Monitoring the Human Health Consequences of Climate Change in the Great Lakes

A report submitted to the International Joint Commission by the Health Professionals Advisory Board

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Prepared for the International Joint Commission Health Professionals Advisory Board
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Foreword

Globally, summer 2024 was the hottest on record,[1] accompanied by heat waves, wildfires, drought, violent storms, and changing plant and animal communities. These directly cause human deaths and injuries, but many more lives are affected by complex downstream effects on ecosystem, water, food, land use, infrastructure, economic, health and emergency response systems. Prompt adaptation and response planning can save lives, especially if we can predict where they are most needed. More lives might be saved by prompt mitigation of greenhouse-gas induced climate change, but progress on this larger scale has been limited.

The Laurentian Great Lakes region experiences these climate change impacts as well, but to date, predictive models are less certain, given the local influence of the enormous lakes and coastal interactions between land and surface waters. The Great Lakes basin is also inhabited by a massive human population distributed across urban, suburban, rural and forested areas, limiting generalizations about human health effects in a particular location. People in the region are experiencing health effects of climate change today, but who, where, and when is partly a matter of local geography, weather, and human vulnerability, infrastructure and planning.

This report posits that measuring and tracking climate-related environmental change, health hazards, and human health outcomes in the many coastal communities ringing the Great Lakes can help improve future modeling, planning and prevention of death, injury and disease. It could identify communities at higher risk, and strategies that better manage risks compared to comparable neighbors. Such tracking can also inform lakewide and basinwide efforts to mitigate, adapt and respond to water quality, water levels and water temperatures. The binational nature of such learning and management places this issue directly in scope of the International Joint Commission (IJC) and the Canada-United States Great Lakes Water Quality Agreement (GLWQA). The IJC's Health Professionals Advisory Board (HPAB) has already gained considerable binational experience from an earlier set of proposed human health indicators related to water quality (Bassil et al. 2015, Graydon et al. 2022, International Joint Commission Health Professionals Advisory Board 2014, 2017, 2021).

What to measure?

This report includes a review of the literature on human health effects related to the aquatic aspects of climate change, and three case studies that illustrate the complex interactions between climate, environment, health hazards and health effects. This informed the construction of a conceptual model that maps the complex cascade from weather change to actual human disease or injury. If we simultaneously measure weather patterns, related environmental changes, resulting hazard exposures, and ultimately human health effects, while also accounting for local variations in human mitigation, adaptation, resilience and vulnerability, we can begin to model health outcomes and which interventions might be most important. It is important to note that the conceptual model was limited to a few major

[1] Reuters 2024. "Summer of 2024 was world's hottest on record, EU climate change monitor says" reuters.com/business/environment/summer-2024-was-worlds-hottest-record-eu-climate-change-monitor-says-2024-09-06/.

climate inputs, and further by lack of knowledge about complex interactions like shoreline effects on heat waves, air quality and groundwater, thus it must be considered incomplete, and likely would be extended in future iterations.

From the conceptual model it was possible to identify a set of metrics appropriate to reflect the status and trends of each shoreline community. Those metrics that appear plausible to implement in the near-term were included. Since both our conceptual model and data availability will likely improve with time, this initial set of indicators are considered partial and will iteratively change.

Figure 1. Simplified graphic of the conceptual model of the cascade of climate-health interactions in the Great Lakes.

How to assemble

A large proportion of the indicator data needed are collected in some form today (such as climate, water quality, and disease data), but the owners of such data are distributed across federal, state, local and Tribal/First Nations governments, academic and other institutions. These agencies have different missions and foci (health, environment, water infrastructure, etc.). Thus, considerable work lies ahead to establish data use agreements, collect the information on an ongoing basis, and collate and disseminate data for scientists, policy-makers and the public. We are inspired in part by the success of the *Lancet Countdown on Health and Climate Change*,[2] which provides a global model for similar goals. We believe the IJC holds vital roles to acknowledge the importance of the task, convene binational partners including the Parties to the GLWQA (Canada and the United States), highlighting insights from these metrics in reports such as the GLWQA Triennial Assessment of Progress, and identifying a trusted and skilled data aggregator/disseminator. The report identifies the Great Lakes Observing System[3] as an appropriate type of organization for the latter task. Again, the evolution of monitoring will be iterative and multi-year, beginning with low-hanging fruit and highest priorities.

Next steps

The vision for this work is to lay the foundation towards developing fulsome indicators that the Parties to the GLWQA could include in their framework for reporting on the status and trend of Great Lakes health and water quality through the governments' triennial State of the Great Lakes reports. To that end, the Parties, states and provinces, First Nations and Tribal governments, watershed management agencies, local governments, academic partners and the public may all have an interest in how this report could contribute to progress reporting and management under the GLWQA to better understand climate/health interactions, the importance of ongoing monitoring of indicators, and the risks of and solutions to climate-induced health threats.

The board, in cooperation with IJC Great Lakes advisory boards, may consider future work to further develop a small number of near-to-ready indicators to the point of implementation. Other areas of focus for potential future work could include: an iterative process for improving the indicators based on evolving understanding and data availability; identifying stewards for individual metrics to help promote data collection, quality and analysis; and identifying a central hub for managing and disseminating indicator data.

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[2] The Lancet, 2023. thelancet.com/countdown-health-climate.
[3] Great Lakes Observing System. glos.org.

Table of Contents

Supplemental Materials of Appendices available at:
ijc.org/sites/default/files/HPAB_HumanHealthConsequencesofClimateChange_SupplementalMaterials__2024.pdf

List of Acronyms

AGI	acute gastrointestinal illness
CDC	(US) Centers for Disease Control and Prevention
CSO	combined sewer overflow
ECCC	Environment and Climate Change Canada
GLISA	Great Lakes Integrated Sciences and Assessments
GLWQA	Great Lakes Water Quality Agreement
HAB(s)	harmful algal bloom(s)
HPAB	Health Professionals Advisory Board
IJC	International Joint Commission
NOAA	US National Oceanic and Atmospheric Administration
USEPA	US Environmental Protection Agency

List of Tables

List of Figures

Acknowledgments

The International Joint Commission (IJC) Health Professionals Advisory Board (HPAB) appreciates the contributions of those who participated in the project workshop (listed in the Supplemental Materials), and those who prepared materials over many years that were reviewed, referenced or reproduced in the completion of this project. Members of this project team participated in their professional expert capacities, but the conclusions, recommendations, findings, and opinions expressed in this report do not necessarily represent those of all members, their employers, affiliated organizations or funders. Any use of product, company, or organization names or citation of references and resources is for information or descriptive purposes only and does not represent endorsement.

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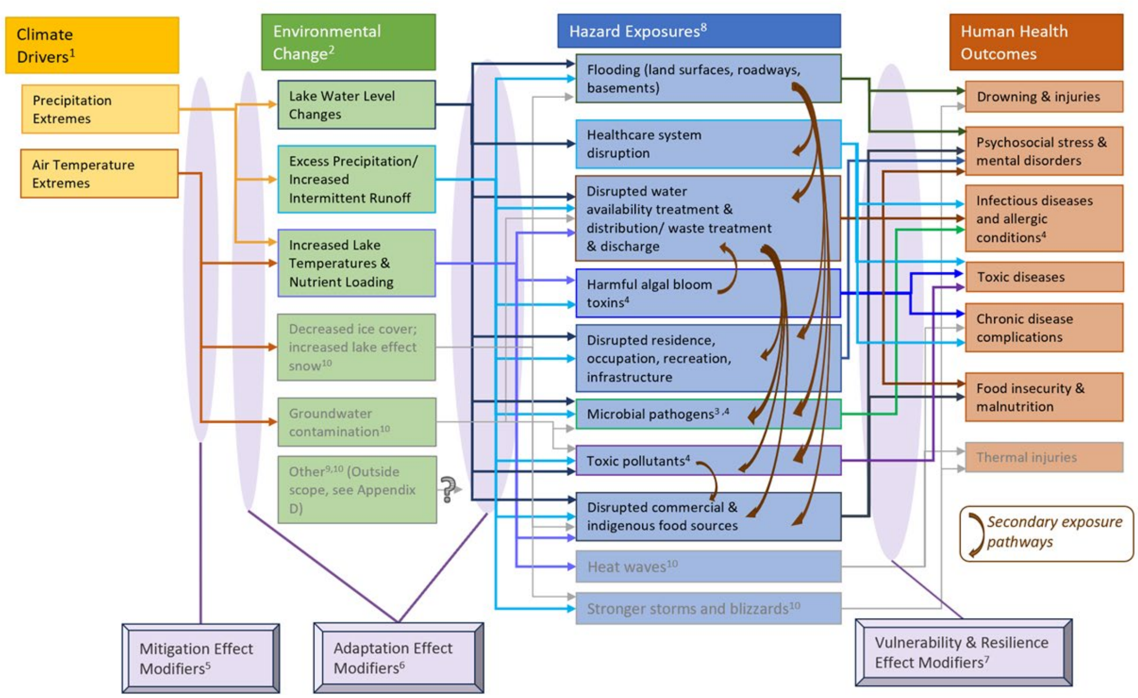
Cover images

Left: Flooding on I-94, June 2021. Credit: Michigan State Police via weather.gov.
Center: Sleeping Bear Dunes National Lakeshore, MI. Credit: Srikanth Peetha via Unsplash.
Right: Lake Erie green waters at the beach with a buoy marking swim area. Credit: USGS, Upper Midwest Water Science Center.

Executive Summary

The International Joint Commission (IJC), through a work group of its Health Professionals Advisory Board (HPAB), is working to develop measurable human health indicators related to climate-driven environmental changes in the Great Lakes basin. The board intends to use these indicators to highlight the relationship of international water management to health resilience in the face of climate change. The indicators are intended to be quantitative measures of human health impacts from climate-related events. As quantitative measures, they can be monitored over time and used to inform adaptive strategies in the Great Lakes basin.

The HPAB work group, in collaboration with a contractor team, performed a literature review, developed a conceptual model (**Figure 2**) and completed an initial assessment of available data and potential indicators in late 2022 through early 2024. The study group concluded that although the state of data and analysis is not yet sufficient to support all desired indicators, substantial information to potentially link climate change drivers more strongly to human health outcomes in the region of interest do exist. The IJC and its HPAB can continue to play key roles in refining indicators and advancing efforts to enhance human health resilience in the face of climate pressures. Findings, gaps, and recommendations resulting from this assessment are described briefly here. See Section 3 of the report for additional details on the conceptual model.



[1]Selected; other climate effects not included. [2]Selected; other environmental changes that are not the focus of this report are included in Supplemental Materials Appendix D with discussion. [3]Includes viral, bacterial, fungal/mold, protozoa. [4]Ingestion, inhalation and dermal exposures. [5]E.g., greenhouse gas reductions. [6]Plans and designs to minimize impacts or exposures. [7]Factors that increase exposures (e.g., residence in flood plain) of effects (e.g., immunodeficiency) and factors that improve capability to recovery (e.g., adequate income, healthcare, psychological resilience). These may occur at the individual or population levels. [8]Note: one type of exposure may create secondary exposures. [9]Other factors include, but are not limited to, lake thermal stratification changes, lake acidification, changed species distributions (including disease vectors) and migrations, coastal weather changes (e.g., inversions). [10]Additional discussion in Supplemental Materials Appendix D.

Figure 2. Conceptual model of climate-health interactions.

Recommended climate change-related human health indicators

Table 1 summarizes the proposed indicators, along with key information for each. Indicators listed in the table are categorized into the four groups described in the conceptual model (climate drivers, environmental change, human risk exposures, and human health outcomes). In addition, the table adds a fifth category for indicators related to adaptation, vulnerability and resilience modifiers.

Table 1. Summary of indicators used in the conceptual model of climate-health interactions.

Indicator	Subindicator
Climate Drivers	
Increased precipitation	Increase in rainfall intensity (in/hr or mm/hr) of the 1% heaviest storms
	Total precipitation (in or mm) falling in the 1% heaviest storms
	Total annual precipitation (in or mm)
Extreme precipitation following dry spells	The number of annual extreme precipitation events that follow an extended dry period
Air temperature	Annual average surface temperature
	Frequency and duration of heat waves
Environmental Change	
Lake surface temperatures	Average surface water temperatures
Nutrient (phosphorus) concentrations	Offshore total phosphorus concentrations measured in µg/L for each of the Great Lakes
Harmful algal blooms	Percentage of each lake (<16 m in depth) where at least one algal bloom was detected during the April–October season each year
Change in lake levels	Anomalies in annual mean water levels relative to the base period of 1918 to 1990 for each lake
Hazard Exposures	
Number of drinking water advisories	Number of drinking water advisories per year within a defined geographic region
Number of flooding events	Total reported flood episodes annually
Biological hazards of source water	E. coli (in counts per 100 mL) measured daily
	Nitrate concentrations (in mg/L or other standard units) measured daily
	Turbidity (in nephelometer turbidity units) measured daily
Algal toxins in source water	Microcystin-LR concentrations in water (µg/L), measured weekly
Combined sewer overflows	Number of communities with combined storm-sewer systems
	Percent of wet weather captured, averaged across combined storm-sewer systems
	Annual number of untreated combined sewer overflow events
	Annual volume of untreated combined sewer overflow events
Beach closures	Percentage of days in the swimming season that beaches were closed due to high *E. coli* levels
Closed healthcare facility days due to flooding	Total days per year that healthcare facilities close due to flooding or flood-related impacts
Climate-related threats to Indigenous food sources	Estimated fish stocks and harvest levels
	Precipitation levels during critical wild rice growth season (spring)
	High water levels during critical wild rice growth season (spring)
Human Health Outcomes	
Reportable cases of waterborne gastrointestinal illness	Monthly and yearly occurrences of waterborne gastrointestinal illness within a defined geographic region
Changes in mental health/sentiment	Change in sentiment based on analysis of social media posts, following extreme weather events
Mortality due to extreme heat	Mortality from exposure to extreme heat in persons over 65
Deaths from flooding	Number of deaths attributable to drowning per year per 100,000 people
Economic damage from extreme weather	Total annual damage (in millions of dollars) from weather events within the Great Lakes basin
Adaptation, Vulnerability and Resilience Modifiers	
Vulnerability and adaptation assessments completed	Percentage of cities/counties in the Great Lakes basin that have completed climate change vulnerability and adaptation assessments
	Percentage of healthcare facilities that have completed their own vulnerability and adaptation assessments or are covered by existing assessments

Findings

Human health outcomes attributable in part to climate change impacts on the Great Lakes also may be influenced by other factors such as nonaquatic environmental change, health system performance and infrastructure maintenance. Adequate information may exist in many cases, however, to demonstrate meaningful relationships among climate, environment and proposed indicators. These indicators, in turn, may be useful for assessing the adequacy of planning and adaptation, and guiding impactful responses to growing climate-driven stresses and environmental challenges that impact human health in the region. Several significant findings related to project objectives are listed here:

- Although relationships among factors influencing human health are complex, existing data indicate an increasing influence of climate drivers and environmental change on human health in the Great Lakes. These drivers are increasing the risk of exposure to biophysical hazards and pathogens resulting in associated injury, distress and illness. Monitoring the strength of drivers and effects can improve planning and reduce risks to human health.

- Monitoring of key indicators can improve understanding of the relative importance of different drivers and effects, which is critical to prioritizing investments for protection of human health from these threats including mitigation of the drivers and increasing the resilience of the impacted communities. Monitoring the status of resilience indicators can complement the monitoring of climate-related drivers.

- Because of the high natural variability of the region's weather, some climate change signals can be challenging to detect at annual scales, so the most robust patterns may be appropriate to assess at decadal or longer scales. However, other phenomena, such as the local impacts of individual extreme storms, occur over periods of hours to days, so this granularity is important to capture as well for event-specific and aggregate analysis. This suggests that data to inform indicators of climate change impacts on human health should be captured at a variety of temporal and spatial scales that support the appropriate retrospective evaluation to guide forecasting and to inform resource allocation.

- Multiple studies show a strong correlation in the region between indicators of environmental justice and other socioeconomic inequities, and the vulnerability of communities to human health impacts from climate change, such as increasing flooding frequency due to greater storm intensity. Indicator development should be conducted with differences in community vulnerabilities and inequities in resilience in mind to increase the value for just and equitable preventive planning.

- Because most water-related infrastructure decisions are made at the local municipal scale, it is important that indicators can be reported at the finest spatial resolution that available data will support to increase their usefulness to municipal planners and decision-makers.

- Harmonization of data across political boundaries is an ongoing challenge. The establishment and maintenance of seamless datasets that span boundaries is a critical component of the development of useful indicators that can inform the implementation of cross-jurisdictional agreements, treaties, and compacts.

- While the interactions of climate drivers, effect relationships and effect modifiers can be extraordinarily complex, many actions to mitigate effects, adapt to changes, decrease exposure and vulnerability, and increase individual and community resilience can have cross-cutting benefits that span multiple change, exposure, or impact categories.

Gaps

As stated previously, direct linkages between climate and health can be difficult to distinguish within a complex biophysical and socioeconomic context. Substantial progress has been made in this area, but much more work remains. Identification and tracking of indicators may help identify targeted adaptation and mitigation strategies that are likely to be helpful and can promote learning between affected communities as appropriate indicators could reveal which effect modifiers reduce human risk exposures and human health outcomes most strongly. Areas where additional data collection, analysis, and research are needed are described briefly here:

- Scales, gradients, and trends of effect relationships and effect modifiers are important to define but are not well understood at present. As a result, prioritization of investments based on expected impacts and quantitative understanding of collective synergistic benefits is rare.

- It is unclear what climate-specific actions versus general resilience actions would be most impactful to human health (e.g., flood insurance improvements, data infrastructure investment, improved monitoring, housing reform). Policy development that includes robust economic and health benefit predictions and intercomparisons among communities over time would help reduce some of this uncertainty.

- Although many climate drivers and environmental response variables are tracked regionally and nationally, these datasets are not well harmonized across the international border. This is also true for health-related data. The IJC has helped spur harmonization of hydrologic data and may be able to similarly impact environmental and health data of high priority.

- Human-lake interaction studies are quite limited in the health domain apart from those concentrating on swimming exposure to pathogens, including consideration of mental health. Concepts such as *blue infrastructure* and *blue mind* that show mental health benefits of spending time near water could be linked with climate and health studies to explore mitigation of climate anxiety by advancing related practices.

Next steps

With this report, the board intends to contribute to progress reporting and management under the GLWQA to better understand climate/health interactions, highlighting the importance of ongoing monitoring of indicators, and acknowledging the risks of and solutions to climate-induced health threats. This report lays out the rationale for basinwide integrated tracking of climate, environment, hazard and health outcome metrics for Great Lakes shoreline communities; a partial conceptual model to guide the selection of such metrics (limited by the project scope); and a first proposed set of indicator metrics.

The goal of this work is to lay the foundation towards developing indicators that the Parties to the GLWQA could include in their framework for reporting on the status and trend of Great Lakes health and water quality through the governments' triennial State of the Great Lakes reports. To that end, the Parties, states and provinces, First Nations and Tribal governments, local governments, watershed management agencies, academic partners and the public may all have an interest in how future work building on this report may refine and expand the conceptual model toward the development of indicator metrics of climate-health interactions. The adoption and use of such indicators could help achieve three objectives:

1. Support better modeling of the interactions of climate with health in the unique Great Lakes environment through consistent, ongoing data collection and mechanisms for reporting and sharing.

2. Enable Great Lakes shoreline communities to identify opportunities to implement and improve activities that address climate adaptation and protect human health.

3. Support the implementation of climate adaptation actions across the Great Lakes basin that address emerging health challenges in accordance with the GLWQA objectives and other relevant Great Lakes management and policy measures.

The board, in cooperation with IJC Great Lakes advisory boards, may consider a pilot project to further develop a small number of near-to-ready indicators to the point of implementation. This could prioritize three to five indicators that are not yet mature.

Other areas of focus for potential work in the future include: an iterative process for improving the indicators based on evolving understanding and data availability; identifying stewards for individual metrics to help promote data collection, quality and analysis; identifying a central hub, such as the Great Lakes Observing System, for managing and disseminating indicator data. The goal would be to bring these indicators and their supporting data to a state where they can be actionable by health professionals and agencies across jurisdictions with the goal of improving resilience to climate change impacts of human health in Great Lakes communities.

1.0 Introduction

Climate change is leading to powerful changes in weather patterns and the environment that will challenge human health all over the world, including in Great Lakes shoreline communities. Evidence suggests environmental changes are already occurring due to the additional heat energy in the atmosphere. Global monthly surface temperatures over the last approximately 30 years have been consistently higher than the average for the 20th century, as shown in **Figure 3** (NOAA 2023).

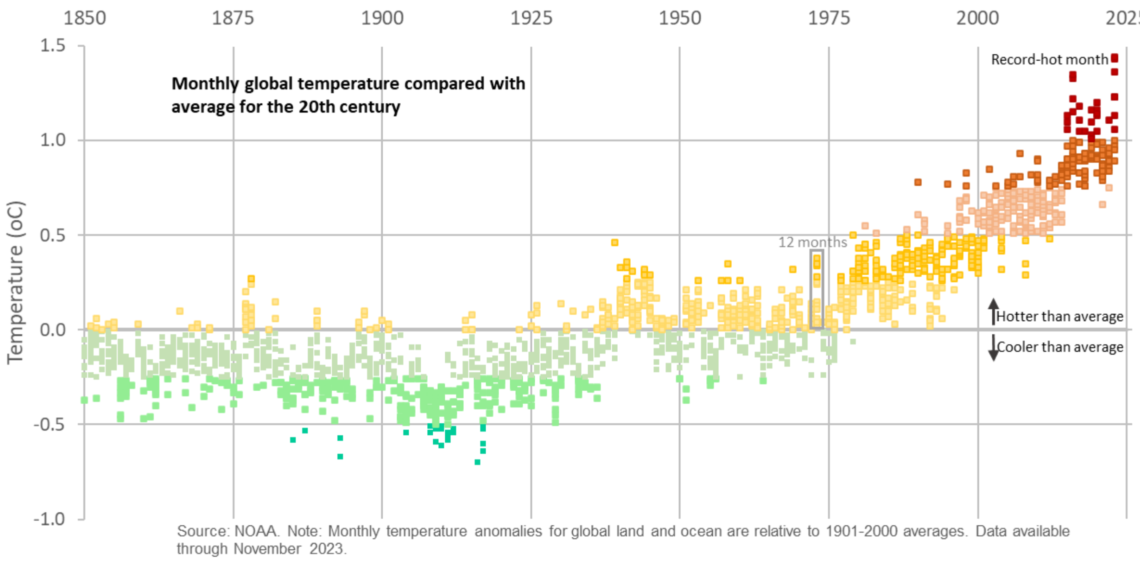


Figure 3. Comparison of global monthly surface temperatures to 20th century average.

These changes are also being felt within the shoreline communities of the Laurentian Great Lakes of Canada and the United States. In the Great Lakes basin, climate change is affecting precipitation and temperature patterns, as evidenced by less lake ice; less snow cover on land; larger and more intense storm events that result in flooding and more pollution-containing runoff; longer dry or drought periods between rain events; higher ambient air and lake temperatures that can result in heat waves and changes in habitat and growing periods for plants and animals, including potential disease vectors; and increased risk of wildfires (Bush and Lemmen, 2019).

The Intergovernmental Panel on Climate Change found that the health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (Smith et al., 2014). However, what health challenges should be expected, how fast they might occur, and what adaptive and mitigation measures should be taken to protect human health are still uncertain. This is especially true in the Great Lakes basin, as current, general climate change predictive models do not accurately represent the influence of the Great Lakes on the atmosphere and local weather patterns (US Global Change Research Program 2022). The proximity of shoreline communities to such large bodies of water creates unique environmental hazards including wave action, lake-effect precipitation, atmospheric inversions, and infrastructure exposure to shifting lake levels and temperatures. The Great Lakes serve as carbon sinks and buffers to climate-related health hazards (cooling air temperatures, for example [Wang et al., 2023]), but rapid climate-related changes to several of these characteristics, such as surface water warming, is proceeding rapidly and introducing greater uncertainty. Additionally, Great Lakes natural resources are managed separately by two bordering nations, but are also governed with oversight and guidance from a treaty-based organization (the International Joint Commission) that is charged with alerting governments to risks and opportunities related to water flows and quality. For all these reasons, monitoring environmental changes, related health hazards, and health outcomes is an important tool toward both understanding and preventing potential health risks in the region.

The International Joint Commission (IJC Health Professionals Advisory Board (HPAB) seek to identify measurable indicators of human health related to climate-driven environmental changes in the Great Lakes basin. This requires more than simple counts of health events, since human health outcomes result from multiple inputs that include environmental change, but also unequal hazard exposures and vulnerability; actions taken to mitigate, adapt to, or respond to these hazards; and variability unrelated to climate such as occupational or recreational activities. Thus, understanding health effects of climate change requires monitoring of an interrelated cascade of climate, environment, economic, policy, and behavioral factors. Accounting for multiple effects and effect modifiers offers a possibility that indicator data could be used to better measure interactions and improve future modelling. The need for this multifactorial web explains:

1) why a conceptual model was an integral part of this report,
2) why collecting and analyzing such varied data over time may be needed to attribute health changes appropriately to climate, and
3) which effect modifiers might best reduce health risks.

These indicators are intended to be quantitative measures of human health impacts due to discrete climate-related events such as storms and long-term trends in water quality and quantity in the Great Lakes. As quantitative measures, they can be monitored over time and used to inform adaptive strategies in the Great Lakes basin.

1.1 Background

The IJC regularly reports on the state of the Great Lakes ecosystem health and makes recommendations as part of its role in supporting the Great Lakes Water Quality Agreement (GLWQA) between the U.S. and Canada (IJC 2023). As part of the 2012 update to the GLWQA, the IJC has developed nine indicators and 40 sub-indicators to track progress across the basin and by individual Great Lakes. **Table 2** provides a summary of the most recent assessment from the 2022 State of the Great Lakes (ECCC and USEPA, 2022a).

Table 2. Ecosystem health indicator results for the Great Lakes, 2022 State of the Great Lakes Report (ECCC and USEPA, 2022a)

Great Lakes Ecosystem Health Indicator	2022 Assessment: Status and Trends
Drinking water	Status: Good; Trend: Unchanging
Beaches	Status: Good; Trend: Unchanging to Improving
Fish consumption	Status: Fair; Trend: Improving
Toxic chemicals	Status: Fair; Trend: Unchanging to Improving
Habitat and species	Status: Fair; Trend: Unchanging
Nutrients and algae	Status: Fair; Trend: Unchanging
Invasive species	Prevention: Status: Good; Trend: Unchanging
	Impact: Status: Poor; Trend: Unchanging
Groundwater	Status: Good; Trend: Undetermined
Watershed impacts and climate trends	Watershed Impacts: Status: Fair; Trend: Unchanging
	Climate Trends: No overall assessment

Note: Color coding indicates overall ecosystem health characterization: green is *good*; yellow is *fair*; red is *poor*; gray is *undetermined.*

Ecosystem health, expressed as *poor* status or *declining* trend for several indicators or subindicators, can be an early warning of potential risks to human health. Nevertheless, it is important to note that the purpose of these indicators is to assess ecosystem health rather than human health. Also of note is that while many of these indicators may be influenced by climate change, only one explicitly characterizes climate change effects (and was not assessed in 2022).

In 2014, the board proposed indicators of human health related to Great Lakes water quality (IJC HPAB 2014) for use in GLWQA monitoring (**Table 3**). These were not primarily focused on anticipated changes from climate change, although several of the indicators are reused as appropriate in this report.

Table 3. Human health indicators developed by the IJC Health Professionals Advisory Board (IJC HPAB 2014)

Water Quality Objective	Indicator Name	Hazard Measured
Drinking water	Chemical integrity of source water	Atrazine, estrogenicity, and cyanotoxins sampled at intakes of drinking water treatment systems
	Biological hazards of source water	*E. coli, Cryptosporidium parvum, Giardia lamblia*, nitrates and turbidity sampled at intakes of drinking water treatment systems
Recreational water contact	Illness risk at Great Lakes beaches	95th percentile of numbers of *E. coli* measured as most probable number per colony-forming units *E. coli* per 100 ml at Great Lakes beaches
	Identified risks at Great Lakes beaches	Main pollution sources identified at beaches that employ a Beach Sanitary Survey or Environmental Health and Safety Survey
Fish consumption	Contaminant levels in Great Lakes edible fish species	A common set of fish species[1], chemicals, and methods for assessment across different areas in the Great Lakes

[1] These fish species are lake trout (*Salvelinus namayacush*), walleye *(Sander vitreus)*, yellow perch *(Perca flavescens)*, lake whitefish *(Coregonus clupeaformus)*, and smallmouth bass *(Micropterus dolomieu)*.

Notably, these indicators have been slow to be adopted for GLWQA reports of progress. In part this is due to the challenge of assembling both environmental and health data comparably across the Great Lakes' binational borders (Bassil et al., 2015). The board supported these indicators through a proof-of-concept project that combined disease incidence data from cities in both Canada and the United States and analyzed these in light of extreme weather events. Specifically, this study identified an association between heavy rains occurring after longer dry periods and an increase in waterborne illness (Graydon et al., 2022; IJC HPAB 2017; IJC HPAB 2021). This is one weather pattern predicted for Great Lakes communities due to climate change (Wilson et al., 2023). This pilot study successfully studied relationships between acute gastrointestinal illnesses (AGI) and climate-related environmental factors in shoreline communities, supporting both the feasibility and utility of this current monitoring proposal.

The board work group is optimistic about the potential to collect and analyze these indicators for several reasons and notes that the IJC has successfully fostered improvements in information sharing and harmonization, such as the harmonized hydrologic mapping across the Canada/US border. Also, given the increasingly standardized methods of collection and aggregation of health data related to the use of standardized electronic medical records and public health data systems, access and use of health data is expected to improve. Remote sensing and Great Lakes-wide aggregation and sharing of environmental data (for example the Great Lakes Observatory System) further buttress this optimism.

This report, in contrast to the board's 2014 indicators, proposes a network of indicators that cover potential climate effects from environmental changes, from exposure to health hazards to health outcomes (as diagrammed in the conceptual model described in Section 3). In addition, the report emphasizes the importance of monitoring human activities that modify these effect pathways, such as the mitigation of effect pathways, adaptation to effect pathways, reduction of vulnerability, or improved resilience to these factors. This more complex but comprehensive approach can help improve the attribution of health effects to climate change, improve the prediction of health effects, and perhaps most importantly, help identify successful strategies to reduce injury and disease.

1.2 Scope and limitations

Given the IJC's focus on the aquatic environment across the Canada/US transboundary, the scope of this report focuses on water-related impacts.For example, while the hazard of forest fire smoke is not generally addressed in this report, if changes to the Great Lakes affect the distribution of pollutants, this might be in scope. Due to budget and time restrictions, the board project work plan prioritized:

- flooding
- precipitation extremes affecting pathogen and pollution runoff
- temperature and nutrient changes affecting:
    - algal and other ecological disruptions and
    - water availability and safety (e.g., drinking water supply)

The workplan also included three other foci that were considered optional:

- changes in water level and temperature affecting ambient air temperatures and heat waves,
- changes in blizzard and high winds occurrences due to water temperature and air humidity changes, and
- impacts on wild rice, fishing and other food sources.

Thus, the conceptual model and indicators proposed in this report represent a partial slice and not a catalog of all climate change-related human health pathways and effects. It is important to note that there are other climate-health interactions that are not fully elucidated in this report. Our hope is that subsequent efforts will further expand the scope of both the conceptual model and the indicator set.

The project workgroup further constrained characteristics of the model and indicators as follows:

1) Geographic focus on shoreline communities, rather than entire watersheds. Many of the environmental changes and hazards considered are specific to the land-lake interface (e.g., wave action, lake-effect weather).

2) Geographic granularity to the municipal (minor jurisdiction) level to the extent possible. Climate exposure and vulnerability, as well as adaptive measures and other effect modifiers, are likely to vary markedly from community to community based on location, capacity and resources, demographics, and other community characteristics.

3) Temporal granularity may vary, but to the extent possible it should be granular (e.g. daily) so as to enable the study of relationships between specific events (e.g., floods, heat waves, or blizzards) and associated health effects. It is better to have the option to aggregate temporal data than to be restricted to aggregate data.

4) To the extent possible, baselines and ongoing future monitoring should be established.

5) To the extent possible, indicators and data sets already in use should be mimicked for ease of implementation and prior validation.

6) Most indicators should be quantitative or categorical (e.g., yes/no); however, qualitative indicators may be used when relevant.

7) Indicators may relate to individuals and individual events (e.g., numbers of disease cases), or to systems and populations as appropriate (e.g., drinking water treatment system adaptations).

As quantitative measures, the proposed indicators are intended to be monitored over time and used to inform adaptive strategies in the Great Lakes basin, such as the adaptive management framework developed by the IJC to assess, test and act to mitigate the impacts of climate change (IJC 2021). However, it is important to note the challenges associated with indicators, particularly those that measure human health outcomes. These challenges include being able to discern a climate change signal from the data, the potential inability to proactively prioritize adaptation and mitigation strategies due to the length of the monitoring period required to evaluate several of the proposal indicators, and humans interact with the natural and built environments in unpredictable ways, which can confound interpretation of indicator data (Kreibach and Sairam, 2022).

The project was executed as a series of tasks, including:

1) a literature review;
2) a conceptual model linking climate change and health outcomes, with indicators that could support identification, mitigation, and /or response;
3) an invitational workshop of experts in the field; and
4) development of recommended human health indicators to be documented in a draft and final report.

Each of these tasks are summarized in the following sections, with the deliverable task memos included as appendices, when developed.

2.0 Literature Review

A literature review was initiated at the project's outset to identify human health indicators already in use, inform the conceptual model, and identify potential case studies for each environmental focus area. As the project progressed, additional resources were identified and considered. The literature review included peer-reviewed publications, agency reports, white papers, newspaper articles, publications supporting potential project case studies, web-based toolkits, and map-based information. While the focus of this project is on the Great Lakes basin, the literature review also considered data and information outside the Great Lakes if it was deemed useful for documenting human health indicators already in use and in developing the conceptual model.

The review included medical (e.g., human health-focused) literature, such as materials published by the US Centers for Disease Control and Prevention (CDC) and American and Canadian Public Health Association and those published in the medical journal *Lancet* (APHA 2023; CPHA 2023; Romanello et al., 2022; Romanello 2023). It also included more environmental resource-focused materials (e.g., climate-driven indicators), such as the National Oceanic and Atmospheric Administration Great Lakes Integrated Sciences and Assessments (GLISA)[1] reports and Great Lakes climate change dashboard, and the Fifth National Climate Assessment report led by the US Global Change Research Program. A subset of applicable chapters from the National Climate Assessment were reviewed in detail in the 2022 draft and 2023 final versions (Chapters 1, 2, 4, 11, 12, 15, 16, 18, 24, 31, and 32) (Baker et al., 2022; Bolster et al., 2023; Chu et al., 2023; Davis et al., 2023; Hayden et al., 2023; Jay et al., 2023; Mach et al., 2023; Marvel et al., 2023; Payton et al., 2023; Wasley et al., 2023; Whyte et al., 2023; Wilson et al., 2023).

Over 120 references and web-based toolkits were considered during the literature review. Key findings include:

- There is a substantial amount of information available on climate change and variability in the Great Lakes, but forecasting is challenging.
- Extreme events have clear impacts on human health, but the climate change signal is difficult to extract, and indicators are not well developed.

[1] GLISA's original name stood for the Great Lakes Integrated Sciences and Assessments to align with the federal RISA program title. In 2022, Congress directed the National Oceanic and Atmospheric Administration to change the name of the federal RISA program to the Climate Adaptation Partnerships (CAP) program to better describe the work now conducted by its regional teams since the program's inception in the 1990s. During this transition period, we are referring to ourselves as 'GLISA, the Great Lakes CAP/RISA team,' moving away from the RISA-affiliated name. "Climate" acknowledges the program's focus on long-term change and variability. "Adaptation" encompasses approaches to reduce negative impacts of climate change and maximize emerging opportunities. "Partnerships" refers to the web of collaborative relationships between researchers and community decision makers within the regions. It also refers to the larger connections among regional teams that support the peer-to-peer learning that builds local capacity and expertise for national impact. More information is at: glisa.umich.edu/about/mission.

- General investments in community resilience in the Great Lakes basin through adaptation measures (e.g., reductions in combined sewer overflows, reduction in flooding impacts) will likely bear fruit in terms of improved human health.

- Government agencies, academic institutions, and larger cities or regional groups are producing many helpful resources for use in climate resiliency planning, but implementation funding is a critical limitation, as well as the challenge of implementing a coordinated approach (particularly across international borders) and consistent use of standards (data standards, standard indicator definitions, etc.).

A technical memorandum, which is included in the Supplemental Materials as Appendix A, was prepared to describe the methods and results of the initial literature review. A spreadsheet-based database with details from the initial set of articles was also provided to the board work group.

The literature review materials fell into these categories:

1) **Data and model results**, which were used to inform the conceptual model and to better understand the current and projected environmental changes to the Great Lakes, and identification of human health risks. Examples of these resources include the Fifth National Climate Assessment report (US Global Change Research Program 2023), the GLISA dashboard website, recent reports by Health Canada (Berry and Schnitter, 2022) and Status of Tribes and Climate Change Working Group 2021 report.

2) **Description of indicators**, used mainly to inform the identification and selection of human health indicators. They also verified the completeness of the conceptual model. Examples of these resources include the Lancet journal's annual "Countdown Report" issues (Romanello et al., 2022; Romanello et al., 2023) and World Health Organization reports (World Health Organization 2021, 2022).

3) **Records of observed flooding, extreme precipitation, or harmful algal bloom (HAB) events resulting in human health impacts**, used mainly to identify candidate case studies. Examples include the extensive reporting on the urban flooding in Detroit, Michigan in 2021 (Sampson et al., 2021), the contamination of drinking water in Toledo, Ohio (Kennedy 2022) and the 1993 cryptosporidium outbreak in Milwaukee, Wisconsin (Hoxie et al., 1997).

Information collected through the literature review was incorporated into the conceptual model. **Table 4** provides a summary of the literature review process and outcomes.

Table 4. Summary of literature review

Focus Area	Materials Reviewed	Frequently Listed Human Health Effects	Examples of Linked Environmental Causes; Hazard Exposures; and Adaptive, Vulnerability, and Resilience Effect Modifiers
Flooding-related	45	Drowning and other injuries, respiratory disease, waterborne disease, vector-borne disease, stress and anxiety, skin rashes, asthma, hypothermia	- Lake water level fluctuation - Precipitation pattern changes - Lower income level - Mold in flooded homes - Microbial and toxic runoff - Wastewater management system characteristics - Disrupted housing, worksites, and other infrastructure - Disruption of food and water supplies
Extreme precipitation	42	Gastrointestinal illness, waterborne diseases (virus, bacteria, protozoa pathogens), asthma	- Precipitation pattern changes (frequency, intensity, depth) - Increased combined sewer overflow/sanitary sewer overflows - High levels of microbial pathogens (e.g., *E. coli* levels) - More frequent anomalous weather events - Lower income level - Flooding
Elevated lake temperatures and nutrient runoff	26	Exposure and illness (liver, gastrointestinal, skin) from harmful algal blooms	- Excess nutrients - Increase in toxins from harmful algal blooms - Elevated temperatures
Air temperatures/ heat waves	31	Cardiopulmonary illness, heat-related stress, mental health, asthma, heat stroke/heat exhaustion	- Temperature increases - Poor air quality - More-frequent anomalous weather events - Higher humidity - Increasing wildfire frequency - Higher ground-level ozone levels and particulate matter - Elevated lake temperatures
Blizzards/winds	8	Respiratory disease, hypothermia, injuries	- More frequent anomalous weather events -Reduced ice cover -Extreme precipitation events
Food sources	23	Malnutrition, mental health, indigenous cultural displacement	- Degraded water quality - Expanded range of pests and invasive species due to ecosystem changes - Decreased biodiversity - Flooding and drought - Toxic and nutrient runoff - Flood disruption of production facilities. - Drinking water disruptions.

Some materials did not lend themselves to inclusion in the project database because they were web-based toolkits, map-based data summaries, or the documentation could not be downloaded. **Table 5** provides a list of the web resources considered in the literature review.

Table 5. Web-based resources identified in literature review

Organization or Program	Description	Website URL
US Global Change Research Program	U.S. Climate Resilience Toolkit (see especially the Climate Mapping for Resilience and Adaptation section)	toolkit.climate.gov
US Global Change Research Program	Climate and Health Assessment	health2016.globalchange.gov
United Nations	The Intergovernmental Panel on Climate Change	ipcc.ch
National Environmental Modeling and Analysis Center (housed at UNC Asheville)	Climate Explorer at the city level	crt-climate-explorer.nemac.org
Graham Sustainability Institute (University of Michigan)	Great Lakes Climate and Demographic Atlas (Great Lakes Adaptation Assessment for Cities)	graham.umich.edu/glaac/great-lakes-atlas
US Global Change Research Program	Fourth National Climate Assessment	nca2018.globalchange.gov
Great Lakes Integrated Sciences and Assessments (University of Michigan)	Great Lakes Regional Climate Change Maps	glisa.umich.edu/great-lakes-regional-climate-change-maps
National Academies Science, Engineering, Medicine	Climate resources to understand and prepare for climate change	nationalacademies.org/topics/climate

The following climate change-driven conditions were listed in multiple sources:

1) Changes in precipitation extremes
2) Increased air temperatures (and higher humidity)
3) Changes in the natural and built environments

Recent Great Lakes-based sources (ECCC and NOAA, 2022) have documented trends in temperature and rainfall that suggest climate change may already be impacting the basin. Trends in air temperature, water temperature, and precipitation show an increasing trend since 1950 in most of the Great Lakes (**Figure 4**), as shown by the gray trendline in each chart. Lake Superior, the coldest and deepest Great Lake, shows the clearest increasing trend in these factors.

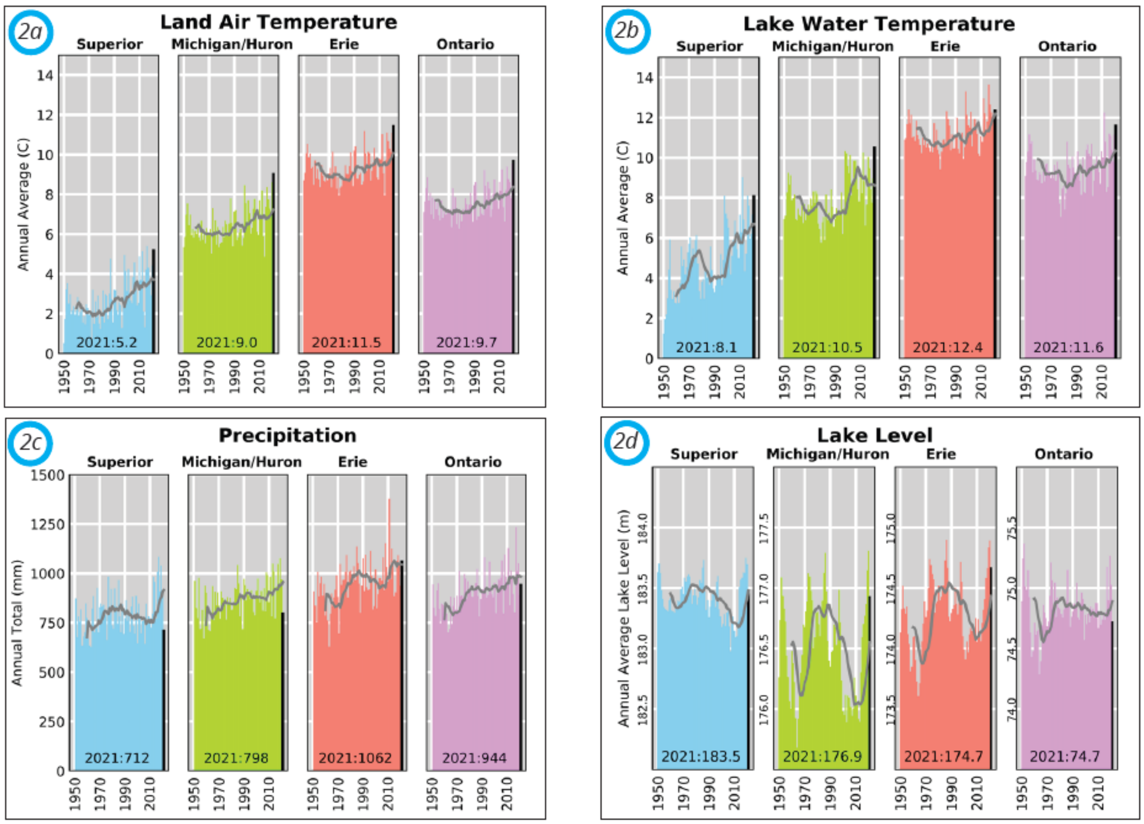


Figure 4. Historical trends in precipitation, temperature and water levels in the Great Lakes (ECCC and NOAA, 2022).

The climate change conditions listed above can lead to numerous risks to human health, with the most commonly listed including:

1) Flooding
2) Drought
3) Extreme heat
4) Extreme weather events
5) Water quality
6) Air quality
7) Wildfires
8) Declining food security/water scarcity
9) Vector-borne disease
10) Waterborne disease

The recently published Fifth National Climate Assessment (US Global Change Research Program 2023) assessment notes the health of Midwestern populations (which includes the US portion of the Great Lakes basin) is at risk from increased extreme heat, precipitation, drought and flooding, along with reductions in air quality and increased incidence of vector- and waterborne illnesses (Baker et al., 2022; Wilson et al., 2023). Physical injury and illness may also influence mental health and can reduce quality of life and community function as traditional forms of connection and culture are lost or diminished. While most resources tended to focus on the adverse effects of climate change, the most recent Intergovernmental Panel on Climate Change report (IPCC 2022) notes that some effects of climate change could be positive. For example, while soybean and corn yields are expected to decrease in North America due to climate impacts (primarily related to changes in precipitation patterns with too much rain in the spring and extended periods of no rain in the summer), wheat yields are projected to increase.

The general approach to characterizing human health impacts from climate change-driven environmental factors follows typical risk assessment practice, as described here using flood-related impacts as an example:

1) Identify environmental conditions leading to hazards (e.g., lake levels or precipitation extremes leading to flooding).

2) Identify secondary hazard relationships (e.g., flooding disrupts infrastructure, distributes pathogens and toxins, enables mold growth, etc.).

3) Assess which populations are most exposed to the hazards (e.g., living in flooded zones) or otherwise more vulnerable to hazards. Numerous resources (Status of Tribes and Climate Change Working Group 2021; IPCC 2022) cited the larger impacts that climate change conditions have on the elderly, indigenous and First Nations people, low-income populations, people of color, pregnant women, and children.

4) Assess adaptive or emergency response measures that modify exposure or health effects (e.g., wastewater management systems, hardened civic and healthcare infrastructure, vaccinations, etc.).

5) Measure health outcomes (disease and injury, mental or economic distress) attributable to hazard exposures.

As described in the Status of Tribes and Climate Change Working Group report, Indigenous peoples are particularly susceptible to the impacts of climate change because of their cultural and spiritual connection to the natural world. The availability of "first foods," which include traditional foods, medicines and technologies, is threatened by climate change and is an important part of the health and well-being of Indigenous peoples. The ability to maintain tradition and connection to the environment is important to US Tribes' sense of identity, autonomy, and well-being. Mental health issues are associated with the displacement of communities affected by extreme weather events, or the inability to support oneself in culturally significant and traditional ways, such as through subsistence fishing, hunting and gathering, etc. Indigenous peoples are more susceptible to other anticipated effects of climate change, such as temperature and precipitation extremes, increased exposure to vector-borne pathogens, and decreased air quality, because they have higher rates of illnesses that increase vulnerability like asthma, cardiovascular disease and diabetes, all of which is exacerbated by disparities in healthcare.

The indicators developed previously by the IJC are still relevant and can be tied to human health impacts. Indicators based on exposure pathways could be an effective way to link climate change-driven environmental conditions and corresponding human health impacts. Alternatively, directly measuring human health conditions could also serve as indicators. Both approaches were suggested in the 2016 US Global Change Research Program Executive Summary (Crimmins et al., 2016).

Several topics and questions were raised by work group members that were not established targets of the literature review, but that may also influence health effects of climate change in the Great Lakes. These included, for example:

- How might changes to lake water levels, contamination, or changes in water consumption patterns affect the quantity and quality of groundwater?
- How might climate change influence human migration into or out of shoreline communities, and how might these influence human health?
- How might acidification (from dissolved atmospheric carbon dioxide) affect Great Lakes ecosystems and human health?[1]
- How might heat-related changes to lake thermal stratification affect food webs and other environmental factors that could affect human health?
- To what extent might lake water temperature changes affect heat waves in shoreline communities?
- How might temperature-related shoreline weather changes, such as changes to atmospheric inversions or other barriers to air flow at the shoreline, affect heat waves and/or the concentration of air pollutants such as wildfire smoke along the shoreline?
- How might temperature-related changes to species niches and seasonal migration (in water or on land) alter the distribution of plants, animals and microorganisms, including possible disease vectors or food webs?
- How might the lakes be used for carbon sequestration to reduce greenhouse gases, and how might these actions affect lake ecosystems and human health?
- What effect might wildfire smoke or other climate-related pollutants (e.g., heavy metals or acids in smoke) have on lake ecosystems?

[1] The National Oceanic and Atmospheric Administration Ocean, Coastal, and Great Lakes Region Acidification Research Plan Chapter 11 Great Lakes Acidification Research, oceanacidification.noaa.gov/sites/oap-redesign/11.%20Great%20Lakes.pdf, accessed January 28, 2024.

Several of these potential weather-ecosystem interactions are acknowledged in the conceptual model but are greyed-out for future consideration. It should also be noted that part of the reason for recommending future consideration is that the direction and magnitude of effects and secondary effects remain in question at this time.

3.0 Conceptual Model

A conceptual model linking climate-driven environmental change to specific health outcomes and indicators (measurable metrics) that could support identification, mitigation, and /or response was developed using the results of the literature review and input from the board project team and workshop participants. As per the project work plan, the conceptual model considered four areas:

1) Map predicted relationships between weather changes on aquatic environmental conditions and human health consequences to identify a set of indicators to reflect water-related human health risks from climate change.

2) Consider how social, economic, cultural, and political factors influence predicted relationships.

3) Use the conceptual model and the literature review to identify indicators and data sources, and how they could be used to study, predict, and potentially mitigate climate-health interactions.

4) Illustrate three or four climate-health interactions to describe the nature and degree of population health outcomes and how indicator data might guide possible adaptive/resilience interventions.

A technical memorandum, which is in the Supplmental Materials as Appendix B, was prepared to describe the development of a conceptual model.

3.1 Background on other climate change-health effects models

Several candidate conceptual models were identified during the literature review, as summarized in **Table 6**.

Table 6. Potential conceptual models

Organization	Source Document or Website (Hyperlinked)	Description of Conceptual Model*
Health Canada	Water Quality, Quantity, and Security	Examples of the direct and indirect ways that climate change can alter water quality/quantity and affect health
US Centers for Disease Control and Prevention	Climate Effects on Health	Shows relationships among source water, drinking water, stormwater, and wastewater under changing climate, plus seven potential human health impacts
World Health Organization	Climate Change and Health	Links more extreme weather to water quality impacts (pathogens, algal blooms)
US Global Change Research Program	The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment	Links extreme rainfall and flooding to waterborne diseases and mental health impacts
US Environmental Protection Agency	Understanding the Connections Between Climate Change and Human Health	Connects precipitation extremes and extreme weather events to reduced water quality and increases in infectious agents
US National Institutes of Health	The Interplay of Environmental Exposures and Mental Health: Setting an Agenda	Describes individual and community mental health impacts of disasters and more chronic climate change impacts

The primary water-related health risks in these models are associated with extreme precipitation events and coastal storms that produce flooding and water quality impacts such as increased pathogens and toxic algal blooms in drinking water and at swimming beaches. Intermediate physical factors such as infrastructure, geography or ecology are also mentioned. Mental health impacts due to traumatic or chronic stress are also considered in some model diagrams and tables. Certain other interactions, such as the effect of warming waters on heat waves, land-lake weather interface (e.g., coastal inversions) on smoke and other toxic air exposures; and possible effects on groundwater quantity or quality remain fairly undefined.

Indicators and data sources to support study, prediction and mitigation of climate-health interactions are available in Canada and the United States, although direct causal linkages may not be possible to establish in all cases. For example, increased occurrence of algal blooms may be expected because of climate change (e.g., Chapra et al., 2017), but other factors could be to blame such as shifts in agricultural practices (e.g., Jarvie et al., 2017) and associated nutrient loads from watersheds to lakes. Likewise, increased reports of gastrointestinal illnesses related to swimming might be reported in certain areas, but a direct climate change linkage may be difficult to tease out. Canadian beach surveillance programs and risk in a climate change context were recently reviewed (Young et al., 2022). Indicators associated with the study, prediction, and mitigation of focus area climate-health interactions are summarized in **Table 7**.

Table 7. Example indicators of climate-health interactions

Climate-Health Interaction	Indicators
Recreational swimming health	- Acute gastrointestinal disease reports - Beach pathogen counts (e.g., *E. coli*) - Beach closure data - Nearshore harmful algal bloom occurrence and toxicity - Combined sewer overflow frequencies and volumes discharged
Source water drinking water quality	- Monitoring buoy and intake sonde data - Drinking water plant monitoring data - Drinking water notices (boil water, do not drink) - Drinking water plant upgrades - Reports of algal blooms near water intakes
Flooding impacts	- River flows, lake levels, and news reports - Residential, commercial, and infrastructure insurance claim data - Disaster declarations and evacuation notices - Major investments in flood control, especially in urban areas

Associated data to guide interventions include data are summarized in **Table 8**. Additional relevant data would include population density, ages and elevations of housing stocks, demographic and public health data, and specific information on stormwater management and associated infrastructure issues and mitigation timelines and budgets in Great Lakes municipalities. Climate change forecasts with the lowest possible uncertainty within the scope limitations addressed above (Xue et al., 2022) would also be helpful in predicting future conditions and providing engineering solutions, where appropriate, to mitigate impacts.

Table 8. Example data sources and indicators

Organization	Source Document or Website (Hyperlinked)	Description of Data and Indicators
Environment and Climate Change Canada (ECCC)	ClimateData.ca	Data portal to support decision makers across a broad spectrum of sectors and locations by providing the most up-to-date climate data in easy-to-use formats and visualizations
ECCC	Overview of freshwater quality monitoring and surveillance	Numerous links to information and data from monitoring and surveillance programs in the Great Lakes and other freshwater systems in Canada
US Centers for Disease Control and Prevention	One Health Harmful Algal Bloom System	Collects information to help CDC and partners better understand human and animal illnesses linked to harmful algal blooms and help prevent illnesses caused by them
Great Lakes Integrated Sciences and Assessments	Great Lakes Climatologies	Summaries of climatology for select sites (stations), multi-county areas (climate divisions), and each Great Lake, developed in partnership with the Office of the State Climatologist
National Oceanic and Atmospheric Administration	Severe Weather Data Inventory	An integrated database of US severe weather records that provides access to data from a variety of sources
National Oceanic and Atmospheric Administration	Lake Erie Harmful Algal Bloom Resources	Forecasts and historical data on algal bloom occurrence and toxicity in Lake Erie
Swim Drink Fish Canada	The Swim Guide	Provides real-time information on beach safety based on monitoring results
Michigan Dept. of Environment, Great Lakes, and Energy	BeachGuard	Data on current and historical beach closures and *E. coli* counts for the State of Michigan

3.2 Great Lakes climate change: health outcome conceptual model

The board work group and contractor team worked through several versions of a conceptual model of climate-health interactions in the Great Lakes region. The conceptual model design began with identifying four domains of change in a descending cascade, as shown in **Figure 5:**

1) major climate change drivers of environmental change (*climate drivers,* yellow box);
2) resulting projected changes to the aquatic environment (*environmental changes,* green box);
3) resulting health hazard exposures (*hazard exposure,* blue box); and
4) illness, injury, or distress that result from hazard exposures (*health outcomes,* orange box)

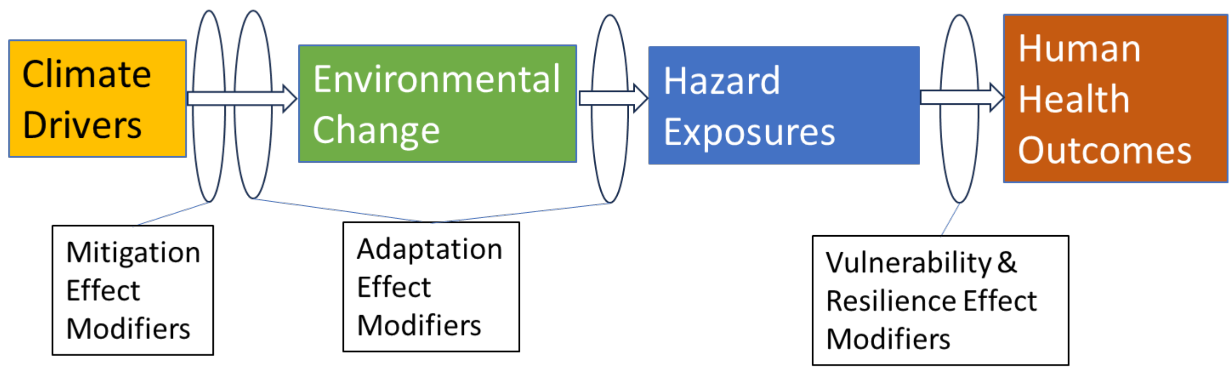
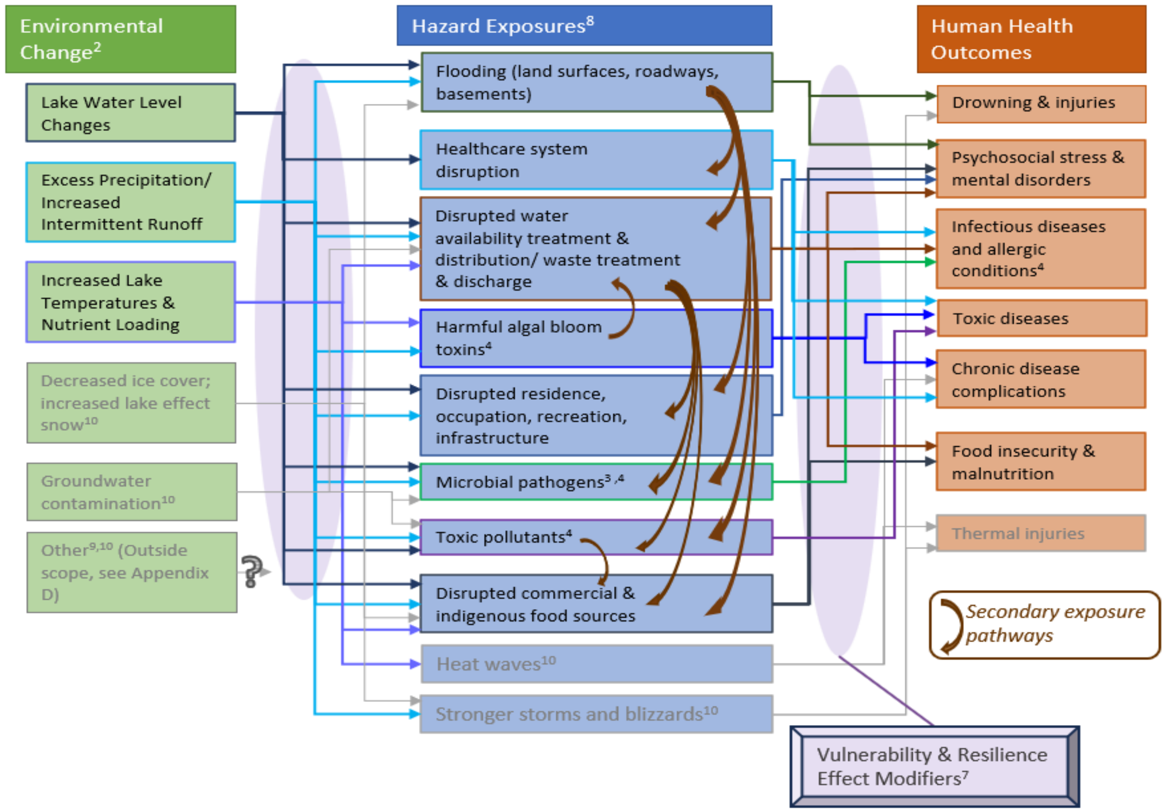


Figure 5. Conceptual model domains

Effect arrows connect items in one domain to those they affect in the next (**Figure 6**). Relationships between environmental changes to hazard exposures and exposures to health outcomes are indicated by arrows (effect arrows). Multiple effect arrows may influence any given particular item; thus the cascade of relationships forms more of a network than a set of simple linear effect (multiple arrows connected to infectious diseases in the Human Health Outcomes bolded to illustrate this). Several effect arrows may land on a particular exposure or outcome, and the model is silent on the relative intensity of the effects, or whether multiple effects might be additive, synergistic, or even antagonistic. Often this data is lacking, and it is hoped that careful collection of indicator data could clarify the nature of these relationships. We also acknowledge many items are influenced by additional factors independent of climate change. For example, gastrointestinal infections, a type of infectious disease, are influenced by food preparation, handwashing, diaper exposures, camping and watersports, etc. These are not displayed in the model.



[1]Selected; other climate effects not included. [2]Selected; other environmental changes that are not the focus of this report are included in Supplemental Materials Appendix D with discussion. [3]Includes viral, bacterial, fungal/mold, protozoa. [4]Ingestion, inhalation and dermal exposures. [5]E.g., greenhouse gas reductions. [6]Plans and designs to minimize impacts or exposures. [7]Factors that increase exposures (e.g., residence in flood plain) of effects (e.g., immunodeficiency) and factors that improve capability to recovery (e.g., adequate income, healthcare, psychological resilience). These may occur at the individual or population levels. [8]Note: one type of exposure may create secondary exposures. [9]Other factors include, but are not limited to, lake thermal stratification changes, lake acidification, changed species distributions (including disease vectors) and migrations, coastal weather changes (e.g., inversions). [10]Additional discussion in Supplemental Materials Appendix D.

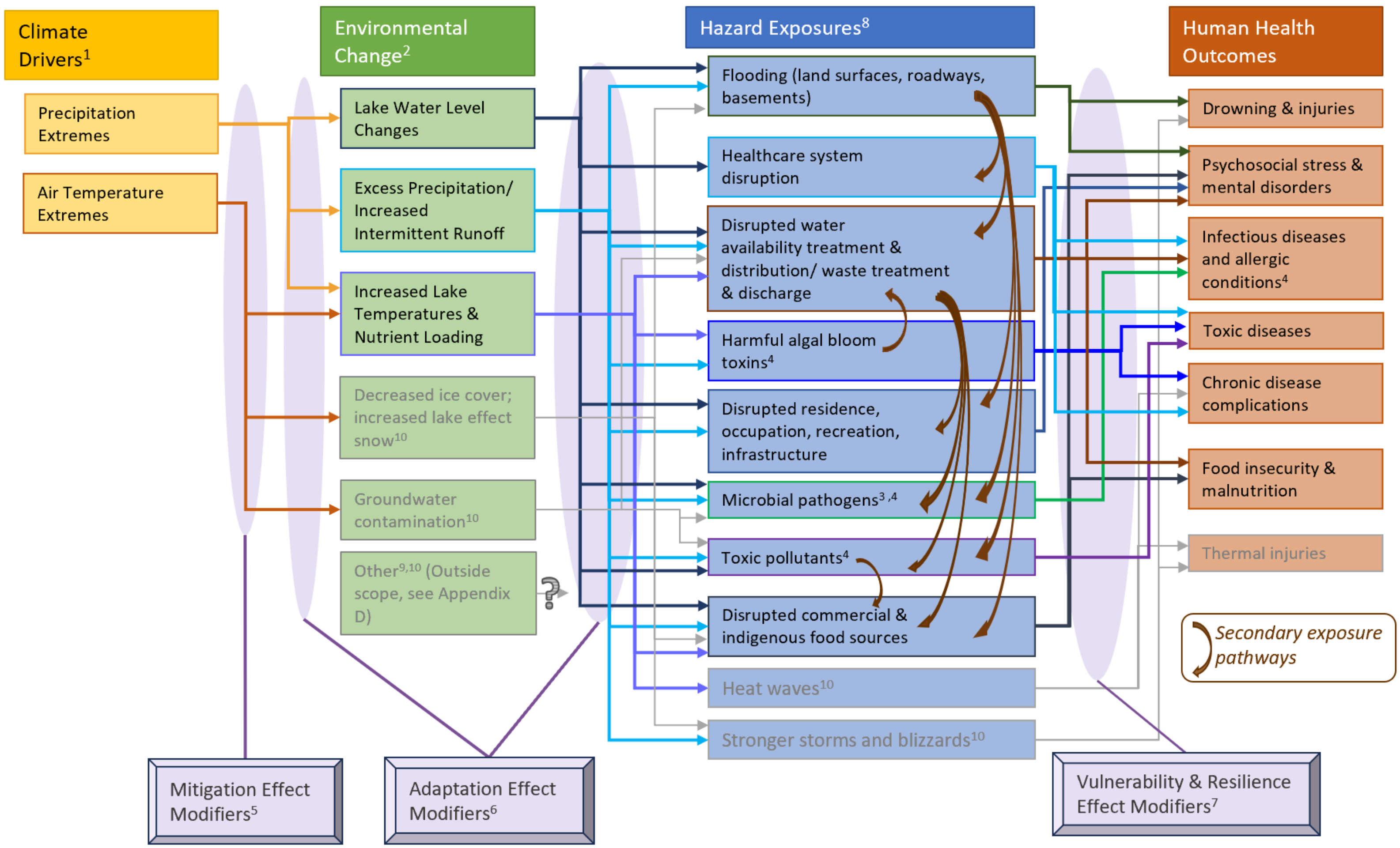
Figure 6. Conceptual model item relationships, partial example

Finally, effect modifiers are acknowledged, including factors that could mitigate climate change (like reducing greenhouse gases); minimize environmental change or hazard exposure (like upgrading storm and wastewater management systems); reduce the vulnerability of populations (like moving homes from flood plains); or improve resilience (like vaccinations, or hardening health facilities). This process allowed an expansive model connecting outcomes to drivers and potentially accounting for co-factors and confounders. If the vision of basinwide, comparable and granular data is achieved, the data could help modelers better refine causal relationships and identify outliers that might offer health-preserving solutions.

Human behavioral feedback loops may complicate the relationships in the conceptual model. For example, investments in managing untreated wastewater volumes might create a sense of false security that undercuts emergency evacuations when needed. For another example, if people lose confidence in lake-sourced drinking water systems (for fear of microbial contamination), they may choose bottled water as an alternative. This would deprive drinking water treatment systems of revenue, inhibiting system upgrades while also generating additional greenhouse gases in the transport, bottling and retailing of bottled water.

The experts workshop conducted for the project also provided valuable feedback regarding the importance of including healthcare and community infrastructure as well as more consideration of effects to Indigenous communities and resources in the conceptual model and indicators. The conceptual model (**Figure 7**) was developed to provide as full an accounting of the climate-health interactions as the literature review and board work group expertise could support for the environmental areas of interest.

Resource constraints restricted the focus of the conceptual model primarily to water levels, precipitation extremes, and lake temperature and nutrient loading. For this reason, elements in the model unrelated to these are greyed out, and the workgroup did not focus on these additional factors in the conceptual model or indicator selection. This does not imply in any way that greyed-out parts of the model are not important; rather they must be addressed or potentially expanded in the future to ensure full accounting. We understand that factors such as ice cover, air quality, and groundwater contamination are affected by climate drivers and in turn affect human health, and that our conceptual model and list of potential indicators (see Section 6) are not exhaustive.



[1]Selected; other climate effects not included. [2]Selected; other environmental changes that are not the focus of this report are included in Supplemental Materials Appendix D with discussion. [3]Includes viral, bacterial, fungal/mold, protozoa. [4]Ingestion, inhalation and dermal exposures. [5]E.g., greenhouse gas reductions. [6]Plans and designs to minimize impacts or exposures. [7]Factors that increase exposures (e.g., residence in flood plain) of effects (e.g., immunodeficiency) and factors that improve capability to recovery (e.g., adequate income, healthcare, psychological resilience). These may occur at the individual or population levels. [8]Note: one type of exposure may create secondary exposures. [9]Other factors include, but are not limited to, lake thermal stratification changes, lake acidification, changed species distributions (including disease vectors) and migrations, coastal weather changes (e.g., inversions). [10]Additional discussion in Supplemental Materials Appendix D.

Figure 7. Conceptual model of climate-health interactions

The conceptual model emphasizes the interactions between the environmental changes in the project work plan (flooding, extreme precipitation, and increased lake temperatures with increased nutrient loading) and exposure pathways, but also accounts for changes in precipitation patterns (ice cover and lake-effect snow) and groundwater contamination, which were added through the review process with the board work group. Effect arrows from the three focal environmental changes are color coded to help distinguish their effects. Brown (vertical) arrows indicate secondary effects between one hazard category and another (for example, flooding could affect water treatment operations, and both might affect exposure to microbial pathogens). Footnotes at the bottom of the figure provide additional detail and descriptions of the components in the conceptual model.

The model acknowledges that the magnitude of effects can be modified by additional factors, like climate change mitigation, adaptation of infrastructure, addressing the needs of more vulnerable populations, and increasing resilience through effective response planning and implementation. These are represented by circles around the effect pathways, and each purple "effect modifier" box might represent dozens of different specific items. For one example, improving stormwater retention, or adding ozonation to water treatment are just two of many potential adaptive steps that might reduce microbial exposures. Some examples of effect modifiers include:

- Mitigation: Increase greenhouse gas sequestration, encourage low-carbon transport;
- Adaptation: upgrade wastewater management or water treatment, shoreline buffer zones;
- Vulnerability: special attention to children, elders, immunocompromised and chronically ill, ensure racial and socioeconomic equity, engage indigenous populations;
- Resilience: harden health system facilities, vaccinations, education, climate-oriented emergency response planning and plan exercises.

If indicators are developed to represent these modifiers it would help explain variation in outcomes, help identify communities that are proactively engaged in preventing public health consequences of climate change, and potentially illuminate which modifications are most protective.

4.0 Case Studies

Three case studies in the Great Lakes basin were extracted from the literature review and discussions with the board work group. Each case study addresses one of the three climate change-driven environmental change and associated human health outcomes. The case studies were also assessed through the lens of the conceptual model to ensure that the model captured the interactions described in each case study. **Table 9** provides a summary of the case studies compiled for this project, and **Figure 8** shows the three case study locations.

Table 9. Summary of case studies

#	Case Study Title	Climate Change Effect	Exposure Pathways	Human Health Outcome(s)
1	2014 Toledo Water Crisis	Harmful algal bloom (via higher temperatures and increased nutrient loading)	Harmful algal bloom toxins Disrupted water treatment and distribution	Toxic diseases Chronic disease complications Psychological stress & mental disorders Food insecurity
2	Cryptosporidiosis in Hamilton, ON	Extreme precipitation	Disrupted water treatment and distribution Microbial pathogens Toxic pollutants	Infectious diseases Toxic diseases Psychological stress & mental disorders
3	2021 Urban Flooding in Detroit, MI	Flooding (via extreme precipitation and elevated lake water levels)	Urban flooding, Disrupted residence, infrastructure, etc. Disrupted wastewater collection, treatment, and discharge	Drowning and injuries Psychological stress & mental disorders Infectious diseases Chronic disease complications

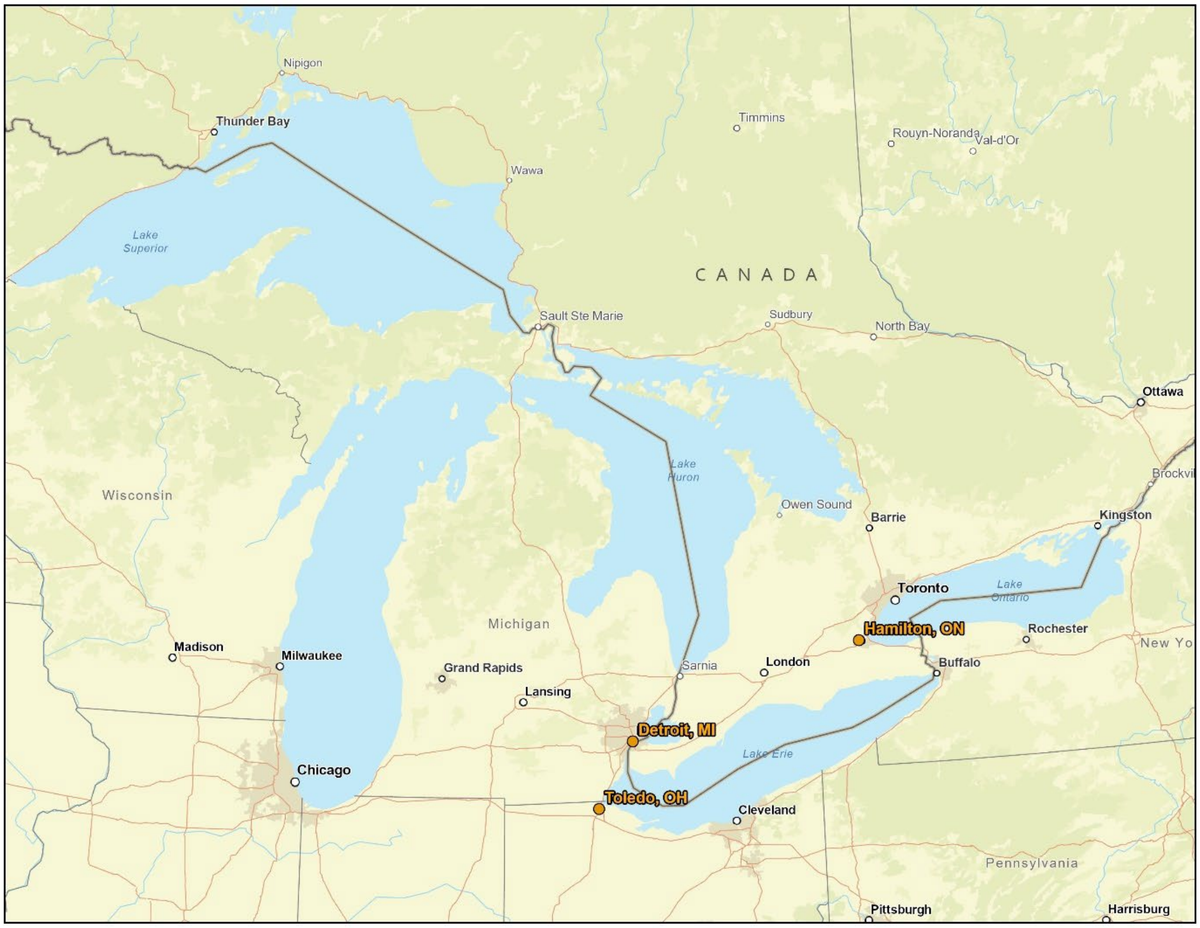
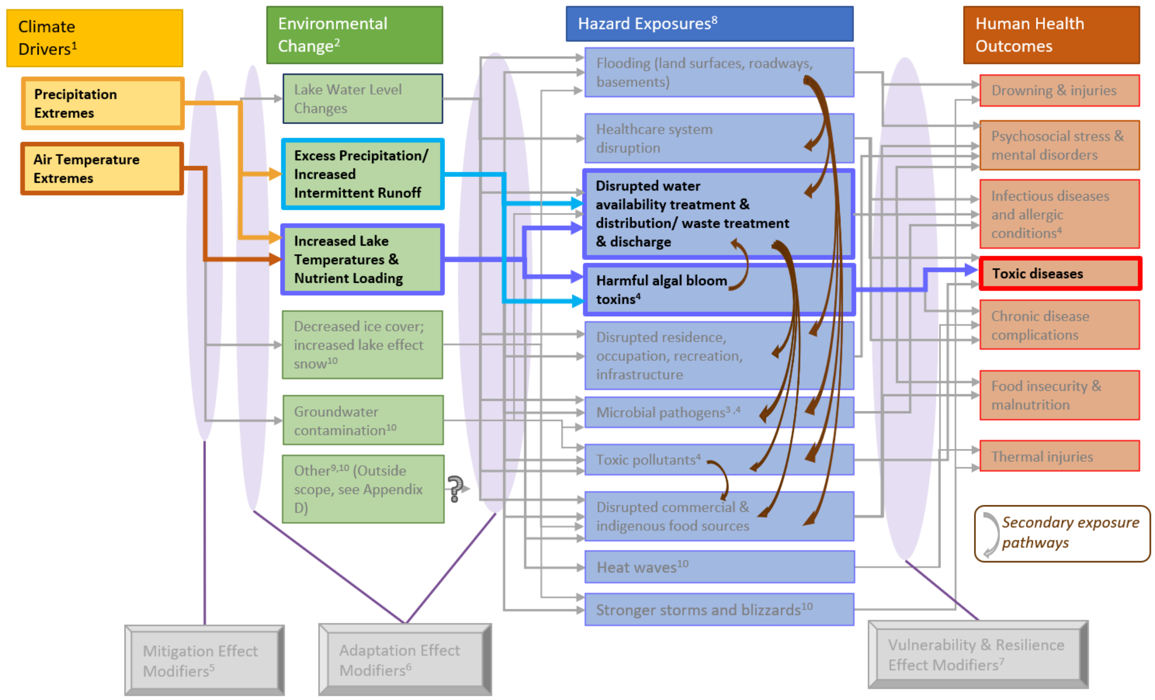


Figure 8. Case study locations

4.1 Case study: Toledo, Ohio water crisis, 2014

4.1.1 Introduction

Freshwater harmful algal blooms (HABs) are a growing global problem, with documented cases increasing rapidly and climate change playing a role in their intensification (Chapra et al., 2017). The issue has received international attention following a high-profile incident that impacted the drinking water of over 400,000 people in the Toledo, Ohio area in 2014. Since then, there has been substantial progress in research, monitoring, regulations, planning, and water treatment to address the problem. **Figure 9** maps the events described in this case study to the conceptual model described in Section 3 above.



[1]Selected; other climate effects not included. [2]Selected; other environmental changes that are not the focus of this report are included in Supplemental Materials Appendix D with discussion. [3]Includes viral, bacterial, fungal/mold, protozoa. [4]Ingestion, inhalation and dermal exposures. [5]E.g., greenhouse gas reductions. [6]Plans and designs to minimize impacts or exposures. [7]Factors that increase exposures (e.g., residence in flood plain) of effects (e.g., immunodeficiency) and factors that improve capability to recovery (e.g., adequate income, healthcare, psychological resilience). These may occur at the individual or population levels. [8]Note: one type of exposure may create secondary exposures. [9]Other factors include, but are not limited to, lake thermal stratification changes, lake acidification, changed species distributions (including disease vectors) and migrations, coastal weather changes (e.g., inversions). [10]Additional discussion in Supplemental Materials Appendix D.

Figure 9. Mapping the Toledo, OH harmful algal bloom case study to the conceptual model

4.1.2 Climate drivers

Increased air temperatures associated with climate change also result in increased water temperatures in lakes and streams. Another climate change-driven environmental effect is excess precipitation, which increases surface runoff and can increase nutrient loads delivered into waterways. The changes in these conditions can foster the formation of harmful algal blooms, such as those experienced in the Toledo area.

There have been increased calls for aggressive reductions in nutrient loading from wastewater discharges and from agriculture. Some research also indicates that climate change may contribute to reduced loading (Kalcic et al., 2019). Responding effectively to harmful algal blooms and their associated risks will require reducing nutrient inputs that drive algal blooms in lakes, rivers and reservoirs, as well as finding better ways to protect drinking water and those who engage in water-based recreation. Utility managers can apply lessons from Toledo to deal effectively with harmful algal blooms.

4.1.3 Environmental change/hazard exposures

Algal blooms were common in Lake Erie in the 1960s and 1970s, but aggressive reduction of phosphorus from wastewater sources led to their decline in the 1990s and early 2000s. Since then, blooms have rebounded, covering record-setting areas of the lake in 2011 and again in 2015 following unusually wet springs. Modeling and monitoring results link the current blooms primarily to nonpoint agricultural inputs of nutrients from runoff and tile drains, primarily from the Maumee River watershed in the western end of Lake Erie.

In early August 2014, a moderate-sized algal bloom in western Lake Erie was concentrated by winds from the north near the Toledo drinking water intake. Although such conditions were not uncommon, the toxicity and concentration of this bloom (Steffen et al., 2017) surpassed the ability of Toledo's drinking water utility to completely remove the HAB-derived liver toxin, microcystin, from the water.

4.1.4 Human health outcomes

The result was the issuance of a "Do Not Drink" order for over 400,000 customers in the area, mobilization of emergency management personnel to distribute bottled water for three days, and economic losses of millions of dollars (US) to businesses that had to close or destroy potentially contaminated products. Additional health impacts were created by the lack of safe water for hospitals, which resulted in cancellation of scheduled surgeries and a reduced ability to treat patients. County residents reported physical (16 percent) and mental (10 percent) health impacts from the crisis in a later survey (McCarty et al., 2016). A previous harmful algal bloom-related crisis in Carroll Township near Toledo resulted in issuance of a "Do Not Drink" order impacting 2,000 residents in 2013, and later in 2014, residents of Pelee Island, Ontario faced a similar crisis to that of Toledo that lasted nearly two weeks.

The Toledo incident pointed out several shortcomings of the system that existed at the time for dealing with the growing problem of freshwater harmful algal blooms in drinking water. Monitoring was relatively infrequent, guidelines for safe concentrations of toxins were unclear, and protocols for adjusting treatment and other actions necessary for effectively responding to a toxic bloom incident were inadequate. Although an experimental satellite-based monitoring and forecasting system for Lake Erie was in place, it did not provide information on expected algal toxin concentrations or on the expected three-dimensional distribution of algal cells within the water column, which is important for predicting raw water quality at subsurface intakes.

4.1.5 Conclusions

Since the Toledo incident, progress has been made by Canada and the United States in setting a nutrient reduction goal of 40 percent for the western Lake Erie watershed. Similar approaches have been shown to be effective in reducing blooms in other water bodies. A real-time network of continuous water quality monitoring instruments has been deployed in Lake Erie since 2015. The US Environmental Protection Agency (USEPA) issued new guidance on safe concentrations in drinking water for some algal toxins and has expanded research in this area. The CDC developed the One Health Harmful Algal Bloom System, a voluntary reporting system available to public health departments and their environmental health or animal health partners.

Utilities like those in Toledo have upgraded their toxin testing and treatment capabilities and developed more sophisticated communication systems for keeping their customers aware of the status of water conditions during the summer algal bloom season. The State of Ohio has supported development of an online map-based portal that shows the most recent testing results for algal toxins from drinking water utilities and swimming beaches around the state.

Most of the costs of actions to respond to HABs in Lake Erie drinking water are paid by downstream customers rather than by those responsible for upstream sources of nutrients (Alliance for the Great Lakes, 2022). Smith et al. (2019) estimated the 30-year cost of harmful algal blooms on the Canadian side of Lake Erie at CDN$5.3 billion (US$3.9 billion). The impact of the Toledo crisis alone was tabulated at US$65 million (CDN$88.4 million) (Bingham et al., 2015).

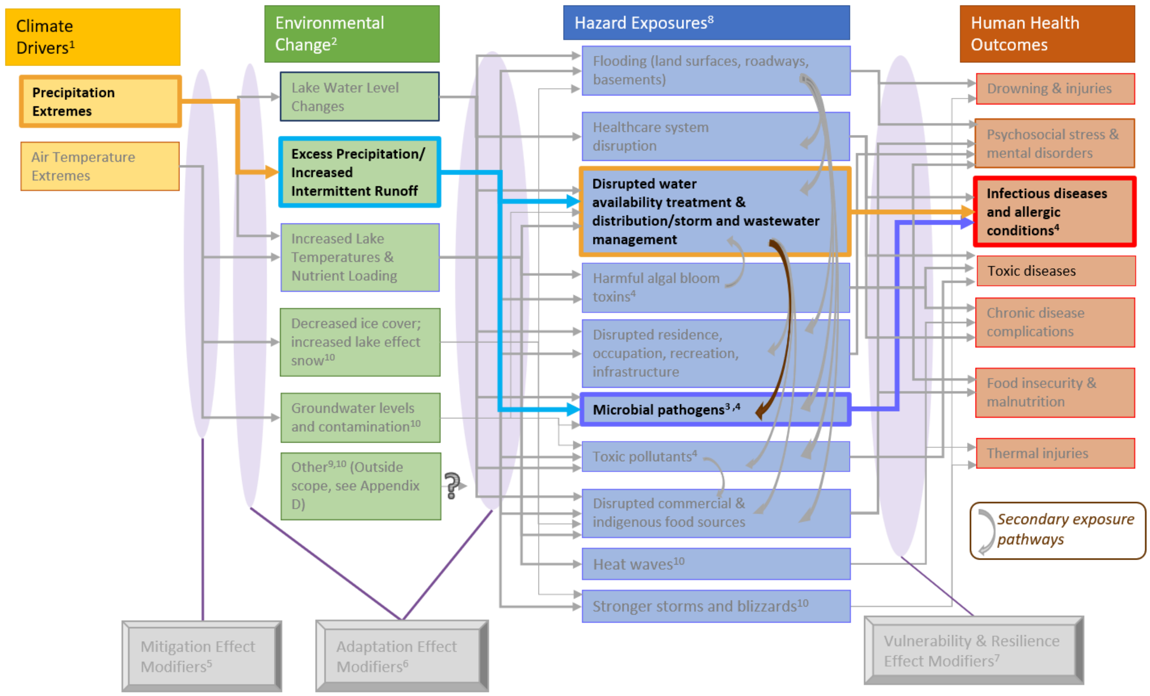
Rapid advances continue to be made in understanding the biology of bloom formation and toxin production, as well as in the most-effective approaches to reducing blooms. In the meantime, the drinking water managers and recreation managers who need to deal with the situation as it exists today are benefitting from innovations from their peers who are finding what works in protecting the public through better situational awareness, process engineering, communication systems and emergency planning.

4.2 Case study: *Cryptosporidiosis* in Hamilton, Ontario

4.2.1 Introduction

Cryptosporidiosis is an acute gastrointestinal disease (AGI) that results from ingestion the environmentally hardy oocyst of the parasite *Cryptosporidium* (CBC News 2017; Health Canada 2016; IJC HPAB 2021) which can be excreted by cattle. Human disease is associated with contact with infected cattle, contamination of drinking water, recreational water, or food or direct fecal contact in settings like day care centers (CDC 2024a). A major waterborne outbreak of cryptosporidiosis in Milwaukee, Wisconsin in 1993 during heavy springtime rains and runoff raised questions about the vulnerability of other cities relying on Great Lakes surface water for drinking as well as recreation (Mac Kenzie et al., 1994). Ontario's incidence of human cryptosporidiosis consistently exceeds Canadian national averages (Nwosu et al., 2022). To date, Hamilton, Ontario has had comparatively low cryptosporidiosis incidence, but its watershed is surrounded by those having poor to very-poor surface water quality scores (Conservation Ontario, 2024) and by health districts having much higher cryptosporidiosis incidence (Nwosu et al., 2022). Various studies have linked increases in cryptosporidiosis (and another parasite, giardiasis*)* with extreme precipitation events (Chhetri et al., 2017; IJC HPAB 2021). Such events may wash animal (or human) fecal material into streams and lakes. Wastewater treatment, drinking water treatment, and protection or treatment of recreational water features stand between such runoff and human exposure. Chlorination by itself is relatively ineffective against *Cryptosporidium*. Combined sewer outflows (comingling storm water with sewage) potentially allow greater contamination of surface waters sufficient to overwhelm these protective systems.

The conceptual model developed for the IJC HPAB linking climate change to human health outcomes was applied to this case study (**Figure 10**), linking climate-related precipitation extremes to stressors on wastewater management, water treatment and potential exposure to and disease from infectious agents like *Cryptosporidium*.



[1]Selected; other climate effects not included. [2]Selected; other environmental changes that are not the focus of this report are included in Supplemental Materials Appendix D with discussion. [3]Includes viral, bacterial, fungal/mold, protozoa. [4]Ingestion, inhalation and dermal exposures. [5]E.g., greenhouse gas reductions. [6]Plans and designs to minimize impacts or exposures. [7]Factors that increase exposures (e.g., residence in flood plain) of effects (e.g., immunodeficiency) and factors that improve capability to recovery (e.g., adequate income, healthcare, psychological resilience). These may occur at the individual or population levels. [8]Note: one type of exposure may create secondary exposures. [9]Other factors include, but are not limited to, lake thermal stratification changes, lake acidification, changed species distributions (including disease vectors) and migrations, coastal weather changes (e.g., inversions). [10]Additional discussion in Supplemental Materials Appendix D.

Figure 10. Mapping the Hamilton, ON *Cryptosporidiosis* case study to the conceptual model.

4.2.2 Climate drivers

One of the main climate drivers in the Great Lakes is precipitation extremes, the impacts of which are already being seen across the region (Taekema 2019). Much of the region is expected to see an increase in heavy precipitation events in the coming decades as climate change progresses (Draaisma 2022). The combined effect of precipitation totals clustering into heavier, fewer storm events and the polarization of wet and dry seasons across the Great Lakes may together increase the chance of extreme precipitation events as well as prolonged dry periods by extending the time between rainfall events (and potential build-up in soil of *Cryptosporidium* oocysts) (IJC HPAB 2021). These heavy precipitation events have many impacts, including infrastructure and property damage, as well as the potential to overwhelm infrastructure that was not designed for these climate change-forced precipitation pattern changes (Taekema 2019). In Ontario, more extreme rainfall is expected to increase infrastructure costs by as much as CDN$6.2 billion (US$4.5 billion) by the year 2030 under a high-emissions climate change scenario (Draaisma 2022; Financial Accountability Office of Ontario 2022). There are several studies that link the incidence of *cryptosporidiosis* with rainfall patterns, particularly the increase in incidence one to four weeks after there is a period of extended dry weather followed by an excessive rainfall event (Health Canada 2016; IJC HPAB 2021).

4.2.3 Environmental change/hazard exposures

Extreme precipitation storms can lead to an environmental change: increased intermittent runoff. Higher, and more concentrated, runoff can lead to increased chances of combined sewer overflow (CSO) discharge events in areas that have combined sewer systems in place. In combined sewer systems, stormwater and wastewater flow through the same pipes, which normally drain directly to the wastewater treatment plant during dry weather. During wet weather, though, the combined volume of wastewater and stormwater can overwhelm the sewer system and breach the flow regulators in place; this combination flow then empties into nearby water bodies, untreated or only partially treated. This overflow is a CSO (USEPA 2023). Hamilton, Ontario has a combined sewer system and has had between 60-150 CSO events per year in the last few years (City of Hamilton, 2023a, 2023b). From 2019 to 2022, there was a total volume of 13 billion liters (3.4 billion gallons) discharged from CSO events in Hamilton (City of Hamilton, 2023a, 2023b). In addition, Hamilton experienced years of untreated sanitary sewage discharges to local waterways due to incorrect pipe connections within the sewer system (City of Hamilton 2023c; Mitchell 2022).

These events can lead to bacteria, debris and other hazardous substances ending up in destination water bodies where people can unintentionally be exposed to them and risk infection or sickness (USEPA 2023; City of Hamilton 2023d). *Cryptosporidium* oocysts are the most important of the parasite's life cycle—a thick-walled, round, and environmentally stable cell that contains sporozoites, the infectious agents of the life cycle—and are commonly found in sewage and surface waters, as well as in treated water, although much less often (Health Canada 2016). Humans can be a significant source of *Cryptosporidium* in surface waters, especially in those used for recreation (Health Canada 2016). With each CSO event comes potential human health risks associated with water bodies for recreation or drinking water sourcing. Since *Cryptosporidium* is also transmitted person-to-person in water recreation and day care facilities, the initiation of a few human cases can lead to ongoing transmission in these other settings.

In addition to contamination from CSO events, increased intermittent runoff can lead to high concentrations of surface contaminants being washed downstream in one large flush, which can then lead to higher concentrations of those pollutants and contaminants in the destination water body within a brief period. Prolonged dry spells between heavy rainfall events are also expected with climate change. Pollutants including oocysts can accumulate in the dry periods and be mobilized downstream during wet events. Southern Ontario has widespread cattle farming, a persistant source of Cryptosporidium oocysts nearby Hamilton's major watershed, and is associated with higher rates of disease to the north and west (Nwosu et al., 2019).

Other climate-related environmental changes affect the quality of drinking water treatment and distribution. In 2021, the City of Hamilton blamed increasing surface water temperatures for episodes of drinking water chlorine levels falling below provincial safety standards (Van Dongen 2021), after average water temperatures in Lake Ontario hit 25-year record highs (Van Dongen 2020). City officials intensified chlorine treatment in 2024 (Van Dongen 2024). However, chlorine alone is generally insufficient to clear Cryptosporidium oocysts. Milwaukee, WI has deployed ozone treatments, and another Southern Ontario community uses ultraviolet exposure to reduce the risk of *Cryptosporidium* in treated water (Pintar et al., 2012). However, these treatments are not persistant, and infiltration of polluted stormwater into distribution pipes (2031 kilometers in the Hamilton system) (City of Hamilton, 2023e) can also occur, particularly in very wet conditions.

4.2.4 Human health outcomes

Cryptosporidiosis has been a reportable disease in Canada since 2000, and there are consistently several hundred cases per year across the country (CBC News 2017; Draaisma 2022; Health Canada 2016; Taekema 2019). There was an outbreak of this illness in 2001, when drinking water in North Battleford, Saskatchewan became contaminated and hundreds of residents were infected; as a result, this year is an outlier when looking at the annual case count (CBC News 2017). Reported cases have also risen since 2018; however, this was due to the introduction of polymerase chain reaction testing for cryptosporidiosis, which is far more sensitive than previous testing methods (Johnson et al., 2020). In Ontario, there are usually a few hundred cases per year, but in 2018 and 2019, there was an increase in confirmed cases, again likely due to the introduction of polymerase chain reaction testing for this illness (Public Health Ontario 2022).

To our knowledge, Hamilton, Ontario has not experienced a major cryptosporidiosis outbreak to date, and its highly urbanized watershed enjoys relatively low human case counts, in contrast to other communities in Southern Ontario with heavier cattle concentrations (Nwosu et al., 2022). However, when the board examined the multi-year relationship between *Cryptosporidium* cases (and those of another waterborne parasite, *Giardia lamblia*) and extreme precipitation following prolonged dry spells, Hamilton was noted to have a statistically significant pattern of elevated case counts occurring three to six weeks after extreme precipitation spikes. The HPAB study could not identify if risks were associated with drinking water consumpton, recreational water exposure, or other *Cryptosporidium* exposures, but cases were observed year-round, and not just during peak water recreation and outdoor sports months (IJC HPAB 2021). Thus the association between extreme precipitation and elevated case counts is observed in Hamilton as it has been in other cities, which may worsen as the intensity of climate-driven environmental change intensifies (Chhetri et al., 2017, 2019). [Note: the HPAB study was a proof-of-concept for binational integration of aquatic environmental and human health data, similar in concept to the indicators proposed in this report.]

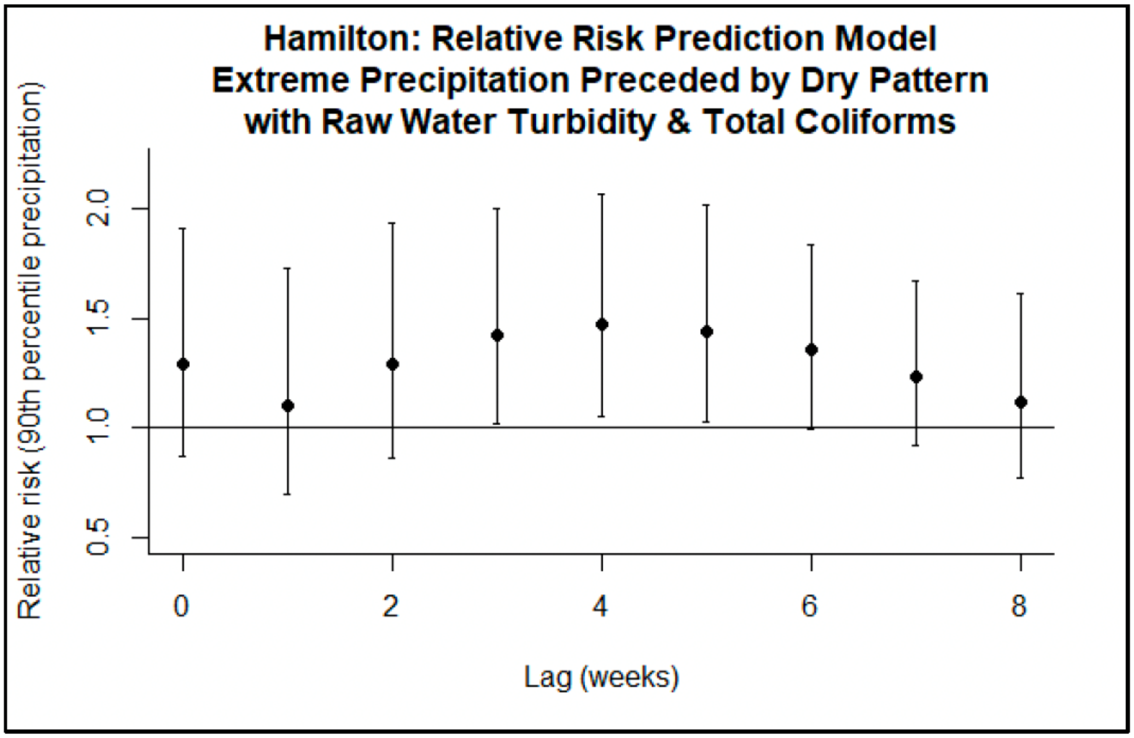


Figure 11. The adjusted relative risk of cryptosporidiosis and giardiasis plotted by weeks after an extreme precipitation event in Hamilton, Ontario. Figure from IJC HPAB 2021.

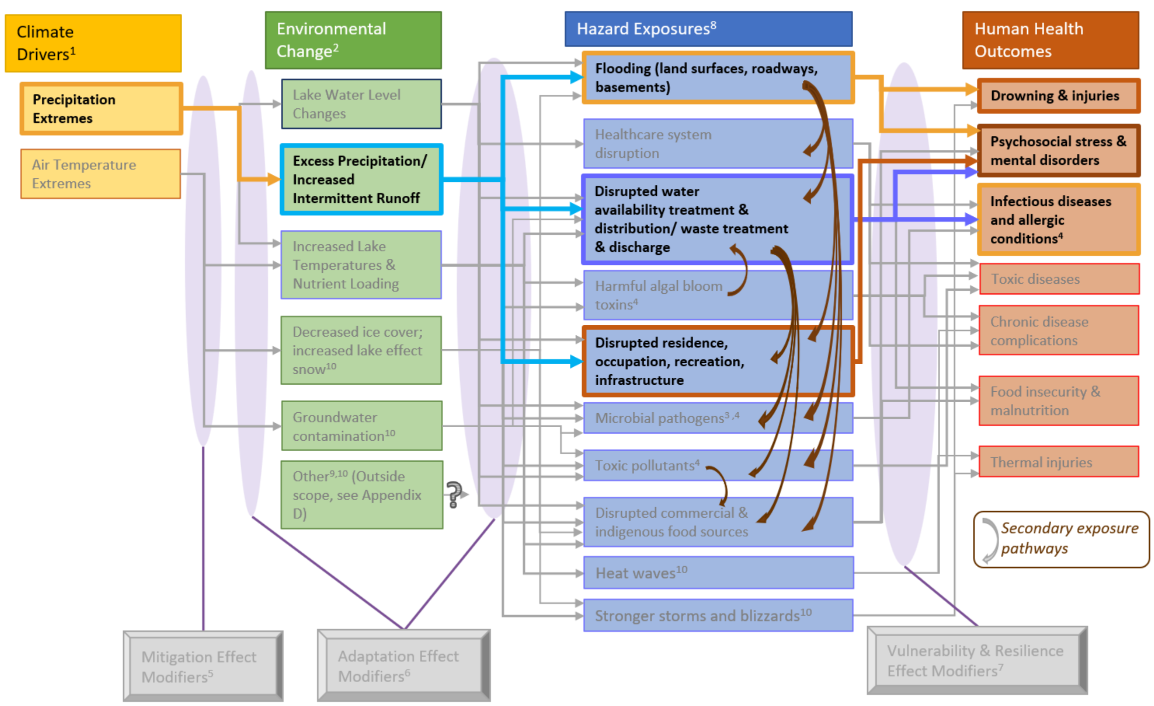
4.2.5 Conclusion

With climate change causing intense periodic precipitation, and subsequently increased intermittent runoff, there are new or heightened risks for human health. One of these human health risks that may see an increase with climate change is cryptosporidiosis. This case study fits the conceptual model very well; there are several items that fit into each of the conceptual model's components. The impact of climate change on cryptosporidiosis in the Great Lakes region can be monitored and modeled over time in shoreline communities (adjusted for adaptive changes like improvements to wastewater management or drinking water protection and treatment) so that this human health risk can be reduced.

4.3 Case study: urban flooding in Detroit, Michigan

4.3.1 Introduction

Climate change is disrupting the usual balance of nature. One major effect of climate change in the Laurentian Great Lakes is urban flooding. Warmer weather is feeding more intense storms, the effects of which are acutely felt in urban areas, leading to localized flooding. Urban areas are particularly vulnerable to flooding due to the amount of impervious surface. Additionally, older urban areas, like Detroit, Michigan, have combined storm and sanitary sewer systems, which are not sized to handle the increased runoff, and overflow with water that has mixed with raw, untreated sewage. This case study is focused on the June 25-26, 2021, extreme storm event in Detroit, Michigan that led to widespread urban flooding. The event was preceded by moderate to severe drought conditions and experienced three to five inches of rain across the area, with some localized areas (mainly along the Interstate 94 corridor) seeing six to eight inches. A state of emergency was subsequently declared by Michigan Governor Gretchen Whitmer, and a national disaster was declared by President Joe Biden. Similar flooding events had been observed in the region during extreme storms in 2014 and 2016. **Figure 12** maps the events described in this case study to the conceptual model described in Section 3 above.



[1]Selected; other climate effects not included. [2]Selected; other environmental changes that are not the focus of this report are included in Supplemental Materials Appendix D with discussion. [3]Includes viral, bacterial, fungal/mold, protozoa. [4]Ingestion, inhalation and dermal exposures. [5]E.g., greenhouse gas reductions. [6]Plans and designs to minimize impacts or exposures. [7]Factors that increase exposures (e.g., residence in flood plain) of effects (e.g., immunodeficiency) and factors that improve capability to recovery (e.g., adequate income, healthcare, psychological resilience). These may occur at the individual or population levels. [8]Note: one type of exposure may create secondary exposures. [9]Other factors include, but are not limited to, lake thermal stratification changes, lake acidification, changed species distributions (including disease vectors) and migrations, coastal weather changes (e.g., inversions). [10]Additional discussion in Supplemental Materials Appendix D.

Figure 12. Mapping the Detroit urban flooding case study to the conceptual model

4.3.2 Climate drivers

The main climate driver of urban flooding is precipitation extremes. Both the amount of rainfall and the intensity of storms have increased across the United States. In the Great Lakes region, the five-year maximum daily precipitation increased 18 percent and the number of five-year, two-day events increased 63 percent from 1901-2016 (GLISA 2024a). Additionally, from 1958-2016, the 99th percentile precipitation increased 42 percent (GLISA 2024a).

4.3.3 Environmental change/hazard exposures

As discussed in the introduction, urban areas experience increased runoff due to increased and more-intense precipitation. This issue is worsened by older urban areas served by combined storm and sanitary sewer systems. Storm runoff is mixed with the normal sanitary flow and overflows into waterways, roadways, and basements when the system exceeds capacity. Additionally, the sewer collection systems were designed for an 'unchanged' climate and cannot handle the additional capacity conveyed by more intense and frequent precipitation. This makes sewer overflows more common in urban areas.

Another environmental change due to climate change is increasing temperatures. For every one degree Fahrenheit increase in temperature, the atmosphere gains 5 percent moisture holding capacity. From 1951-2020, observed temperature in the Great Lakes region has increased 2.3°F, with a 3.9°F increase in the winter months (December to February). Temperatures are projected to increase anywhere from 3 to 6°F from 2040-2059 (GLISA 2024b).

Lastly, as of the 2020 census, Detroit is 77.7 percent Black or African American, so this can also be considered an environmental justice issue.

Overwhelmed combined sewer systems represent one source of flooding in urban areas, increasing the odds of human contact with untreated sewage. Detroit's combined sewer system is designed to handle approximately three inches over 24 hours, and during the June 2021 event, areas in the region saw nearly double that amount (Great Lakes Water Authority 2021). Also, Detroit's topography is flat, with only a 108-foot change in elevation over its 139 square miles. The raw sewage contains numerous microbial pathogens and potential disease vectors. Flood waters also contain surface pollutants, especially from roads, that would normally be discharged to sewer systems during rain events. Many basements in Detroit experienced raw sewage backups, and standing water remained in numerous roadways for days after the event. The exposure risks were amplified by the standing water.

4.3.4 Human health outcomes

There was at least one recorded drowning death in Dearborn, Michigan during the June 2021 storm event (Spencer and Ainsworth, 2021). Flooding events cause repeated stress during new rainfall events (Larson et al., 2021). The two quotes below are from Detroit residents impacted by urban flooding during the June 2021 storm event (Sampson et al., 2021):

- "…you can't pay me for the stress I feel every time I see a heavy rain happen. There's no paying for that."

- "…I used to enjoy hearing the sound of rain, it was very calming, relaxing, and helped put me to sleep. Now it's the source of great anxiety. It rained yesterday and the day before and the first thing I do is look in my basement…"

In addition to potential exposure to microbial pathogens, flood waters can cause unseen damage to buildings and structures by inducing the growth of mold. Mold is known to exacerbate asthma conditions and can cause headaches, eye irritation, sneezing and skin rashes.

4.3.5 Conclusion

Extreme precipitation caused by climate change is leading to flooding events in urban areas (Southeast Michigan Council of Governments 2020). Although the case study focused on a singular event in Detroit, flooding threatens all urban areas and is exacerbated in older cities that still have combined sewer systems (Southeast Michigan Council of Governments 2022). The conceptual model worked successfully when analyzing the June 2021 Detroit storm event, capturing key outcomes. The model is well-developed for this type of climate change-induced outcome(s) analysis and inclusive of climate-health impacts seen across the Laurentian Great Lakes region.

5.0 Experts Workshop

A virtual experts workshop, held on two half days over September 18 and 19, 2023, was designed to identify trackable human health indicators and to provide feedback on the conceptual model designed to describe relationship between climate drivers and potential human health outcomes. In addition to IJC staff and the support contractor team, approximately 15 climate change and Great Lakes experts participated in the workshop.

The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group could speak and present their points of view. Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations.

Day 1 of the workshop was focused on the conceptual model described in Section 3. The board work group co-chairs (Dr. Seth Foldy and Barry Jessiman) shared thoughts on impacts of climate change drivers and health outcomes in the Great Lakes. They also provided an overview of the GLWQA, the role of the board, and how the present project fits within that role. Dr. Peter Berry served as the keynote speaker and provided valuable perspective on climate change-driven health risks, health indicators, and quantifying resilience of health systems. Dr. Berry also presented several criteria for indicator selection, including:

- **specific**, based on an association between climate and health
- **actionable**, related to climate and health conditions that are amenable to adaptive actions
- **measurable**, based on timely and unbiased data of acceptable quality
- **understandable**, applicable and acceptable to stakeholders and potential users
- **representative** of the issues and areas of concern
- **consistent** and comparable over time and space
- **robust** and unaffected by minor changes in method, scale, or data
- **scalable**, capable of being used at different scales
- **cost-effective**, capable of being constructed and used at an acceptable cost benefit ratio
- **sustainable**, able to provide data for the next 20-30 years

The three case studies described in Section 4 were presented at the workshop to characterize the application of the conceptual model and to describe health impacts of climate change in the Great Lakes. Two small breakout groups dedicated an hour to evaluating whether the conceptual model accurately describes relationship between climate change and human health outcomes and whether the case studies adequately demonstrate the connection between climate change and human health.

Day 2 of the workshop was focused on proposing indicators, evaluating the data needs and public uses, identifying policy and science gaps, and developing strategy and recommendations for establishing climate-environmental-human health indicator surveillance across the Great Lakes. The project co-chairs opened the day with their perspectives on these areas, followed by additional discussion among the workshop participants via two breakout groups for the following topics: flooding, algal toxins, heat waves, CSO elimination or reduction, increasing lake temperatures, and urban heat islands.

High-level observations and recommendations from workshop general discussions and breakout sessions are included below:

- There is a need to consider audience, like health systems, public health officials, or the general public, when addressing indicators.
- Time scale is important when considering indicators:
    - There is a difference between long-term and short-term impacts that needs to be considered.
    - Acute versus long-term events have different effects and need to be considered appropriately.
- Cumulative and compounding impacts need to be considered because different adaptation and mitigation modifiers can affect one another. Indicators were sought that related to the different domains of the conceptual model (climate drivers, environmental changes, hazard exposures, and health outcomes, as well as effect modifiers).
- There is a need to consider community and health system capacity as it can vary significantly.
- Considering the risk to the healthcare system is also important.
- There is a need to include more communication and data-sharing between countries.
- Impacts on subpopulations of concern, including Indigenous communities and vulnerable groups, should be differentiated from impacts to the general population where possible.

6.0 Proposed Indicators

6.1 Introduction

The identification of potential indicators to track the human health impacts of climate change was based on the following:

1) Previous IJC previous work on indicators for ecosystem health and human health, as described in Section 1.

2) Examples of relevant indicators from the literature review task, described in Section 2.

3) A review of indicators used or proposed in the public health field, based largely on the Lancet Countdown 2022 Special Issue (Romanello et al., 2022) and World Health Organization reports (World Health Organization 2021, 2022), and

4) Examples of existing indicators from climate change-focused resources such as GLISA and the Fifth National Climate Assessment.

Proposed indicators were based on meeting one or more of these criteria:

1) Coverage of all stages of the conceptual model, including climate drivers, environmental change, human health exposures, health outcomes, and adaptation measures,

2) A connection to water, in keeping with the IJC's mandate under the GLWQA,

3) Data availability,

4) Ability to monitor indicators, and

5) Effect of non-climate factors, e.g. separating AGI cases resulting from climate change-driven factors (e.g. increased runoff associated with more extreme storms) from AGI cases due to, for example, food poisoning.

The first two factors were essential criteria for the indicators proposed in this section. The remaining criteria speak to the readiness of each proposed indicator to be implemented. Note that indicators are proposed below that may not yet be readily available or that may not easily isolate a climate signal. For these indicators, a longer implementation horizon is likely needed. Sections 6.1.1 and 6.1.2 include a general discussion of data availability for the proposed indicators.

The scope of this effort constrained to address climate drivers of environmental temperature and precipitation extremes, and to health exposures and outcomes primarily mediated by three aquatic environmental challenges (e.g., lake levels, runoff and precipitation, and lake temperatures and nutrients), but not other factors such as ice cover, air quality, or groundwater contamination. We understand that these and other climate drivers can and do affect human health, and that our conceptual model (see Section 3) and list of potential indicators are not exhaustive.

Table 10 summarizes the proposed indicators, along with key information for each. Indicators listed in the table are categorized into the four groups described in the conceptual model (climate drivers, environmental change, hazard exposures, and human health outcomes); in addition, the table adds a fifth category (effect modifiers) for indicators related to adaptation, vulnerability and resilience modifiers. There are many potential effect modifiers that could influence the relationships between climate drivers and human health outcomes (see vertical grey boxes in the conceptual model in **Figure 7**). Examples include mitigating climate change by reducing greenhouse gas emissions, adapting to anticipated stressors by improving water and sewage systems and stormwater management, reducing human risk exposures by changing flood planning zones, and enhancing resilience of the healthcare system by protecting health facilities and improving equitable access to safe environmental conditions. Therefore, we propose that such effect modifiers be considered for indicators going forward, although only a modest set is proposed in this report.

Table 10 is organized into indicator categories (referencing back to the conceptual model) with companion sub-indicator measures. The table also includes the following additional columns:

- **Existing Indicator?**: whether the subindicator has already been proposed (or is currently in use) by the IJC, Lancet, World Health Organization, or other organizations (e.g., GLISA).

- **Data Availability?**: characterization of the availability and temporal granularity of the data needed to calculate the subindicator, further discussed below.

- **Timeframe for Indicator Update**: this column indicates the timeframe or interval over which the indicator is recommended to be updated. However, the underlying data can be captured at a higher frequency, either on an ongoing basis or following specific events, to allow for additional analytics (also see footnotes to **Table 10**).

- **Effect of Non-climate Factors**: characterization of the extent to which the subindicator is likely to be influenced or driven by factors other than climate change.

Table 10. Indicator summary

Indicator	Subindicator	Existing Indicator?	Data Availability	Timeframe for Indicator Update	Effect of Non-climate Factors
Climate Drivers					
Increased precipitation	Increase in rainfall intensity (in/hr or mm/hr) of the 1% heaviest storms	Yes	Good	Annual; however, aggregating the data into multi-year periods for evaluation may yield more insight as an indicator of climate change. 1, 2	Low
	Total precipitation (inches or mm) falling in the 1% heaviest storms	Yes	Good		Low
	Total annual precipitation (inches or mm)	Yes	Good		Low
Extreme precipitation following dry spells	The number of annual extreme precipitation events that follow an extended dry period	No	Fair		Low
Air Temperature	Annual average surface temperature	Yes	Good		Low
	Frequency and duration of heat waves	Yes	Good		Low
Environmental Change					
Lake surface temperatures	Average surface water temperatures	Yes	Good	Annual 1	Low
Nutrient (phosphorus) concentrations	Offshore total phosphorus concentrations measured in µg/L for each of the Great Lakes	Yes	Fair	Annual 1	Medium
Harmful algal blooms	Percentage of each lake (<16 m in depth) where at least one algal bloom was detected during the April–October season each year	Yes	Fair	Annual	Medium
Change in lake levels	Anomalies in annual mean water levels relative to the base period of 1918 to 1990 for each lake	Yes	Good	Annual 1	Medium
Hazard Exposures					
Number of drinking water advisories	Number of drinking water advisories per year within a defined geographic region	No	Fair	Annual 2	Medium
Number of flooding events	Total reported flood episodes annually	No	Fair	Annual 2	Medium
Biological hazards of source water	*E. coli* (in counts per 100 mL) measured daily	No	Fair	Annual, or more frequently (e.g. weekly, monthly) 1	High
	Nitrate concentrations (in mg/L or other standard units) measured daily	No	Fair		High
	Turbidity (in nephlometer turbidity units, or NTU) measured daily	No	Fair		High
Algal toxins in source water	Microcystin-LR concentrations in water (µg/L), measured weekly	No	Fair	Weekly	High
Combined sewer overflows	Number of communities with combined storm-sewer systems	No	Good	Annual	Not applicable
	Percent of wet weather captured, averaged across combined storm-sewer systems	No	Good	Annual	Not applicable
	Annual number of untreated combined sewer overflow events	No	Fair	Annual 1	High
	Annual volume of untreated combined sewer overflow events	No	Fair	Annual 1	High
Beach closures	Percentage of days in the swimming season that beaches were closed due to high *E. coli* levels	Yes	Fair	Annual 1	High
Closed healthcare facility days due to flooding	Total days per year that healthcare facilities close due to flooding or flood-related impacts	No	Poor	Annual 2	Medium
Climate-related threats to Indigenous food sources	Estimated fish stocks and harvest levels	No	Poor	Annual 1	Medium
	Precipitation levels during critical wild rice growth season (spring)	No	Good	Annual 1	Low
	High water levels during critical wild rice growth season (spring)	No	Fair	Annual [1]	Medium
Human Health Outcomes					
Reportable cases of waterborne gastrointestinal illness	Monthly and yearly occurrences of waterborne gastrointestinal illness within a defined geographic region	No	Fair	Annual 1	High
Changes in mental health/sentiment	Change in sentiment based on analysis of social media posts, following extreme weather events	Yes	Poor	Annual or event-triggered 1,2	Medium
Mortality due to extreme heat	Mortality from exposure to extreme heat in persons over 65	Yes	Fair	Annual 2	Medium
Deaths from flooding	Number of deaths attributable to drowning per year per 100,000 people	No	Fair	1-3 years 2	High
Economic damage from extreme weather	Total annual damage (in millions of dollars) from weather events within the Great Lakes basin	No	Fair	Annual 2	High
Adaptation, Vulnerability and Resilience Modifiers					
Vulnerability and adaptation assessments completed	Percentage of cities/counties in the Great Lakes basin that have completed climate change vulnerability and adaptation assessments	No	Poor	Annual	Not applicable
	Percentage of healthcare facilities that have completed their own vulnerability and adaptation assessments or are covered by existing assessments	No	Poor	Annual	Not applicable

[1] Daily data collected for shoreline jurisdictions for future analytics.
[2] Discrete event data collected for shoreline jurisdictions for future analytics.

6.1.1 Health data sources

Traditional sources of public health data can be used for several indicators of human health outcomes, such as death records and mandated reports of illness to public health authorities. These are typically available (with appropriate data-use protections) from state or provincial health authorities. However, many health events still go unreported (either due to lack of reporting systems or incomplete reporting). As paper health care records are replaced by electronic medical records, and as data elements become increasingly standardized by government and industry, automation of data collection and reporting can be improved.

One relevant example is the aggregation of indirect but highly suggestive data like symptoms (e.g., diarrhea), test orders and test results (gastrointestinal pathogen tests), pharmaceutical use (e.g., anti-diarrheals) and other disease signals, often in near-real time. Interestingly, many such efforts emerged to attempt earlier detection of *Cryptosporidium* and other waterborne disease outbreaks (Berger et al., 2006). The United States enjoys some degree of nationally standardized (but geographically spotty) routine collection of such syndromic surveillance data (CDC 2024b) but we have not located a similar Canadian program.

A newer surveillance approach is to enable query of large banks of electronic health records on an aggregate basis, which has been established in a few US locations (e.g., Bacon et al., 2019). Again, these are infrequently available at present in both nations, but may evolve into a source of health event surveillance over time.

Finally, new national data collection efforts such as the United States' "All of Us" program (National Institutes of Health 2024) enlists the voluntary sharing (by patients, for anonymized analysis) of both electronic health record and survey data (along with genomic information). This offers the possibility, for example, of surveying beach use while searching for subsequent infections. Again, we did not encounter a Canadian equivalent at this time. As public participation in such initiatives increase, however, they may provide a promising source of health outcomes data across the Great Lakes, and to better determine health results of climate-related disasters and steps taken to mitigate them (Phuong et al., 2022).

6.1.2 Other data sources

The left side of the conceptual model presented in Section 3 includes *climate drivers* and *environmental changes*. Many of the elements of this portion of the conceptual model rely on environmental data, such as precipitation, temperature, and lake levels that have been collected for some time by various agencies, universities and municipalities in both Canada and the United States. These data can often be accessed via online data portals (e.g., Great Lakes Observing System, United State Geological Survey, USEPA Water Quality Portal, Environment Canada). Often, data at the state/provincial, county, city, or utility level that are not openly available online can be requested directly from the organization. These data may require some reformatting for additional data processing, as would be needed for the indicators developed for this project.

Indicators that reflect source water quality are routinely collected and used by drinking water treatment system operators. These (such as *E. coli* counts or cyanotoxin measures) are not all routinely reported to environmental regulators, however. Utilities may also be concerned about reporting such data publicly for several reasons. Enhancing the confidence of such potential data reporters may be critical to accessing the data needed for some of the indicators.

Other data that support the development of, or factor into, one or more of the indicators described in this project may also be necessary to support the objectives of the project. For example, the USEPA's Environmental Justice Screening and Mapping Tool (Version 2.11), EJScreen, makes multiple US data layers available that can show pollution, socioeconomic indicators, and health disparities, among other factors.[1] Canada's EJ Atlas shows specific sites where environmental justice issues have been identified around the Great Lakes and elsewhere, as shown by clickable icons (Temper et al., 2015).

6.2 Indicator descriptions

6.2.1 Increased precipitation

Increase in extreme precipitation events is one of the clearest changes in climate observed in the Great Lakes region (GLISA 2024a). Impacts that are likely to occur as a result of increasing precipitation include increased surface runoff that transports nutrients and other pollutants into the Lakes, increased flooding risk, and an increased likelihood of combined sewer overflows. Precipitation trends are generally well-studied and tracked across the Great Lakes. Several indicators for precipitation are already reported by GLISA, USEPA and ECCC (as part of the State of the Great Lakes report), and other organizations. These include changes in the heaviest precipitation events as well as trends in total precipitation.

Indicators:

- Increase in intensity (e.g., the amount of precipitation per minute or per hour) of the one percent heaviest storms, averaged over a 30-year period and compared to the baseline period 1951-1980. This indicator increased 5.1 percent by 1981-2010 (GLISA 2024a).

- Total precipitation (in or mm) falling in the one percent heaviest storms averaged over a 30-year period, compared to the baseline 1951-1980. This indicator measures the extent to which precipitation is becoming concentrated in the heaviest storms and showed a 20.2 percent increase by 1981-2010 over the Great Lakes basin (GLISA 2024a).

- Total annual precipitation (in or mm). This indicator shows an increasing trend in the overall Great Lakes basin (see **Figure 13**). Lake by lake trends are either unchanging (Lake Superior) or increasing (all other lakes) (ECCC and USEPA, 2022b).

[1] The USEPA EJScreen tool is available at: ejscreen.epa.gov/mapper

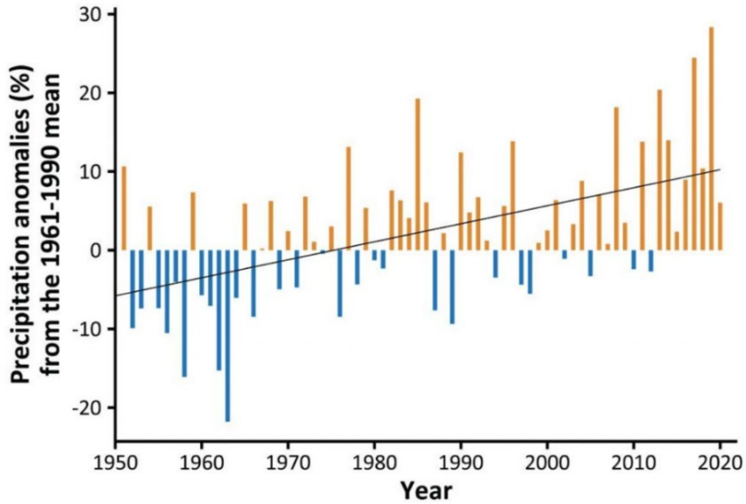


Figure 13. Total annual precipitation in the Great Lakes Basin (ECCC and USEPA, 2022b)

Data Sources:

United States precipitation data for individual weather stations can be accessed at ncei.noaa.gov/cdo-web. United States 30-year climate normals can be accessed at ncei.noaa.gov/products/land-based-station/us-climate-normals.

Canadian precipitation data can be accessed at canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/precipitation-access.html.

Historical climatological data for 235 monitoring stations within the Great Lakes (both Canada and the United States) can be accessed on the GLISA website, at glisa.umich.edu/climate-data/great-lakes-climatologies.

Data and methods used to calculate State of the Great Lakes indicator are available at stateofgreatlakes.net/wp-content/uploads/2022/07/Precipitation-Amounts-Subindicator-Report-SOGL-2022.pdf.

6.2.2 Extreme precipitation following dry spells

As temperatures warm, the potential for both wetter and drier conditions can increase. While annual precipitation totals have generally increased, the seasonal and regional distribution of precipitation can also change (GLISA 2024a). An earlier study found that an abrupt precipitation spike following an extended dry period correlated with an increased risk of acute gastrointestinal illness in communities that source their drinking water from the Great Lakes (IJC HPAB 2021).

In the Great Lakes region, precipitation totals during the fall, winter and spring have increased in most locations, while summer precipitation has remained stable or declined. Additionally, the distribution of the intensity of precipitation events has also changed so that more precipitation is falling during heavier storms. These combined effects, the clustering of precipitation into heavier storms and the polarization of wet and dry seasons, may increase the chance of both extreme precipitation events and prolonged dry periods by extending the time between rainfalls (GLISA 2024a).

Indicators:

- The number of annual extreme precipitation events (defined as weeks with total precipitation above the 90th percentile weekly precipitation) that follow an extended dry period (i.e., a period of at least 30 days with no more than 0.1 mm of rainfall per day), calculated using the methodology developed by Chhetri et al. (2017).

Data Sources:

United States precipitation data can be accessed at ncei.noaa.gov/cdo-web/. United States 30-year climate normals can be accessed at ncei.noaa.gov/products/land-based-station/us-climate-normals.

Canadian precipitation data can be accessed at canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/precipitation-access.html.

Historical climatological data for 235 monitoring stations within the Great Lakes (both Canada and US) can be accessed on the GLISA website, at glisa.umich.edu/climate-data/great-lakes-climatologies/.

6.2.3 Air temperatures

Average air temperatures are rising across the Great Lakes due to climate change. Since 1951, annual average temperatures have increased by 2.3°F (1.3 °C) across the eight US Great Lakes states: Illinois, Indiana, Michigan, Minnesota, Ohio, New York, Pennsylvania, and Wisconsin (see **Figure 14**) (GLISA, 2024b). Average air temperatures across Canada have increased by 1.9°C from 1948 to 2022. However, a comparable indicator could not be identified for the Canadian portion of the Great Lakes basin. An indicator based on air temperatures could be a first step towards including other temperature-driven effects of climate change on human health, such as heat waves.

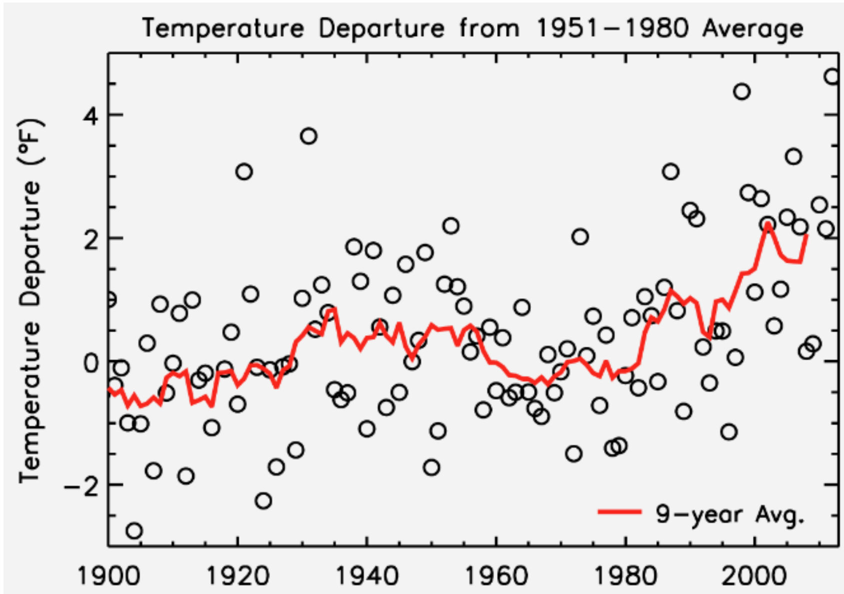


Figure 14. Annual average temperature, expressed in terms of departure from the 1951-1980 long-term average, across the US Great Lakes states (GLISA 2024b)

Indicators:

- Annual average surface temperature expressed as a nine-year rolling average, °C or °F
- Number and duration of heat waves. The US Global Research Program has developed an indicator based on data across 50 metropolitan areas in the United States.

Data Sources:

Definitions and data for the indicator are available at globalchange.gov/indicators/heat-waves.

United States surface temperature data can be accessed at ncei.noaa.gov/cdo-web. United States 30-year climate normals can be accessed at ncei.noaa.gov/products/land-based-station/us-climate-normals.

Canadian data for surface air temperatures are available at canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/surface-air-temperature-access.html.

Historical climatological data for 235 monitoring stations within the Great Lakes (both Canada and the United States) can be accessed on the GLISA website, at glisa.umich.edu/climate-data/great-lakes-climatologies.

6.2.4 Lake surface temperatures

The Great Lakes have warmed faster than the nearby air temperature in recent years. Lake Superior summer (July-September) surface water temperatures increased approximately 4.5°F (2.5°C) from 1979-2006, a significantly faster rate than regional atmospheric warming. Declining winter ice cover is the largest driving factor behind the lakes' accelerating warming (GLISA 2024b).

Indicators:

- Average surface water temperatures (°C or °F). This indicator is currently tracked and reported for all five Great Lakes and shows an increasing trend from 1980-2020 (ECCC and USEPA, 2022b).

Data Sources:

Historical climatological data for 235 monitoring stations within the Great Lakes (both Canada and the United States) can be accessed on the GLISA website, at glisa.umich.edu/climate-data/great-lakes-climatologies.

Data and methods used to calculate State of the Great Lakes indicator are available at stateofgreatlakes.net/wp-content/uploads/2022/07/Surface-Water-Temperature-Subindicator-Report-SOGL-2022.pdf.

6.2.5 Nutrient (phosphorus) concentrations

Phosphorus and nitrogen are key nutrients for the growth of algae and other primary producers. However, too much phosphorus can lead to harmful algal blooms and nuisance algae in the Great Lakes, which can be detrimental to the environment, the economy and human health. Conversely, too little phosphorus can result in not enough algae to support healthy Great Lakes food webs and can threaten the sustainability of fisheries (ECCC and USEPA 2022c). Climate change may also lead to alternations in the timing and amounts of fertilizer application and subsequent precipitation-driven run-off of these nutrients.

Indicators:

- Offshore total phosphorus concentrations measured in µg/L for each of the Great Lakes. Status and trends in offshore phosphorus concentrations are tracked and reported by the State of the Great Lakes report; trends were reported as "unchanging" for all five lakes in the most recent assessment (ECCC and USEPA 2022a).

Data Sources:

Data and methods used to calculate State of the Great Lakes indicator are available at stateofgreatlakes.net/wp-content/uploads/2022/07/NutrientsInLakesSubindicatorReport_SOGL2022.pdf.

ECCC collects total phosphorus data to calculate nutrient status and trends in the offshore waters of Lakes Superior, Huron and Georgian Bay, Erie, and Ontario. The indicator trends and their underlying data can be accessed at canada.ca/en/environment-climate-change/services/environmental-indicators/phosphorus-levels-off-shore-great-lakes.html.

6.2.6 Harmful algal blooms (HABs)

HABs are made up of cyanobacteria, which sometimes produce toxins such as microcystin. These toxins can impact drinking water safety and may be harmful to people, wildlife and pets when present at high levels. The presence of HABs, for example, severely impacted the drinking water supply of over 400,000 people in Toledo, Ohio in 2014 (see case study discussed in Section 4.1). However, not all HABs are equally harmful; some may not have toxic levels of microcystin, while others may occur in remote areas with less risk of human exposure. This indicator is a conservative measure to focuses solely on the occurrence of HABs; revisions may be needed in the future to better understand the risk of human health exposures and associated negative outcomes.

Indicators:

- Percentage of each lake (<16 m in depth) where at least one algal bloom was detected during the April-October season each year. Status and trends in the annual extent of algal blooms are tracked and reported by the State of the Great Lakes report and was reported as improving for Lake Erie and unchanging for the other four lakes in the most recent assessment (ECCC and USEPA 2022c). Indicator levels were reported as "good" for Lakes Superior and Ontario, "fair" for Lakes Michigan and Huron, and "poor" for Lake Erie.

Data Sources:

The National Oceanic and Atmospheric Administration provides seasonal HAB forecasts during July to October each year, which can be accessed at coastalscience.noaa.gov/science-areas/habs/hab-forecasts/lake-erie.

HABs data from the US National Oceanic and Atmospheric Administration's monitoring network in Lake Erie and Saginaw Bay in Lake Huron are available online at glerl.noaa.gov/res/HABs_and_Hypoxia/habsMon.html.

Data and methods used to calculated the State of the Great Lakes indicator are available at stateofgreatlakes.net/wp-content/uploads/2022/07/HarmfulAlgalBloomsSubindicatorReport_SOGL2022.pdf.

6.2.7 Change in lake levels

While lake levels vary naturally, more drastic increases and decreases in water elevation are a response to other climate change factors including increased precipitation and runoff, increased temperatures and higher evaporation rates, drought, and ice cover that is higher or lower than historical norms. Between the years 2015 and 2020, all of the Great Lakes experienced higher than average water levels, following a period of time between 1998 and 2013 during which water levels were below average (GLISA 2024). **Figure 15** presents fluctuations in Great Lakes water levels between the years 1920 and 2020. As the population within the Great Lakes basin increases, monitoring water levels will become increasingly important because lake level fluctuations can impact fisheries, coastal wetlands, shoreline infrastructure, and recreation.

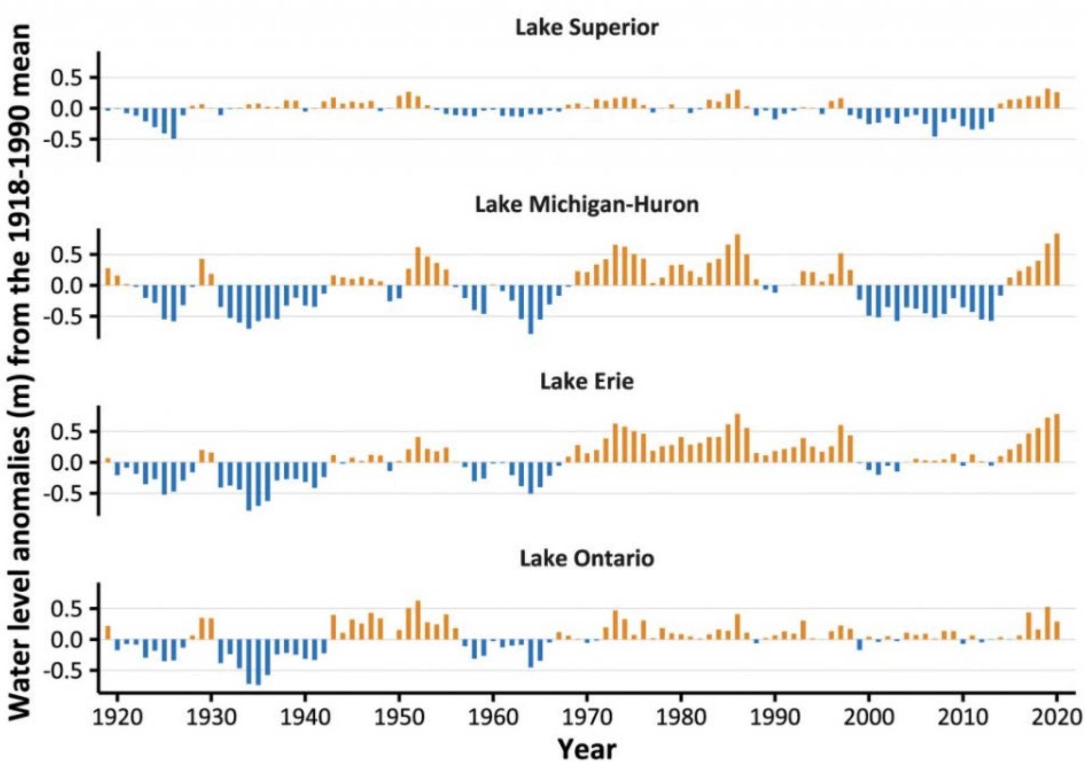


Figure 15. Changes in water levels in the Great Lakes (ECCC and USEPA, 2022b)

Indicators:

- Long-term water level variability, which assesses trends in the anomalies of annual mean water levels relative to the base period of 1918 to 1990 over the period of record for each of the Great Lakes. Status and trends in water levels are tracked and reported by the State of the Great Lakes report. Although short-term trends have been more variable, as discussed above, an analysis of long-term trends (visualized in **Figure 13**) shows that while Lake Erie water levels are increasing, there are no consistent trends within Lake Superior, Lake Michigan-Huron and Lake Ontario (ECCC and USEPA, 2022b).

Data Sources:

GLISA provides updated resources regarding lake levels in their sustained assessment of the Great Lakes. Information and resources specific to lake levels may be found here: glisa.umich.edu/sustained-assessment/lake-levels.

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Coordinating Committee) is a collaboration of Canadian and US governments to manage hydraulic and hydrologic data related to the Great Lakes and the St. Lawrence River, including data regarding water level management:greatlakescc.org.

The State of the Great Lakes reports for 2022 include an assessment of several indicators. The "Watershed Impacts and Climate Trends" indicator provides information about water levels: stateofgreatlakes.net/indicators/climate (ECCC and USEPA, 2022b).

6.2.8 Number of drinking water advisories

The State of the Great Lakes reports for 2022 report that, overall, treated drinking water sourced from Great Lakes surface waters is of good quality. Data from Ontario was used to assess trends in drinking water quality, and it was determined that drinking water quality did not change substantially between the years of 2011 and 2020. Data from the United States will be incorporated in future reports (ECCC and USEPA, 2022d).

Assessing the quality of treated drinking water in the Great Lakes basin can be challenging due to differing methods of monitoring and reporting protocols in Canada and the United States. An indicator that monitors the annual number of drinking water advisories may provide a consistent way of monitoring trends in drinking water quality and adequacy of water treatment and distribution infrastructure. In the United States, drinking water advisories are reported to the state enforcer of the Safe Drinking Water Act, which requires public notification in the event of unsafe, or potentially unsafe, drinking water. The number of drinking water advisories reported in a given year can be requested from state government agencies. In Canada, most drinking water advisories are reported using a national, web-based data management system, making them accessible and easy to track (University of Michigan Water Center 2022).

Indicators:

- Number of drinking water advisories per year within a defined geographic region. The relevant geographic region should be defined based on the areas where the Great Lakes serve as a drinking water source.

Data Sources:

The State of the Great Lakes reports for 2022 include an assessment of several indicators. The "Drinking Water" indicator provides information about treated drinking water quality: stateofgreatlakes.net/indicators/drinking-water (ECCC and USEPA, 2022d).

The University of Michigan Water Center summarizes data on drinking water advisories here: graham.umich.edu/system/files/pubs/Drinking-Water-Advisories.pdf.

The Government of Canada provides information on boil water advisories as an environmental indicator here: canada.ca/en/environment-climate-change/services/environmental-indicators/boil-water-advisories.html.

6.2.9 Number of flooding events

Heavier rain events are becoming increasingly common due to climate change (GLISA, 2024a). This pattern increases the chance of flooding, as dry ground is less able to absorb the sudden influx of rainwater. Data in both Canada and the United States regarding precipitation quantity and frequency is abundant. The Government of Canada maintains the Canadian Disaster Database, which tracks disaster events that meet a set list of criteria.

Indicators:

- Total reported flood episodes annually, within the Great Lakes basin or selected subregions.

Data Sources:

The Climate and Hazard Mitigation Planning Tool provides total reported episodes of flooding, as well as other data related to extreme rainfall and flooding: champ.rcc-acis.org.

The CDC Environmental Public Health Tracking Network includes data on a range of environmental factors that affect public health, including precipitation and flooding, and is available here: ephtracking.cdc.gov

The Canadian Disaster Database includes information on large disasters that meet certain criteria, and is available here: publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx.

6.2.10 Biological hazards of source water (measured by *E. coli*, nitrates and turbidity)

This indicator is summarized from the 2014 IJC HPAB report on human health indicators (IJC HPAB 2014). The presence of *E. coli*, nitrates and turbidity in source waters likely points to runoff from nearby septic systems and agricultural activities, and represents a hazard to human health, with effects including increased risk of acute gastrointestinal illness from viral, bacterial, and parasitic pathogens (including *E. coli*). Monitoring for the presence of *E. coli* would allow governments to identify trends in endemic, seasonal, and episodic presence of sewage and agricultural effluent and other contaminated runoff, examine seasonal and geographic distribution of selected *E. coli*, and analyze the effectiveness of management actions taken to reduce the impact of pathogens and nitrate in source waters. This indicator also recommends monitoring for nitrate as a marker for overall nutrient inputs that cause risk to human health, and for turbidity as a surrogate measure for the presence of pathogens.

Indicator:

- *E. coli* (in counts per 100 mL) measured daily at intakes to drinking water treatment plants, utilizing a standardized methodology.
- Nitrate concentrations (in mg/L or other standard units), monitored daily at intakes to drinking water treatment plants using a standardized methodology.
- Turbidity (measured and reported in nephlometer turbidity units monitored daily at intakes to drinking water treatment plants using a standardized methodology

Data sources:

Standard methods already exist for routine monitoring of biological hazards in source waters, and many datasets are readily available. Although requirements differ between Canada and the United States, utilities regularly monitor and report on source water contamination, and turbidity measurement data is likely available for most drinking water treatment plants. Requirements for the measurement and reporting of nitrate also exist for the purposes of establishing maximum contaminant levels for drinking water, although specific requirements vary between the two countries. Additionally, Ontario's Provincial Water Quality Network provides source water monitoring using *E. coli* as an indicator.

Monitoring for pathogens *C. parvum* and *G. lamblia* should be included in this indicator; however, at present data availability is limited. Methods for determining the presence of both pathogens are complex and expensive, and thus less often utilized. Nevertheless, direct measurements of pathogens provide a straightforward linkage between source water quality and potential human health risks, so we recommend that these pathogens be included in this indicator. Additionally, while methods for measuring and reporting turbidity are standardized between Canada and the United States, both countries have developed different methods for measuring and reporting nitrate, as well as the three pathogens identified above.

6.2.11 Algal toxins in source water

This indicator is summarized from the 2014 IJC HPAB report on human health indicators (IJC HPAB 2014). The presence of cyanotoxins provides useful information regarding the likely presence of harmful algal blooms. Drinking water is the primary focus of this indicator, but presence of cyanotoxins also has health implications for other users of affected waters such as fishers and swimmers.

Cyanotoxin measurements can provide evidence of trends in seasonal and geographic variability of source water contamination, allow governments to infer the level of hazard/impact of source water contamination, analyze the effectiveness of management actions taken to reduce the overall level of contaminants in source waters, and determine if improvements to potable and wastewater treatment systems are needed, and what improvements would be most effective in preventing chemically contaminated waters from reaching the consumer.

Indicator:

- Microcystin-LR concentrations in water (µg/L), measured weekly at drinking water intakes using a standardized methodology.

Data sources:

The cyanobacterial toxin microcystin-LR is routinely measured for surface drinking water intakes in Ontario and the United States. In the future, monitoring could be expanded to include the cyanobacterial toxins anatoxin-a and cylindrospermospin. Both of these toxins were listed, along with microcystin-LR, on the USEPA Third and Fourth Candidate Contaminant Lists, which identified unregulated contaminants of concern that are known or expected to occur in public water systems.

Monitoring of cyanotoxins should include all three cyanobacterial toxins presented above (microcystin-LR, anatoxin-a, and cylindrospermospin); however, current data availability favors microcystin-LR. It would also be useful to monitor toxins other than cyanotoxins, but for the purposes of this indicator, cyanotoxins are chosen as a representative. Currently, multiple methodologies exist for measuring cyanotoxins in surface waters, with varying sensitivity and accuracy. A standardized methodology should be chosen to facilitate an analysis of trends across the Great Lakes.

6.2.12 Combined sewer overflows

Combined sewer overflows (CSOs) contain a mixture of (partially treated or untreated) sanitary sewage and stormwater runoff. They occur when the rainfall amount during a storm event causes excess runoff that exceeds the capacity of the local community sewer system. To prevent the sewer system from backing up into residents' basements or to the streets, excess flow in the system is routed directly to local waterways without treatment. These events release a large amount of fecal pollution to local streams, rivers, and lakes. Once in the receiving water, pathogens in these untreated, fecal-polluted discharges pose a health risk to recreational users of the waterway, typically in the form of acute gastrointestinal illness.

The board considered CSOs as part of the development of their human health indicators in 2014 in the description of their indicator to identify sources of risk at Great Lakes beaches:

> Use of Great Lakes coastal beaches is an important recreational activity for the over 30 million people who live in the Great Lakes basin. Although exact figures are not available, there are estimates that millions of people each year use beaches on the Great Lakes… Targeted epidemiological studies have shown a number of adverse health outcomes (including gastrointestinal and respiratory infections) to be associated with fecally polluted recreational water. This can result in a significant burden of disease and economic loss (IJC HPAB 2014).

Numerical criteria have been established for indicator fecal bacteria by Canadian provinces and US states to protect the public from recreating in waterways during periods where the risk of acute gastrointestinal illness (AGI) is high due to elevated levels of fecal pollution. Beach monitoring for indicator fecal bacteria is conducted during the recreation season (nominally May through October) at a regular frequency (daily, weekly, biweekly) to inform decisions on whether to close beaches. The beach closure indicator, described in Section 6.2.13, is a complementary indicator to this indicator.

In addition, as part of the United States' CSO control policy, wastewater utilities in the Great Lakes are required to post public notifications within four hours of the occurrence of a CSO discharge event. Communities with combined sewer systems are required to reduce the frequency and volume of their untreated discharges through the development of 'Long-Term Control Plans.' To date, these communities have made substantial progress in reducing these untreated discharges. Between 2004 and 2020, CSO communities across the United States reduced CSO volume by 50 percent. In some areas, such as Southeast Michigan, the amount of wet weather volume captured and treated exceeds 95 percent on an annual basis. As these communities continue to invest in additional control measures to reduce CSO frequency and volume, the amount of untreated CSO will continue to decline.

Therefore, the indicators proposed for this project may serve as a method to measure the success of mitigation activities. However, given the changes in precipitation, with larger and more intense storms, sewer systems in the Great Lakes will continue to be challenged to maintain the level of service that they were designed for. In that regard, a flat long-term trend may reflect the offsetting mitigation benefits of more controls with the climate change-driven effects of changing precipitation patterns continuing to stress the sewer systems.

Sub-indicators:

- Number of communities with combined storm-sewer systems.
- Percent of wet weather captured, averaged across combined storm-sewer systems. Wet weather capture is the volume of water that is retained in the combined storm sewer system, expressed as percentage of total wet weather flow over a defined period.
- Annual number of untreated combined sewer overflow events.
- Annual volume of untreated combined sewer overflow events.

Data Sources:

In 2018, the USEPA passed the Public Notification Requirements for Combined Sewer Overflows to the Great Lakes, requiring timely notice requirements to the public for combined sewer overflows by CSO communities in the Great Lakes basin. As part of the implementation, EPA has published the National Pollutant Discharge Elimination System permits for the CSO communities in each state in the Great Lakes. These reports can be accessed here: epa.gov/npdes/combined-sewer-overflows-great-lakes-basin. This site is a comprehensive resource for finding information on CSO discharge events to the Great Lakes in the United States.

In some cases, links to the annual CSO notice reporting data may also be available (e.g., Indiana) on the USEPA's CSO Great Lakes Basin site. Depending on the state, data on CSO discharges that occurred by permittees may be readily available. For example, Michigan, makes data available on their searchable MiEnviro site mienviro.michigan.gov/ncore/external/overflow/list.

The government of Canada provides access to wastewater system effluent reported data, including CSO locations, activations, and volumes: open.canada.ca/data/en/dataset/9e11e114-ef0d-4814-8d93-24af23716489. This site includes links to spreadsheets of wastewater data as well as a map-based viewer. The specific dataset containing CSO data of interest can be accessed via this site: data-donnees.az.ec.gc.ca/data/substances/planinfrastruture/wastewater-systems-effluent-regulations-reported-data/Resaeu-Wser-unitaires-combined.xlsx.

Note that there is a lag in reporting of a year or more for some wastewater utilities so this indicator would function as a retrospective indicator and/or long-term trend indicator. More recent data may be available from state or local reporting.

6.2.13 Beach closures

The State of the Great Lakes reports for 2022 indicates that, overall, monitored beaches in the Great Lakes are safe for swimming and recreational use for the millions of residents and tourists that visit them each year. Additionally, 10-year trends indicate that the health and safety of monitored beaches is improving at beaches surrounding Lake Huron and Lake Ontario, and does not appear to be changing, for better or for worse, at beaches surrounding Lake Superior, Lake Michigan, and Lake Erie (ECCC and USEPA, 2022e).

Beaches may be closed to the public when the measured levels of pathogens like *E. coli* are higher than is generally considered to be safe for human health. Monitoring methodologies and criteria for measuring safe levels of *E. coli* differ between Canada and the United States (ECCC and USEPA, 2022e). An indicator tracking beach closures can serve as a proxy for contaminated waters, as beach closure data may be more readily available in both Canada and the United States than data about pathogens in the water, especially when considering differing monitoring and reporting protocols between the two countries. Currently, most beach closures are not based on the presence of HABs, although the presence of HABs may be detected and noted when testing for *E. coli*.

Indicator:

- Percentage of days in the swimming season (generally from Memorial Day/Victoria Day weekend to Labor Day but may vary by county) that beaches were closed. Over the last 10 years, beaches on all Great Lakes except Lake Erie were closed for less than 10 percent of the season; beaches on Lake Erie were closed for less than 20 percent of the season (ECCC and USEPA, 2022f).

Data Sources:

The USEPA provides information on beach advisories here: watersgeo.epa.gov/beacon2.

The National Oceanic and Atmospheric Administration also provides resources regarding beach closures in the United States: ecowatch.noaa.gov/thematic/beach-closures.

In Ontario, updated information about beach closures or advisories may be found at: eohu.ca/en/my-environment/public-beach-water-advisories and ontarioparks.com/beachresults.

The Swim Guide site (theswimguide.org) tallies beach advisory data in both Canada and the United States on an annual, quarterly, or monthly basis by beach.

6.2.14 Closed facility days due to flooding or flood-related impacts

Facilities such as hospitals, schools, and senior centers, among others, are vulnerable to increased flooding events associated with climate change. Facilities in coastal areas are especially at risk. A 2022 research article found that half or more of hospitals within 25 of 78 metropolitan statistical areas on the US Atlantic and Gulf Coasts are at risk of flooding even from a relatively weak hurricane (Tarabochia-Gast et al., 2022). This indicator focuses on the impacts of climate-related severe weather events on healthcare facility operations.

Indicators:

- Total days per year that healthcare facilities close due to flooding or flood-related impacts such as utility loss. Can also be expressed as a percentage of total facility-days per year.

Data Sources:

Challenges to implementing this indicator to include a lack of consistent data to measure this indicator and utilize it across both Canada and the United States. Such data is difficult to find for either country, and the data that are available use different methodologies. Standardized surveys would need to be implemented to collect this data in areas where it is not already being tracked. What constitutes a climate change-related event would also need to be defined, as well as the types of facilities included.

6.2.15 Climate-related threats to Indigenous food sources

Traditionally, the Great Lakes have supported subsistence fishing and other culturally-significant food sources such as *manoomin*, or northern wild rice. These practices are vulnerable to climate change. *Manoomin* shallow waters (1 to 3 feet) for successful growth (Great Lakes Indian Fish and Wildlife Commission 2018), conditions that are threatened by climate change-induced precipitation and flooding increases in the Great Lakes basin. The development of dams has also degraded *manoomin* habitat in many areas (Great Lakes Indian Fish and Wildlife Commission 2023). An increase in weather extremes would likely make *manoomin* harvests less reliable as conditions in the basin oscillate between wet and dry conditions. An increase in the prevalence of severe storms also threatens *manoomin* harvests (Hazzard 2023). Finally, warmer nighttime temperatures may increase susceptibility of wild rice to disease such as brown spot disease (Great Lakes Indian Fish and Wildlife Commission 2023). Recent assessments of climate change vulnerability have concluded that manoomin was extremely vulnerable to climate change (Great Lakes Indian Fish and Wildlife Commission 2018).

Several Great Lakes fish species are culturally significant to Indigenous communities, and many of these species are being impacted by climate change. For example, of ten culturally-important fish species reviewed by the Great Lakes Indian Fish and Wildlife Commission, two species (tullibee and lake whitefish) were found to be "extremely vulnerable" under a worst-case climate change scenario, while four other species were likely to be "highly vulnerable" (Great Lakes Indian Fish and Wildlife Commission 2023). Therefore, it is recommended that one or more of these fish species be selected for an indicator based on estimated fish stocks and/or harvest levels.

The indicators presented below are initial recommendations. An alternative approach could be based on climate change vulnerability scores for these species developed by the Great Lakes Indian Fish and Wildlife Commission (2023). Further work may be required to select the most appropriate parameters to be used use in developing one or more indicators. Any work on indicators to track climate impacts on culturally-significant resources should ideally be led by or conducted in close consultation with the affected Indigenous communities. Romanello et al. (2022) also present an indicator related to the shortened growing season for major food crops globally due to increased temperatures.

Sub-indicators:

- Precipitation and lake water levels during critical wild rice growth season (spring).
- Nighttime temperatures during wild rice growth season (spring and summer).
- Estimated fish stocks and harvest levels for selected culturally-significant species.

Data Sources:

Data sources for precipitation are discussed under Section 6.2.1, Increased precipitation.

Data sources for lake levels are discussed under Section 6.2.7, Lake levels.

The Great Lakes Indian Fish and Wildlife Commission (2018 and 2023) describe a methodology to develop climate change vulnerability scores for species of cultural significance, including various species of fish, and present the results of this assessment.

6.2.16 Incidence of delected reportable cases of waterborne gastrointestinal illness

Pathogens causing gastrointestinal illness in humans may be foodborne, waterborne, vectorborne, or may result from person-to-person contact. There is evidence that the prevalence of these pathogens can be influenced by weather and climatic conditions, and therefore may be influenced by climate change patterns. For example, studies have shown a positive relationship between temperature and pediatric gastrointestinal infections, as well as between increased temperatures and the prevalence of the organisms causing *Salmonella*. An increased frequency of natural disasters as a consequence of climate change may also expose people to waterborne, vectorborne, or foodborne pathogens at an increased rate (Ghazani et al., 2018).

Indicators:

- Monthly and yearly occurrences of gastrointestinal illness within a defined geographic region. The region of interest could be the Great Lakes basin, or subregions including specific states/provinces, counties/census divisions, or municipalities.

Data Sources:

In Canada there is limited national surveillance for the systematic collection of waterborne disease outbreak data. Each province and territory has different lists of reportable diseases, case reports, investigation practices, and mechanisms for assessing outbreaks.

Recent data on Diseases of Public Health Significance in Ontario is reported through the integrated Public Health Information System, and is available here: publichealthontario.ca/en/Data-and-Analysis/Infectious-Disease/Infectious-Diseases-Monthly.

US data on the number of probably and confirmed cases of waterborne AGI are available thorugh the CDC WONDER database, at wonder.cdc.gov. Data are available by yearly or weekly totals, and can be broken down by region and state as well as the specific type of disease.

The Minnesota Department of Health provides data and trends on diseases on their website: health.state.mn.us/diseases. Other Great Lakes states may have their own data collection and reporting mechanisms.

Wastewater epidemiological surveillance is an emerging field that applies analytical techniques to wastewater to estimate consumption of substances, exposure to pollutants, and/or levels of pathogens or antimicrobial resistance at the community level. It has the potential for generating near real-time data on geographical and temporal trends without the need for self-reported surveys for use as an early warning system and monitor the effectiveness of public health measures. The Canadian Wastewater Survey was launched in March 2019, and data from this initiative can be accessed at statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5280. In the United States, the National Wastewater Surveillance System was launched in 2020 and can be accessed at cdc.gov/nwss/wastewater-surveillance.html.

6.2.17 Changes in mental health/sentiment

Climate change is affecting mental health and psychological wellbeing. Acute temperature increase, heatwaves, and humidity have all been associated with worsened mental health outcomes. Climate hazards can disrupt food production, affect livelihoods and residences, and cause water scarcity and other hardships that increase stress and negatively impact mental health. Marginalized and vulnerable populations are often disproportionately affected by mental health impacts related to climate change, which can worsen pre-existing mental health inequalities, especially where health care is inadequate. Indigenous people may be more strongly affected by climate change. Older people, women, and religious or ethnic minorities are particularly at risk of adverse mental health outcomes, and young people have been shown to be more prone to anxiety, phobias, depression and other stress-related impacts. The effects of the climate crisis have given rise to emerging concepts such as climate change anxiety, solastalgia, eco-anxiety and ecological grief (Romanello et al., 2022).

Besides the effects of psychological stress caused by the impacts of climate change on people's lives and livelihoods, certain weather events such as episodes of extreme heat may have a more direct effect on mental wellbeing. Wang et al. (2014), for example, analyzed health and climatic records for Toronto from 2002 to 2010, and found a significant increase in emergency room visits related to specific mental and behavioral diseases following episodes of extreme heat (defined as 28°C). The association was strongest within one to four days after exposure to high temperatures.

Indicators:

- Change in sentiment based on analysis of social media posts, following extreme weather events (including temperature and heavy precipitation).

Data Sources:

Romanello et al. (2022) present an indicator that analyzed data from social media posts and found a negative change in sentiment following adverse weather events such as heat waves. A similar approach could be implemented for the Great Lakes region.

Statistics Canada publishes the annual Self-Rated Mental Health indicator at statcan.gc.ca/health-sante/mental-health-sante-mentale-eng.htm. This indicator provides a very high-level overview of the state of mental health of Canadians.

6.2.18 Mortality due to extreme heat

A study of 43 countries published in May, 2021, estimated that 37 percent of heat-related deaths are attributable to human-induced climate change (Vicedo-Cabrera et al., 2021). Using a generalised exposure-response function to provide an estimate of heat-related deaths globally, Romanello et al. (2022) found that annual heat-related mortality of people older than 65 years increased by an estimated 68 percent between 2000-2004 and 2017-2021. The USEPA also publishes an annual indicator of heat-related deaths, including deaths caused by heat (all year) and deaths where heat was the cause or a contributing factor (from May through September) (USEPA 2024).

Indicators:

- Mortality from exposure to extreme heat in persons older than 65 years.

Data Sources:

United States data for the underlying cause of death are available through the CDC WONDER database at wonder.cdc.gov.

Data on causes of death in Canada are tracked by Statistics Canada and are available at ouvert.canada.ca/data/dataset/fe0dfe77-dfcf-42e0-811c-1ee84cd3840a.

CDC's Environmental Public Health Tracking Program tracks several indicators under the topic area of heat-related illness, including heat-related mortality, which can be accessed at ephtracking.cdc.gov/indicatorPages. This data is also available through CDC WONDER.

The Canadian Vital Statistics-Death Database, available at statcan.gc.ca/n1/en/surveys/3233, is an administrative survey that collects demographic and medical (cause of death) information annually from all provincial and territorial vital statistics registries on all deaths in Canada.

Statistics Canada publishes data on mortality by ICD-10 code. Data on external causes of mortality can be accessed at statcan.gc.ca/t1/tbl1/en/tv.action?pid=1310015601.

6.2.19 Deaths from flooding

Climate change is likely to lead to an increase in heavy storm events, and this in turn has the potential to lead to increased flooding in the region. Impacts from flooding are discussed in Section 4.3, which describes a case study of urban flooding in the Detroit metropolitan area. Potential impacts from flooding include property damage, injuries, and in extreme cases, even deaths. This indicator focuses on trends in deaths that can be attributed to drowning. Note that only a subset of total drowning deaths would be likely to occur as a result of flooding, but by tracking changes in the number of drowning deaths over time, this indicator may be helpful in identifying the compounding effects of climate change on public health. However, efforts to reduce drowning deaths, such as increasing public awareness and improved search and rescue capabilities, may counter any increase caused by climate change.

Indicators:

- The number of deaths attributable to drowning per year per 100,000 people, within a geographic region.

Data Sources:

The CDC Wonder database stores public health and mortality data, including deaths attributable to accidental drowning, and is available at wonder.cdc.gov.

The Climate and Hazard Mitigation Planning Tool provides total reported deaths and injuries from severe weather events, including flooding, extreme heat, winter weather, and wildfire: champ.rcc-acis.org.

The National Oceanic and Atmospheric Administration Storm Events Database includes information on a range of severe weather events from 1996 and is available at ncdc.noaa.gov/stormevents.

Statistics Canada publishes data on mortality by ICD-10 code. Data on external causes of mortality can be accessed at statcan.gc.ca/t1/tbl1/en/tv.action?pid=1310015601.

The Government of Canada maintains the Canadian Disaster Database, which tracks disaster events that meet a set list of criteria: publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx.

6.2.20 Economic damage from extreme weather

Climate change is increasing the frequency and severity of extreme weather events in the Great Lakes region and beyond. One way to visualize this trend is by tracking the number of major extreme events that lead to US$1 billion (CDN$1.4 billion) or more in damage. During 2023, there were 28 such events in the United States, and 17 that affected the eight Great Lakes states (NOAA National Centers for Environmental Information 2024). There is an increasing trend in the number of such major extreme events (see **Figure 17**). The numbers of various types of events are shown by the colored bars, and the total cost is shown by the red (annual cost) and black (five-year rolling average) lines.

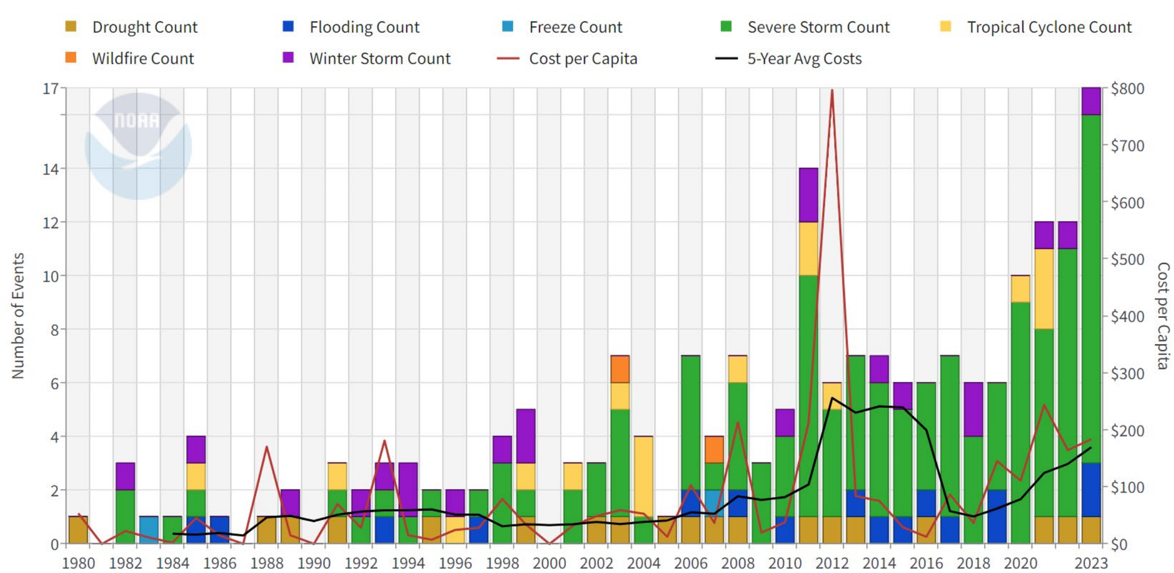


Figure 16. Billion-dollar disaster events in the Great Lakes states (Consumer Price Index-adjusted) (NOAA National Centers for Environmental Information 2024)

It is important to note that there are several factors that can affect the number and cost of disasters (NOAA National Centers for Environmental Information 2024). The costs of major disasters are increasing over time due to a combination of:

- Increased exposure (e.g., values at risk of possible loss). Looking at costs per capita rather than total costs may at least partially offset this effect.
- Changing vulnerability (e.g., how much damage can potentially be caused by extreme weather at a given location or to a given asset), and
- Changes in the frequency and severity of some types of weather extremes due to climate change.

Inflation also affects the ability to compare costs over time. To account for this, the costs shown here have been corrected using the Consumer Price Index, and the graphic also includes events that caused less than US$1 billion (CDN$1.4 billion) in damage at the time of the event, but exceed US$1 billion (CDN$1.4 billion) in damages after adjusting for inflation using the US Consumer Price Index.

Indicators:

- Total annual damage (in millions of dollars) from weather events within the Great Lakes basin, or subregions.

Data Sources:

The Climate and Hazard Mitigation Planning Tool provides total reported crop damage and property damage from severe weather events, including flooding, extreme heat, winter weather and wildfire: champ.rcc-acis.org. Data, including trends over time, can be viewed by state or county.

The National Oceanic and Atmospheric Administration produces an annual data product focusing on billion-dollar weather and climate disasters, which summarizes damages from severe weather and other climate-related events that individually cause greater than US$1 billion (CDN$1.4 billion) in damages. Data going back to 1980 can be filtered by region, including by Great Lakes States, and can be accessed at: ncei.noaa.gov/access/billions.

The Canadian Disaster Database, maintained by Public Safety Canada, provides data on a range of disasters including natural and other events. The data can be narrowed down by type of event (including natural weather-related disasters), province, and timeframe of interest. The database can be accessed at: publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx.

6.2.21 Vulnerability and adaptation assessments completed

The World Health Organization has developed a framework to build climate-resilient health systems (World Health Organization 2015). One of the key steps in this framework is to conduct climate change vulnerability and adaptation assessments. The objective of these assessments is to identify populations who are most vulnerable to different kinds of health effects, to identify weaknesses in the systems that should protect them, and to specify interventions to respond. vulnerability and adaptation assessments can also improve evidence and understanding of the linkages between climate and health, serve as a baseline analysis against which changes in disease risk and protective measures can be monitored, identify knowledge gaps, provide the opportunity for building capacity, and strengthen the case for investment in health protection.

In addition to World Health Organization guidance, the Canadian and US governments have provided information and guidance on increasing resilience in the healthcare sector. The US Climate Resilience Toolkit, for example, includes a section on Sustainable and Climate-Resilient Health Care Facilities available at: toolkit.climate.gov/tool/sustainable-and-climate-resilient-health-care-facilities-toolkit. Health Canada also provides resources for healthcare professionals and facilities, including funding. HealthADAPT, for example, was a multi-year capacity-building program managed by Health Canada that invested approximately CDN$3.5 million (US$2.6 million) in partnership with 10 health authorities across five provinces and territories, to support the health authorities address climate change-related health risks.

While vulnerability and adaptation assessments can be conducted at a variety of levels in the health system, from national, state, and local governments to individual facility levels, it is recommended that this indicator track these assessments at individual health facilities or groups of facilities, while also considering that facilities may be covered under higher-level vulnerability and adaptation assessments.

This indicator also tracks cities and counties that have completed vulnerability and adaptation assessments, recognizing that health facilities are dependent on infrastructure and systems outside their control (e.g., roads, utilities) for the proper functioning. Climate-related severe weather events have the potential to indirectly impact healthcare facilities by damaging this infrastructure, and city or county-level vulnerability and adaptation assessments are a first step to ensure these systems are also climate-resilient.

Subsequent steps towards resilience would include the development and implementation of adaptation plans, which may be tracked in the future under additional indicators.

Indicators:

- Percentage of cities/counties in the Great Lakes basin that have completed climate change vulnerability and adaptation assessments.
- Percentage of healthcare facilities that have completed their own vulnerability and adaptation assessments or are covered by existing assessments.

Data Sources:

The Climate Disclosure Project conducts global surveys of cities on climate change preparedness, including whether cities have conducted initial vulnerability assessments. Climate Disclosure Project data can be accessed via its Open Data Portal at data.cdp.net. Currently, the Climate Disclosure Project dataset includes 172 cities in the United States.

Limited data are currently collected on healthcare facilities (or other public health organizations) that have completed vulnerability and adaptation assessments. The data that do exist suggest that health systems are not adequately prepared for climate change impacts. In a survey of 34 local public health officials in Michigan, only 35 percent stated that climate change is a priority for their departments, but a majority agreed that climate change has had and will have an impact on their jurisdictions (Carter et al., 2021). Further, only 25 percent were aware of federal and state expertise and resources in providing assistance related to climate change and health.

7.0 Conclusions

Findings, gaps and recommendations resulting from this project are described here. Although the state of data and analysis is not yet sufficient to support all desired indicators, substantial information to potentially link climate change drivers more strongly to human health outcomes in the region of interest do exist. The IJC and HPAB can continue to play key roles in refining indicators and advancing efforts to enhance human health resilience in the face of climate pressures.

7.1 Findings

We acknowledge that the outcomes attributable in part to climate change may also be contributed to by other factors, such as non-aquatic environmental challenges, health system performance, infrastructure maintenance, *et cetera*. However, adequate evidence exists for meaningful relationships between climate, environment, and the proposed indicators; thus, the proposed indicators may be useful to assess the adequacy of planning, adaptation and response to growing climate drivers and environmental challenges. Human health outcomes attributable in part to climate change impacts on the Great Lakes also may be influenced by other factors such as non-aquatic environmental change, health system performance, and infrastructure maintenance. Adequate information may exist in many cases, however, to demonstrate meaningful relationships among climate, environment, and proposed indicators. These indicators, in turn, may be useful for assessing the adequacy of planning and adaptation, and guiding impactful responses to growing climate-driven stresses and environmental challenges that impact human health in the region. Several significant findings related to the project objectives are listed here.

- Although relationships among factors influencing human health are complex, existing data indicate an increasing influence of climate drivers and environmental change on human health in the Great Lakes. These drivers are increasing the risk of exposure to biophysical hazards and pathogens resulting in associated injury, distress and illness. Monitoring the strength of drivers and effects can improve planning and reduce risks to human health.

- Monitoring of key indicators can improve understanding of the relative importance of different drivers and effects, which is critical to prioritizing investments for protection of human health from these threats including mitigation of the drivers and increasing the resilience of the impacted communities. Monitoring the status of resilience indicators can complement the monitoring of climate-related drivers.

- Because of the high natural variable of the region’s weather, some climate change signals can be challenging to detect at annual scales, so the most robust patterns may be appropriate to assess at decadal or longer scales. Other phenomena, however, such as the local impacts of individual extreme storms, occur over periods of hours to days, so this granularity is important to capture as well for event-specific and aggregate analysis. This suggests that data to inform indicators of climate change impacts on human health should be captured at a variety of temporal and spatial scales that support the appropriate retrospective evaluation to guide forecasting and to inform resource allocation.

- Multiple studies show a strong correlation in the region between indicators of environmental justice and other socioeconomic inequities, and the vulnerability of communities to human health impacts from climate change, such as increasing flooding frequency due to greater storm intensity. Indicator development should be conducted with differences in community vulnerabilities and inequities in resilience in mind to increase the value for just and equitable preventive planning.

- Because most water-related infrastructure decisions are made at the local municipal scale, it is important that indicators can be reported at the finest spatial resolution possible that available data will support to increase their usefulness to municipal planners and decision-makers.

- Harmonization of data across politcal boundaries is an ongoing challenge. The establishment and maintenance of seamless datasets that span boundaries is a critical component of the development of useful indicators that can inform the implementational of cross-jurisdictional agreements, treaties, and compacts.

- While the interactions of climate drivers, effect relationships, and effect modifiers can be extraordinarily complex, many actions to mitigate effects, adapt to changes, decrease exposure and vulnerability, and increase individual and community resilience can have cross-cutting benefits that span multiple change, exposure, or impact categories.

7.2 Gaps

As stated previously, direct linkages between climate and health can be difficult to distinguish within a complex biophysical and socioeconomic context. Substantial progress has been made in this area, but much more work remains. Identification and tracking of indicators may help identify targeted adaptation and mitigation strategies that are likely to be helpful and can promote learning between affected communities as appropriate indicators could reveal which effect modifiers reduce human risk exposures and human health outcomes most strongly. Areas where additional data collection, analysis, and research are needed are described briefly here.

- Scales, gradients and trends of effect relationships and effect modifiers are important to define but are not well understood at present. As a result, prioritization of investments based on expected impacts and quantitative understanding of collective synergistic benefits is rare.

- It is unclear what climate-specific actions versus general resilience actions would be most impactful to human health (e.g., flood insurance improvements, data infrastructure investment, improved monitoring, housing reform). Policy development that includes robust economic and health benefit predictions and intercomparisons among communities over time would help reduce some of this uncertainty.

- Although many climate drivers and environmental response variables are tracked regionally and nationally, these datasets are not well harmonized across the international border. This is also true for health-related data. The IJC has helped spur harmonization of hydrologic data and may be able to similarly impact environmental and health data of high priority.

- Human-lake interaction studies are quite limited in the health domain apart from those concentrating on swimming exposure to pathogens, including consideration of mental health. Concepts such as *blue infrastructure* and *blue mind* that show mental health benefits of spending time near water could be linked with climate and health studies to explore mitigation of climate anxiety by advancing related practices.

7.3 Next steps

The vision for this work is to lay the foundation towards developing fulsome indicators that the Parties to the GLWQA could include in their framework for reporting on the status and trend of Great Lakes health and water quality through the governments' triennial State of the Great Lakes reports. To that end, the Parties, states and provinces, First Nations and Tribal governments, local governments, watershed management agencies, academic partners and the public may all have an interest in how this report could contribute to progress reporting and management under the GLWQA to better understand climate/health interactions, the importance of ongoing monitoring of indicators, and the risks and solutions to climate-induced health threats. To advance implementation of these indicators into the GLWQA reporting framework, coordination with Annex 10 Ecosystem Indicator and Reporting Task Team leads can promote discussion of further actions.

The board, in cooperation with IJC Great Lakes advisory boards, may consider a pilot project to further develop a small number of near-to-ready indicators to better understand data sources, data acquisition, data dissemination and to obtain information on the use of indicators by affected communities and other users. This could prioritize three to five indicators that are not yet mature.

Other areas of focus for potential work in the future include:

- an iterative process for improving the indicators based on evolving understanding and data availability;

- encouraging stewards for individual metrics, identified on the basis of familiarity with underlying concepts and data sources and interest in facilitating the analysis and use of such longitudinal data, to initiate discussions of implementation with data source organizations and analysts and help promote data collection, quality and analysis.

- identifying a central hub, such as the Great Lakes Observing System, to manage indicator data acquisition, and the storage and dissemination of the indicators and appropriate metadata to support users.

The goal would be to bring these indicators and their supporting data to a state where they can be actionable by health professionals and agencies across jurisdictions with the goal of improving resilience to climate change impacts of human health in Great Lakes communities.

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