWQO – Provincial Water Quality Objectives
RAP – Remedial Action Plan
SIP – State Implementation Plan
SOGL – State of the Great Lakes
SOLEC – State of the Lakes Ecosystem Conference
SOLRIS – Southern Ontario Land Resource Information System
SWMRS – Seasonal Water Monitoring and Reporting System (Canada)
WISCLAND – Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data
WIC – Women Infant and Child (Wisconsin health clinics)

Other
AAQC – Ambient Air Quality Criterion (Ontario)
AFO – Animal Feeding Operation
AHCCD – Adjusted and Homogenized Canadian Climate Data
AIS – Aquatic Invasive Species
ALB – Asian Longhorned Beetle
AMIC – Annual Maximum Ice Coverage
AMO – Atlantic Multi-decadal Oscillation
AOC – Area of Concern
AOU – Area of the Undertaking
AQI – Air Quality Index
BA – Abnormal Barbels
BAV – Beach Action Value
BKD – Bacterial Kidney Disease
BMP – Best Management Practices
BOD – Biochemical Oxygen Demand
BR – Biotic Response
BUI – Beneficial Use Impairments
CAFO – Concentrated Animal Feeding Operations
CANGRD – Canadian Gridded Temperature and Precipitation Anomalies Dataset
CBT – Caffeine Breath Test
CC/WQR – Consumer Confidence/Water Quality Report
CCR – Consumer Confidence Report
CESI – Canadian Environmental Sustainability Indicators
CEC – Chemicals of Emerging Concern
CEPA – Canadian Environmental Protection Act, 1999
CMA – Census Metropolitan Area (Canada)
CMC – Chemicals of Mutual Concern
CSO – Combined Sewer Overflow
CSSC – Chicago Sanitary Ship Canal

CUE – Catch per Unit of Effort
DJF – December, January, February – meteorological Winter
DNA – Deoxyribonucleic acid
eDNA – Environmental Deoxyribonucleic acid
DRP – Dissolved Reactive Phosphorus
DWS – Drinking Water System (Canada)
EAB – Emerald ash borer
EAGLE – Effects on Aboriginals of the Great Lakes program (Canada)
EAPI – External Anomaly Prevalence Index
ENSO – El Nino Southern Oscillation
EMS – Early Mortality Syndrome
EO – Element Occurrence
EPR – Extended Producer Responsibility
ESV – Early Successional Vegetation
FCGO – Fish Community Goals and Objectives
FCO – Fish Community Objectives
FD – Focal Discoloration
FIADB – Forest Inventory and Analysis Database (USDA Forest Service)
FEPS – Flood Erosion Prediction System
FQI – Floristic Quality Index
FRs – Flame Retardants
FTU – Formazin Turbidity Unit
GBBG – Great Black-backed Gull
GCMs – Global Circulation Models
GHG – Greenhouse Gases
GIA – Glacial Isostatic Adjustment
GIS – Geographic Information System
GLATOS – Great Lakes Acoustic Telemetry Observation System
GLB – Great Lakes Basin
GLEI – Great Lakes Environmental Indicators
GMO – Genetically Modified Organisms
HABs – Harmful Algal Blooms
HUC – Hydrologic Unit Code
IBI – Index of Biotic Integrity
IEC – Index of Ecological Condition
IGLD – International Great Lakes Datum (water level)
IMAC – Interim Maximum Acceptable Concentration
IPM – Integrated Pest Management
ISA – Impervious Surface Area
ISSA – Invasive Species System Approach
IUGLS – International Upper Great Lakes Study
IWM – Integrated Watershed Management
JJA – June, July, August - meteorological Summer
LE – Lesion
LEL – Lowest Effect Level
LOSL – Lake Ontario and upper St. Lawrence River
LU/LC – Land use/Land cover
MAC – Maximum Acceptable Concentration
MACT – Maximum Available Control Technology

MAM – March, April, May - meteorological Spring
MCL – Maximum Contaminant Level
MEI – Modified Environmental Index
MDR – Mean Deviation Ratio
MRDL – Maximum Residual Disinfectant Level
MSA – Metropolitan Statistical Area (U.S.)
MSWG – Municipal Solid Waste Generation
NAO – North Atlantic Oscillation
NCCA – National Coastal Condition Assessment
NLCD – National Land Cover Dataset
NOAEC – No Observable Adverse Effect Concentrations
NOAEL – No Observable Adverse Effect Level
NOBOB – No Ballast On Board (also Cargo Laden vessels)
NTU – Nephelometric Turbidity Units
OIT – Organisms in Trade
OTI – Oligochaete Trophic Index
PBT – Persistent Bioaccumulative Toxic (chemical)
PCA – Principal Components Analysis
PDO – Pacific Decadal Oscillation
PEL – Probable Effect Level
PICA – Priority Island Conservation Areas
PNP – Permit Nutrient Plans (U.S.)
RBI – Richards-Baker Flashiness Index RG – Raised Growths
RWQC – Recreational Water Quality Criteria
SDWIS – Safe Drinking Water Information System (U.S.)
SON – September, October, November - meteorological Autumn
SPP. or spp. – Species
SQI – Sediment Quality Index
SSO – Sanitary Sewer Overflow
STAR – Science to Achieve Results
SUV – Sport Utility Vehicle
TAC – Total Allowable Catch
TCC – Total Category Change
TCR – Total Coliform Rule
TDI – Tolerable Daily Intake
TEQ – Toxic Equivalent
TIGER – Topological Integrated Geographic Encoding and Reference (U.S. Census Bureau)
TIS – Terrestrial Invasive Species
TM – Thematic Mapper
T&O – Taste and odour
TRI – Toxics Release Inventory (U.S.)
TT – Treatment Technique
UNECE – United Nations Economic Commission for Europe
VGI – Volunteer Geographic Information
VKT – Vehicle Kilometers Traveled
WQI – Water Quality Index
WTP – Water Treatment Plant
WWTP – Waste Water Treatment Plant
YOY – Young-of-year