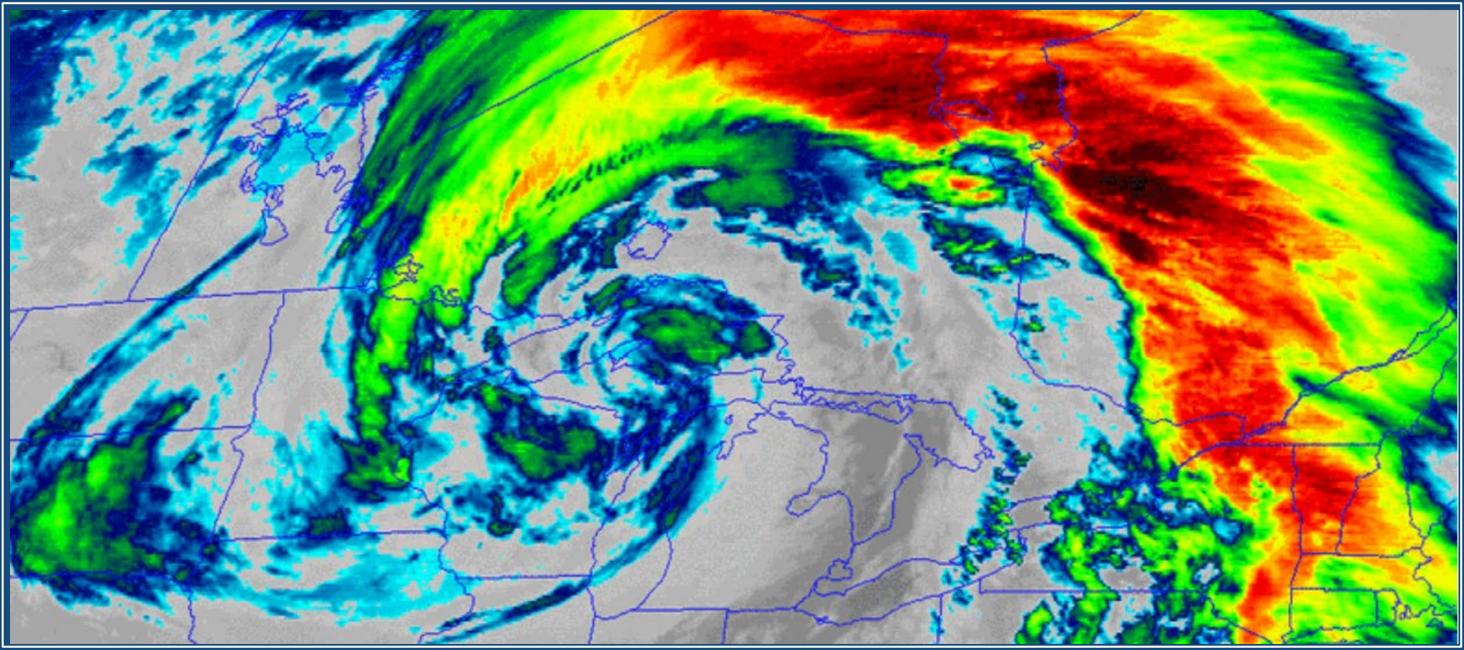
Operationalizing an Early Warning System for the Great Lakes



GLEW
hild_C

LimnoTech
Water Environment | Scientists Engineers

AECOM

Prepared for:

International Joint Commission

June 2023

On the cover: Enhanced infrared satellite image from November 11, 1998 (top panel; NOAA and University of Wisconsin, https://www.wlfi.com/archive/november-10-1975-bomb-how-it-brought-wind-storm-severe-weather-outbreak-blizzard-conditions-disaster/article_7b7a279b-4194-5599-9a67-026af5fabbcb.html; bottom panel: State of Michigan Emergency Operations Center https://www.partnersinarch.com/projects/State-of-Michigan-Emergency-Operations-Center_PJ18.html). These systems are operational analogs for the Great Lakes Early Warning System, which is intended to detect environmental threats to the lakes.

CONTRIBUTORS

Lucinda Johnson, University of Minnesota-Duluth & work group co-chair
Michael Twiss, Algoma University & work group co-chair

Maggie Xenopoulos, Trent University
Michael Price, Great Lakes Indian Fish & Wildlife Commission
John Livernois, University of Guelph
Karen Kidd, McMaster University
Gail Krantzberg, McMaster University
Rebecca Rooney, University of Ottawa
Gavin Christie, Fisheries and Oceans Canada (retired)
Ram Yerubandi, Environment and Climate Change Canada
Jon Allan, University of Michigan
Carolyn Johns, Toronto Metropolitan University
Elaine Faustman, University of Washington
Glenn Miller, University of Nevada
Henry Lickers, Commissioner, International Joint Commission
Al Steinman, Grand Valley State University
Craig Stow, National Oceanic and Atmospheric Administration
Roger Knight, Great Lakes Fishery Commission
Chris Vandergoot, Great Lakes Acoustic Telemetry Observation System
Susan Doka, Fisheries and Oceans Canada
Terry Brown, U.S. Environmental Protection Agency
Scott Sowa, The Nature Conservancy
Dave Allan, University of Michigan (retired)
Jon Hortness, U.S. Geological Survey
Bernard Crimmins, Clarkson University
Katya Kovalenko, University of Minnesota--Duluth
Michelle Selzer, Michigan Department of Agriculture and Rural Development
Ngan Diep, Ontario Ministry of Environment, Conservation and Parks
Sean Backus, Environment and Climate Change Canada

Matthew Child, International Joint Commission (Great Lakes Regional Office)
Lizhu Wang, International Joint Commission (Great Lakes Regional Office)
Victor Serveiss, International Joint Commission (US Section) (retired)
Robert Phillips, International Joint Commission (Canadian Section) (retired)

John Bratton, LimnoTech
Tad Slawecki, LimnoTech
Mike Donahue, AECOM

Workshop participants listed in Appendix B also made essential contributions to this effort.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acronyms

AAFC – Agriculture and Agri-Food Canada
AIS – Aquatic Invasive Species
Annex 3 – Chemicals of Mutual Concern Annex and Subcommittee of the GLWQA
Annex 4 – Nutrients Annex and Subcommittee of the GLWQA
Annex 8 – Groundwater Annex and Subcommittee of the GLWQA
Annex 10 – Science Annex and Subcommittee of the GLWQA
ASLO - Association for the Science of Limnology and Oceanography
BOGLS – Biogeochemistry of the Great Lakes System
CDC – Centers for Disease Control (U.S.)
CDL – Cropland Data Layer (U.S.)
CIGLR – Cooperative Institute for Great Lakes Research (NOAA-affiliated)
CSMI – Cooperative Science and Monitoring Initiative
DFO – Department of Fisheries and Oceans (Canada)
DNA – Deoxyribonucleic Acid
ECCC – Environment and Climate Change Canada
eDNA – Environmental DNA
EU – European Union
EWS – Early Warning System
FAO – Food and Agriculture Organization of the United Nations
FORENV – Environmental Foresight System (EU)
GLANSIS – Great Lakes Aquatic Nonindigenous Species Information System
GLEAM -- Great Lakes Environmental Assessment and Mapping
GLEC – Great Lakes Executive Committee
GLEI – Great Lakes Environmental Indicators
GLERL – Great Lakes Environmental Research Laboratory (NOAA)
GLEWS – Great Lakes Early Warning System
GLFC – Great Lakes Fishery Commission
GLFCFHC -- Great Lakes Fishery Commission Fish Health Committee
GLIER -- Great Lakes Institute for Environmental Research
GLIFWC – Great Lakes Indian Fish & Wildlife Commission
GLISA -- Great Lakes Integrated Sciences and Assessments
GLWQA – Great Lakes Water Quality Agreement (Protocol of 2012)
GLRI – Great Lakes Restoration Initiative (U.S.)
HNLC – High-Nutrient, Low-Chlorophyll
IAGLR – International Association for Great Lakes Research
ICF – Information Coordination and Flow
IJC – International Joint Commission
LC-PFCA -- Long-Chain Perfluorocarboxylic Acid

MECP – Ontario Ministry of Environment, Conservation, and Parks
MPART -- Michigan PFAS Action Response Team
NAWQA – National Water-Quality Assessment (USGS)
NCWQR – National Center for Water Quality Research (Heidelberg University) NLCD – National Land Cover Database (U.S.)
NOAA – National Oceanic and Atmospheric Administration (U.S.)
OECD -- Organization for Economic Co-operation and Development
OMAFRA – Ontario Ministry of Agriculture, Food and Rural Affairs
PCR – Polymerase Chain Reaction
PFAS – Per- and Polyfluoroalkyl Substances
PFOA – Perfluorooctanoic Acid, its salts, and precursors
PFOS – Perfluorooctane Sulfonate, its salts, and precursors
PUFA -- Polyunsaturated Fatty Acid
RCA – Regional Conservation Authority (Canada)
REAP – Researching Effectiveness of Agricultural Programs
RNA – Ribonucleic Acid
SOLEC – State of the Lakes Ecosystem Conference
SPC – Science Priority Committee of the IJC SAB
SWAT – Soil & Water Assessment Tool
TAP – Triennial Assessment of Progress
TEK – Traditional Ecological Knowledge
USDA – U.S. Department of Agriculture
USEPA – U.S. Environmental Protection Agency
USFWS – U.S. Fish & Wildlife Service
USGS – U.S. Geological Survey
WG – Workgroup
WQB – IJC Water Quality Board

Glossary

Addressability. Criteria for evaluation of addressability will vary between threats and will therefore be set by the **Threat Team**. However, addressability should generally reflect the feasibility of monitoring for critical conditions (e.g., **threshold**) and the existence of suitable responses to those conditions.

Champion. Person who is selected or volunteers to lead a **Threat Team** based on interest, experience with the threat, and expertise and enthusiasm for leadership.

Chatter. Qualitative input derived from observation and analysis of social media, news feeds, and other textual phenomena that may characterize development or impacts of a stressor, threat or impact.

Data anomalies. Unexplained or unexpected values, trends or other characteristics observed in a **data stream** that may signal impacts from a previously unknown threat.

Data stream. An ongoing data collection effort that provides regular measurements of selected parameters. A data stream may be based on periodic grab samples or on automated in-situ measurements.

EWS support staff. Paid staff who are part of the **GLEWS Committee** and are available to provide administrative, logistical, and technical support as needed in all three framework blocks.

GLEWS Committee. Group of Subject Matter Experts charged with managing process and information flow related to evaluating and developing related EWSs for suspected and unknown threats.

Importance. Criteria for evaluation of importance will vary between threats and will therefore be set by the Team. However, importance will generally consider urgency and spatial extent.

Library - Data Streams. Repository of information about **data streams** identified by **Experts** and **Stakeholders**.

Library – Existing EWS Designs. Repository of information about the design and other aspects of early warning systems already in existence for the Great Lakes or other comparable geographic locations.

Library - Possible Threats. Repository of potential ecosystem threats identified by **Experts** and **Stakeholders**, including a record of actions taken by the **GLEWS Committee** concerning the threat.

Monitoring of chatter. Informal surveillance of and by **Stakeholders** of trade publications, news articles, social media, gray literature, etc. to assist in the identification of **possible threats.**

Stakeholders. Those with a real or perceived interest in mitigating suspected or unknown threats. Examples may include NGOs and foundations, commercial and recreational interests, emergency response personnel, resource managers, and landowners. Members of Indigenous communities are typically considered to be sovereign "rights holders", as specified in treaties and international agreements, rather than "stakeholders", in situations where these rights may be impacted by suspected threats.

Stressor. An environmental factor that causes stress to organisms or ecosystems due to introduction of a foreign biotic or abiotic element (e.g., pollutant, non-native species), or by pushing a natural factor (e.g., temperature, water level) outside of its normal range. A threat is a potential stressor that has not yet impacted the system sufficiently to demonstratively cause stress.

Subject Matter Experts. Individuals with a strong body of knowledge about particular threats and ecosystem health elements in the Great Lakes.

Threat Team. A group assembled to address a **suspected threat** or **data stream** anomaly.

Threat – Possible. A threat to ecosystem health that can be described and may potentially have an impact on ecosystem health in the Great Lakes.

Threat – Suspected. A threat to Great Lakes ecosystem health that can be described along with its likely impact on ecosystem health. Suspected threats may be subjected to additional scrutiny (Understand & Design) to evaluate **importance** and **addressability** of the threat.

Threat – Unknown. A threat to Great Lakes ecosystem health that has not been explicitly identified and described. The existence of unknown threats may be signaled by **data anomalies** in **data streams**.

Threshold. Observable critical value or condition at which warnings should be issued or actions taken related to a given threat.

EXECUTIVE SUMMARY

LimnoTech and its project partner, AECOM Technical Services prepared this report to summarize the process and results of the project titled, "Operationalizing an Early Warning System for the Great Lakes" on behalf of the International Joint Commission Science Advisory Board (IJC-SAB). Recent history reveals that emerging threats to the Great Lakes are often not adequately anticipated by agencies and resource managers. Foreseeable problems may be forecasted or detected but remain unaddressed for various reasons until they become crises. Therefore, there is a need to coordinate and enhance Great Lakes science capabilities for anticipation and management or prevention of potential threats through the design and implementation of a Great Lakes Early Warning System (GLEWS).

This project was intended to develop an analytical protocol for a GLEWS that could provide a Decision Framework to identify benchmarks and indicator thresholds of various groups of threats and stressors and, in so doing, rank and prioritize or re-prioritize them for action on an iterative or cyclical basis. Three project tasks involving information gathering and analysis (literature review, case studies, and expert workshop) were generally conducted sequentially, with the results of each informing the subsequent tasks. Different analytical approaches were considered, leading to a draft GLEWS Decision Framework. Testing of the draft Framework was conducted through its application to the case studies and its review at an in-person Experts Workshop where knowledge was shared.

The set of suspected stressors and threats[1] examined in the case studies and further evaluated in the Experts Workshop consisted of:

1. Changes in concentrations of nitrogen and other key non-phosphorus nutrients.
2. Climate change impacts on agricultural ranges and practices, and on aquatic species ranges.
3. Introduction and spread of fish pathogens.
4. Shifts in groundwater usage and related ecological impacts.
5. Occurrence and impacts of contamination by per- and polyfluoroalkyl substances (PFAS).

A sixth case study on unknown stressors was also included to expand the "suspected" examples. General GLEWS findings, conclusions, and lessons learned through completing the case studies and discussing the draft Framework and synthesis results at the Experts Workshop and with WG members include the following:

- Several structures, programs, and knowledge systems that exist within IJC and externally can be leveraged or adapted to implement elements of the GLEWS, including IJC advisory boards, committees of other commissions, Indigenous Knowledge systems, agency reporting systems, community science networks, and outdoor recreation groups.

[1] *Stressors* are defined here as chemical, biological, physical, or human factors that negatively influence the condition of Great Lakes water quality and aquatic ecosystems. *Threats* are potential stressors that have not yet manifested in ways that are substantial enough to cause negative impacts (not known to be present or minimal impacts to date) but are identified as presenting a future risk of negative impacts. The distinction is subtle, and the terms are used somewhat interchangeably in this report.

- Although IJC itself does not have sufficient resources to conduct or fund the research and monitoring needed to fill critical gaps related to suspected threats, it may be able to provide staff to coordinate binational assessment activities and development of tracking and scoping documents through its boards and working groups and related strategic partnerships that can guide federal agencies and external organizations in conducting priority research and monitoring.
- Some threats may have both upper and lower thresholds of impacts, which complicates defining threat states and management responses; natural baselines and ranges are also not known in all cases.
- Professional societies (e.g., the International Association for Great Lakes Research [IAGLR], which has a primary focus on aquatic ecology) can play a convening role in horizon scanning and threat assessment. Some threats, however, fall outside the purview IAGLR and similar biophysically oriented scientific societies and may require engagement with other professional organizations and communities to develop detection, monitoring, and warning approaches that encompass the full range of threats to the Basin.
- In addition to guiding further research and monitoring, initial threat assessment can lead to "warn", "adapt", or "watch/no further action" decisions.
- Connections among research and monitoring of suspected threats and organizations that can act on warnings need to be strengthened, but such organizations do not exist for all threats in all jurisdictions.

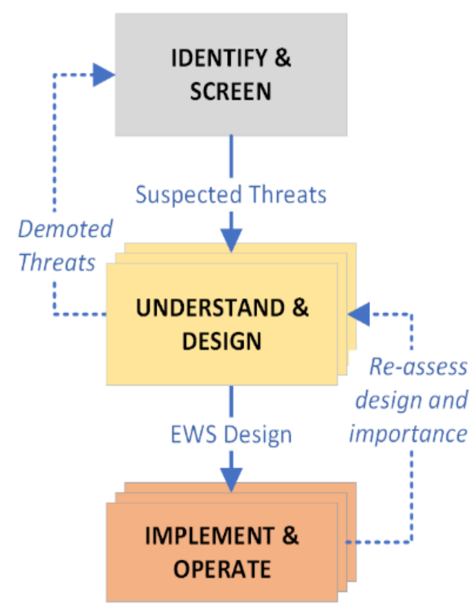


Figure 1. Summary diagram of GLEWS Decision Framework elements.

The resulting GLEWS Decision Framework is conceptualized as an organized and managed collection of individual threat-specific early warning systems (EWSs). The Framework is intended to address Unknown Threats and Suspected Threats and is organized into three major functional blocks: Identify & Screen, Understand & Design, and Implement & Operate (Figure 1).

Recommendations for Implementation

1. Develop terms of reference for a provisional GLEWS Committee that will exist as a standing subcommittee or workgroup under the IJC Water Quality Board, including its composition, membership, duration of terms, provisions for outside expert composition, meeting frequency and format, IJC staff support, funding needs, data management framework, and reporting structure. An initial proposed size range would be 12-16 appointed individuals, a subset of whom would be WQB members, including public sector, private sector, and academic subject matter experts in horizon scanning.
2. Coordinate the establishment of the GLEWS Committee with IJC Commissioners, First Nations, Tribes, Métis, IJC staff and boards, federal agencies, other commissions, states and provinces, and key stakeholder groups such as IAGLR.
3. Develop scoping documents for the GLEWS technical infrastructure for decision-support including data, models, tracking of published research, and communications subsystems.
4. Undertake a pilot project to implement GLEWS following development of the terms of reference and refinement of structural and operational characteristics based on interview, survey, and workshop outcomes.

1 INTRODUCTION

LimnoTech and its project partner, AECOM Technical Services, have prepared this report that summarizes the process and results of the project titled, "Operationalizing an Early Warning System for the Great Lakes". The study was performed for a work group (WG) of the International Joint Commission Science Advisory Board (IJC-SAB). Here we provide an overview of the project including a short description of the need that it has addressed, the programmatic and institutional context, and the objectives. We also provide a short outline of the organization of this report and the sequencing of project tasks and report content.

1.1 Project Background

The study was conducted to meet needs identified by the IJC-SAB and WG, executing a Scope of Work that was approved by IJC Commissioners. Its relevance to the binational Great Lakes Water Quality Agreement (GLWQA) and its starting point as a successor effort to a Phase 1 study are described briefly here for context.

1.1.1 Addressing an Unmet Need – Great Lakes Early Warning System

Recent history has shown that emerging threats (e.g., the dreissenid mussel invasion in the early 1990s) are often not adequately anticipated by agencies which, in fairness, are generally not explicitly charged with early warning roles. Even when problems are anticipated, incorrect determinations that preventive actions are not necessary are common. Foreseeable problems may be forecasted or detected but remain unaddressed until they become full-blown crises.

Therefore, there is a need to coordinate and enhance Great Lakes science capabilities for anticipation and management or prevention of potential threats through the institution of a Great Lakes Early Warning System (GLEWS). The project described here was intended to develop an analytical protocol for a GLEWS that could provide a Decision Framework to identify benchmarks and indicator thresholds of various groups of threats and stressors and, in so doing, rank and prioritize or re-prioritize them for action on an iterative or cyclic basis. Knowledge gained from these and related efforts, including other IJC studies and from sources of Traditional Ecological Knowledge (TEK), will facilitate the next critical step in operationalizing a GLEWS--employing a risk analysis approach to identify, categorize and prioritize the likelihood and severity of potential stressors and threats on the basis of their probability of occurrence and potential impact.

1.1.2 Relevance to Great Lakes Water Quality Agreement

The four tasks of the project (Literature Search/Analysis, Case Studies, Workshop, and Reporting) were ultimately designed to assist the IJC in addressing Article 8.3.(b) of the GLWQA.

This part of the GLWQA article calls upon the IJC and its Water Quality Board to identify emerging Great Lakes issues by delivering an effective and efficient approach to assessment of risks associated with threats and stressors. This responsibility is of great importance to the aquatic health of the Great Lakes. In order to assist the IJC and its Water Quality Board in fulfilling its GLWQA responsibility, the IJC's Science Advisory Board undertook the development of the conceptual GLEWS outlined in this report.

The project was conducted with the recognition that ecological problems are often fraught with high levels of scientific as well as regulatory and legal complexity, which increases the challenge of establishing an effective Early Warning System (EWS) to identify and respond to ecological stressors and their interactions. Further, many institutional challenges, such as governmental agencies that cannot identify and respond to ecological threats due to limited authorities, budgetary constraints, and competing priorities, were also recognized.

1.1.3 GLEWS 1 Report - An Overview

The project followed an initial phase conducted by the same contractor team in support of IJC. The Phase 1 project report, which was titled, "Towards a Great Lakes Early Warning System," is accessible here: https://ijc.org/en/sab/towards-great-lakes-early-warning-system. The GLEWS was envisioned as a means to allow the Great Lakes scientific and management communities to "get ahead of the curve" in addressing emerging and anticipated issues before they threaten the ecological integrity of the Great Lakes - St. Lawrence River Basin. Toward that end, a multi-faceted approach was implemented consisting of a literature review, review of existing models of early warning systems and frameworks that could be adapted for a GLEWS, interviews, survey, and Experts Workshop to (1) identify and prioritize emerging and anticipated threats and stressors; and (2) develop a conceptual Framework for a GLEWS to characterize these threats and stressors and link them to response actions.

Phase 1 project outcomes included the identification and prioritization of several dozen threats to ecological integrity, notably aquatic invasive species (AIS), harmful algal blooms (HABs), hypoxia, chemicals of emerging concern, nanoparticles, natural disasters, spills, airborne contaminants, bioaccumulative contaminants, habitat degradation, surface water availability, microplastics, emerging diseases, endocrine disruptors, groundwater quantity and quality, water chemistry, waterborne illnesses and "unknown unknowns". Identified stressors included climate change, nutrients, population growth, land management, unsustainable waste disposal practices, infrastructure failure, legacy contamination, and terrorism. Complementing these ecological stressors are social stressors that include ignorance, apathy, complacency, disincentives, economic drivers, lack of resources, policy decision-making and short-term thinking, lack of vigilant detection of ecosystem change, and lack of outreach.

Based on the threats and stressors analysis, and a review of the alternative frameworks for a GLEWS, a recommended alternative was selected and developed for consideration by the SAB and IJC. The recommended Framework calls for the initial development of a distinct and formalized entity, namely, a subcommittee of the SAB within the IJC structure comprised primarily of federal agency subject matter experts, supported by one or more IJC staff, and responsible for the following five functions: identifying and monitoring current, emerging and evolving threats and stressors; prioritizing the threats and stressors based on anticipated and demonstrated ecological and socio-economic impacts; recommending response actions designed to avoid, mitigate or otherwise address the identified threats and stressors; documenting response actions taken and associated outcomes; and addressing (and offering recommendations concerning) gaps and unmet needs that compromise the ability to identify, characterize and prioritize the array of current, emerging and evolving threats and stressors in the Great Lakes basin.

Recommended next steps included refining GLEWS structural and operational characteristics; designing and implementing assigned functions, and evaluating and refining GLEWS. Recommended deliverables for a pilot project implementing GLEWS included quarterly meetings of the GLEWS membership; quarterly updates; sponsorship of one or more conference sessions dedicated to identifying threats and stressors and associated response actions; identifying gaps and unmet needs and formulating recommendations; and an annual report to the IJC summarizing activities and outcomes to date.

1.2 Project Goal

Having identified a preferred organizational framework in the Phase 1 project, the IJC then sought a process for evaluation and communication of risks associated with differing threats and stressors and their combinations. This process was expected to combine an analytical protocol for identification of data sources, indicators, and methods with a Decision Framework that could both identify action limits for different categories of threats and stressors, and rank and prioritize candidate threats and stressors. The project incorporated systematic approaches for identifying, assessing and prioritizing ecosystem threats and stressors, and ultimately for selecting solutions in the GLEWS operational design. Physical, chemical, biological, economic, institutional, and governance aspects of the issue were all considered in some detail.

1.3 Report Organization

The three project tasks that involved information gathering and analysis (literature review, case studies, workshop) were generally conducted sequentially, with the results of each informing the subsequent tasks. This report describes how different analytical approaches were considered, leading to a draft GLEWS Decision Framework. The selection process for five case studies and the testing of the draft Framework through its application to those five case studies are then described. The report then records highlights of an Experts Workshop in which the Decision Framework and case study results were presented and discussed, and provides an overall project synthesis and a set of recommendations. A consolidated set of more than 180 bibliographic references is available at the end of the report followed by an appendices containing the tables of potential threats and the Experts Workshop Report.

2 METHODOLOGY

The contractor team participated in multiple planning, coordination, and review calls with Workgroup leadership and full membership, and IJC staff throughout the project, beginning in 2021 and continuing through project completion. These included a virtual Kick-Off Meeting shortly after project initiation to confirm an understanding of project requirements, and then regular meetings to prepare for and execute project tasks. Internal contractor team calls and email exchanges also took place regularly. More detailed descriptions of task-specific methods and approaches follow.

2.1 Literature Review and Decision Framework (Task 1)

The contractor team, with input from the WG and IJC staff, reviewed the global literature, including peer-reviewed and gray material, along with relevant websites, to develop a nuanced understanding of the analytical approaches and best practices associated with other Early Warning Systems. The review included material relevant to systems identified in the SAB's Phase 1 effort but not necessarily characterized in detail concerning analytical capabilities and capacities; other systems and material were identified through a combination of WG recommendations, web-based keyword searches, and bibliographic searches. Risk knowledge categories assessed included (among others) approaches, indicators, natural variability, detection of novel events, and the existence, availability, and accessibility of relevant datasets. Input from subject matter experts, including particularly J. David Allan (Professor Emeritus, University of Michigan) and William J. Sutherland CBE (University of Cambridge), was used to ascertain perspectives on ranking and prioritization.

Following completion of the review, a narrative risk assessment process, a stressor matrix, and a graphical depiction of the GLEWS Decision Framework were developed collaboratively by the contractor team, WG leadership and members, and IJC staff to evaluate threats and stressors identified in the Phase 1 study, in the literature review, and in other Great Lakes stressor mapping efforts. The process assessed the scope, likelihood, and severity of potential impacts from five key categories of stressors (chemical, nutrients, climate change, biological, human & behavioral). A generalized analytical methodology was developed that identified data sources, response indicators, benchmarks, and (where applicable) tipping points for the stressor categories. The narrative risk process and analytical methodology provided the basis for a Decision Framework template encapsulating a general process through which risk assessments can be performed for different stressor types.

2.2 Case Study Analyses (Task 2)

In collaboration with WG members, five case studies were developed based on the application of the preliminary analytical protocol and Decision Framework to selected stressors. For each stressor, a comprehensive risk analysis was performed that defined the threat in detail, identified potentially relevant data types and sources, identified appropriate methods for assessing trends and risk levels, and identified an appropriate analytical protocol and Decision Framework to assess whether risk levels call for action. Where indicated, the preliminary protocol and framework from Task 1 were updated to reflect insights gained from the comprehensive risk assessment case studies.

2.3 Workshop to Refine Decision Framework (Task 3)

An in-person Experts Workshop was executed to review the applicability of the project's updated analytical protocol and Decision Framework, evaluate whether the protocol and Framework could be operationalized with extant data and information, and consider the feasibility of integrating the protocol and Framework into the previously identified preferred organizational structure for further implementation. The workshop considered the effectiveness of the Framework and approach for identifying data needs and appropriate methods for assessing trends and risk levels, and in identifying appropriate protocols for risk-based assessment of the urgency for action. Preparation for the Workgroup included defining the workshop structure and content; identifying and inviting participants; preparing draft workshop agenda and other materials; facilitating the workshop; managing presentations and notetaking; and preparing and submitting a workshop report. Workshop materials included a detailed description of the analytical protocol and Decision Framework developed in Task 1 as well as a summary of draft findings from Task 2. More details on the workshop can be found in the Workshop Report included as Appendix 1.

2.4 Draft and Final Reports (Task 4)

The contractor team prepared a draft final report based on the activities performed in Tasks 1, 2, and 3. The draft report was submitted to and reviewed by the IJC and the WG and revised and finalized, incorporating comments and suggestions received, especially regarding draft recommendations.

3 LITERATURE REVIEW

The contractor team reviewed literature related to analytical approaches for early warning systems, including both retrospective and prospective approaches. Short descriptions of references that fall under each of the categories mentioned as examples in the project's Performance Work Statement follow. An analytical approach was also applied in a group setting in virtual workshops on December 17, 2020, and February 3, 2021, as part of the project, and the output was subsequently prioritized by the contractor team in the selection of Task 2 case study topics described below in Section 5 of this report. This process was summarized in a memo dated June 29, 2021.

3.1 Advance warning approaches

Hazard and threat mapping, changing variance patterns, predictive models (statistical and mechanistic), and scenario analysis. One of the most extensive recent mapping exercises for the Great Lakes that looked at stressor locations was the GLEAM Project (Allan et al., 2013), building on the work of the earlier GLEI Project (Danz et al., 2005). Additional related work on stressor interactions was conducted by an IJC-sponsored workgroup (SAB-SPC, 2020). New numerical models have been used in Lake Ontario and Lake Erie to forecast and run scenarios of nutrient impacts that produce harmful algal blooms, excess macroalgae, and bottom water hypoxia, using data from in-lake sensors and satellites as input (Rowe et al., 2019; Bocaniov et al., 2020; Hui et al., 2021). A recent study examined the relative risks and benefits of Great Lakes fish consumption and concluded that interspecific differences may be more important than geographic (inter-lake) differences in most cases (Strandberg et al., 2020). Similar analyses over time may be appropriate for tracking changing risks.

3.2 Response indicators

Stress & response relationships, thresholds & benchmarks. Stress-response relationships in the Great Lakes have been examined for decades (e.g., Rapport, 1983; Niemi et al., 2009) and have led to the development of indicators that form the basis of the *Triennial Assessment of Progress* (TAP, 2020), for example. *The State of the Great Lakes Report* is also an excellent example of indicators in action and can be accessed at https://binational.net/wp-content/uploads/2022/07/State-of-the-Great-Lakes-2022-Report.pdf. Research on thresholds and tipping points in Great Lakes ecosystems has shown congruence across communities in response to a land-use change threshold (Kovalenko et al., 2014). Climate stressors may be particularly prone to non-linear responses, early signs of which may sometimes be detectable (Lenton, 2011; Kravtsov et al., 2018).

3.3 Understanding of natural range of variation

Early warning signals in time-series data. Carpenter et al. (2011), through whole-lake manipulation experiments, were able to demonstrate using statistical analysis that early warning signals are detectable as an ecological regime shift approaches. These signals of imminent regime change consisted of increases in the range or frequency of natural variation from background conditions. In theory, it may be possible to determine similar early warning signals that would apply to the Great Lakes. In practice, such statistical predictions may be more challenging at this scale than they proved to be for the smaller experimental lake systems. That said, thoughtful analyses of long time-series may make such predictions possible (e.g., Austin and Colman, 2007 [Lake Superior temperature and ice data signaling differential climate change impacts]; Anderson et al., 2021 [deep Lake Michigan thermal data signaling stratification shifts]). Such analyses, however, require long-term, or dense data sets to enable such patterns to be detected.

3.4 Novel event detection

Aquatic invasive species sightings or genomic detection (for example). Programs to detect the introduction of new species to the Great Lakes and monitor their spread are fairly advanced and are expanding to include sophisticated techniques such as monitoring for environmental DNA and RNA. This has been applied for years for tracking Asian carp in Chicago waterways (e.g., Jerde et al., 2013), and is now expanding to invertebrates across the Great Lakes (Klymus et al., 2017). A centralized database has been established (Sturtevant et al., 2004; GLANSIS, 2022), and watchlists for potential new species have also been developed (Davidson et al., 2016). USEPA has also made use of volunteer crowdsourcing for the analysis of a large collection of underwater lakebed videos (Wick et al., 2020; 589 volunteers; https://www.zooniverse.org/projects/USEPA/deep-lake-explorer) to assist biologists in understanding the spatial impacts of benthic invasive species at greater resolution.

3.5 Sources of data and information

Informing early warning including agency-based monitoring programs and sensors, academic studies, data collection to satisfy regulatory requirements, etc. Detections of threats such as emerging contaminants or changing contaminant trends are part of programs such as the USGS tributary monitoring of water and sediment (Baldwin et al., 2022) and USEPA and ECCC fish contaminant monitoring and surveillance (ECCC, 2021a). Academic institutions are distributed around the Great Lakes and are therefore able to mobilize quickly to study unexpected events in their areas such as novel algal blooms in Lake Superior, oil spills, and the use of autonomous sensor platforms.

3.6 Availability and accessibility of data and information

Derived from both formal and informal monitoring conducted by Tribal and Indigenous peoples. A companion IJC project that began in 2021 is underway titled, *Building a Framework*

Toward Bridging Traditional Ecological Knowledge [TEK] *and Western*[2] *Science*. The project seeks "to advance knowledge on how TEK can have a meaningful role in the primarily Western science approach to IJC advice, and to develop recommendations on a framework through which TEK and Western science can collaborate within this structure within the Great Lakes." Related recent documents include *Guidance Document on TEK Pursuant to the GLWQA* (U.S. Caucus of the TEK Task Team of the Annex 10 Science Subcommittee, 2021) and *2019 Tribal Great Lakes Restoration: Culturally Inspired Restoration* (GLIFWC, 2019). These documents and similar recent publications make clear that the interconnectedness of traditional Indigenous cultures with the environment can be a great asset. As stated in the 2021 *Guidance Document (p. 11)*:

> As it relates to management decisions, TEK provides intensive knowledge in specific and defined geographic regions and, in this way, adds depth to more general and often more geographically widespread data offered by western science. In addition, by focusing on the interconnectedness of the whole, TEK can, and sometimes has, **acted as an early warning system** [*emphasis added*] for emerging issues, imbalances, and changes in relationships, thereby helping to set priorities for study and action.

In comparison with Western science approaches, TEK observations are generally less available and accessible for use in threat analysis. This is due to the format of much of the knowledge, as it is contained in the lived experience of tribal elders and transmitted via stories, oral histories, songs, ceremonies, and customary laws. There is also hesitancy to share such information in many cases due to a history of cross-cultural appropriation, exploitation, and misuse. That said, there may be great mutual benefit in collaborations, especially at local scales and across long timeframes such as those relevant to climate change and ecological adaptation beyond the decadal scale. This collaborative approach of merging Western science and TEK methods and perspectives has been termed "Two-Eyed Seeing" (e.g., Almack et al., 2022; Gobin et al., 2022).

3.7 Related IJC reports

In addition to the Phase 1 report described above, "Towards a Great Lakes Early Warning System," IJC advisory boards and contractors have prepared several related reports in recent years. These are described briefly here and embedded hyperlinks to the full documents are provided.

Information Coordination and Flow in the Great Lakes Basin (2018). LimnoTech partnered with the Great Lakes Commission to help the IJC Science Advisory Board's Information Coordination and Flow (ICF) Workgroup better understand the status of data collection and flow in support of environmental decision-making in the Great Lakes region. The project

[2] *"Western" science refers to positivist approaches to the scientific explanation of natural phenomena from a Eurocentric viewpoint.*

approach included an expert workshop and the development of a formal process for assessing the state of information flow in a given topic area. The process was tested against two topic areas – invasive species and water recreation. The project also worked to identify ways to enhance consideration and integration of traditional ecological knowledge into environmental decision-making in the Great Lakes. The final report examined how coordination and flow of information take place in the Great Lakes across sectors, scales, and through time, and provided recommendations for improvements, including identification of best practices and significant barriers.

An Evaluation of Stressor Interactions in the Great Lakes (2020). A LimnoTech-AECOM team supported the IJC Stressor Interactions Workgroup under the Science Priority Committee of the Science Advisory Board in characterizing stressor interactions in the Great Lakes, with particular emphasis on 11 pairs of priority interacting stressors. The team also identified additional research, surveillance, and monitoring activities that are required to fill knowledge gaps. The project included an initial review of international literature on stressor interactions, followed by organizing and facilitating an expert workshop and a proceedings report. The final report evaluated ways in which IJC can understand and communicate the potential of nonlinear effects to result in ecological damage from the cumulative impact of several stressors. Results were also presented at the annual meeting of the International Association for Great Lakes Research.

Development of a Decadal Science Strategy for Binational Great Lakes Research (Summary Report available here with the full report available upon request).

The IJC Great Lakes Science Advisory Board has an ongoing role in identifying important data gaps and priority research needs, and in coordinating Great Lakes research. LimnoTech supported IJC in collaborative development of a comprehensive science strategy for a decadal-scale, binational program of Great Lakes research through information synthesis (background white paper and compilation of research and monitoring budgets across the basin), a three-phase online survey, and two focused workshops with reports, as well as a research managers' workshop. The Science Strategy complements and informs management and restoration activities with the science necessary to ensure dollars are spent with the greatest return on investment, and to ensure that the management actions implemented will be lasting and will stand up to new pressures on the ecosystem. The plan is both overdue and timely, given: 1) the immense changes the system has experienced over a period of less than 20 years, 2) the potential far-reaching impacts of ongoing change, both recognized and unknown, 3) the uncertainty engendered by our current lack of understanding or quantification of many of the principal drivers and processes involved in these changes, and 4) the significant past and ongoing investment deemed necessary to restore the Great Lakes and fulfill the promise of the GLWQA. The project was considered a companion effort to a U.S.-only science planning project led by USGS and initiated by requests from the U.S.

Congress. The final public plan summary was released as the *Great Lakes Science Strategy for the Next Decade* on November 30, 2022, and is available at: https://www.ijc.org/en/sab/GL-Science-Strategy.

3.8 Summary of key findings and their relevance

Identification of past signals that could have served as early warning signs of an important negative change in systems such as the Great Lakes is always easier in hindsight than by looking at current signals and determining what they may portend. That said, the expansion of real-time monitoring networks and the development of increasingly sophisticated artificial intelligence and machine learning approaches to extracting key signals and patterns out of large amounts of data show great promise as ways to improve ecological foresight and trigger preemptive actions. The missing component at present is shifting the process from project-specific actions (e.g., small academic research projects, proof-of-concept pilot exercises, and case studies) to a sustained programmatic structure.

The *Triennial Assessment of Progress* is an example of such a program, with a formal synthesis product, but its focus is retrospective rather than prospective and it has no direct linkage to response actions once a changing pattern or trend is detected. A program that effectively combines the approaches described above (e.g., threat mapping, identification and tracking of response indicators, ongoing time-series analysis, proactive threat tracking and detection of invasion or threshold exceedance, automated signal processing, periodic topical deep-dive studies) would require dedicated resources in the form of staff, facilities, data management and processing systems, and communications systems for status reporting and alerts.

At this time, no such system exists for the Great Lakes except for specific threats such as Asian carp invasion, fish pathogen introduction at hatcheries, or non-ecological threats such as severe storms, human infectious disease outbreaks, or financial system irregularities. Integrated approaches involving regular structured horizon-scanning meetings with subject matter and ecosystem experts, as well as Indigenous Elders with deep TEK wisdom, would also be of great value in advancing a GLEWS, with or without a more resource-intensive quantitative program oriented toward data ingestion and signal processing. Any such program will require supporting research activities and associated funding.

4 CASE STUDY ANALYSES

The contractor team was originally tasked with applying a risk assessment process and analytical methodology – in collaboration with the SAB and Workgroup members – for three stressors as case studies. The requirement was modified to call for the development of five case studies based on consideration of the most suitable suspected stressors in each of the five key stressor categories (chemical, nutrients, climate change, biological, human/behavioral). The team developed a set of criteria for the selection of the specific case studies, described below. Subsequently, they applied a draft risk assessment process and analytical methodology to each of these threats and refined the process and methodology to reflect discoveries from the application. The suspected threats for each category most suitable for the development of case studies were:

- PFAS/PFOA impacts (Chemical)
- Changing lake impacts of nutrients other than P (nutrient ratios, micronutrients) (Nutrients)
- Changes in biological community and agricultural ranges (Climate Change)
- New fish pathogens (Biological)
- Changing competition for groundwater with ecological impacts (Human/Behavioral)

4.1 Selection of Case Studies

The case studies presented below were identified through virtual meetings and contractor team review and ranking as described below.

4.1.1 Virtual Meetings with Topical Breakouts

The contractor team facilitated virtual meetings with 40+ expert participants each on December 17, 2020, and February 3, 2021. In these meetings, breakout groups for each category identified and discussed known, suspected, and unknown threats, and associated stressors, risk knowledge, detection, monitoring and analysis within the category. The discussions and identified threats/stressors were captured in separate shared worksheets by an assigned recorder. A total of 121 stressors (see full-page tables below) were identified across the five categories (Table 1).

	Known	Suspected	Unknown	Total
Biological	11	5	6	22
Chemical	6	7	9	22
Climate Change	13	15	5	33
Human	13	5	6	24
Nutrients	7	7	6	20
Total	50	39	32	121

Table 1. Counts of identified stressors.

4.1.2 Contractor Team Review

The contractor team reviewed the worksheets developed by the five groups and combined them into a single worksheet with consistent formatting (See attached "Ordered Synthesis" table). Three groups (Nutrients, Climate Change, and Biological) had indicated preferred choices; for each of these groups, the Contractor Team reviewed the full list of identified threats and agreed that the preferred choices were appropriate and suitable. For the other category groups (Chemical and Human & Behavioral), Contractor Team members ranked and discussed the identified threats to reach a consensus on the most appropriate choices for consideration as a case study. The choices were combined into a 3x5 matrix below anticipating the selection of three case studies (Table 2).

Table 2. Case studies considered and selected (yellow). The first and second rows were ranked by the dimensions described in the text below and in Table 3, and are listed from highest to lowest composite score from left to right. The third-row entries (unknown category) were not ranked and are listed in no particular order.

GLEWS Priority Case Study Topics					
Top candidates for known category:	Changing mercury fluxes and biotic uptake	Increasing lake water temperatures, especially deep water	Increasing coastal and riverine development	New invasive species or range expansions	Changing lake impacts of agricultural P and N losses
Top candidates for suspected category:	PFAS/PFOA impacts	Changes in biological community and agricultural ranges	Changing competition for groundwater with ecological impacts	New fish pathogens	Changing lake impacts of nutrients other than P (nutrient ratios, micronutrients)
Top candidates for unknown category:	Emerging contaminants in tributaries and fish (monitoring, archiving model)	Increasing extreme weather event frequency, intensity, and future trends	Environmental disasters, spills/releases	New synergies with invasives (e.g., climate-driven range expansion or species interactions)	Climate change impacts on lake stratification, internal loading, HAB toxicity or biomass

4.1.3 Ranking

For the known and suspected threats, the contractor team jointly scored the selections from each category along the previously identified dimensions of Data, Affect, Eurocentric/TEK Balance, Spatial Extent, Threat Interaction, and Emerging Issue. The qualitative scores for each category, which were entered using a scale from 1 to 5, were summed into a total score for each threat (Table 3).

The ranking process was used to (1) prioritize consideration of known threats and their history in the formulation of a draft process and methodology, and (2) set the order of case study application to suspected threats, thereby informing the Framework refinement early on with details reflecting more-important threats.

GLEWS CASE STUDY SCORING MATRIX - 1 June 2021

	Total	Data	Affect	Western/TEK	Spatial Extent	Stressor Interaction	Emerging Issue
KNOWN							
Changing mercury fluxes and biotic intake	**24**	4 Need to better understand fluxes	5 Widespread consumption advisories	4 Good TEK contribution on population health	5	3	3
Increasing lake water temperatures, especially deep water	22	2	4 Concern about future changes to stratification and hypoxia	2 Limited TEK for deep-water data	5	5	4
Increasing coastal and riverine development	19	3 Inconsistent, not well-integrated into analyses	3 Localized	3	4 Associated with population	4 Impacts habitat -> life cycles, etc.	2 Chronic issue
New invasive species, or range expansions	23	4	4	4	4 More pronounced in lower lakes	4	3
Changing lake impacts of agricultural P and N losses	21	4 Data are best where impacts have already been observed	4 Eutrophication	2 Areas of impact generally not associated with tribes	3 Associated with ag watersheds	4	4
SUSPECTED							
PFAS/PFOA impacts	22	4 Rapidly improving	3 Impacts are now being publicized and addressed	1 TEK not readily available for novel organic contaminants like PFAS	5 Bioaccumulative	4	5 Trending topic in many realms
Changes in biological community and agricultural ranges	21	3 Much data, but not uniform across the basin, and not yet well-analyzed for this.	3 Generally subtle gradients in time and space.	3	4 Basinwide issue, but varies from one lake to the next	5	3 Ongoing topic, but not highly visible in research or media
Changing competition for groundwater with ecological impacts	**25**	3 Data exist, but are not generally linked to impacts.	5 Huge implication for both water quality and quantity, etc.	4 GW, ecological elements can be found	5 Focused somewhat on high-extraction areas (mining, bottled water, ...)	4	4 Many ongoing GW studies, more attention in recent years.
New fish pathogens	23	3	5 Food web implications; high spreading potential	4	4 Assumed more of an issue in the lower GL	4 Multi-stressor impact on individual exacerbated	3
Changing lake impacts of nutrients other than P (nutrient ratios, micronutrients)	19	4 Good for (e.g.) Si/N, more limited for Co, Fe	2 Consensus on impacts not yet well-defined	2 TEK may be limited to secondary measures, e.g. fish population	4 Primarily lower GL issue in conjunction with P	4	3

Table 3. Excerpt from contractor team scoring sheet.

The selected known threats ordered by total score were:

- Changing mercury fluxes and biotic intake (24/30)
- New invasive species, or range expansions (23)
- Increasing lake water temperatures, especially in deep water (22)
- Changing lake impacts of agricultural P and N losses (21)
- Increasing coastal and riverine development (19)

The selected suspected threats ordered by total score were:

- Changing competition for groundwater with ecological impacts (25/30)
- New fish pathogens (23)
- PFAS/PFOA impacts (22)
- Changes in biological community and agricultural ranges (21)
- Changing lake impacts of nutrients other than P (nutrient ratios, micronutrients) (19)

The consultant team did not rank the selected unknown threats and suggested a two-stage early warning approach for this group – non-categorical and categorical. In brief, a truly unknown threat cannot reasonably be assumed to be in any particular category, so a non-categorical approach based on both surveillance (e.g., looking for changes and trends in long-term detailed monitoring of key parameters and sentinel species) and forecasting (based on horizon scans, scenario planning, reference to other localities, and similar techniques) was suggested as a starting point. However, the presence of a change indicating a threat, or forecasting of a future threat, would be expected to quickly segue into identification of relevant categories that could be used as a basis for literature review and expert elicitation to refine measurement and provide confirmation of the threat. An "unknown" case study was expected to be informed by retrospective reviews of previous instances where unknown threats were identified and acted upon.

The information collected in the virtual meetings (Table 4 on the following pages) and the evaluation criteria were also used to assist in the development of a screening-level framework. The draft process and methodology were informed by the completed literature review and consideration of the known and unknown threats from each category. Key elements of the Framework address detection, analysis, decision, and response for threats. The column headings in the table represent different components and phases of threat analysis for an EWS, including for known, suspected, and unknown threats. These are described briefly here:

Threat Description: a short word or phrase that names the threat.

Example of Stressor Description Resulting from Threat: illustration(s) of how the threat could stress the ecosystem.

Risk Knowledge – Prepare for Threats and Stressors -- Foresight: summary of how the likelihood, severity, and intensification of the threat could be determined in advance or monitored once it is present (USEPA, 1995).

Risk Knowledge – Identify Threats and Stressors – Risk Knowledge and Understanding: advance warning approaches that are specific to the threat including hazard and threat mapping, changing variance patterns, predictive models (statistical and mechanistic), scenario analysis; response indicators; understanding of natural range of variation; novel event detection; sources of data and information; availability and accessibility of data and information.

Detection/Monitoring/Analysis – Determine Presence of Threat and Stressor – Detection Mechanisms: ways in which the presence or intensification of a specific threat signal can manifest and be detected and quantified above the diverse, heterogeneous, and variable background conditions.

Detection/Monitoring/Analysis – Decision for Taking Action – Analysis: the methods and status of analysis for determining an action threshold relative to detection and monitoring data, and the nature and governance aspects of the associated warning or response action once a threshold is established and data indicate that the threshold has been exceeded.

As described above, the case study selection process evaluated multiple criteria as applied to the list of over 100 potential Great Lakes stressors and threats that can impact water quality and ecosystems. The list included both known and suspected stressors and threats. The set of suspected stressors and threats examined in the following GLEWS case studies and further evaluated in the Experts Workshop consisted of:

1. Changes in concentrations of nitrogen and other key non-phosphorus nutrients.
2. Climate change impacts on agricultural ranges and practices, and on aquatic species ranges.
3. Introduction and spread of fish pathogens.
4. Shifts in groundwater usage and related ecological impacts.
5. Occurrence and impacts of contamination by per- and polyfluoroalkyl substances (PFAS).

A sixth case study on unknown stressors was also included to expand the "suspected" examples. General GLEWS findings, conclusions, and lessons learned through completing these case studies include the following:

- Organizational structures, programs, and knowledge systems that currently exist within IJC and externally (Figure 2) can be leveraged or adapted to implement many elements of the GLEWS, including IJC advisory boards, committees of other commissions, Indigenous Knowledge systems, agency reporting systems, community science networks, and outdoor recreation groups.
- Although IJC itself does not have sufficient resources to conduct or fund the research and monitoring needed to fill critical gaps related to suspected threats, it may be able to provide staff to coordinate binational assessment activities and development of tracking and scoping documents through its boards and working groups and related strategic partnerships that can guide external organizations in conducting priority research and monitoring.
- Some threats may have both upper and lower thresholds of impacts, which complicates defining threat states and management responses; natural baselines and ranges are also not known in all cases.
- Some threats fall outside the normal scope of interests of the Great Lakes research community (e.g., exemplified by the International Association for Great Lakes Research [IAGLR], which has a primary focus on aquatic ecology) and may require engagement with other professionals and communities to develop detection, monitoring, and warning approaches.
- In addition to guiding additional research and monitoring, initial threat assessment can lead to "warn", "adapt", or "watch/no further action" decisions.
- Several structures, programs, and knowledge systems that exist within IJC and externally can be leveraged or adapted to implement elements of the GLEWS, including

IJC advisory boards, committees of other commissions, Indigenous Knowledge systems, agency reporting systems, community science networks, and outdoor recreation groups.

- Although IJC itself does not have sufficient resources to conduct or fund the research and monitoring needed to fill critical gaps related to suspected threats, it may be able to provide staff to coordinate binational assessment activities and development of tracking and scoping documents through its boards and working groups and related strategic partnerships that can guide federal agencies and external organizations in conducting priority research and monitoring.
- Some threats may have both upper and lower thresholds of impacts, which complicates defining threat states and management responses; natural baselines and ranges are also not known in all cases.
- Professional societies (e.g., the International Association for Great Lakes Research [IAGLR], which has a primary focus on aquatic ecology) can play a convening role in horizon scanning and threat assessment. Some threats, however, fall outside the purview of IAGLR and similar biophysically oriented scientific societies and may require engagement with other professional organizations and communities to develop detection, monitoring, and warning approaches that encompass the full range of threats to the Basin.
- In addition to guiding further research and monitoring, initial threat assessment can lead to “warn”, “adapt”, or “watch/no further action” decisions.
- Connections among research and monitoring of suspected threats and organizations that can act on warnings need to be strengthened, but such organizations do not exist for all threats in all jurisdictions.

While we recognize that our recommendations and in particular, the case studies, are decidedly biological, chemical, and hydro-geophysical, we remain highly attuned to the human behavioral and social elements of these and other case studies and conditions. The trajectory of population and demographic changes, land (agricultural and other) and water use patterns (water demand functions), and social and cultural expectations will have an ongoing and profound influence on many of the issues of concern throughout the Great Lakes over the next many decades.

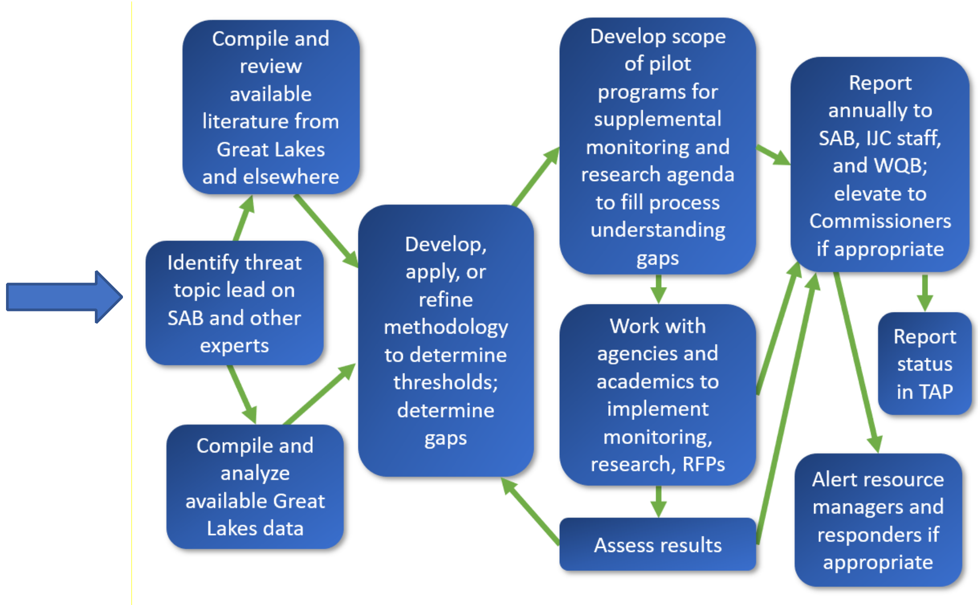


Figure 2. Schematic diagram of the GLEWS process for review of suspected threats.

The diagram in Figure 2 includes technical and governance elements. Note that the "Assess results" step includes an arrow that potentially cycles back to an earlier step. It may also be essential to involve managers early in the process of threat definition and identification, as well as in providing later review of draft reporting.

A generic decision tree that shows a GLEWS approach for dealing with a suspected threat such as the case study examples reviewed here is shown below (Figure 3). The pathways include a loop for dealing with inadequate data and understanding in the upper right, and actions stemming from an “adequate” pathway in the lower left, leading to “warn”, “adapt”, “watch”, or "no further action” endpoints. The five case studies show that this Framework is generally applicable to suspected threats at the level of detail shown. The success of a GLEWS will depend on the development and refinement of threat-specific decision trees with more detail.

The process for implementing a GLEWS merits consideration of the type of threat, its potential impact, and how it fits within existing governance structures and partnerships in the basin. This study recognizes the existence of distinct management groups in the basin with responsibilities for water quality, fisheries, water quantity, aquatic invasive species, coastal lands, watersheds, and urban areas, among other management domains, which each need to be accommodated in the GLEWS process. For example, the fisheries committees coordinated by the Great Lakes Fishery Commission could be engaged in the process when a threat affects fish communities or fisheries directly or indirectly. Also, many agencies and groups already have threat monitoring and communication protocols in place that should be incorporated into GLEWS implementation. That said, there is no single entity that plays a consolidating and integrating role in compiling threat information across geographies, disciplines, and resource areas, and in curating a ‘library’ of threats in various states of development and emergence, including those deemed unimportant or not yet important after review cycle iterations (Figure 3), but which should be considered again in the future.

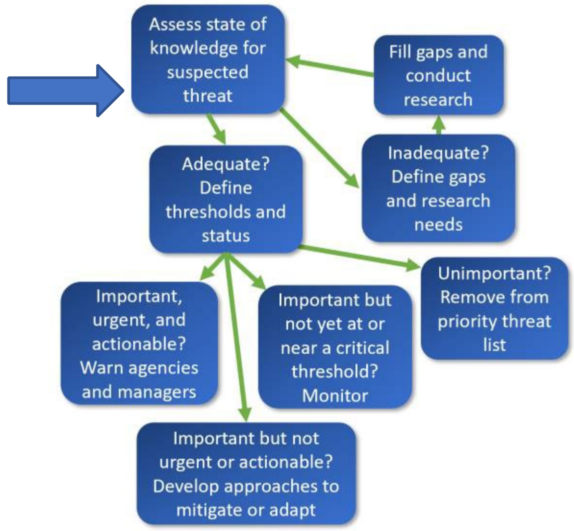


Figure 3. Simple decision tree describing GLEWS steps for a suspected threat.

Nutrient limitation *– the condition of an organism or group of organisms (e.g., phytoplankton) not growing or reproducing as rapidly as theoretically possible due to the absence or low bioavailability of one or more nutrients or micronutrients, which can be influenced by environmental conditions (e.g., inadequate light, bioavailability of toxic substances).*

4.2 Case Study 1: Nitrogen and Other Key Non-Phosphorus Nutrients

The focus of research and management of nutrients to control eutrophication in the Great Lakes and other freshwater systems has been on phosphorus (P) for many years (Schindler, 1977). Recent debate on the relative importance of P vs. N and N:P ratios continue (contrast Schindler et al., 2016 and Paerl et al., 2020), however, newer research, looking at a larger group of nutrients as potential stressors and management targets, augments this discussion. Some non-P nutrients can be addressed by similar approaches to the management of P loading, but others would require more customized measures.

Figure 4 and Tables 5 and 6 below show the approximate four-axis matrix positions of the threat, key technical elements, and key governance elements related to the evaluation of the potential threat posed by non-P nutrients. The general flow of information and decisions in the tables is

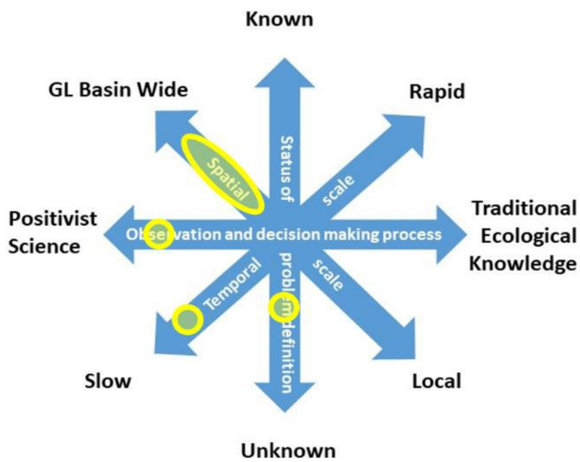


Figure 4. Placement of non-P nutrients on the four cardinal threat categorization axes based on professional judgment of the contractor team and Work Group, indicated by yellow circles or the ellipse.

from left to right, with cycling back to earlier steps for reassessment as more information becomes available.

Knowledge of the status and trends of N in the Great Lakes is more complete than for the other non-P nutrients, but neither N nor other non-P nutrients are understood well enough at present in the Great Lakes to move them from the "suspected" category of threats to the "known" category. For example, when the GLWQA Annex 4 Subcommittee was setting nutrient reduction goals for Lake Erie in 2015 they concluded that setting a target for N reduction would be premature based on the state of knowledge (GLWQA, 2015).

Nitrogen forms and some other non-P nutrients have been monitored by ECCC and other organizations for many years. Among the most significant historical shifts in N cycling in the lakes was the impact of intensive logging in the late 1800s and early 1900s (Guiry et al., 2020). A comprehensive early study of trace elements in each of the Great Lakes (Rossman and Barres, 1988) has not been repeated in the last 35 years.

Because N and micronutrients are essential for life in the Great Lakes, their thresholds include both upper and lower bounds on safe or healthy concentrations and bioavailability. Unlike toxic pollutants, ecosystem problems can arise from excess nutrients (too much of a good thing) as well as insufficient concentrations (too little of a necessary thing). There does appear to be a linkage between N and other non-P nutrients and the toxicity of cyanobacterial blooms in Lake Erie and possibly elsewhere (Newell et al., 2019). That said, there is insufficient information and understanding at this time to determine these boundaries in most parts of the system, so further research is needed to guide the development of warning criteria and appropriate management responses. Proactively guiding research and conducting periodic assessments of progress may be the most productive GLEWS activity for this threat at this time (see Tables 5 and 6).

Table 5. Summary of Early Warning Technical Elements for the N and Micronutrient Changes Stressors.

Drivers	Foresight	Risk Knowledge and Understanding	Detection Mechanisms	Analysis	Action Trigger
Nitrogen forms with limiting role on primary productivity and influence on cyano-bacteria species and toxin production	Review existing research from the Great Lakes, lab experiments, and more extensive work in estuaries and their watersheds	Assemble existing information on nitrogen forms and trends from monitoring programs, with a focus on recent changes in loads, concentrations, forms, ratios, or rates	Compile analytical datasets from Great Lakes and tributaries; monitor current and future data and loading calculations	Determine response threshold values (upper and lower) for concentrations, forms, ratios, or rates in specific water bodies or basins	Exceedance of tipping points (too high or too low) in concentrations, forms, ratios, or rates of change in drivers or response; inform larger GLEWS
Micronutrients with potential limiting role in phytoplankton productivity or nutritional value for upper food web: iron, zinc, silica, calcium, cadmium, cobalt, boron, copper, and molybdenum	Track lab, mesocosm, and limno- logical research broadly including elements, speciation, cycling, impacts on algal biomass and toxicity	Review existing programs for monitoring micronutrient baselines in lake basins; develop research agenda for field process studies, lab studies, and biogeochemical	Determine thresholds for impacts of changes in micronutrient concentrations, forms, ratios, or rates of change in lake basins	Track basin-specific research projects; analyze new monitoring data as they become available; assess state relative to thresholds	Exceedance of tipping points (too high or too low) in concentrations, forms, ratios, or rates of change in drivers or response; inform larger GLEWS

Table 6. Summary of Early Warning Governance Elements for the N and Key Nutrient Changes Stressors.

Subject Matter Experts	Lead Agencies and Organizations	Lead Programs	Frequency of Review	Internal IJC Actions	External Communications
Identify lead and supporting N experts in the Great Lakes and elsewhere, including chemical oceanog-raphers	USGS, ECCC, USEPA, NCWQR, IAGLR	Annex 4, NCWQR tributary sampling, USGS NAWQA, GLRI, *R/V Lake Guardian* and *Limnos* sampling	Annual and three-year status relative to thresholds (if known); review of ongoing research	Report annually to technical staff and WQB; elevate to Commiss-ioners as appropriat e	Report status in TAP, inform management agencies if specific actions can be identified to reduce or increase key sources to achieve desired state
Identify lead and supporting micronutrient experts in the Great Lakes and elsewhere, including chemical oceanog-raphers	ECCC, USEPA, MECP, NOAA, CIGLR, IAGLR	CSMI, *R/V Lake Guardian* and *Limnos* sampling, other existing monitoring transects (Isle Royale, Muskegon)	Annual and five-year; research progress and status relative to thresholds (if known)	Report annually to technical staff and WQB; elevate to Commiss-ioners if significant	Report status in TAP, inform management agencies if specific actions can be identified to reduce or increase key micronutrients to achieve desired state

4.2.1 Case Topic Overview

4.2.1.1 Issue Characterization (includes literature review)

Changes in the trophic status of the Great Lakes have received significant attention in recent years, including both eutrophication triggered by point source and nonpoint nutrient loads (e.g., Watson et al., 2016) as well as oligotrophication driven by dreissenid mussel invasion and filter feeding in the four lower Great Lakes (Li et al., 2021). The primary focus of monitoring and management has been reduction of phosphorus loading, with initial emphasis on point sources and particulate non-point loads, followed by more recent attention to dissolved P (Baker et al., 2014; Joosse and Baker, 2011). Nitrogen (N) has also received more attention in recent years, especially in Lake Erie as a potential co-limiting nutrient for cyanobacterial blooms and toxin production (Venkiteswaran et al., 2017; Chaffin et al., 2018; Newell et al., 2019; Paerl et al., 2020; Wagner et al., 2021) and in connecting waters and drowned river mouths (Steinman et al., 2016). Changing nutrient ratios of N:P have also been considered as drivers of ecological shifts, especially in Lake Superior and Lake Erie (Elser et al., 2000; Sterner et al., 2020; Prater et al., 2017). Hypotheses, field measurements, and experiments considering other limiting micronutrients have also been published. These other nutrients include iron (Twiss et al., 2000 and 2005; Sterner et al., 2004; North et al., 2007; Havens et al., 2012; Sorichetti et al., 2016; Leung et al., 2021; Wagner et al., 2021), zinc (Twiss et al., 2005; Intwala et al., 2008), silica (Carrick and Lowe, 2007), calcium (Gopalakrishnan and Kashian, 2020), cadmium (Twiss et al., 2005; Intwala et al., 2008), cobalt (Twiss et al., 2005; Downs et al., 2008; Intwala et al., 2008; Fan et al., 2021; Kelly et al., 2021), boron (Downs et al., 2008), copper (Twiss et al., 2005; Downs et al., 2008; Kelly et al., 2021), manganese (Twiss et al., 2005), and molybdenum (Twiss et al., 2005; Downs et al., 2008; Kelly et al., 2021; Wagner et al., 2021).

4.2.1.2 Rationale for Selection

As a suspected threat to Great Lakes food webs, but also a potential target for effective management, nitrogen and micronutrients merits more attention. Nitrogen cycling is complex and involves multiple dissolved and gaseous forms including nitrate, nitrite, ammonium, urea, nitrous oxide, diatomic nitrogen gas, and ammonia. Lakewide surveys of multiple N species are routinely conducted by ECCC and USEPA but the full suite of inorganic and organic nitrogen forms, their redox chemistry, and fluxes are rarely monitored in the Great Lakes and tributaries, except as part of intensive process studies.

Micronutrients are routinely monitored in the Canadian Great Lakes by ECCC but the body of research and analysis of their importance for desirable or harmful primary producers in the basin is relatively small. In contrast, oceanographic research on micronutrients is abundant, particularly in high nutrient-low chlorophyll (HNLC) regions of the ocean such as the North Pacific (Jickells et al., 2005).

There is the potential that eutrophic systems (Bay of Quinte, Hamilton Harbor, Sodus Bay, the west basin of Lake Erie, Saginaw Bay, Green Bay) could be managed more effectively by looking at P management approaches in combination with N and micronutrients (Paerl et al., 2020), rather than concentrating only on P. An additional consideration is that recent unusual phytoplankton blooms in Lake Superior may be driven by or augmented by the presence of micronutrients like iron, in an otherwise oligotrophic system. Iron has been delivered to the lake in extreme runoff events in Duluth/Apostle Islands (2012), Houghton (2018), and Thunder Bay (2019) (Sterner et al., 2020; Reinl et al., 2020 and 2021). Increasingly warm surface waters during summer may also be a factor (O'Bierne et al., 2017).

4.2.1.3 Lead Agencies Responsible for Planning and Action

The most appropriate agencies to pursue monitoring and basic research on micronutrients in the Great Lakes would include ECCC and DFO in Canada; along with USEPA, NOAA, and USGS in the U.S. The roles and flow of information to the primary decision-makers from these monitoring and research programs should be formalized including responsibilities for

a) collecting the data, b) analyzing the data, c) reporting the results, and d) making funding allocations, management decisions, and setting regulatory policy. Academic research, where much of the related work to date has been performed, will also continue to contribute. A scoping initiative was funded by the Chemical Oceanography Program of the National Science Foundation in 2013 titled, *Biogeochemistry of the Great Lakes System* (BOGLS; Baskaran and Bratton, 2013). Sterner (2021) laid out the value of the Great Lakes as a biogeochemical testbed for macronutrient cycling.

4.2.2 Early Warning Approach

Given limited knowledge of changing N and micronutrient concentrations as "suspected" stressors or threats, improved understanding could be tracked by an early warning board or working group or highlighted as an important area for additional study and investment (see Figure 2). Substantial datasets exist within ECCC, MECP, USEPA, USGS, and NCWQR for N concentration, speciation (forms), ratios, and loads for several areas of the lakes, and fixation studies have also been performed (Natwora and Sheik, 2021). Many of these datasets could be analyzed more extensively and holistically to develop stress-response indicators, threshold guidance and provide assessments of threat potential. A new effort to compile and evaluate existing N data may be productive, potentially including numerical biogeochemical modeling (Rowe et al., 2014), data mining, and machine learning approaches.

Regarding micronutrients, repeat sampling at select stations and isolated studies have been performed over several decades, but the existing data may be amenable to re-examination with threshold and warning applications in mind. As with N, a systematic compilation and analysis of micronutrient data from the Great Lakes, and a literature review of recent studies in all lakes may be useful (e.g., Twiss, 2008), including work in other large temperate lakes. A symposium of subject matter experts may be an efficient way to access the current state of knowledge and catalog data holdings, which may be widely dispersed. A subset of the longer list of micronutrients may be useful to develop as an initial research target area.

Another way to focus studies and GLEWS considerations may be to intensively study localized parts of the Great Lakes where trophic conditions and blooms seem to be changing rapidly, such as areas of new *Dolichospermum* blooms in Lake Superior (Sterner et al., 2020; Reinl et al., 2020 and 2021), or conditions that led to the recent absence of the common *Planktothrix* blooms in Sandusky Bay or unusual summer diatom dominance in Muskegon Lake (Mancuso et al., 2021). Results of localized studies should be consolidated and analyzed to determine if larger-scale patterns (e.g., more intense weather systems across the region) are manifesting in local bloom incidents. Micronutrient sampling and analysis require equipment that is completely free of trace metals, sampling approaches that avoid contamination from sampling vessels themselves, and the use of appropriately sensitive and applicable analytical methods for all elements (Twiss et al., 2000). This limits the ability of many investigators to perform these types of studies due to challenges with proper vessel configuration, lab designs and setups, and analytical instrumentation (Nriagu et al., 1993).

Once adequate data compilation and literature review have been completed, it may be possible to develop baseline information for parts of the lakes on N and micronutrient status and trends and to potentially develop upper and lower thresholds to guide future assessment and incorporation into a warning system, if warranted. The GLWQA Annex 4 Subcommittee has been assessing the state of knowledge regarding the role of N in eutrophication for several years, and it may be one of the appropriate groups under which to concentrate some of the ongoing efforts related to this threat.

Technical sessions that assemble experts at the IAGLR annual meeting to refine understanding of this threat and promote the exchange of information and data from different parts of the Great Lakes and other large lakes could also be productive. This topic is also widely discussed at ASLO conferences as well, bringing a global perspective to this issue. This would leverage existing forums where many experts are already assembled in a typical year.

4.3 Case Study 2: Climate Change Impacts on Agriculture and Aquatic Species

Climate change is a stressor with many impacts, including changes to agricultural practices and in-lake biological communities. A representation of the placement of this threat on the four cardinal threat axes is shown in Figure 5. Because of the causative relationship between changes to agricultural practices and changes in biological communities, the focus here is set on agricultural changes and associated impacts on streams and river mouth areas. A focus on climate-driven agricultural changes may provide earlier warnings and opportunities to undertake better pre-emptive rather than reactive mitigative actions. Causative relationships between agricultural changes and aquatic biological changes are not well-characterized. Better sharing of crop and practice data and analysis of impacts by non-agronomists will promote understanding of causative relationships, leading to the identification of feasible actions. Changes in urbanization and silviculture will also be induced by climate change but are not addressed in detail in this case study. GLEWS can leverage extant tributary and lake physicochemical monitoring data and programs, as well as biological datasets (Tables 7 and 8).

Lake Superior - likely the most-rapidly changing of the Great Lakes – as well as the northern parts of Lake Michigan and Lake Huron, illustrate some of the difficulties in implementation of an appropriate EWS. Agriculture is an emerging stressor that is currently limited in the northern forested parts of the Basin at present, but both the northern upper lake areas and their basins are not monitored sufficiently to support the integrated assessment of agricultural and biological changes necessary to identify and track linked changes at high resolution. Increased vulnerability to existing invasives (e.g., dreissenid mussels) or new invasive aquatic organisms arriving through expanded port and shipping activities may be difficult to identify and mitigate with current monitoring as lake waters warm up and chemistry changes.

Table 7. Summary of Early Warning Technical Elements for the Climate Change Stressor.

Drivers	Foresight	Risk Knowledge and Understanding	Detection Mechanisms	Analysis	Action Trigger
Changes in temperature and precipitation patterns change agricultural extent, crops, and practices with downstream implications for tributary and lake health	Monitor and predict changes in agricultural land use and usage of fertilizer and chemicals while linking to tributary and lake ecosystem changes.	Develop understanding of impacts of agricultural land use and practice changes on key tributary and lake ecosystem indicators	Track changes in agricultural land use (area, irrigation, fertilizer) and linked tributary and lake ecosystem health indicators such as loadings and biological community.	Determine baseline conditions (current land use, crops, practices, etc.) and monitor changes to establish trends.	Based on empirical data or model simulations, establish thresholds for rate of change or total magnitude of indicators of extent of agricultural practice.

Table 8. Summary of Early Warning Governance Elements for the Climate Change Stressor.

Subject Matter Experts	Lead Agencies and Organizations	Lead Programs	Frequency of Review	Internal IJC Actions	External Communications
Identify land use and planning researchers engaged with changes in anthropogenic land uses and experts in tributary and lake ecosystem health indicators	USDA, AAFC, OMAFRA, state agencies, NOAA	AAFC Agricultural Climate Solutions Program, U.S. Global Change Research Program, USDA climate-smart farming programs, NOAA GLISA	Annual review of status with respect to thresholds; annual review of ongoing research into linkages between ag changes and tributary/lake ecosystem health.	Report triennially to technical staff and WQB; elevate to Commissioners as appropriate	Report status in TAP, inform management agencies if specific actions can be identified to achieve desired state or protect sensitive watersheds and receiving waters

4.3.1 Case Topic Overview

Issue Characterization. Climate change is a known stressor. Projected changes in the Great Lakes region by 2100 include increases of 3.3° to 6.1° C in average air temperature and likely continued increase in total annual precipitation, though precipitation projections vary between models, particularly on a seasonal basis (GLISA, 2023) and from east to west across the Basin. These changes will affect hydrology, tributary loadings, and lake thermal regimes and habitat (Figure 6; Anderson et al., 2021; Austin and Colman, 2008).

Rationale for Selection. Two different climate change impacts were identified, prioritized, and selected by workshop participants and the contractor team amongst many candidates.

- **Direct changes in the biological communities** within the Great Lakes will likely be driven by climate change-induced alterations to land use, hydrology, loadings, and lake thermal regimes. For example, warmer air temperatures will change some winter precipitation to rain (Champagne et al., 2019) and reduce ice cover, leading in turn to warmer water temperatures, while warmer tributary temperatures will also contribute to warmer water temperatures. These changes in tributary temperature will be accompanied by new flow and loading regimes reflecting changes in frequency and intensity of hydrology and water quality events. At the same time, stratification and hypoxia are likely to increase and occur earlier in the season, stressing productivity (Anderson et al., 2021), and competing species better adapted to warmer temperatures may outcompete "native" species. The increased variability in lake level fluctuations may affect the region's wetlands in the same manner as shifts in forest species abundance, ranges, and diversity that are already occurring.

- **Indirect changes in biological communities because of changes in agricultural practices** are a logical response by the producer and forestry/silviculture community to changes in temperature and precipitation, with warmer-condition crops migrating northwards and displacing previous crops. This may be accompanied by a general expansion northwards of cropland, except as limited by soil types). Cranberries, wild rice, grapes, and fruit orchards may be lost, while new crops such as ginseng will be seen. For existing crops, there will be changes in timing (and seed) that reflect new precipitation patterns and changes in growing season, and accompanying changes in soil and water management (irrigation and tile drainage), pesticides and herbicides usage, and conservation practices. Beyond traditional crops, shifts in forestry and silviculture practices and management are expected as well.

  These changes will affect timing and nature of sediment, nutrient, and pesticide and herbicide loads on top of climate-induced changes in tributary temperature, flow timing, and volume.

Further discussion between the contractor team and consulting experts Diep, Selzer, and Sowa **led to the selection of agricultural changes as the primary focus** for this case study (Figure 6). This selection reflects the relationship between agricultural impacts as a proximate response to climate change and in-lake biological impacts as an ultimate response integrating multiple aspects of climate change, including changes to tributary loadings attributable to climate change-induced changes in agricultural practices. Focusing on the proximate response may also provide insights leading to earlier warnings that, in turn, can support better mitigative or preventative actions.

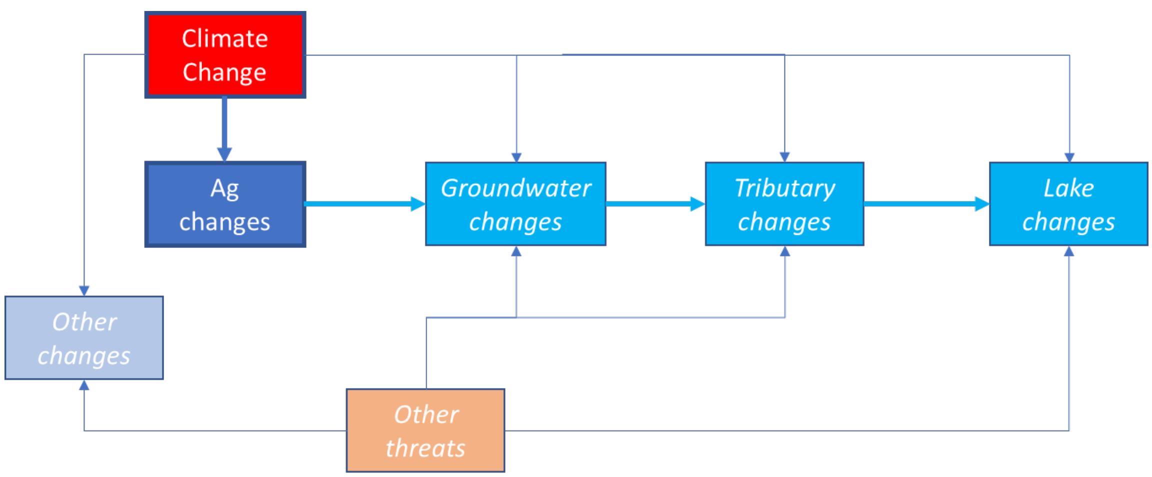


Figure 6. Climate change directly impacts both agriculture and the Great Lakes; direct changes to agriculture also impact tributaries and the lakes.

The discussion also noted that changes in agricultural practices are just some of the many ways that climate change affects human behaviors; other behaviors with proxy effects on the biological community include forest composition management and human population distribution. Expansion of the early warning system to monitor, understand, and act additionally upon forest and urban changes and development is conceptually straightforward and a desirable goal.

Changes in the biological communities within the Great Lakes are also considered in this case study in brief with the recognition that monitoring, understanding, and acting upon such changes will have commonalities with changes caused by other stressors.

4.3.2 Current Early Warning Mechanisms

Monitoring, Tracking and Decision-making Processes

Agriculture. A high-level overview of US agriculture may be supported by the USGS NLCD and USDA CDL land cover datasets, which are updated triennially (NLCD) and annually (CDL). Cropland and forestry/silviculture area and practices are monitored in more detail in the US by state agencies and by the USDA, while AAFC (Federal) and OMAFRA (Provincial) provide detail in Canada. Wild rice and other select crops covered by traditional ecological knowledge provide a useful corroborative complement to these activities.

Other agencies, including USGS, USEPA, ECCC, MECP, and state agencies provide indirect feedback on agricultural impacts through tributary loading programs and physicochemical lake monitoring. There is not yet a preferred flow of monitoring information to any authoritative party for tracking of trends, nor a recognized set of actions or actors for preventive or mitigative steps, though the REAP project (Zacharda, 2020) provides some insight into the effectiveness for water quality of long-term changes in voluntary on-farm decision-making.

Biology. Biological conditions are reasonably well-monitored across the Great Lakes basin by Indigenous agencies, USFWS, DFO, USGS, and state/provincial agencies. However, Lake Superior - which is possibly at greatest risk - is under-monitored. Deep lake and ice cover changes are well documented in Lake Superior by the Large Lakes Observatory in Minnesota and NOAA-GLERL (Mason et al., 2016), and the fish community is fairly well understood – though warming-induced migration of cold-water fish further offshore is likely to lead to future biases. Benthic community data are sparse, especially nearshore, with the Coastal Wetland Monitoring Program monitors intensively on a sparse 5-year cycle. Traditional ecological knowledge may again be of value.

Gaps and Unmet Needs

Agriculture. Improved characterization of trends and understanding of connections to tributary/ lake impacts are needed, including better access to and sharing of practices and crops/forestry and silviculture (and changes therein). Trends in the area under cultivation, cropping, forestry and silviculture extent, fertilization/pesticide/herbicide application areas, and prevalence of irrigation and tile drainage will require additional data collection, while improving understanding of connections between agricultural land use and impacts to tributaries and the Great Lakes will make identification of possible mitigative actions easier. Similarly, detailed characterization of forestry, silviculture, and agricultural practices is insufficient, with inadequate detail or extent for data already being collected, and new types of data likely to be needed

Biology. There are opportunities for research, such as hypothesizing and monitoring for specific shifts induced by climate change, and for improved monitoring, especially in water and forestry/silviculture land-use changes.

4.3.3 Literature Search Outcomes

Thermal regime shifts – such as shortened winter seasons, higher subsurface temperatures and earlier stratification, as seen in Lake Michigan, will impact surface freshwater ecosystems (Anderson et al., 2021).

Changes in anthropogenic uses of the land surface associated with growing urban populations and high agricultural production in Southern Ontario will combine with new precipitation and temperature patterns to change the delivery of nutrients to the lower Great Lakes (Eimers et al., 2020). Similarly, water, sediment and nutrient yields modeled for four Lake Erie watersheds show greater increases associated with more pronounced climate changes, perhaps suggesting a tipping point (Bosch et al., 2014; Verma et al., 2015). However, Lake Erie nutrient runoff could be lower due to increased evapotranspiration and decreased snowfall (Kalcic et al., 2019; Kujawara et al., 2020).

On a national scale, climate change is expected by USDA to lower corn, soy and wheat production. (Crane-Droesch et al., 2019), although adaptive crop migration has globally mitigated the impacts on cereal crops of high-temperature exposure (Sloat et al., 2020). In particular, corn and soybean cultivation are considered likely to shift northwards in the Great Lakes region and irrigation needs to increase (Wuebbles et al., 2019). Climate change impacts may be exacerbated by existing long-term issues, such as soil degradation and groundwater depletion (FAO, 2017). In situ adaptation is also taking place, often through changes in agronomic practices or cultivar selection. USDA (2021) has produced a new national plan for climate adaptation and resilience. Forest composition and silviculture are also expected to shift, with birch/aspen and spruce moving north, and replacement by hardwoods (Duveneck et al., 2014).

Efficient water use and balancing yield and sustainability (choosing to maintain soil health for the long term) should be part of future agricultural practices in our time of climate change, which also impact soil quality, fisheries, biodiversity and more (FAO, 2018). Digital agriculture is making fine-scale and more sustainable management of agricultural practices possible and adoption is rapid (Green et al., 2021).

Mahdiyan et al. (2021) evaluated water quality time-series data for at least 20 years from 36 lakes in Ontario and Wisconsin sampled between 1976 and 2016, and found that precipitation, air temperature, and morphology explained 73.1% of the variation in water quality trends for the Great Lakes.

4.4 Case Study 3: Introduction and Spread of Fish Pathogens

Fish pathogens are microorganisms (e.g., bacteria, viruses) that can infect fish to cause sickness and death. Disease transfer between fish can occur with direct contact as well as through localized water transfer. Fish die-offs caused by pathogens can occur in relatively confined environments such as hatcheries, aquaculture facilities, as well as net-pens in lakes. Die-offs may also occur in wild populations in lakes and streams, although stresses from other factors (e.g., low DO, thermal upwellings, energy expenditure from spawning) may make them more susceptible to the effects of disease. Fish pathogens have always been present in the Great Lakes to a certain extent, as elsewhere, but anthropogenic activities (e.g., boat ballast discharges, degraded ecosystems, climate change) may accelerate the introduction of new pathogens to the ecosystem. Increased instances of currently known pathogens, and the very real potential for future pathogen introductions, have the potential to significantly disrupt the Great Lakes ecosystem, both in the water and on land where birds/mammals utilize fish as a food source. Hence the topic is highly relevant to the prospective structure and operation of GLEWS (Figure 7, Tables 9 and 10). The Great Lakes Fishery Commission Fish Health Committee (GLFCFHC) presently coordinates efforts between the US and Canada (including states and provinces) concerning reporting fish pathogen events and communication between the government entities. It is recommended that the 2014 Program Model of the GLFCFHC be updated and that one or more professional staff run the fish pathogen GLEWS. While monitoring should continue to occur at key locations (hatcheries, aquaculture facilities, ballast release areas), increased efforts and education should also be focused on commercial/recreational fisheries and supporting industries (e.g., live hauling of baitfish and fish for private lakes or food).

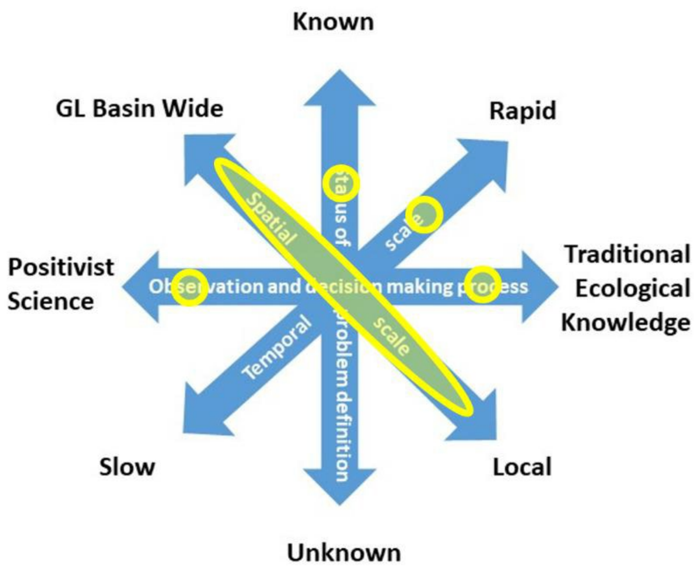


Figure 7. Placement of fish pathogens on the four cardinal threat categorization axes based on professional judgment, indicated by yellow circles or the ellipse. As with climate change, there are two circles on the Positivist-TEK axis, depicting placement on both halves of the axis but disconnection between the two bodies of knowledge and communities of practice.

Table 9. Summary of Early Warning Technical Elements for the Fish Pathogen Stressor.

Drivers	Foresight	Risk Knowledge and Understanding	Detection Mechanisms	Analysis	Action Trigger
Localized outbreaks of new pathogens that can affect the health of captive and wild fish populations that may enter or already exist in the Great Lakes; threat to commercial and recreational fishing industry.	Review existing research, modeling, and monitoring outcomes (local and basin-wide) to determine threats and stressors. Assess the vulnerability (e.g., monitoring of fish health condition) of potentially affected fish.	Intensity of vectors and potential for introduction of new pathogens is high. Risk-related knowledge is primarily focused at the local level due to outbreaks. There also is a risk of inter-lake transfer of pathogens through human actions, flowing water, or swimming fish. Coordination of risk assessment across the basin (or at least between connected lakes) is important	Monitoring of major sources and vectors of new pathogens, including captive and wild fish populations, water/fish/bait transfers; federal agency modeling/ monitoring as well as local scale (point source) sampling.	Enhance understanding needed of when pathogens from major sources and vectors are most likely to infect fish and how the potential for spread can be minimized.	At local level, presence of current outbreaks and potential for spread. At basin-wide level, communication regarding transport of pathogens (e.g., transportation of bait fish).

Table 10. Summary of Early Warning Governance Elements for the Fish Pathogen Stressor.

Subject Matter Experts	Lead Agencies and Organizations	Lead Programs	Frequency of Review	Internal IJC Actions	External Communications
Identify lead and supporting fish pathogen experts in the Great Lakes and elsewhere	Members of the Great Lakes Fishery Commission especially their Fish Health Committee; national/state/ local management agencies; aquaculture facilities	At basin-wide level: GLEC because the issue goes beyond habitats and species to include ballast water, climate, ground-water (potentially)	Annual review of basin-wide research, modeling and monitoring programs, and analysis of localized issues	Report annually to technical staff and WQB; elevate to Commissioners as appropriate	Focus on federal, state, provincial, regional and local agencies in Canada and the US (as appropriate); engagement of the Fish Health Committee; report status of analysis and geographic areas of priority concern; recommend actions that can be taken to address threats and stressors

4.4.1 Case Topic Overview

Fish pathogens have undoubtedly been present in aquatic ecosystems for millennia, but the demand for food and recreation as well as the type/frequency of vectors to transport pathogens emphasizes the importance of this issue in the Great Lakes. While fish pathogen outbreaks occur frequently in confined fisheries operations (hatcheries, aquaculture facilities), the logistics of tracking outbreaks in wild populations is more difficult; such die-offs may cause public/media reactions.

In addition to the ecological ramifications of a major fish pathogen outbreak, the "Great Lakes commercial, recreational, and tribal fisheries are collectively valued at more than $7 billion annually and support more than 75,000 jobs" (Great Lakes Fishery Commission). For example, commercial fisheries largely depend on unstocked native species (whitefish, percids, some lake trout, catfish). State hatcheries mostly focus on salmonids for sport fisheries while federal hatcheries mostly address lake trout and other species for restoration purposes. Private hatcheries generally raise bait, food, and sport fish.

There is a potential for a highly transmissible pathogen to escape confined fisheries operations and infect wild populations; the results could be devastating to the Great Lakes fishery. General public use and tourism could be negatively impacted as a result.

These pressures underscore the need to develop a monitoring and response mechanism that is not largely reactive. Ensuring that a GLEWS identifies and responds to current and emerging fish pathogen threats - before they become significant problems - is therefore a priority.

The rationale for selection of fish pathogens as a case study to inform the development and operation of GLEWS is based primarily on the following items:

1. *The foundation of a fish pathogen GLEWS already exists*: The Fisheries Health Committee of the Great Lakes Fishery Commission has been coordinating and documenting the efforts of fish pathogen monitoring for many years.

2. The Great Lakes commercial, recreational, and tribal fisheries: These are collectively valued at more than $7 billion annually and support more than 75,000 jobs. A large fish pathogen outbreak could significantly impact this industry, tourism, and local community recreation.

Fish pathogen research is quite extensive, with a significant amount occurring since the advent of molecular tools such as PCR and next-generation sequencing to genetically identify and detect specific pathogens. For this review, we will exclude laboratory-based studies that are narrow in scope. Google Scholar was used for this exercise using the search terms "Great Lakes" and "fish pathogen" in tandem. The search returned 533 results; pertinent documents are listed in the reference section for this case study. A review of the peer-reviewed articles and government reports listed at the end of this case study provided the following key findings regarding the current/prospective ecological impacts of fish pathogens in the Great Lakes:

1. The Great Lakes Fish Health Committee Model Program represents a solid foundation upon which to build a GLEWS for fish pathogens. The committee consists of national, state, and provincial government representatives that report findings of fish pathogens to one another on a biannual basis (GLFC 2021; GLFCFHC 2009, 2021; Phillips et al., 2014).
2. Technological advancements in organism genome sequencing (e.g., PCR, next-generation sequencing) offer an opportunity to quickly create markers to detect novel and emerging fish pathogens (Bayliss et al., 2017; Shoemaker et al., 2015).
3. Key locations and vectors for fish pathogens include (e.g., Fenichel et al., 2008; McEachran et al., 2021; Kim et al., 2015) fish hatcheries, aquaculture facilities, translocation of sportfish (e.g., salmonids) across the Great Lakes basin for stocking/relocation, baitfish release, and boat ballast release from cargo ships. Confined fisheries (e.g., hatcheries and aquaculture) have been experiencing fish pathogen outbreaks for decades, leading to the use of antibiotics in some situations (Mugimba et al., 2021).
4. Fish pathogens have the potential to spread quickly within a population and be transported easily to new locations by various vectors (Chapman et al., 2021; Escobar et al., 2018; Faisal et al., 2012).
5. New fish pathogens are being discovered regularly (Loch and Faisal 2015; Mohiuddin and Schellhorn 2020; Walker and Winton 2010).

4.4.2 Early Warning Approach

At present the primary Great Lakes entity for coordinating the monitoring, surveillance, and tracking of fish pathogens is the Great Lakes Fishery Commission's Fish Health Committee (GLFCFHC; see Phillips et al., 2014). The GLFCFHC is a bi-national group with government representatives from each nation and state/province. Representatives convene twice a year to report the results of their fish pathogen monitoring program. The GLFCFHC's "Model Program" cited above details the most recent protocols, and the document abstract is presented here in its entirety:

> *Fish diseases are known to have exerted unacceptably high natural mortality on some of the most-valuable fish populations in the Great Lakes, and, notwithstanding suppression efforts, their existence continues to present risks to fishery sustainability. To minimize these risks, the Great Lakes Fish Health Committee (formerly the Great Lakes Fish Disease Committee) formalized in 1985 a Great Lakes Fish Disease Control Policy and Model Program for which this document is the first update. This update is intended to further encourage the initiation of basin-wide fish health initiatives and to improve their implementation among the agencies signatory to A Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007). The specific goals of this update are to prevent the introduction of new pathogens into the Great Lakes basin, to halt the spread within the Great Lakes of established pathogens deemed destructive, and to provide a system for classifying the disease status of fish hatcheries. To accomplish these goals, fish pathogens are classified into one of three groups: emergency pathogens—those that have not been detected previously from fish in the Great Lakes basin, are known to cause epizootic events in their enzootic range, and call for containment and eradication; restricted fish pathogens—those that have been detected in fish from the Great Lakes basin, are known to cause epizootic events in hatcheries or in the wild, and call for containment and minimization of effects; and provisional fish pathogens—those under scrutiny and of concern to at least one member agency of the fish health committee, owing primarily to unknown life-history strategies and possible unwanted effects. To achieve containment of fish pathogens, standards are provided for disease testing, hatchery classification and certification, importation of fish, and transportation of fish and fish products. Implementation of these measures is expected to reduce the risks of disease outbreaks resulting from importation of new disease agents into the Great Lakes basin or from transfers of infected fish between individual Great Lakes drainages.*

4.4.3 Recommended Features – Structural

1. One or more professional staff persons with a) proficiency/special expertise in Great Lakes fish pathogen issues; b) a working knowledge of threats, and c) an understanding of management efforts presently underway and remaining gaps/unmet needs.
2. Update the GLFCFHC 2014 Model Program. This effort should not only include an update to pathogens of concern but also create mechanisms consistent with an Early Warning System to alert pertinent monitoring/management/research/aquaculture/commercial and recreational fishing stakeholders.
3. Focused monitoring efforts at locations likely to produce fish pathogen outbreaks: Great Lakes regional hatcheries, aquaculture facilities, bait shops, live haulers, and harbors where ballast releases occur.

4.4.4 Recommended Features – Operational

1. Keep abreast of other fish pathogen monitoring programs. This is especially important for locations that are overseas, particularly those that are located where cargo ships take on ballast water. Pathogens that are detected elsewhere, but not presently detected in the Great Lakes region, should be considered for monitoring in some fashion in the Great Lakes. Create a "most-wanted" list.
2. Develop a centralized clearinghouse of fish pathogen research, which is voluminous and rapidly evolving. Create a central repository of information that tracks existing/new pathogens from monitoring programs.
3. An alert system to convey localized results to government and other stakeholders.
4. Educate commercial and recreational anglers on how to identify fish that may be affected by pathogens; give them a consistent basin-wide mechanism to report and/or provide fish/tissue. A smartphone app could be developed and promoted to facilitate this effort.

4.5 Case Study 4: Shifts in Groundwater Usage and Related Ecological Impacts

Groundwater quantity and quality issues, shown in Figure 8 concerning cardinal threat axes, are receiving increased attention, yet efforts to anticipate, prevent or otherwise respond to such issues are compromised by a general lack of understanding of the resource and its relationship to the ecology of the Great Lakes Basin. Consequently, the topic is highly relevant to the prospective structure and operation of a GLEWS that advances knowledge and understanding of the resource while also identifying and responding to current and emerging issues. Based on a comprehensive literature review that elicited a series of findings relevant to GLEWS structure and function (Tables 11 and 12), it is proposed that GLEWS be staffed, in part, by one or more professional staff with a) proficiency and special expertise in Great Lakes groundwater issues; b) a working knowledge and quality/quality threats, stressors and related issues; c) an understanding of management efforts presently underway; and d) an ability to identify and facilitate addressing gaps/unmet needs. With the assistance of a proposed "Experts Panel" and the larger research and management community, GLEWS staff will advance the development and use of a single Basin-wide groundwater model; promote uniformity and consistency in the gathering, analysis, and housing of groundwater data and relevant models; coordinate with IJC's Annex 8 Subcommittee and other key entities; and prepare a periodic report that identifies current and emerging groundwater trends, issue and prospective response actions resulting from "horizon scanning" and related efforts.

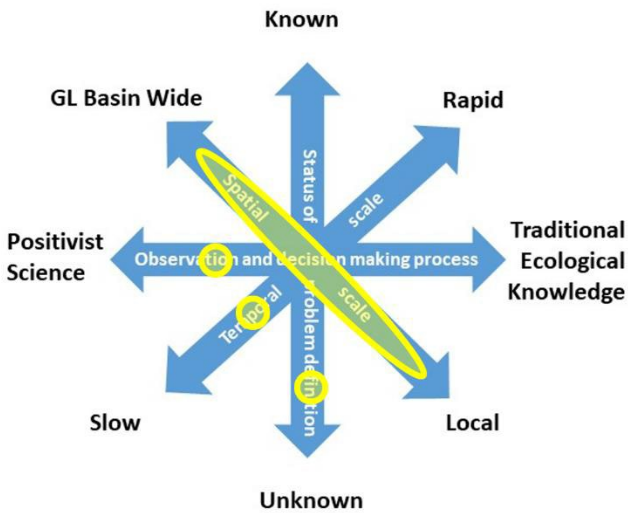


Figure 8. Placement of groundwater threats on the four cardinal threat categorization axes based on professional judgment, indicated by yellow circles or the ellipse.

Table 11. Summary of Early Warning Technical Elements for Groundwater Stressors.

Drivers	Foresight	Risk Knowledge and Understanding	Detection Mechanisms	Analysis	Action Trigger
Localized shortages and quality concerns; Annex 8 of the Great Lakes Water Quality Agreement; limited basin-wide understanding of groundwater status; heightened interest due to Great Lakes-St. Lawrence River Basin Water Resources Compact 2008), increasing conflicts, emerging contaminants in groundwater.	Review existing research, modeling and monitoring outcomes (local and basin wide) to determine threats and stressors regarding demand and quality trends.	Limited understanding at present of groundwater quantity (stocks, flows), quality, interactions, and the relationship of ground and surface waters. Risk-related knowledge is primarily focused at the local level due to quantity/ quality concerns.	Primarily local emphasis with monitoring by groundwater-dependent communities; federal agency modeling/ monitoring identifies basin-wide issues	Enhance understanding needed of quality/ quantity and surface/ groundwater interactions at basin-wide level, and identify/ prioritize local areas at risk from quantity/ quality standpoints.	At local level, anticipated exceedance of quality and quantity to preclude/ compromise residential use. At basin-wide level, modeling and monitoring that suggest prospective widespread adverse impacts of groundwater shortages and quality concerns.

Table 12. Summary of Early Warning Governance Elements for Groundwater Stressors.

Subject Matter Experts	Lead Agencies and Organizations	Lead Programs	Frequency of Review	Internal IJC Actions	External Communications
Identify lead and supporting groundwater (quantity and quality) experts in the Great Lakes and elsewhere.	US Environmental Protection Agency, US Geological Survey, Environment and Climate Change Canada, Natural Resources Canada, Food and Agriculture Canada and state/region agencies and municipalities	At basin-wide level: Annex 8 of the Great Lakes Water Quality Agreement, USGS and ECCC modeling/ monitoring programs.	Annual review of basin-wide research, modeling and monitoring programs, and analysis of localized issues	Report annually to technical staff and WQB; elevate to Commissioners as appropriate	Focus on federal, state, provincial, regional and local agencies in Canada and the US (as appropriate); report status of analysis and geographic areas of priority concern; recommend actions that can be taken to address threats and stressors

4.5.1 Case Study Overview

4.5.1.1 Issue Characterization

Groundwater resources in the binational Great Lakes Basin have historically received little attention compared to surface waters, despite their critically important role in the socio-economic and ecological health of the Basin. Recognition of this importance has increased in recent years due, in part, to challenges associated with both quality and quantity considerations. Yet, our understanding of groundwater resources remains limited. For example, the U.S. Geological Survey (USGS) recently stated that "The extent to which groundwater quantity and quality affect the overall function of the Great Lakes system is currently unknown" (Carl et al., 2021).

Increased pressure on limited groundwater resources- resulting in localized shortages (Jasechko and Perrone 2021) and contamination issues (Lall et al., 2020) - has raised the profile of groundwater, and key "unknowns" have been identified. Among many others, these include the nature of surface and groundwater interactions; the extent to which groundwater withdrawals are adversely affecting resource availability; the presence and dispersal characteristics of anthropogenic contaminants; competition among multiple users of the resource; the impacts of climate change on groundwater resources; balancing human demand with ecosystem requirements; and the absence of consistency and coordination in data gathering, analysis, and modeling activities.

This lack of understanding of groundwater resources, combined with the socio-economic and ecological importance of the resource, as well as an increase in the frequency and severity of groundwater quality and quantity issues, results in a largely reactive management mode. Complicating this is a current inability to forecast human demand with any precision and the lack of understanding of the human dimensions of groundwater usage. Ensuring that a GLEWS identifies and responds to current and emerging groundwater threats- before they become significant problems- is, therefore, a priority.

4.5.1.2 Rationale for Selection

The rationale for the selection of groundwater as a case study to inform the development and operation of GLEWS is based primarily on the following three items:

1. *Priority interest of the two Parties and the IJC:* Annex 8 of the 2012 Great Lakes Water Quality Agreement (GLWQA) calls upon the US and Canadian Governments to "contribute to the achievement of the General and Specific Objectives of this Agreement by coordinating groundwater science and management actions." (USA and Canada, 2012). Under this Annex, the two governments committed to establishing science priorities; coordinating binational activities; identifying groundwater impacts on the Great Lakes; analyzing contaminants; assessing information gaps and unmet needs; and analyzing other factors (e.g., climate change) that may affect the impact of groundwater on the Great Lakes. Toward that end, progress on Annex 8 is to be reported at Great Lakes Executive Committee meetings every six months, with accomplishments to be described in a progress report that addresses relevant and available groundwater science. Consequently, the selection of groundwater as a case study will assist the parties and the IJC in meeting Annex 8 objectives.

2. *State of knowledge regarding the ecological impacts of groundwater use and management*: The literature notes a limited understanding of ground/surface water interactions within the binational Great Lakes Basin, while also acknowledging increased ecological threats from both groundwater withdrawals and contamination issues. Hence, both the quantity and quality of groundwater resources are of growing concern, warranting consideration of "suspected" stressors or threats to the ecological integrity of the system.

   State of knowledge considerations are of heightened importance given increased pressure for surface water diversions due to contaminant concerns in groundwater-dependent communities such as Waukesha, WI (Forest 2017); agricultural withdrawals for irrigation and impacts on quantity (impact on aquifer and associated stream flows) and quality (increasing salinity and nitrates) (Steinman et al., 2022); availability and land subsidence concerns associated with large-scale groundwater withdrawals such as bottled water operations in Michigan; and (largely unknown) groundwater/surface water interactions in light of fluctuating Great Lakes water levels. There are numerous references in the literature as to the need for an enhanced understanding of such given approval and implementation of the Great Lakes Basin Water Resources Compact.

3. *Long-standing interest in groundwater analysis capabilities of an early warning system:* As early as 1991, the IJC's former Council of Great Lakes Research Managers called for the development of an early warning system through its report on Indicators of Ecosystem Health and a related paper that appeared in *Hydrobiologia* (Cairns et al., 1993). In those articles, the development of a program based upon three types of indicators (i.e., compliance, diagnostic, early warning) was proposed as the basis for a comprehensive approach to management that featured a predictive capability to identify and address threats and stressors before their adverse ecosystem impacts. Impacts of groundwater usage were explicitly identified as a relevant consideration. A binational initiative advanced through the State of the Lakes Ecosystem (SOLEC) conferences and reports featured a series of indicators of ecosystem health that advanced this interest and provided, in part, a basis for a GLEWS (U.S. Environmental Protection Agency 2013).

There presently exists no single mechanism for the monitoring, surveillance and tracking of groundwater resources on a Basin-wide level, or forecasting demand based upon a firm understanding of the human dimensions of groundwater use. The GLWQA calls for a reporting function via Annex 8 and, as such, provides a limited capability for providing a Basin-wide overview of current and emerging issues.

A primary challenge in detecting the presence and current and prospective impacts of groundwater usage on the ecological health of the Great Lakes is the highly decentralized nature of groundwater management efforts (Allee 1993). While federal agencies such as USEPA ECCC)have a role in characterizing the issue and documenting overall groundwater usage, day-to-day management responsibilities (and associated laws, policies and programs) are found primarily at the state and municipal levels. Over 8.2 million people in the binational Great Lakes basin rely upon groundwater for their drinking water, and groundwater sources account for the consumption of approximately 4.5 billion liters per day (Great Lakes Commission 2019). Yet, groundwater management can be described- at best- as a loosely organized system. Typically, issues of groundwater quantity and quality are addressed at the local level and, when multi-state concerns arise, the Great Lakes Water Resources Compact is invoked when out-of-basin diversion is proposed to address water usage needs when a groundwater-dependent community is faced with groundwater contamination issues (Great Lakes-St. Lawrence River Basin Water Resources Compact 2008).

A comprehensive analysis of groundwater science as related to the GLWQA documented the multiple parties involved in groundwater science and management at the binational (i.e., IJC); federal (i.e., ECCC, Natural Resources Canada, Agriculture and Food Canada, USEPA, US

Geological Survey); state and provincial; regional (i.e., Conservation Authorities) and municipal levels (Grannemann 2016).

4.5.2 Literature Search Outcomes

4.5.2.1 Literature Reviewed

Peer-reviewed and government documents – focusing on the management as well as technical aspects of groundwater –were reviewed in preparation for case study development. An emphasis was placed on IJC analyses to identify the evolution of the issue as it relates to Annex 8 of the GLWQA and, in general, the development of indicators for Great Lakes ecosystem health. While the literature is extensive, a carefully selected subset was reviewed to elicit the findings presented in the following section.

4.5.2.2 Findings

A review of the peer-reviewed journal articles and government reports listed in the reference section for this case study elicits the following findings regarding the current/prospective ecological impacts of groundwater usage affecting both groundwater quantity and quality:

- A centralized and standardized means of gathering, organizing, and analyzing data is needed to better understand groundwater usage and associated impacts from a Basin-wide standpoint. At present, data gathering efforts are fairly extensive and largely localized (i.e., state, provincial, municipal), generally lacking a basin-wide focus and single strategy. (Mohapatra and Mitchell 2009).

- While numerous groundwater models have been developed and are actively applied, they generally tend to focus on only a portion of the basin, use discrete data sets, and are not coordinated with other similar efforts. Key questions identified in the literature touch upon both water quantity and quality concerns: groundwater contribution to lake-level fluctuations/ water balance; nutrient loading and pathways; climate change impacts on water temperature/environmental flows; water availability, suitability, and sustainability for various uses including ecosystem function; and floodplain function and management. Consequently, additional attention is being focused on basin-wide model development (International Joint Commission, 2018; Frey et al., 2020; Xu et al., 2021).

- Leadership is an ongoing question –which agency or agencies will standardize data gathering, establish and maintain a basin-wide model, and interpret and release results? (Duda 1989 and 1994).

- There appears to be a disconnect between data gathering/modeling activities and efforts to identify and address current and anticipated problems where groundwater usage is (or may) compromise ecological health.

- Science-related gaps and unmet needs are extensive and include the need to assess regional scale discharges to surface water; the geographic distribution of known and suspected sources of contamination; improved tools for monitoring, assessment, and surveillance; research on local-scale groundwater/surface water interaction; the role of groundwater in affecting aquatic habitat; and the impacts of urban development on groundwater quantity and quality (Grannemann and Von Stempvoort, eds., 2016).

- There is an insufficient understanding of ground/surface water interactions at present; this limits the ability to fully understand and detect groundwater influences that may compromise the ecological health of the Great Lakes Basin (Kornelson and Coulibaly, 2014).

- Groundwater plays a critical role in sustaining ecosystems and adapting to climate variability and change. For this reason, the strategic importance of groundwater is increasing and, as a result, a need exists to better understand the relationship between groundwater and climate. (Taylor et al., 2013).

- Effective groundwater management requires intergovernmental cooperation basin-wide, including at the subnational level, through a prospective entity like an "independent IJC Ecosystem Review Board" with fact-finding capabilities. (Alee, 1993; Duda, 1994).

- Given observed trends toward low streamflow in North America, new approaches to estimating associated statistics are needed; some have been applied to various regions of North America. (Blum et al. 2018; Christiansen et al., 2014; Cho et al., 2019).

- Water quality is a consideration given low flow scenarios and the potential impact associated with nutrient over-enrichment, particularly in the lower Great Lakes, where an acceleration of water column warming and stimulation of algal growth have been pronounced. (Choquette et al., 2019; Eimers et al., 2020; Knights et al., 2017; Safaie et al., 2021).

- Little attention is paid to groundwater in the Great Lakes basin, even though its volume is roughly equal to that contained in Lake Michigan. Relatively little is known of its quality and quality, despite its critical role in the water balance of the system. Further, increasing competition for groundwater in the coming years- as well as the effects of climate change, diversions, overuse and pollution- suggest that it can compromise the "social and economic fabric" of the region (Campana et al., 2006; Forest, 2017; Kettren, 2006; Byun and Hamlet, 2018).

  Pollutant sources of concern, in addition to those noted above, include nutrients, salts, metals, metalloids, petroleum hydrocarbons and fuel additives, chlorinated solvents and additives, radionuclides, pharmaceuticals and other emerging domestic chemicals, pathogens, chemical contaminants, septage, sludge, leaking underground storage tanks, abandoned wells, de-icing compounds, confined animal feedlot operations, and conveyance losses (International Joint Commission 1993; Grannemann and Von Stempvoort, eds. 2016; Robinson 2015).

- Indicators of ecosystem health related to groundwater can be a powerful tool for an early warning of environmental degradation, provided they are matched to management goals (Cairns et al., 1993; Council of Great Lakes Research Managers 1991).

- When the GLWQA was first signed in 1972, groundwater was not explicitly addressed, as it was perceived to be a separate consideration from surface water. (Grannemann and Von Stempvoort, eds., 2016). Later iterations of the Agreement, especially Annex 8, explicitly recognize groundwater and call for tracking and reporting mechanisms regarding groundwater usage and its impacts on water quality and quality as related to the ecological health of the Great Lakes Basin. Presently, groundwater and surface water are widely considered to be a single, integrated resource (Norman and Bakker 2004; Winter et al., 1998).

- The prospective depletion of groundwater resources via diversion and consumptive use suggests the need for policymaking based upon governance arrangements driven by sound science (Steinman et al., 2011).

4.5.3 Early Warning Approach

4.5.3.1 A. Recommended Features – Structural

"Lessons learned" from the literature review suggest the need for a GLEWS that features the following:

1. One or more professional staff persons with a) proficiency or special expertise in Great Lakes groundwater issues; b) a working knowledge of quality and quantity threats, stressors and related issues; c) an understanding of management efforts presently underway; d) familiarity with both the scientific and human dimensions of groundwater usage; and e) awareness of remaining gaps/unmet needs.
2. Development, maintenance and/or oversight of a basin-wide groundwater monitoring network and a linked model to be broadly used to identify current and emerging issues.
3. Development, maintenance and/or oversight of data management protocols to promote uniformity at the Basin-wide level.
4. Assembly of a binational "Experts Panel" on groundwater issues, to include key members of the research and management community at various levels of government and academia. The focus should be on "horizon scanning" and the annual conference of the International Association for Great Lakes Research (IAGLR) should be considered as a prospective venue.

4.5.3.2 Recommended Features –Operational

Once these structural features are in place, the functions of the GLEWS staff member(s) should be specified to include activities such as:

1. Promote the development and use of a single Basin-wide groundwater model with predictive capabilities regarding the prospective impacts of current and emerging threats and stressors.
2. Promote uniformity and consistency in groundwater data gathering/analysis and provide for broad accessibility to a repository to hold such data.
3. Promote the development and use of data gathering and modeling coordination documents that provide for the identification of/response to current and emerging groundwater threats and stressors.
4. Promote an enhanced understanding of the human dimensions of groundwater usage to improve forecasts and trend analysis.
5. Provide support services to the Experts Panel, including regularly scheduled meetings, agenda development and information sharing.
6. Maintain close communications with the IJC Annex 8 Subcommittee membership and other key entities in the conduct of all activities.
7. Prepare a report (at least annually) that identifies current and emerging groundwater trends and issues resulting from "horizon scanning" and related efforts.

4.6 Case Study 5: Contamination by Per- and Polyfluoroalkyl Substances (PFAS)

PFAS refers to a group of persistent and bioaccumulative organic pollutants that have been manufactured and widely used for decades (Interstate Technology Regulatory Council, 2020; Detroit Public TV, 2021), but their potential toxicity and widespread occurrence in the environment were not widely known until the last 5-10 years. Attention was brought to their potential human health impacts by a 2001 class-action lawsuit filed against a manufacturer based on practices and exposure related to facilities in West Virginia. Studies in the Great Lakes region have found potentially harmful concentrations of PFAS associated with airports and military installations related to PFAS in firefighting foam, as well as manufacturing facilities, landfills, wastewater treatment plants, and many other sources (Figure 9). PFAS are present in non-stick coatings, lubricants, waterproof fabrics, stain-protected fabrics, food containers, and many other products. The complexity of the class of components referred to as PFAS continues to expand and harmonized terminology and general definitions of PFAS are beginning to stabilize (Wang et al., 2021; OECD, 2018, 2021).

Great Lakes federal, state, and provincial agencies have conducted widespread PFAS sampling programs to assess conditions and to support the establishment of health advisory limits. Minnesota set the first PFAS health risk limits in the region in 2007, and USEPA set a PFAS advisory limit of 70 parts per trillion (ppt) for two compound subclasses in drinking water in 2016 (Detroit Public TV, 2021). Canada established Maximum Acceptable Concentrations of the

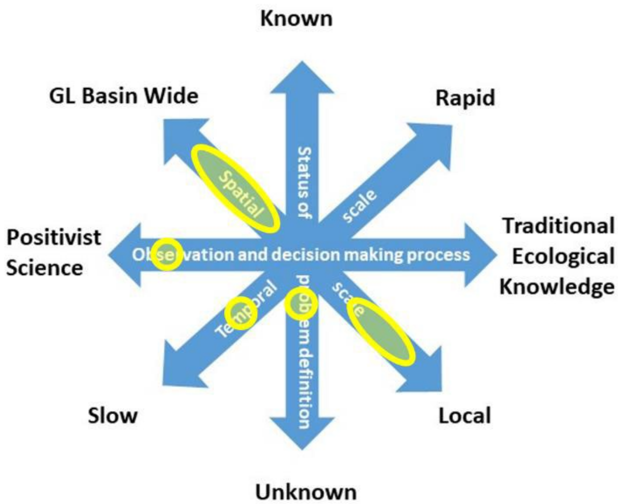


Figure 9. Placement of PFAS on the four cardinal threat categorization axes based on professional judgment, indicated by yellow circles or the ellipse. The two ellipses on the spatial scale reflect the presence of localized sources, especially in urban areas, but basin-wide impacts on fish and wildlife via bioaccumulation and potential atmospheric deposition.

PFAS classes of PFOA and PFOS of 200 and 600 ppt, respectively. The State of Michigan established the Michigan PFAS Action Response Team (MPART) in 2017, which released a report on PFAS in the state in 2018 and became a permanent body in 2019. PFAS have been detected in most environmental media in the Great Lakes, including fish, animal, and human tissues and blood (Giesy et al., 2006; Remucal, 2019). The health implications, sources, fate, trends, and effective mitigation measures of PFAS in the region are topics of ongoing research, which feeds into the GLEWS approach for the threat (Tables 13 and 14).

Table 13. Summary of Early Warning Technical Elements for the PFAS Stressors.

Drivers	Foresight	Risk Knowledge and Understanding	Detection Mechanisms	Analysis	Action Trigger
PFAS contamination in environ- mental media, food webs, and humans that can impact health	Review existing research from the Great Lakes, track related developments outside the region	Assemble existing information on occurrence and trends from monitoring programs, with a focus on recent changes	Compile analytical datasets from Great Lakes and tributaries; monitor current and future data on occurrence, sources, and loading	Determine response threshold values for concentrations, classes, and media in specific water bodies or basins	Exceedance of advisory levels in water concentra- tions, species impacts, fish and human impacts, or rates of change; inform larger GLEWS

Table 14. Summary of Early Warning Governance Elements for the PFAS Stressors.

Subject Matter Experts	Lead Agencies and Organizations	Lead Programs	Frequency of Review	Internal IJC Actions	External Communications
Identify lead and supporting experts in the Great Lakes from recent literature and agency program staff	ECCC, USEPA, CDC, USGS, state/provincial agencies and boards	Annex 3, ECCC Chemical Mgmt. Plan Monitoring and Surveillance Program, USEPA Fish Monitoring and Surveillance, USGS NAWQA	Annual and three-year status relative to thresholds (if known); review of ongoing research	Report annually to technical staff and WQB; elevate to Commissioners as appropriate	Report status to GLEC and in TAP, inform management agencies if specific actions can be identified to reduce key sources to achieve desired state

4.6.1 Case Topic Overview

PFAS investigations in the U.S. and Canada in general (Houde et al., 2006; Buck et al., 2011), and in the Great Lakes in particular, began in the early 2000s (Giesy et al., 2006; De Silva et al., 2011). Sediment and soil studies of PFAS have been used to determine spatial and temporal patterns (Myers et al., 2012; Chu and Letcher, 2017; Codling et al., 2018a, 2018b; Christensen et al., 2019). Food web studies have been performed at all trophic levels (e.g., Crimmins et al., 2014, 2018, 2019; Point et al., 2021) in at least one of the Great Lakes, with a particular focus on Lake Ontario (Martin et al., 2004; Kannan et al., 2005; Furdui et al., 2007; Houde et al., 2008;

Ren et al., 2021) and Lake Huron (Ren et al., 2022). Research has been performed to identify sources (Asher et al., 2012; Wang et al., 2014; Lin et al., 2021), highlighting urban areas and developed watersheds as primary sources, consistent with patterns for other organic pollutants. PFAS in Great lakes birds and eggs have also been examined (Letcher et al., 2015 [herring gull]; Sun et al., 2020 [peregrine falcon]; Wu et al., 2020 [eagle]). Studies of PFAS in Great Lakes fish have also been linked to human consumption impacts (Baygi et al., 2021).

4.6.2 Early Warning Approach

ECCC (2021b) has developed a draft strategy for PFAS risk management for the Great Lakes. The strategy identifies three key gaps pertaining to PFAS risk mitigation and management:

1. a lack of source information;
2. a lack of cost-effective analytical methods, routine monitoring and surveillance; and
3. a lack of data that are available in a consistent, standardized format, including environmental trends and exposure data.

Building on this strategy and companion state, provincial, and federal U.S. strategies, the GLEWS (Tables 13 and 14) should track their implementation and advance opportunities for binational coordination and information exchange, in coordination with the GLWQA Annex 3 Subcommittee. Given the activity by government agencies and researchers on the topic of PFAS contamination in the Great Lakes and elsewhere, along with evolving regulations on drinking water standards, discharge permit limits, and mitigation of sources, the understanding of the PFAS threat is more mature than for some other areas, but it may still be appropriate for IJC through GLEWS to play a leadership role in binational coordination of this rapidly evolving field. It will be essential to track and potentially steer PFAS work in the Great Lakes to promote harmonized approaches, integration across disciplines and agencies, and rapid transfer of approaches and advances across the border in both directions.

4.7 Case Study 6: Unknown Stressors

Identifying and characterizing unknown threats to water quality in the Great Lakes is intrinsically a difficult process. However, many approaches have been developed and applied to similar problems in a range of knowledge domains, including (e.g.) military intelligence, corporate strategy development, and conservation. These approaches are often grouped under the labels of foresight or future studies.

Horizon scanning and scenario planning are two commonly applied foresight approaches. Horizon scanning – systematic examination of widely-ranging information to identify emerging issues – has been famously applied annually since 2009 to identify emerging issues in global biological conservation (Sutherland et al. 2019). Various methods of scenario planning – creative thinking to envisage alternative futures – have been used in forestry and other environmental domains to identify items of concern. Both approaches can be informed by surveillance of environmental conditions and by media monitoring.

Engagement in a strategic foresight process can deliver benefits beyond the direct outcomes.

Participants build valuable networks, realize attitude changes that prepare them for addressing long-term issues and challenges through attitude changes, and help establish a foresight-friendly culture. Additionally, the process helps build the shared understanding and commitment necessary to address “wicked” problems. The success of the strategic foresight process depends heavily on effective internal communications to reach the outcome and external communication to realize understanding and action.

Horizon scanning, scenario planning, or other strategic foresight approaches for unknown stressors will require organizational infrastructure to implement effectively. The nature of the infrastructure and level of necessary funding will depend on the approach(es) selected for the GLEWS and on the scale of application.

Foresight, on an individual basis, is usually an unconscious process: we all think about the future. In an organizational context, processes and methodologies need to be explicitly put into place to support foresight. Foresight informs strategic thinking by generating options before making choices and taking action (Conway, 2006). Foresight for early warning can be informed by environmental sampling and observation, by citizen science and by media monitoring (European Commission. Directorate-General for the Environment & University of the West of England (UWE), Science Communication Unit, 2016).

Strategic foresight is commonly implemented in a six-step process: scope-setting, collection of inputs, signal analysis, interpretation, determination of actions, and implementation (Cook et al., 2014a). As shown in Table 15, there is a wide range of tools available for these steps (Cook et al., 2014b).

Horizon scanning - collecting and organizing a wide range of information to identify emerging issues - is one of the two commonly used tools for foresight, along with scenario planning – a broader method relying on creative thinking to envisage alternative futures (Cook et al., 2014).

Table 15. Some of the tools used to structure steps in a strategic foresight exercise. Adapted from (Cook, Wintle, et al., 2014).

1. ***Setting the scope:*** *determine system limits of interest and identify key problems, important actors, and exercise participants*	2. ***Collecting inputs:*** *collect and organize material from a wide range of sources about past and current trends and potential sources of change and search for early signs of change*	3. ***Analyzing signals:*** *integrate data from different sources, explore potential signals, emerging trends, drivers, interdependencies, and model potential impacts of changes*	4. ***Interpreting information:*** *expose assumptions, investigate sources of uncertainty, consider alternative futures, agree on a desired future, and explore consequences of decisions*	5. ***Determining how to act:*** *identify actions effective at promoting the desired future across a range of possible future conditions and timeframes and develop indicators of change*	6. ***Implementing the outcomes:*** *include relevant actors, implement the agreed strategic plan, and monitor signposts to determine when strategies need to be adapted*
Issues trees: used to identify the key elements of an issue that need to be considered (HSC 2014)	**Horizon scanning:** used to collect and organize a wide array of information to identify emerging issues (Glenn and Gordon 2009)	**Driver analysis:** a process to identify and group trends, determine the drivers of these trends, and the relationships between drivers (HSC 2014)	**Scenario planning:** a tool to explore alternative visions of the future based on key uncertainties and trends (Peterson et al. 2003)	**Backcasting:** used to visualize barriers to achieving a goal and the steps needed to overcome those obastacles (Dreborg 1996)	**Action research:** an iterative process for improving action designed around planning, acting, learning, and reflecting (McNiff & Whitehead 2003)
Stakeholder analysis: a process to identify stakeholders with an interest is an issue (Reed et al. 2009)	**Literature review:** summary of relevant published information	**Trend impact analysis:** projection based on past trends to infer the consequences of similar or different trajectories in key variables (Glenn & Gordon 2009)	**Causal layered analysis:** a tool to expose hidden assumptions and help create a new narrative to promote a desired change (Glenn & Gordon 2009)	**Roadmaps:** for identifying the actions required to overcome any barriers (HSC 2014)	**Adaptive management:** a process for learning about the effectiveness of management by monitoring outcomes (Walters & Holling 1990)
System maps: conceptual representation of a system, with a set of elements and the relationships between them (HSC 2014)	**Workshops:** assembles experts to identify the most significant emerging issues via an iterative scoring process (Sutherland et al. 2011)	**Statistical modeling and analysis:** using mathematical concepts to describe a system, study the effects of different components, and make predictions about system behavior and the effects of alternative actions (Glenn & Gordon 2009)	**Visioning:** participants describe the ideal scenario in detail and share and refine the vision, often exploring barriers and key actors, the resources required and the steps involved in achieving the vision (Glenn and Gordon 2009)	**Decision modeling:** alternatives are scored against multiple, weighted criteria or objectives to determine which alternative performs best across all objectives (Glenn & Gordon 2009)	**Change management:** an approach to transitioning individuals or groups to a desired state (Andrews et al. 2008)
		Cross-impact analysis: structures thinking about how one event impacts the likelihood of other events; probablilites are assigned subjectively or are underpinned by mathematical relationships (Glenn & Gordon 2009)	**Futures wheel:** a structured brainstorming tool exploring the primary, secondary, and tertiary impacts of a trend or event (Glenn & Gordon 2009)	**Risk analysis:** a process for assessing and dealing with hazards (Burgman 2001)	

Horizon scanning is distinguished by "its emphasis on "weak signals" (early indicators of potential change), comprehensive scanning of all sectors, an emphasis on external trends and developments, and the inclusion of possible wild cards (low-probability, high-impact events)" (Bengston, 2013). Domain experts are expected to provide both insight (actively scanning the present environment for understanding) and foresight; horizon scanning takes insight into the future (Duvenage, 2012). The ongoing annual horizon scan of global conservation issues (Figure 10) starting in 2009 (Sutherland et al., 2010) provides an example of a recurring process that additionally has been the subject of a retroactive review (Sutherland et al., 2019). Horizon scanning is also used in the European Union's Environmental European Union Foresight System annual cycle [*EU Environmental Foresight System (FORENV) Final Report of 2019-20 Annual Cycle*, 2021].

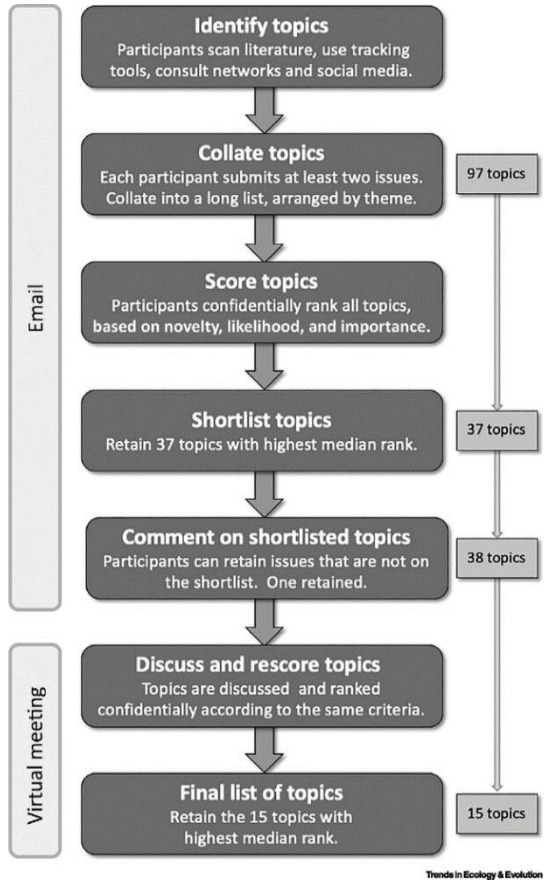


Figure 10. Horizon Scanning Process (Sutherland et al., 2021).

Scenario planning or scenario development techniques and methods are an ongoing area of study, with many approaches cataloged, categorized, and compared by Bishop et al. (2007), Kosow & Gaßner (2008), and Wodak (2014). Scenario planning can effectively bring together diverse domain expertise to address complex systems but may focus more on the product than the process; dominant participants may inadvertently impose their interests into the exercise (Wodak, 2014).

Communication of foresight study outcomes can be challenging, but effective communications between participants lead to successful exercises. In addition, the foresight exercise can yield intangible benefits, such as the creation of networks among participants, increased stakeholder commitment, preparation for addressing long-term issues and challenges through attitude changes, and establishment of a foresight-friendly culture (Nehme et al., 2012).

Foresight studies deal with problems that are "complex, interconnected, contradictory, located in an uncertain environment and embedded in landscapes that are rapidly changing." (Sardar, 2010) Effective outcomes and responses to these "wicked" problems may depend on shared understanding of the problems and shared commitment to the identified solutions. "Shared understanding does not mean we necessarily agree on the problem … Shared understanding means that the stakeholders understand each other's positions well enough to have intelligent dialogue about the different interpretations of the problem, and to exercise collective intelligence about how to solve it" (Conklin, 2006).

5 EXPERTS WORKSHOP

`

Figure 13. Workshop participants pose for a group photo (above); co-chairs, Lucinda Johnson and Michael Twiss consider comments from a participant (note poster showing GLEWS framework and a long list of potential threats posted on the wall) (left); wide view of a plenary session on Day 1 of the workshop (below).

LimnoTech
AECOM

The project included an in-person Experts Workshop to provide feedback on the draft framework from workgroup members and invited experts. Results of that workshop are summarized here. The full workshop report is included as Appendix A.

The workshop was held over two half-days in Windsor, Ontario on September 21 (PM) and September 22 (AM), 2022. In addition to IJC and contractor team staff, 17 experts participated in at least one day of the workshop, with the majority present for both days. The workshop team, composed of IJC staff and contractors, adopted a "Nominal Group Technique" that included small breakout sessions with a pre-assigned Facilitator and Recorder, and a volunteer Rapporteur to report out. The technique ensured that all members of each breakout group had an equal opportunity to speak, and that all ideas were presented and clarified prior to any debate that took place. Augmenting the breakout groups were keynote remarks and "provocateurs" (i.e., a challenge panel) to stimulate thought and discussion among workshop participants. A guest presentation by a remote speaker from Great Britain, Dr. Bill Sutherland, an expert on global-scale ecological horizon scanning, took place early on the second day of the workshop and included questions and answers following the talk. Workshop participants were generally positive in their review comments on the draft GLEWS Decision Framework. Several high-level impressions and suggestions from workshop general discussions and breakout sessions are included in the list below:

- The GLEWS operational approach described in the initial IJC Phase 1 report, presents a reasonable approach to Great Lakes threat detection, evaluation, and warning.
- Additional detail would be helpful regarding criteria to be used for the more subjective ement steps in the framework where decisions about prioritization, importance, and "implementability" would be made.
- It was noted that the GLEWS approach may vary to some degree depending upon the nature of the suspected threat (i.e., whether it is a known threat or not), and the extent to which that threat is already being monitored.
- It was emphasized that the GLEWS should build upon and actively work with other threat detection/early warning systems of relevance to the multinational Great Lakes.
- More context about the entry (upper left of diagram) and exit points (lower right of diagram) of the framework would clarify how the **GLEWS Committee** would function within existing programmatic and governance systems.
- Concerns were expressed about avoiding "analysis paralysis" in that prolonged study or cycling through feedback loops during consideration of suspected threats could delay timely action to adapt to or mitigate threats. Criteria for fast-tracking threats through "initial rapid evaluation" would clarify the bypassing path in the "Understand & Design" box.

There was some skepticism about point "B" at the end of the draft Decision Framework, described as, "Parties take appropriate action". Barriers to appropriate action included institutional cultural inertia in agencies, lack of accountability for effective action, lack of available funding and staff to act, and lack of appropriate technical resources to provide rapid and effective responses to imminent threats of an emerging nature (e.g., threats that differed substantially from oil spills, fires, or floods for which responses are well understood and resources are pre-staged). Feedback from workshop discussions was incorporated into revisions of the draft GLEWS Decision Framework and into draft recommendations for next steps to advance realization of the GLEWS.

6 DECISION FRAMEWORK

Following the approach described above, the contractor team and the Work Group steering team developed a Framework for a Great Lakes Early Warning System. The Framework was developed iteratively and the fifth and final version is described here. The GLEWS Framework is currently conceptualized as an organized and managed collection of individual threat-specific early warning systems (EWSs). The Framework is intended to address Unknown Threats and Suspected Threats and is organized into three major functional blocks: Identify & Screen, Understand & Design, and Implement & Operate (Figures 11 and 12).

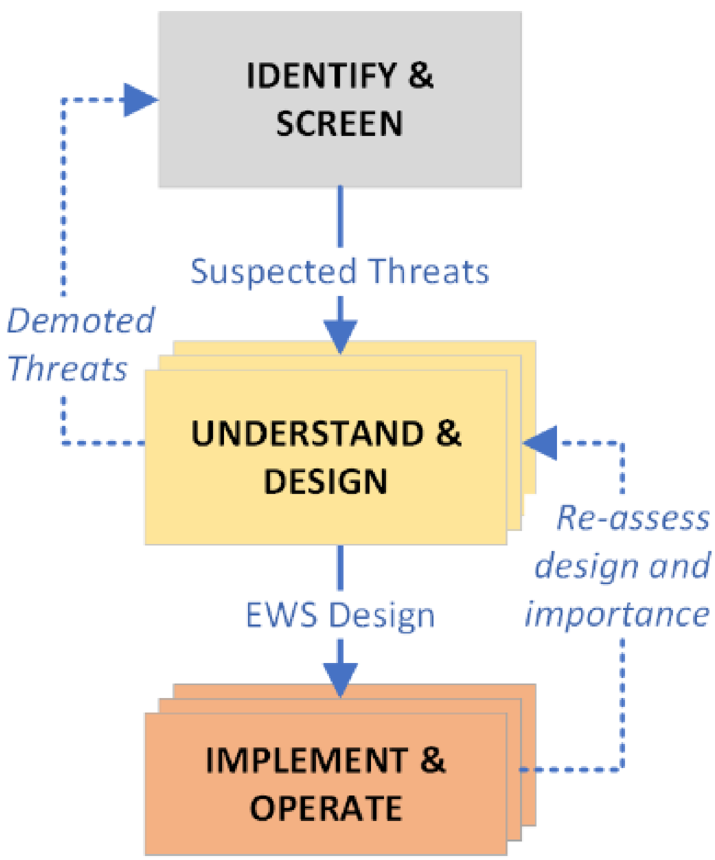


Figure 11. Schematic summary diagram of GLEWS Decision Framework.

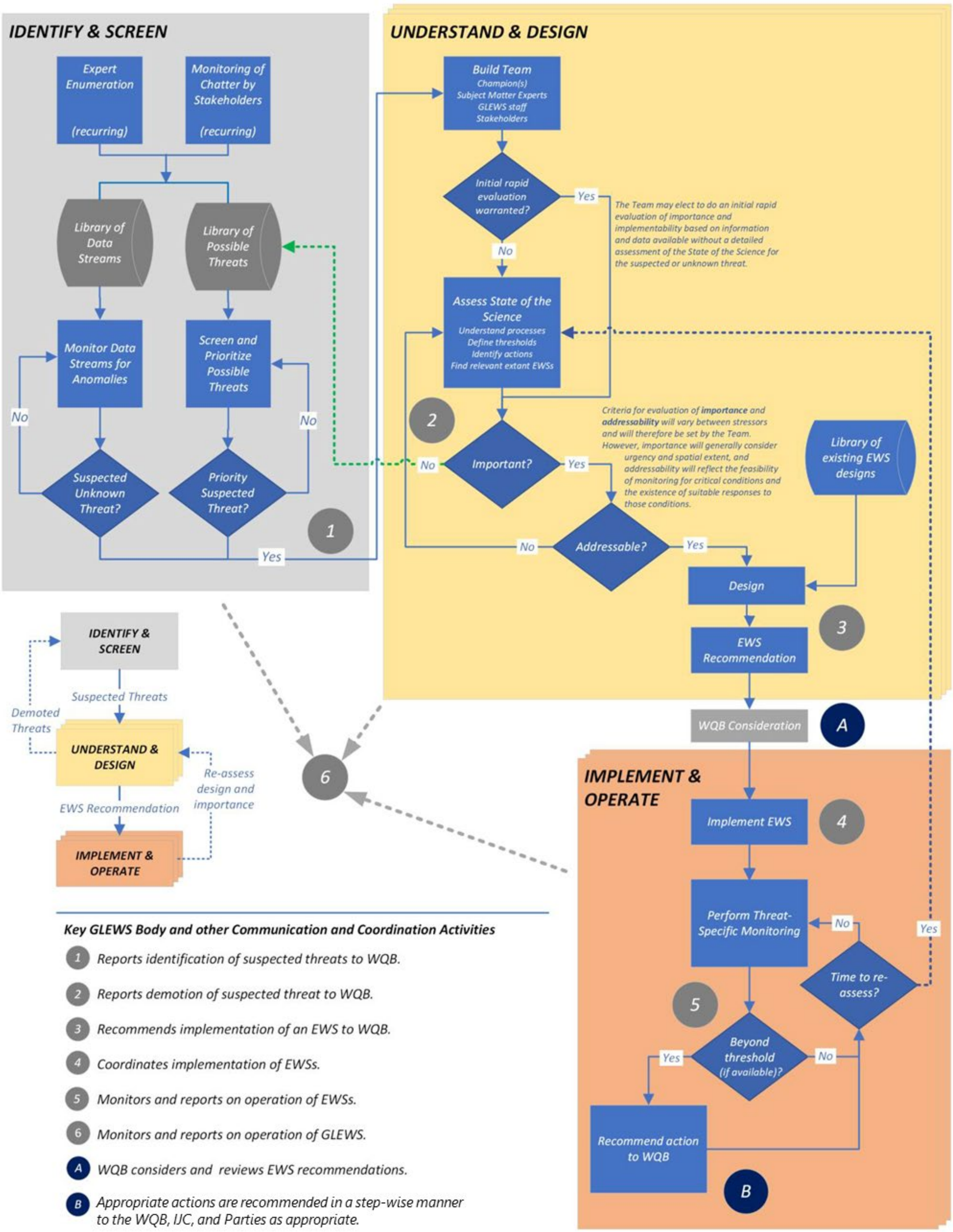


Figure 12. Detailed diagram of GLEWS Decision Framework.

The broad purposes of the three major functional blocks follows. (Note: Words highlighted in bold are defined in the glossary at the beginning of the report.)

- Identify & Screen. (1) Use expert elicitation processes and ongoing monitoring of stakeholder **chatter** to build and maintain libraries of possible threats (for screening and prioritization) and ongoing data collection efforts and data streams (for surveillance for anomalies) and (2) regularly screen data anomalies and possible threats to identify suspected threats for further examination.

- Understand & Design. Build sufficient understanding of the State of the Science for the suspected threat to (1) confirm the threat's **importance** and (2) establish a preferred approach for responding to the threat.

- Implement & Operate. Efficiently implement and operate the EWS as designed – taking full advantage of existing components and systems, and practice adaptive management by periodically revisiting the State of the Science and the confirmation of **importance** and design at appropriate intervals (e.g., quarterly or annually).

The outcome of the step is a list of suspected threats or of **data anomalies** suggesting unknown threats. Separate assessments of each threat's importance and of the **addressability** of the associated EWS in separate Understand & Design efforts; there can therefore be multiple independent Understand & Design efforts going on at a given time. The Understand & Design step will either result in the demotion of the suspected threat and its return to the Library (due to insufficient **importance**) or recommendation and furnishing of an EWS design for implementation and operation. In the Implementation & Operation step, operational monitoring for the threat will continue until reassessment of the State of the Science demonstrates that the threat's **importance** has sufficiently decreased.

Each block is described in more detail below.

6.1 Identify & Screen

In the Identify & Screen block, Experts work to formally enumerate possible threats using forecasting (horizon scans, scenario planning, reference to other localities, and similar techniques) and Delphi approaches while **stakeholders** (e.g., policy makers, emergency response managers, environmental managers, first responders, TEK practitioners from First Nations and Tribes, commercial entities, Sea Grant) less formally **monitor chatter** about threats. Both groups contribute and catalog possible threats to the **Library of Possible Threats,** whose operation and maintenance will be overseen as a recurring effort of the GLEWS enterprise.

A formal process will be undertaken periodically to screen and prioritize threats from the library and to identify **Suspected Threats**. The process will also include analogization to identify previously considered threats that are similar in nature and therefore can inform the development of understanding.

Experts and **Stakeholders** will also be used to identify useful data collection programs that provide useful **data streams** that can be monitored for anomalous results potentially tied to unknown threats to Great Lakes ecosystem health. These data streams will be incorporated into a **Library of Data Streams** (likely including relevant metadata and links to the data stream rather than the data stream itself). The data streams will be periodically subjected to review so that anomalous trends and observations can be discerned, and where results are concerning enough, recommended for deeper inspection.

This surveillance (looking for changes and trends in long-term detailed monitoring of key parameters and sentinel species) provides a non-categorical approach for identification of unknown threats. The presence of a change indicating a threat should quickly segue into identification of relevant threat categories which can then be used as a basis for literature review and expert elicitation to refine measurement and confirm the threat.

The output from this block is a list of suspected unknown threats and/or prioritized suspected threats for which increased understanding and a possible EWS are desired.

6.2 Understand & Design

The Understand & Design block will be in play for each Suspected Threat identified by the Identify & Screen step. There will likely be multiple Understand & Design instances deployed in response to delivery of a list of Suspected Threats, with each instance corresponding to one suspected threat – or occasionally multiple similar suspected threats that share characteristics.

The first action is to form a threat-specific team with a Champion, Subject Matter Experts, EWS support staff, and **stakeholders**. The Team will be responsible for promptly evaluating the importance of the threat as well as its **addressability**. The evaluation will be based on the assessed State of the Science to understand processes, define thresholds for action, identify actions (i.e., preventive, mitigative, adaptive, or reactive), and identify and leverage analogous existing early warning systems.

Following the detailed assessment, the Team will assess whether the suspected threat is important and addressable. Key questions may include whether sufficient process knowledge exists to establish thresholds for action (and detection) as well as to identify importance in terms of scope, urgency, and drivers. If the threat is not deemed sufficiently important, it can be returned to the Library; if it is not addressable, additional assessment is performed.

The Team may elect to do an initial evaluation of **importance** and **addressability** without a detailed assessment of the State of the Science due to urgency or degree of analogy to other threats. This provides an additional screening step informed by Subject Matter Experts' opinions. If the threat is deemed **important** and addressable, the Team will develop a threat-specific preliminary design document for the EWS and communicate the document to the IJC Water Quality Board along with its recommendation to implement an EWS for the threat under consideration. The design should consider the re-use of or harmonization with existing early warning systems (for example, recorded in a **Library of Existing EWS Designs)** addressing similar threats or their components, emphasize accountability and transparency, and identify the organizations that will implement and operate the EWS. The recommendation should align with SMART criteria (i.e., specific, measurable, actionable, realistic and time-bound) for goal setting, in part to address organizational latencies inherent in the multi-party management necessities for the system.

6.3 Implement & Operate

Once the need for an EWS has been confirmed and a design established and accepted by the Water Quality Board, the EWS can be implemented and operated. The original threat Team and other members of the **GLEWS Committee** will either coordinate or play a direct role in the implementation and operation of the threat-specific EWS in conjunction with governmental agencies acting upon their missions and mandates. An initial proposed size range would be 12-16 appointed individuals, who would mostly be agency staff as envisioned in the Phase 1 report. An alternative, supplemental, or associated membership could consist of a subset of WQB members, as well as other public sector, private sector, and academic Subject Matter Experts in horizon scanning. Threat-specific EWS activities will be carefully aligned and coordinated with existing complementary efforts (e.g., aquatic invasive species control, fish pathogens) and the organizations addressing them.

Once implemented, operation of the EWS will be centered on the ongoing collection of appropriate data to be compared to threshold values established in the Understanding & Design block. When measurements are beyond threshold values, warnings are issued and actions are taken.

Periodically, the detailed assessment process for evaluation of the State of the Science in the Understand & Design Block should be repeated. This will support confirmation of ongoing need and adaptation of the EWS to reflect improved understanding, or demotion of the threat and de-activation of the EWS.

6.4 Communication and Coordination

Communications between the **GLEWS Committee**, the Water Quality Board (and – as required - the IJC and the Parties) are expected to include:

- Reporting on identification of possible threats and data anomalies as suspected threats;
- Reporting on demotion (return) of suspected threats not considered important by the threat Team;

- Recommendations for establishment of an EWS;
- Coordination (with other bodies) on the implementation of an EWS.
- Reporting on EWS results (e.g., summary of monitoring activity results, including threshold crossings and actions recommended/taken) and EWS operational performance (confirmation that detection, communication, and coordination of actions are occurring as intended).
- Monitoring of and reporting on the performance of the overall GLEWS.

Communication activities are also shown on the GLEWS framework diagram (Figure 12).

7 PROJECT FINDINGS AND RECOMMENDATIONS

This project developed an analytical protocol for a GLEWS that could provide a Decision Framework to identify benchmarks and indicator thresholds of various groups of threats and stressors and, in so doing, rank and prioritize or re-prioritize them for action on an iterative or cyclic basis. Three project tasks involving information gathering and analysis (literature review, case studies, and expert workshop) were generally conducted sequentially, with the results of each informing the subsequent tasks. Different analytical approaches were considered, leading to a draft GLEWS Decision Framework. Validation of the draft Framework was conducted by its application to five case studies and review at an in-person Experts Workshop.

The set of suspected stressors and threats examined in the case studies and further evaluated in the Experts Workshop consisted of:

1. Changes in concentrations of nitrogen and other key non-phosphorus nutrients.
2. Climate change impacts on agricultural ranges and practices, and on aquatic species ranges.
3. Introduction and spread of fish pathogens.
4. Shifts in groundwater usage and related ecological impacts.
5. Occurrence and impacts of contamination by per- and polyfluoroalkyl substances (PFAS).

A sixth case study on unknown stressors was also included to expand the "suspected" examples. General GLEWS findings, conclusions, and lessons learned through completing the case studies and discussing the draft Framework and synthesis results at the Experts Workshop and with WG members include the following:

- Organizational structures, programs, and knowledge systems that exist within IJC and externally can be leveraged or adapted to implement elements of the GLEWS, including IJC advisory boards, committees of other Great Lakes-related commissions, Indigenous Knowledge systems, agency reporting systems, community science networks, and outdoor recreation groups.
- Although IJC itself does not have sufficient resources to conduct or fund the research and monitoring needed to fill critical gaps related to suspected threats, it may be able to provide staff to coordinate binational assessment activities and development of tracking and scoping documents through its boards and working groups and related strategic partnerships that can guide external organizations in conducting priority research and monitoring.
- Some threats may have both upper and lower thresholds of impacts, which complicates defining threat states and management responses; indicators, natural baselines and ranges are also not known in all cases.
- Professional societies (e.g., the International Association for Great Lakes Research [IAGLR], which has a primary focus on aquatic ecology) can play a convening role in horizon scanning and threat assessment. Some threats, however, fall outside the purview IAGLR and similar biophysically oriented scientific societies and may require engagement with other professional organizations and communities to develop detection, monitoring, and warning approaches that encompass the full range of threats to the Basin.

- In addition to guiding additional research and monitoring, initial threat assessment can lead to “warn”, “adapt”, or “watch-no further action” decisions.
- Connections between research/monitoring of suspected threats and organizations that can act on warnings need to be strengthened in many cases—such organizations do not even exist for all threats in all jurisdictions.

The resulting GLEWS Decision Framework is conceptualized as an organized and managed collection of individual threat-specific early warning systems (EWSs). The Framework is intended to address Unknown Threats and Suspected Threats and is organized into three major functional blocks: Identify & Screen, Understand & Design, and Implement & Operate.

Recommendations for Implementation

1. Develop terms of reference for a provisional GLEWS Committee that will exist as a standing subcommittee or workgroup under the Water Quality Board, including its composition, membership, duration of terms, provisions for outside expert composition, meeting frequency and format, IJC staff support, data management framework, and reporting structure. An initial proposed size range would be 12-16 appointed individuals, composed primarily of agency staff and supplemented by WQB members, including public sector, private sector, and academic subject matter experts in horizon scanning.
2. Coordinate the establishment of the GLEWS Committee with IJC Commissioners, Indigenous groups, IJC staff and boards, federal agencies, other commissions, states and provinces, Tribes and First Nations, IAGLR, and other key stakeholder groups.
3. Develop scoping documents for the GLEWS technical infrastructure for decision support including data, models, tracking of published research, and communications subsystems.
4. Undertake a pilot project to implement GLEWS following development of the terms of reference and refinement of structural and operational characteristics based on interview, survey, and workshop outcomes.

8 REFERENCES

Allan, J.D., McIntyre, P.B., Smith, S.D., Halpern, B.S., Boyer, G.L., Buchsbaum, A., Burton Jr, G.A., Campbell, L.M., Chadderton, W.L., Ciborowski, J.J. and Doran, P.J., 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. Proceedings of the National Academy of Sciences, 110(1): 372-377. https://doi.org/10.1073/pnas.121384111

Allee, D.J., 1993. Subnational Governance and the International Joint Commission: Local Management of US and Canadian Boundary Waters. Natural Resources Journal, 33(1), pp. 133-157.

Almack, K., Dunlop, E.S., Lauzon, R., Nadjiwon, S. and Duncan, A.T., 2022 (*in press*). Building trust through the Two-Eyed Seeing approach to joint fisheries research. Journal of Great Lakes Research.

Anderson, E.J., Stow, C.A., Gronewold, A.D., Mason, L.A., McCormick, M.J., Qian, S.S., Ruberg, S.A., Beadle, K., Constant, S.A. and Hawley, N., 2021. Seasonal overturn and stratification changes drive deep-water warming in one of Earth's largest lakes. Nature Communications, 12(1), pp.1-9. https://doi.org/10.1038/s41467-021-21971-1

Asher, B.J., Wang, Y., De Silva, A.O., Backus, S., Muir, D.C.G., Wong, C.S., Martin, J.W., 2012. Enantiospecific Perfluorooctane Sulfonate (PFOS) analysis reveals evidence for the source contribution of PFOS-precursors to the Lake Ontario food web. Environ. Sci. Technol. 46, 7653-7660. https://doi.org/10.1021/es301160r

Austin, J. and Colman, S., 2008. A century of temperature variability in Lake Superior. Limnology and Oceanography, 53(6), pp.2724-2730.

Austin, J.A., and Colman, S.M., 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback loop. Geophysical Research Letters, 34(6), L06604. https://doi.org/10.1029/2006GL029021

Baker, D.B., Confesor, R., Ewing, D.E., Johnson, L.T., Kramer, J.W. and Merryfield, B.J., 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: The importance of bioavailability. Journal of Great Lakes Research, 40(3), pp.502-517.

Baldwin, A.K., Corsi, S.R., Stefaniak, O.M., Loken, L.C., Villeneuve, D.L., Ankley, G.T., Blackwell, B.R., Lenaker, P.L., Nott, M.A. and Mills, M.A., 2022. Risk-based prioritization of organic chemicals and locations of ecological concern in sediment from Great Lakes tributaries. Environmental Toxicology and Chemistry, 41(4): 1016-1041. https://doi.org/10.1002/etc.5286

Baskaran, M., and Bratton, J., 2013. Investigating Human-Induced Changes of Elemental Cycles in the Great Lakes: Recent Changes in the Biogeochemistry of the Great Lakes System; Detroit, Michigan, 11-13 March 2013.

Baygi, S.F., Fernando, S., Hopke, P.K., Holsen, T.M. and Crimmins, B.S., 2021. Nontargeted Discovery of Novel Contaminants in the Great Lakes Region: A Comparison of Fish Fillets and Fish Consumers. Environmental Science & Technology, 55(6), pp.3765-3774.

Bayliss, S., D. Verner-Jeffreys, K. Bartie, D. Aanensen, S. Sheppard, A. Adams, and E. Feil, 2017. The promise of whole genome pathogen sequencing for the molecular epidemiology of emerging aquaculture pathogens. Front. Microbiol. (online).

Bengston, D. N., 2013. United States Department of Agriculture Forest Service General Technical Report NRS-121 Northern Research Station September 2013 Horizon Scanning for Environmental Foresight: A Review of Issues and Approaches. http://www.nrs.fs.fed.us/

Bishop, P., Hines, A., & Collins, T., 2007. The current state of scenario development: An overview of techniques. In foresight (Vol. 9, Issue 1, pp. 5-25). https://doi.org/10.1108/14636680710727516

Blum, A.G., Archfield, S.A., Hirsch, R.M., Vogel, R.M., Kiang, J.E. and Dudley, R.W., 2019. Updating estimates of low-streamflow statistics to account for possible trends. Hydrological Sciences Journal, 64(12), pp.1404-1414.

Bocaniov, S.A., Lamb, K.G., Liu, W., Rao, Y.R. and Smith, R.E., 2020. High sensitivity of lake hypoxia to air temperatures, winds, and nutrient loading: Insights from a 3-D lake model. Water Resources Research, 56(12): e2019WR027040. https://doi.org/10.1029/2019WR027040

Bosch, Nathan S., Mary Anne Evans, Donald Scavia, and J. David Allan, 2014. Interacting Effects of Climate Change and Agricultural BMPs on Nutrient Runoff Entering Lake Erie. Journal of Great Lakes Research 40 (3): 581-89. https://doi.org/10.1016/j.jglr.2014.04.011

Buck, Robert C, James Franklin, Urs Berger, Jason M Conder, Ian T Cousins, Pim de Voogt, Allan Astrup Jensen, Kurunthachalam Kannan, Scott A Mabury, and Stefan PJ van Leeuwen, 2011. 'Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins', Integrated Environmental Assessment and Management, 7: 513-41.

Byun, K. and Hamlet, A.F., 2018. Projected changes in future climate over the Midwest and Great Lakes region using downscaled CMIP5 ensembles. International Journal of Climatology, 38, pp. e531-e553.

Cairns, J., McCormick., P.V., and B.R. Niederlehner. 1993. A Proposed Framework for Developing Indicators of Ecosystem Health. Hydrobiologia 263: l-44.

Campana, M.E., Muir, A.M. and G.T. Kline, 2006. Dynamics of Transboundary Great Lakes Management: Lessons Learned for North America. Publication No. WRP-16. 29 p.

Carl, L.M., Hortness, J.E., and Strach, R.M., 2021. U.S. Geological Survey Great Lakes Science Forum - Summary of Remaining Data and Science Needs and Next Steps: U.S. Geological Survey Open-File Report 2021-1096, 4 p.

Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R., Brock, W.A., Cline, T., Coloso, J., Hodgson, J.R., Kitchell, J.F., Seekell, D.A. and Smith, L., 2011. Early warnings of regime shifts: A whole-ecosystem experiment. Science, 332(6033): 1079-1082.

Carrick, H.J. and Lowe, R.L., 2007. Nutrient limitation of benthic algae in Lake Michigan: the role of silica. Journal of Phycology, 43(2), pp.228-234.

Chaffin, J.D., Davis, T.W., Smith, D.J., Baer, M.M. and Dick, G.J., 2018. Interactions between nitrogen form, loading rate, and light intensity on Microcystis and Planktothrix growth and microcystin production. Harmful Algae, 73, pp.84-97.

Champagne, Olivier, Altaf Arain, Martin Leduc, Paulin Coulibaly, and Shawn McKenzie, 2019. Future Shift in Winter Streamflow Modulated by Internal Variability of Climate in Southern Ontario. Hydrology and Earth System Sciences Discussions, 1-30. https://doi.org/10.5194/hess-2019-204

Chapman, J., L. Kelly, A. Teffer, K. Miller, and S. Cooke, 2021. Disease ecology of wild fish: opportunities and challenges for linking infection metrics with behavior, condition, and survival. Can. J. Fish. Aquat. Sci. 78: 995-1007.

Cho, E., Jacobs, J.M., Jia, X. and Kraatz, S., 2019. Identifying subsurface drainage using satellite Big Data and machine learning via Google Earth Engine. Water Resources Research, 55(10), pp. 8028-8045.

Choquette, A.F., Hirsch, R.M., Murphy, J.C., Johnson, L.T. and Confesor Jr, R.B., 2019. Tracking changes in nutrient delivery to western Lake Erie: Approaches to compensate for variability and trends in streamflow. Journal of Great Lakes Research, 45(1), pp. 21-39.

Christensen, E.R., Zhang, R., Codling, G., Giesy, J.P. and Li, A., 2019. Poly-and per-fluoroalkyl compounds in sediments of the Laurentian Great Lakes: Loadings, temporal trends, and sources determined by positive matrix factorization. Environmental Pollution, 255, p.113166.

Christiansen, D.E., Walker, J.F. and Hunt, R.J., 2014. Basin-scale simulation of current and potential climate changed hydrologic conditions in the Lake Michigan Basin, United States. US Department of the Interior, US Geological Survey, Scientific Investigations Report 2014-5175.

Chu, S. and Letcher, R.J., 2017. Side-chain fluorinated polymer surfactants in aquatic sediment and biosolid-augmented agricultural soil from the Great Lakes basin of North America. Science of the Total Environment, 607, pp.262-270.

Codling, G., Hosseini, S., Corcoran, M.B., Bonina, S., Lin, T., Li, A., Sturchio, N.C., Rockne, K.J., Ji, K., Peng, H., Giesy, J.P., 2018a. Current and historical concentrations of poly and perfluorinated compounds in sediments of the northern Great Lakes - Superior, Huron, and Michigan. Environmental Pollution 236, 373-381. https://doi.org/10.1016/j.envpol.2018.01.065

Codling, G., Sturchio, N.C., Rockne, K.J., Li, A., Peng, H., Tse, T.J., Jones, P.D., Giesy, J.P., 2018b. Spatial and temporal trends in poly- and per-fluorinated compounds in the Laurentian Great Lakes Erie, Ontario and St. Clair. Environmental Pollution 237, 396-405. https://doi.org/10.1016/j.envpol.2018.02.013

Conklin, J., 2006. Social Complexity Wicked Problems. http://www.cognexus.org

Conway, M., 2006. An Overview of Foresight Methodologies.

Cook, C. N., Inayatullah, S., Burgman, M. A., Sutherland, W. J., & Wintle, B. A., 2014. Strategic foresight: How planning for the unpredictable can improve environmental decision-making. In Trends in Ecology and Evolution (Vol. 29, Issue 9, pp. 531-541). Elsevier Ltd. https://doi.org/10.1016/j.tree.2014.07.005

Cook, C. N., Wintle, B. C., Aldrich, S. C., & Wintle, B. A., 2014. Using Strategic Foresight to Assess Conservation Opportunity. Conservation Biology, 28(6), 1474-1483. https://doi.org/10.1111/cobi.12404

Council of Great Lakes Research Managers, 1991. A Proposed Framework for Developing Indicators of Ecosystem Health. ISBN 1-895086-29-2. July 1991.

Crane-Droesch, Andrew, Elizabeth Marshall, Stephanie Rosch, Anne Riddle, Joseph Cooper, and Steven Wallander, 2019. Climate Change and Agricultural Risk Management Into the 21st Century. www.ers.usda.gov.

Crimmins, B., H. McCarty, S. Fernando, M. Milligan, J. Pagano, T. Holsen, P. Hopke, 2018. Commentary: Integrating Non-Targeted and Targeted Screening in Great Lakes Fish Monitoring Programs. Journal of Great Lakes Research, 44, 1127-1135.

Crimmins, B.S., Holsen T.M., 2019. Non-Targeted Screening in Environmental Monitoring Programs. In: Woods A., Darie C. (eds) Advancements of Mass Spectrometry in Biomedical Research. Advances in Experimental Medicine and Biology, 1140. Springer, Cham. https://doi.org/10.1007/978-3-030-15950-4_43

Crimmins, B.S., Xia, X., Hopke, P.K., Holsen, T.M., 2014. A Targeted/Non-Targeted Method for Perfluoroalkyl Carboxylic Acid and Sulfonate Analysis in Whole Fish Using Quadrupole Time of Flight Mass Spectrometry and MSe. Analytical and Bioanalytical Chemistry, 406, 1471-1480.

Danz, N.P., Regal, R.R., Niemi, G.J., Brady, V.J., Hollenhorst, T., Johnson, L.B., Host, G.E., Hanowski, J.M., Johnston, C.A., Brown, T. and Kingston, J., 2005. Environmentally stratified sampling design for the development of Great Lakes environmental indicators. Environmental Monitoring and Assessment, 102: 41-65.

Davidson, A., Fusaro, A., Sturtevant, R.A. and Kashian, D.R., 2016. Development of a risk assessment framework to predict invasive species establishment for multiple taxonomic groups and vectors of introduction. Management of Biological Invasions, 8(1): 25-36. https://doi.org/10.3391/mbi.2017.8.1.03

De Silva, A.O., Spencer, C., Scott, B.F., Backus, S., Muir, D.C.G., 2011. Detection of a cyclic perfluorinated acid, perfluoroethylcyclohexane sulfonate, in the Great Lakes of North America. Environ. Sci. Technol. 45, 8060-8066. https://doi.org/10.1021/es200135c

Detroit Public TV, 2021. PFAS Around the Great Lakes Region: Actions taken in each state or province and standards set, if any. Great Lakes Now, last updated February 23, 2021, https://www.greatlakesnow.org/2020/03/pfas-standards-actions-state-canada/

Downs, T.M., Schallenberg, M. and Burns, C.W., 2008. Responses of lake phytoplankton to micronutrient enrichment: a study in two New Zealand lakes and an analysis of published data. Aquatic Sciences, 70(4), pp.347-360.

Duda, A.M., 1989. Groundwater Contamination in the Great Lakes Basin: Implication for Multimedia Relations. Chicago-Kent Law Review, 65(2), pp. 465-477.

Duda, A.M., 1994. Achieving Pollution Prevention Goals for Transboundary Waters Through International Joint Commission Processes. Water Science and Technology. 30(5), pp. 223-231.

Duvenage, D., 2012. Horizon scanning…not just for futurists. www.foreknowledge.info

Duveneck, M.J., Scheller, R.M., White, M.A., Handler, S.D. and Ravenscroft, C., 2014. Climate change effects on northern Great Lake (USA) forests: a case for preserving diversity. Ecosphere, 5(2), pp.1-26.

ECCC, 2021a. Great Lakes Fish Contaminants Monitoring and Surveillance Data. https://catalogue.ec.gc.ca/geonetwork/srv/api/records/f1ee1204-e177-4f33-a02a-4dae5319c33a?language=eng

ECCC, 2021b. Draft: Canada's Great Lakes Strategy for PFOS, PFOA, and LC-PFCAs Risk Management, April 2021, 54 p., https://binational.net/wp-content/uploads/2021/04/20210419-DRAFT-GLStrategy-PFOS-PFOA-LC-PFCAs.pdf

Eimers, M., Catherine, Liu, F. and Bontje, J., 2020. Land use, land cover, and climate change in southern Ontario: implications for nutrient delivery to the lower Great Lakes. In: Crossman J., Weisener C. (eds.) Contaminants of the Great Lakes. The Handbook of Environmental Chemistry, vol 101. Springer, pp. 235-249.

Elser, J.J., Fagan, W.F., Denno, R.F., Dobberfuhl, D.R., Folarin, A., Huberty, A., Interlandi, S., Kilham, S.S., McCauley, E., Schulz, K.L. and Siemann, E.H., 2000. Nutritional constraints in terrestrial and freshwater food webs. Nature, 408(6812), pp.578-580.

Escobar, L., J. Escobar-Dodero, and N. Phelps, 2018. Infectious disease in fish: global risk of viral hemorrhagic septicemia virus. Rev Fish Biol Fisheries (online).

EU Environmental Foresight System (FORENV) Final report of 2019-20 annual cycle., 2021. https://doi.org/10.2779/365974

European Commission. Directorate-General for the Environment & University of the West of England (UWE), Science Communication Unit, 2016. Identifying emerging risks for environmental policies. [Publications Office].

Faisal, M., M. Shavalier, R. Kim, E. Millard, M. Gunn, A. Winters, C. Schulz, A. Eissa, M. Thomas, M. Wolgamood, G. Whelan, and J. Winton, 2012. Spread of the emerging hemorrhagic septicemia virus strain, genotype IVb, in Michigan, USA. Viruses 4: 734-760.

Fan, X., Ding, S., Gao, S., Chen, M., Fu, Z., Gong, M., Wang, Y. and Tsang, D.C., 2021. A holistic understanding of cobalt cycling and limiting roles in the eutrophic Lake Taihu. Chemosphere, 277, p.130234.

FAO, 2017. The Future of Food and Agriculture - Trends and Challenges. Rome: FAO.

FAO, 2018. The Future of Food and Agriculture - Alternative Pathways to 2050. Rome: FAO.

Fenichel, E., J. Tsao, M. Jones, and G. Hickling, 2008. Fish pathogen screening and its influence on the likelihood of accidental pathogen introduction during fish translocations. J. Aquatic Animal Health 20(1): 19-28.

Forest, A., 2017. The Approval of Waukesha's Diversion Application under the Great Lakes - St. Lawrence Basin Water Resources Compact- Bad Precedent for the Great Lakes. Canada-United States Law Journal, Case Western Reserve University - School of Law, 41(1), pp. 70-95.

Frey, S.K., Khader, O., Taylor, A., Erler, A.R., Lapen, D.R., Sudicky, E.A., Berg, S.J., and Russell, H.A.J., 2020. A fully integrated groundwater-surface-water model for southern Ontario, in Russell, H.A.J. and Kjarsgaard, B.A. (ed.), Southern Ontario groundwater project 2014-2019: summary report, Geological Survey of Canada, Open File 8536, 245 p.

Furdui, V.I., Stock, N.L., Ellis, D.A., Butt, C.M., Whittle, D.M., Crozier, P.W., Reiner, E.J., Muir, D.C.G., Mabury, S.A., 2007. Spatial distribution of perfluoroalkyl contaminants in lake trout from the Great Lakes. Environ. Sci. Technol. 41, 1554-1559. https://doi.org/10.1021/es0620484

Giesy, J.P., Mabury, S.A., Martin, J.W., Kannan, K., Jones, P.D., Newsted, J.L. and Coady, K., 2006. Perfluorinated compounds in the Great Lakes. In Persistent Organic Pollutants in the Great Lakes (pp. 391-438). Springer, Berlin, Heidelberg.

GLANSIS, 2022. https://www.glerl.noaa.gov/glansis/

GLFC (Great Lakes Fishery Commission, Editor), 2007. A joint strategic plan for management of Great Lakes fisheries (adopted in 1997 and supersedes 1981 original). Great Lakes Fish. Comm. Misc. Publ, 2007-01. Available at http://www.glfc.org/fishmgmt/jsp97.pdf

GLFCFHC, 2009. Great Lakes Fish Health Committee Terms of Reference. http://www.glfc.org/pubs/lake_committees/GLFHC_TOR.pdf

GLFCFHC, 2021. Great Lakes Fish Health Committee Webpage. http://www.glfc.org/fish-health-committee.php

GLIFWC, 2019. 2019 Tribal Great Lakes Restoration: Culturally Inspired Restoration. http://glifwc.org/publications/pdf/2019BIAGLRI.pdf

GLISA [Great Lakes Integrated Sciences and Assessment], 2023. Future Climate Scenarios for the Great Lakes Region accessed 23 February 2023. https://glisa.umich.edu/climate-data/climate-scenarios/

GLWQA, 2015. Recommended Phosphorus Loading Targets for Lake Erie - Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee, 70 p. https://www.epa.gov/sites/production/files/2015-06/documents/report-recommended-phosphorus-loading-targets-lake-erie-201505.pdf

Gobin, J., Duncan, A.T. and Lauzon, R., 2022 (*in press*). Saugeen Ojibway Nation community input and action: Initiating a two-eyed seeing approach for dikameg (*Coregonus clupeaformis*) in Lake Huron. Journal of Great Lakes Research.

Gopalakrishnan, K.K. and Kashian, D.R., 2020. Identification of optimal calcium and temperature conditions for quagga mussel filtration rates as a potential predictor of invasion. Environmental toxicology and chemistry, 39(2), pp.410-418.

Governments of the United States and Canada, 2012. Great Lakes Water Quality Agreement. Annex 8 - Groundwater, pp. 49-59.

Grannemann, N. and D. Von Stempvoort (editors), 2016. Groundwater Science Relevant to the Great Lakes Water Quality Agreement: A Status Report. International Joint Commission, 101 p.

Great Lakes – St. Lawrence River Basin Water Resources Compact, 2005. https://gsgp.org/media/qjpdf1gr/great_lakes-st_lawrence_river_basin_water_resources_compact.pdf

Great Lakes Commission, 2019. Annual Report of the Great Lakes Regional Water Use Database Representing 2019 Water Use Data. https://waterusedata.glc.org/pdf/2019-Water-Use-Report.pdf

Great Lakes Fish Health Committee, 2021. Great Lakes Fish Health Committee Webpage. Available at http://www.glfc.org/fish-health-committee.php

Green, A.G., Abdulai, A.R., Duncan, E., Glaros, A., Campbell, M., Newell, R., Quarshie, P., KC, K.B., Newman, L., Nost, E. and Fraser, E.D., 2021. A scoping review of the digital agricultural revolution and ecosystem services: implications for Canadian policy and research agendas. FACETS 6: 1955-1985.

Guiry, E.J., Buckley, M., Orchard, T.J., Hawkins, A.L., Needs?Howarth, S., Holm, E. and Szpak, P., 2020. Deforestation caused abrupt shift in Great Lakes nitrogen cycle. Limnology and Oceanography, 65(8), pp.1921-1935.

Havens, S.M., Hassler, C.S., North, R.L., Guildford, S.L., Silsbe, G., Wilhelm, S.W., and Twiss, M.R., 2012. Iron plays a role in nitrate drawdown by phytoplankton in Lake Erie surface waters as observed in lake wide assessments. Canadian Journal of Fisheries and Aquatic Sci. 69:(2) 369-381.

Houde, M., Martin, J.W., Letcher, R.J., Solomon, K.R., Muir, D.C.G., 2006. Biological monitoring of polyfluoroalkyl substances: A review. Environ. Sci. Technol. 40, 3463-3473. https://doi.org/10.1021/es052580b

Houde, M., Muir, D.C.G., Tomy, G.T., Whittle, D.M., Teixeira, C., Moore, S., 2008. Bioaccumulation and trophic magnification of short- and medium-chain chlorinated paraffins in food webs from Lake Ontario and Lake Michigan. Environ. Sci. Technol. 42, 3893-3899. https://doi.org/10.1021/es703184s

Hui, Y., Atkinson, J.F., Zhu, Z., Schlea, D. and Redder, T., 2021. Invasive dreissenid mussel effects on phosphorus dynamics in Lake Ontario: insights from integrated hydrodynamic- ecological modeling. Canadian Journal of Fisheries and Aquatic Sciences, 78(12): 1816-1832.

International Joint Commission, 1993. Groundwater Contamination in the Great Lakes Basin- A Summary Report. International Joint Commission (IJC) Digital Archive. 37 p.

International Joint Commission, 2018. Great Lakes Surface and Groundwater Model Integration Review: Literature Review, Options for Approaches and Preliminary Action Plan for the Great Lakes Basin. Prepared by the Great Lakes Science Advisory Board, Research Coordination Committee; submitted to the International Joint Commission, October 2018, 62 p.

Interstate Technology Regulatory Council, 2020. History and Use of Per- and Polyfluoroalkyl Substances (PFAS), Fact Sheet, 9 p. https://pfas-1.itrcweb.org/fact_sheets_page/PFAS_Fact_Sheet_History_and_Use_April2020.pdf

Intwala, A., Patey, T.D., Polet, D.M. and Twiss, M.R., 2008. Nutritive substitution of zinc by cadmium and cobalt in phytoplankton isolated from the Lower Great Lakes. Journal of Great Lakes Research, 34(1), pp.1-11.

Jasechko, S. and D. Perrone, 2021. Global Groundwater Wells at Risk of Running Dry. Science 372: pp. 418-421.

Jerde, C.L., Chadderton, W.L., Mahon, A.R., Renshaw, M.A., Corush, J., Budny, M.L., Mysorekar, S. and Lodge, D.M., 2013. Detection of Asian carp DNA as part of a Great Lakes basin-wide surveillance program. Canadian Journal of Fisheries and Aquatic Sciences, 70(4): 522-526.

Jickells, T.D., An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., Brooks, N., Cao, J.J., Boyd, P.W., Duce, R.A., Hunter, K.A. and Kawahata, H., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. science, 308(5718), pp.67-71.

Joosse, P. J., and D. B. Baker, 2011. Context for Re-Evaluating Agricultural Source Phosphorus Loadings to the Great Lakes. Canadian Journal of Soil Science 91 (3): 317-27. https://doi.org/10.4141/cjss10005

Kalcic, Margaret M., Rebecca Logsdon Muenich, Samantha Basile, Allison L. Steiner, Christine Kirchhoff, and Donald Scavia, 2019. Climate Change and Nutrient Loading in the Western Lake Erie Basin: Warming Can Counteract a Wetter Future. Environmental Science & Technology 53 (13): 7543-50. https://doi.org/10.1021/acs.est.9b01274

Kannan, K., Tao, L., Sinclair, E., Pastva, S.D., Jude, D.J., Giesy, J.P., 2005. Perfluorinated compounds in aquatic organisms at various trophic levels in a Great Lakes food chain. Arch. Environ. Contam. Toxicol. 48, 559-566. https://doi.org/10.1007/s00244-004-0133-x

Kelly, L.T., Champeaud, M., Beuzenberg, V., Goodwin, E., Verburg, P. and Wood, S.A., 2021. Trace metal and nitrogen concentrations differentially affect bloom forming cyanobacteria of the genus Dolichospermum. Aquatic Sciences, 83(2), pp.1-11.

Kettren, L.P., 2006. Resolving High-Capacity Groundwater Withdrawal Conflicts in the Great Lakes Basin. Doctoral Dissertation, Michigan State University, 133 p.

Kim, Y., T. Aw, T. Teal, and J. Rose, 2015. Metagenomic investigation of viral communities in ballast water. Environ. Sci. Technol. 49: 8396-8407.

Klymus, K.E., Marshall, N.T. and Stepien, C.A., 2017. Environmental DNA (eDNA) metabarcoding assays to detect invasive invertebrate species in the Great Lakes. PloS One, 12(5): e0177643.

Knights, D., Parks, K.C. Sawyer, A.H., David, C.H., Browning, T.N., Danner, K.M. and C. D. Wallace, 2017. Direct Groundwater Discharge and Vulnerability to Hidden Nutrient Loads along the Great Lakes Coast of the United States. Journal of Hydrology, Vol. 554, pp. 331-341.

Kornelson, K.C. and P. Coulibaly, 2014. Synthesis Review of Groundwater Discharge to Surface Water in the Great Lakes Basin. Journal of Great Lakes Research, 40(2), pp. 247-256.

Kosow, H., & Gaßner, R., 2008. Methods of Future and Scenario Analysis Overview, Assessment, and Selection Criteria.

Kovalenko, K.E., Brady, V.J., Brown, T.N., Ciborowski, J.J., Danz, N.P., Gathman, J.P., Host, G.E., Howe, R.W., Johnson, L.B., Niemi, G.J. and Reavie, E.D., 2014. Congruence of community thresholds in response to anthropogenic stress in Great Lakes coastal wetlands. Freshwater Science, 33(3): 958-971. https://doi.org/10.1086/676913

Kravtsov, S., Sugiyama, N. and Roebber, P., 2018. Role of nonlinear dynamics in accelerated warming of Great Lakes. In Advances in Nonlinear Geosciences (p. 279-295). Springer, Cham.

Kujawa, Haley, Margaret Kalcic, Jay Martin, Noel Aloysius, Anna Apostel, Jeffrey Kast, Asmita Murumkar, et al., 2020. The Hydrologic Model as a Source of Nutrient Loading Uncertainty in a Future Climate. Science of The Total Environment 724 (July): 138004. https://doi.org/10.1016/j.scitotenv.2020.138004

Lall, U., Josset, L., and Russo, T., 2020. A Snapshot of the World's Groundwater Challenges. Annual Review of Environment and Resources 45: pp. 171-194.

Lenton, T.M., 2011. Early warning of climate tipping points. Nature Climate Change, 1(4): 201-209. https://doi.org/10.1038/nclimate1143

Letcher, Robert J., Guanyong Su, Jeremy N. Moore, Lisa L. Williams, Pamela A. Martin, Shane R. de Solla, and William W. Bowerman. "Perfluorinated sulfonate and carboxylate compounds and precursors in herring gull eggs from across the Laurentian Great Lakes of North America: temporal and recent spatial comparisons and exposure implications." Science of the Total Environment 538 (2015): 468-477.

Leung, T., Wilkinson, G.M. and Swanner, E.D., 2021. Iron availability allows sustained cyanobacterial blooms: a dual-lake case study. Inland Waters, pp.1-13.

Li, J., Ianaiev, V., Huff, A., Zalusky, J., Ozersky, T. and Katsev, S., 2021. Benthic invaders control the phosphorus cycle in the world's largest freshwater ecosystem. Proceedings of the National Academy of Sciences, 118(6).

Lin, Y., Capozzi, S.L., Lin, L. and Rodenburg, L.A., 2021. Source apportionment of perfluoroalkyl substances in Great Lakes fish. Environmental Pollution, 290, p.118047.

Loch, T., and M. Faisal, 2015. Emerging flavobacterial infections in fish: A review. Journal of Advanced Research 6: 283-300.

Mahdiyan, O., Filazzola, A., Molot, L.A., Gray, D. and Sharma, S., 2021. Drivers of water quality changes within the Laurentian Great Lakes region over the past 40 years. Limnology and Oceanography, 66(1), pp.237-254.

Mancuso, J.L., Weinke, A.D., Stone, I.P., Hamsher, S.E., Villar-Argaiz, M. and Biddanda, B.A., 2021. Cold and wet: Diatoms dominate the phytoplankton community during a year of anomalous weather in a Great Lakes estuary. Journal of Great Lakes Research.

Martin, J.W., Whittle, D.M., Muir, D.C.G., Mabury, S.A., 2004. Perfluoroalkyl contaminants in a food web from Lake Ontario. Environ. Sci. Technol. 38, 5379-5385. https://doi.org/10.1021/es049331s

Mason, L.A., Riseng, C.M., Gronewold, A.D., Rutherford, E.S., Wang, J., Clites, A., Smith, S.D. and McIntyre, P.B., 2016. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. Climatic Change, 138(1), pp.71-83.

McEachran M., S. Mor, and N. Phelps. (2021) Detection of pathogens and non-target species in the baitfish supply chain. Management of Biological Invasions 12(2): 363-377.

Mohapatra, S.P. and A. Mitchell, 2009. Groundwater Demand Management in the Great Lakes Basin: Directions for New Policies. Journal of Water Resources Management, Vol. 23, pp. 457-475.

Mohiuddin, M., and H. Schellhorn, 2020. Chapter 13 - Epidemiology and ecology of emerging viruses in two freshwater lakes of the northern hemisphere. In Volume 2: Applied Virology Approaches Related to Human, Animal, and Environmental Pathogens (Academic Press), pp. 243-257.

Mugimba, K., D. Byarugaba, S. Mutoloki, O. Evenson, and H. Munangandu, 2021. Challenges and solutions to viral diseases of finfish in marine aquaculture. Pathogens 10: 673.

Myers, A.L., Crozier, P.W., Helm, P.A., Brimacombe, C., Furdui, V.I., Reiner, E.J., Burniston, D., Marvin, C.H., 2012. Fate, distribution, and contrasting temporal trends of perfluoroalkyl substances (PFASs) in Lake Ontario, Canada. Environ. Int. 44, 92-99. https://doi.org/10.1016/j.envint.2012.02.002

Natwora, K.E. and Sheik, C.S., 2021. Assessment of nitrogen fixation rates in the Laurentian Great Lakes. Journal of Great Lakes Research.

Nehme, C. C., Santos, M. de M., Filho, L. F., & Coelho, G. M., 2012. Challenges in communicating the outcomes of a foresight study to advise decision-makers on policy and strategy. Science and Public Policy, 39(2), 245-257. https://doi.org/10.1093/scipol/scs015

Newell, S.E., Davis, T.W., Johengen, T.H., Gossiaux, D., Burtner, A., Palladino, D. and McCarthy, M.J., 2019. Reduced forms of nitrogen are a driver of non-nitrogen-fixing harmful cyanobacterial blooms and toxicity in Lake Erie. Harmful algae, 81, pp.86-93.

Niemi, G. J., Brady, Valerie J., Brown, Terry N., Ciborowski, Jan J. H., Danz, Nicholas P., Ghioca, Dana M., Hanowski, JoAnn M., Hollenhorst, Tom P., Howe, Robert W., Johnson, Lucinda B., Johnston, Carol A. and Reavie, Euan D., 2009. Development of ecological indicators for the U.S. Great Lakes coastal region - A summary of applications in Lake Huron. Aquatic Ecosystem Health & Management, 12(1):77- 89.

Norman, E. and K. Bakker, 2004. Transboundary Groundwater Governance: An Annotated Bibliography, 19 p.

North, R. L., S. J. Guildford, R. E. H. Smith, S. M. Havens, and M. R. Twiss, 2007. Evidence for phosphorus, nitrogen, and iron colimitation of phytoplankton communities in Lake Erie. Limnology and Oceanography, 52: 315-328.

Nriagu, J.O., Lawson, G., Wong, H.K. and Azcue, J.M., 1993. A protocol for minimizing contamination in the analysis of trace metals in Great Lakes waters. Journal of Great Lakes Research, 19(1), pp.175-182.

O'Beirne, M.D., Werne, J.P., Hecky, R.E., Johnson, T.C., Katsev, S. and Reavie, E.D., 2017. Anthropogenic climate change has altered primary productivity in Lake Superior. Nature Communications, 8(1), pp.1-8.

Organisation for Economic Co-operation and Development (OECD), 2018. Toward a new comprehensive global database of per and polyfluoroalkyl substances (PFASs). https://www.oecd.org/

Organisation for Economic Co-operation and Development (OECD), 2021. Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance. Series on Risk Management No. 61. https://www.oecd.org/

Paerl, H.W., Havens, K.E., Xu, H., Zhu, G., McCarthy, M.J., Newell, S.E., Scott, J.T., Hall, N.S., Otten, T.G. and Qin, B., 2020. Mitigating eutrophication and toxic cyanobacterial blooms in large lakes: The evolution of a dual nutrient (N and P) reduction paradigm. Hydrobiologia, 847(21), pp.4359-4375.

Phillips, K., A. Noyes, L. Shen, and G. Whelan, 2014. Model program for fish health management in the Great Lakes. Gt. Lakes Fish. Comm. Spec. Publ. 14-02. Available at http://glfc.org/pubs/SpecialPubs/Sp14_02.pdf

Point, Adam D., Thomas M. Holsen, Sujan Fernando, Philip K. Hopke, and Bernard S. Crimmins, 2021. Trends (2005-2016) of perfluoroalkyl acids in top predator fish of the Laurentian Great Lakes. Science of the Total Environment, 778: 146151.

Prater, C., Frost, P.C., Howell, E.T., Watson, S.B., Zastepa, A., King, S.S., Vogt, R.J. and Xenopoulos, M.A., 2017. Variation in particulate C: N: P stoichiometry across the Lake Erie watershed from tributaries to its outflow. Limnology and Oceanography, 62(S1), pp.S194-S206.

Rapport, D.J., 1983. The stress-response environmental statistical system and its applicability to the Laurentian Lower Great Lakes. Statistical Journal of the United Nations Economic Commission for Europe, 1(4): 377-405.

Reinl, K.L., Brookes, J.D., Carey, C.C., Harris, T.D., Ibelings, B.W., Morales, Williams, A.M., De Senerpont Domis, L.N., Atkins, K.S., Isles, P.D., Mesman, J. and North, R.L., 2021. Cyanobacterial blooms in oligotrophic lakes: Shifting the high?nutrient paradigm. Freshwater Biology.

Reinl, K.L., Sterner, R.W., Lafrancois, B.M. and Brovold, S., 2020. Fluvial seeding of cyanobacterial blooms in oligotrophic Lake Superior. Harmful Algae, 100, p.101941.

Remucal, C.K., 2019. Spatial and temporal variability of perfluoroalkyl substances in the Laurentian Great Lakes. Environmental Science: Processes & Impacts, 21(11), pp.1816-1834.

Ren, Junda, Adam D. Point, Sadjad Fakouri Baygi, Sujan Fernando, Philip K. Hopke, Thomas M. Holsen, Bernard S. Crimmins, 2022. Bioaccumulation of polyfluoroalkyl substances in the Lake Huron aquatic food web, Science of the Total Environment, 2022, 152974, https://doi.org/10.1016/j.scitotenv.2022.152974

Ren, Junda, Adam Point, Sadjad Fakouri Baygi, Sujan Fernando, Philip K. Hopke, Thomas M. Holsen, Brian Lantry, Brian Weidel, and Bernard S. Crimmins, 2021. Bioaccumulation of perfluoroalkyl substances in a Lake Ontario food web. Journal of Great Lakes Research. DOI:10.1016/j.jglr.2021.08.013

Robinson, C., 2015. Review on groundwater as a source of nutrients to the Great Lakes and their tributaries. Journal of Great Lakes Research, 41(4), pp.941-950.

Rossmann, R. and Barres, J., 1988. Trace element concentrations in near-surface waters of the Great Lakes and methods of collection, storage, and analysis. Journal of Great Lakes Research, 14(2), pp.188-204.

Rowe, M.D., Anderson, E.J., Beletsky, D., Stow, C.A., Moegling, S.D., Chaffin, J.D., May, J.C., Collingsworth, P.D., Jabbari, A. and Ackerman, J.D., 2019. Coastal upwelling influences hypoxia spatial patterns and nearshore dynamics in Lake Erie. Journal of Geophysical Research: Oceans, 124(8): 6154-6175. https://doi.org/10.1029/2019JC015192

Rowe, M.D., Kreis Jr, R.G. and Dolan, D.M., 2014. A reactive nitrogen budget for Lake Michigan. Journal of Great Lakes Research, 40(1), pp.192-201.

SAB-SPC, 2020. An Evaluation of Stressor Interactions in the Great Lakes, 40 p. https://ijc.org/sites/default/files/2020-09/SAB-SPC_StressorInteractionsReport_2020.pdf

Safaie, A., E. Litchman and M.S. Phanikumar, 2021. Decreasing groundwater supply can exacerbate lake warming and trigger algal blooms, Journal of Geophysical Research - Biogeosciences.

Sardar, Z., 2010. The Namesake: Futures; futures studies; futurology; futuristic; foresight-What's in a name? Futures, 42(3), 177-184. https://doi.org/10.1016/j.futures.2009.11.001

Schindler, D.W., 1977. Evolution of phosphorus limitation in lakes: natural mechanisms compensate for deficiencies of nitrogen and carbon in eutrophied lakes. Science, 195(4275), pp.260-262.

Schindler, D.W., Carpenter, S.R., Chapra, S.C., Hecky, R.E. and Orihel, D.M., 2016. Reducing phosphorus to curb lake eutrophication is a success. Environmental Science & Technology, 50(17), pp.8923-8929.

hoemaker, C., D. Xu, B. LaFrentz, and S. LaPatra, 2015. Chapter 1 - Overview of fish immune system and infectious diseases. In Dietary Nutrients, Additives, and Fish Health (Wiley Blackwell), pp. 1-24.

Sloat, Lindsey L., Steven J. Davis, James S. Gerber, Frances C. Moore, Deepak K. Ray, Paul C. West, and Nathaniel D. Mueller, 2020. Climate Adaptation by Crop Migration. Nature Communications 11 (1). https://doi.org/10.1038/s41467-020-15076-4

Sorichetti, R.J., Creed, I.F. and Trick, C.G., 2016. Iron and iron-binding ligands as cofactors that limit cyanobacterial biomass across a lake trophic gradient. Freshwater Biology, 61(1), pp.146-157.

Steinman AD, Uzarski DG, Lusch DP, Miller C, Doran P, Zimnicki T, Chu P, Allan J, Asher J, Bratton J, Carpenter D, Dempsey D, Drummond C, Esch J, Garwood A, Harrison A, Lemke LD, Nicholas J, Ogilvie W, O'Leary B, Sachs P, Seelbach P, Seidel T, Suchy A, Yellich J., 2022. Groundwater in Crisis? Addressing Groundwater Challenges in Michigan (USA) as a Template for the Great Lakes. Sustainability, 14(5):3008. https://doi.org/10.3390/su14053008

Steinman, A., Abdimalik, M., Ogdahl, M.E. and Oudsema, M., 2016. Understanding planktonic vs. benthic algal response to manipulation of nutrients and light in a eutrophic lake. Lake and Reservoir Management, 32(4): 402-409.

Steinman, A.D., Nicholas, J.R., Allan, J.W. and F. Ruswick, 2011. Science as a Fundamental Framework for Shaping Policy Decisions Regarding the Use of Groundwater in the State of Michigan: A Case Study. Journal of Water Policy, Vol. 13. pp. 69-86.

Sterner, R. W., Smutka, T. M., McKay, R. M. L., Xiaoming, Q., Brown, E. T., & Sherrell, R. M., 2004. Phosphorus and trace metal limitation of algae and bacteria in Lake Superior. Limnology and Oceanography, 49(2), 495-507.

Sterner, R.W., 2021. The Laurentian Great Lakes: A Biogeochemical Test Bed. Annual Review of Earth and Planetary Sciences, 49, pp.201-229.

Sterner, R.W., Reinl, K.L., Lafrancois, B.M., Brovold, S. and Miller, T.R., 2020. A first assessment of cyanobacterial blooms in oligotrophic Lake Superior. Limnology and Oceanography, 65(12), pp.2984-2998.

Strandberg, U., Bhavsar, S.P. and Arts, M.T., 2020. Interspecific differences in omega-3 PUFA and contaminants explain the most variance in suggested Great Lakes' fish consumption when risks/benefits are considered together. Journal of Great Lakes Research, 46(3):549-559. https://doi.org/10.1016/j.jglr.2020.03.019

Sturtevant, Rochelle, Donald Evans Secretary, Conrad C Lautenbacher, and Jr Administrator, 2004. NOAA Technical Memorandum GLERL-131 Great Lakes Ecological Forecasting Needs Assessment. www.glerl.noaa.gov.

Sun, J., Letcher, R.J., Eens, M., Covaci, A. and Fernie, K.J., 2020. Perfluoroalkyl acids and sulfonamides and dietary, biological and ecological associations in peregrine falcons from the Laurentian Great Lakes Basin, Canada. Environmental Research, 191, p.110151.

Sutherland, W. J., Clout, M., Côté, I. M., Daszak, P., Depledge, M. H., Fellman, L., Fleishman, E., Garthwaite, R., Gibbons, D. W., de Lurio, J., Impey, A. J., Lickorish, F., Lindenmayer, D., Madgwick, J., Margerison, C., Maynard, T., Peck, L. S., Pretty, J., Prior, S., … Watkinson, A. R., 2010. A horizon scan of global conservation issues for 2010. Trends in Ecology & Evolution, 25(1), 1-7. https://doi.org/10.1016/J.TREE.2009.10.003

Sutherland, W. J., Fleishman, E., Clout, M., Gibbons, D. W., Lickorish, F., Peck, L. S., Pretty, J., Spalding, M., & Ockendon, N., 2019. Ten Years On: A Review of the First Global Conservation Horizon Scan. Trends in Ecology & Evolution, 34(2), 139-153. https://doi.org/10.1016/j.tree.2018.12.003

Sutherland, W.J., Bennett, C., Brotherton, P.N., Butterworth, H.M., Clout, M.N., Côté, I.M., Dinsdale, J., Esmail, N., Fleishman, E., Gaston, K.J. and Herbert-Read, J.E., 2022. A global biological conservation horizon scan of issues for 2023. Trends in Ecology & Evolution, 38(1), 96-107. https://doi.org/10.1016/j.tree.2022.10.005

TAP, 2020. Second Triennial Assessment of Progress (TAP) Report on Great Lakes Water Quality. https://ijc.org/sites/default/files/2020-12/2020-TAP-Report-online.pdf

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M. and Konikow, L., 2013. Ground water and climate change. Nature Climate Change, 3(4), pp.322-329.

Twiss M.R., Auclair, J.-C., and Charlton, M.N. 2000. An investigation into iron-stimulated phytoplankton productivity in the epipelagic Lake Erie during thermal stratification using trace metal clean techniques. Canadian Journal of Fisheries and Aquatic Sciences, 57: 86-95.

Twiss, M.R., 2008. Current knowledge of trace metal biogeochemistry in the water column of Lake Erie. In: Checking the Pulse of Lake Erie (M. Munawar, R.T. Heath, Eds.), Ecovision World Monograph Series, Backhuys Publ., Leiden, The Netherlands, p. 181-205.

Twiss, M.R., Gouvêa, S.P., Bourbonniere, R.A., McKay, R.M.L., and Wilhelm, S.W. 2005. Field investigations of trace metal effects on Lake Erie phytoplankton productivity. Journal of Great Lakes Research, 31 (sup. 2): 168-179.

U.S. Caucus of the TEK Task Team of the Annex 10 Science Subcommittee, 2021. Guidance Document on TEK Pursuant to the GLWQA. https://www.bia.gov/sites/bia.gov/files/assets/bia/wstreg/Guidance_Document_on_TEK_Pursuant_to_the_Great_Lakes_Water_Quality_Agreement.pdf

U.S. Environmental Protection Agency, 2013. State of the Lakes Ecosystem Conference: A Changing Economy, Economic and Environmental Linkages. 54 pp.

USEPA (Science Advisory Board), 1995. Beyond the Horizon: Using Foresight to Protect the Environmental Future. EPA-SAB-EC-95-007. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000PNIV.TXT

USDA, 2021. Action Plan for Climate Adaptation and Resilience, August 2021, 40 p., https://www.sustainability.gov/pdfs/usda-2021-cap.pdf

Venkiteswaran, J.J., Schiff, S.L., Paterson, M.J., Flinn, N.A.P., Shao, H. and Elgood, R.J., 2017. Changing nitrogen deposition with low ?15N? NH4+ and ?15N? NO3? values at the Experimental Lakes Area, northwestern Ontario, Canada. Facets, 2(1), pp.249-266.

Verma, Siddhartha, Rabin Bhattarai, Nathan S. Bosch, Richard C. Cooke, Prasanta K. Kalita, and Momcilo Markus, 2015. Climate Change Impacts on Flow, Sediment and Nutrient Export in a Great Lakes Watershed Using SWAT. CLEAN - Soil, Air, Water 43 (11): 1464-74. https://doi.org/10.1002/clen.201400724

Wagner, N.D., Quach, E., Buscho, S., Ricciardelli, A., Kannan, A., Naung, S.W., Phillip, G., Sheppard, B., Ferguson, L., Allen, A. and Sharon, C., 2021. Nitrogen form, concentration, and micronutrient availability affect microcystin production in cyanobacterial blooms. Harmful Algae, 103, p.102002.

Walker, P., and J. Winton, 2010. Emerging viral diseases of fish and shrimp. Vet. Res. 41:51.

Wang, Z., Buser, A.M., Cousins, I.T., Demattio, S., Drost, W., Johansson, O., Ohno, K., Patlewicz, G., Richard, A.M., Walker, G.W. and White, G.S., 2021. A New OECD Definition for Per-and Polyfluoroalkyl Substances. Environmental Science & Technology, 55(23), pp.15575-15578.

Wang, Z., Cousins, I.T., Scheringer, M., Buck, R.C., Hungerbühler, K., 2014. Global emission inventories for C4-C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, Part I: production and emissions from quantifiable sources. Environment International 70, 62-75.

Watson, S.B., Miller, C., Arhonditsis, G., Boyer, G.L., Carmichael, W., Charlton, M.N., Confesor, R., Depew, D.C., Höök, T.O., Ludsin, S.A. and Matisoff, G., 2016. The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. Harmful Algae, 56:44-66.

Wick, M.J., Angradi, T.R., Pawlowski, M.B., Bolgrien, D., Debbout, R., Launspach, J. and Nord, M., 2020. Deep Lake Explorer: A web application for crowdsourcing the classification of benthic underwater video from the Laurentian Great Lakes. Journal of Great Lakes Research, 46(5): 1469-1478. https://doi.org/10.1016/j.jglr.2020.07.00 9

Winter, T.C., Harvey, J.W., Franke, O.L. and Alley, W.M., 1998. Ground water and surface water: A single resource, US Geological Survey, Circular 1139, 79 p.

Wodak, J., 2014. Scientific Diversity, Scientific Uncertainty and Risk Mitigation Policy and Planning.

Wu, Y., Simon, K.L., Best, D.A., Bowerman, W. and Venier, M., 2020. Novel and legacy per- and polyfluoroalkyl substances in bald eagle eggs from the Great Lakes region. Environmental Pollution, 260, p.113811.

Wuebbles, D, B Cardinale, K Cherkauer et al., 2019. An Assessment of the Impacts of Climate Change on the Great Lakes. Chicago.

Xu, S., S.K. Frey, A.R. Erler, O. Khader, S.J. Berg, H.T. Hwang, M.V. Callaghan, J.H. Davison, E.A. Sudicky, 2021. Investigating groundwater-lake interactions in the Laurentian Great Lakes with a fully integrated surface water-groundwater model, Journal of Hydrology, 594, p.125911.

Zacharda, N., 2020. Researching the Effectiveness of Agricultural Programs in GLRI Priority Watersheds. Ann Arbor, https://www.glc.org/wp-content/uploads/REAP-Final-Report-20200117-WITH-Appx.pdf.

APPENDIX A – Threats Compiled from Virtual Workshop

Table A-1. Threats compiled from virtual workshop (continues on following pages).

ORDERED SYNTHESIS OF THREATS FROM 12/17/2020 WORKSHOP		RISK KNOWLEDGE		DETECTION / MONITORING / ANALYSIS	
		PREPARE FOR THREAT & STRESSOR IDENT. Foresight	IDENTIFY THREATS & STRESSORS Risk Knowledge & Understanding	DETERMINE PRESENCE OF THREAT & STRESSOR Detection Mechanisms	DECISION FOR TAKING ACTION Analysis
Biological - KNOWN					
Known Threat 1 - new invasive species	High Potential/Risk new invasive species	Regular update of the Great Lakes Least Wanted list by the Great Lakes AIS Panel	Regular update of the risk maps for species on the least wanted list	Coordinated implementation of the US and Canadian AIS surveillance frameworks	EDNA detection results in intense field verification, actual detection leads to response protocols for that species being implemented
Known Threat 1 - invasive species - lamprey	Food web disruption (eg top predator collapse)	scar surveys	threat map based on possible habitat	scar surveys	increase in scars exeeds some thershold
Known Threat 1 - Thermal Regime Change (or other known stressor/disease for a species at risk organism)	SAR fish kill due to thermal change (or increased suspended sediment levels, etc..)	Model predictions using in-field monitors and historical data; Water temperature fluctuation tool, gradient of approaches	Maps of thermal regime change across range of SAR; Response indicator: stream temperature	WQ monitoring via stations already present; Early warning sensors for termperature flux	Novel detection of temp spike in new streams/rivers; Change in species at risk populations; Temperature threshold; CTMax from literature; Action Threshold = CTMax exceeded
Known Threat 1 - Dreissenid establishment/proliferation	Reduce trophic transfer efficiency pelagic foodwebs reduce production/availability of LTL organisms nearshore shunt of energy- spatial alteration contribute nutrients for HABs, modify substrate habitat features, support colonization of other AIS, pathogens	continuation of research that has postulated, and/or substantiated these stressos	identify response thresholds of mussel abundance or biomass where impacts occur, particularly at scales (e.g., a reef) where management options may exist	Periodic monitoring of mussel populations in each Great Lake for abundance/biomass estimates special attention given to specific areas where control may be feasible, such as reefs, small embayments, rivers	Track trends in populations at lake and local scales use available response thresholds to guide decisions implement control in local areas coordinate efforts with Invasive Mussel Collaborative
Known Threst 2 - Recurring pathogen outbreaks (VHSv, Botulism e)	Mortality of native biota (fishes, birds, herps)	must have appropriate protocols in place for collection and testing of specimens	uncertainty remains (mechanisms of production, transfer/uptake rates, lethal doses, env. factors ,etc)	various types of surveillance and sampling; public reports, monitoring at sites with prior history; various fauna types	substantial mass mortality events with verification of likely cause; mgt to minimize pathogen transfer
Asian carp	Competition with native species	interagency coordination; research	published research, simulations of impacts,	coordinated monitoring (ACRCC, Great Lakes agencies)	ACRCC triggers in the CAWS; early detection surveys;
	food web disruption		pathway identification, interagency coordination	presence of carps, evidence of establishment and impacts	LEC's Grass Carp Response Strategy;
Increased double-crested cormorants/other birds	Increased mortality on native fishes loss of native vegetation (cormorants)	changes in migratory and resident bird abundance research on food consumption levels	studies have demonstrated mortality can adversely affect local fish populations	changes in migratory numbers of avian predators and in breeding colonies in Great Lakes	coordination needed between federal and state agencies for managing birds protected by federal laws
Known and suspected threat: Habitat loss	Loss of habitat, decrease in population sizes due to sedimentation, changing water levels, species thermal limits	Habitat modeling (e.g. GLAHF), Traditional knowledge, Positivist science, Mixture	Threat maps, Response Indicators: population sizes of sensitive species, extent of valuable habitat (e.g. vegetated littoral zone)		
One Known threat identified: Focus on a group of species with high risk that are known on the door step	Data/information sources: List of unwanted species				
Other threats also mentioned: A group of AIS on door step (144 high risk sp potential living here with high risk), a subset of species are on the door step, another subset are current tracked because they are traded. Any of them can be a case study					
Biological - SUSPECTED					
Suspected Threat 1 - new pathogen	Potential new fish pathogen	Use Artifical Intellegence to scan news and scientific literature for global occurrences and patterns of introductions of new pathogens to freshwater systems	Regular review and prioritization of pathogens that are increasingly showing up in other freshwater ecosystems and identifying potential sources and locations in the Great Lakes	Add high potential/risk pathogens to existing surveillance efforts and/or fish collection efforts where signs of disease or stress are added to those surveys	Direct detection in surveillance leads to response protocols; suspected presence through signs of disease leads to initiation of survey
Suspected Threat 1 - invasive species from watch list	food web disruption (eg baitfish explosion or collapse); habitat disruption (eg mussels)	Glansis watch list	habitat requirments for each invasive species	monitor at probable points of entry, citizen alerts	first observation
Suspected Threat 1 - Invasive fish - first detection	Negative impact on species at risk and other native species	Model predictions of range spread (citation); Invasive species prediction tool (citation); Special session at IAGLR on effect of invasive species on species at risk, and Mixture	Response indicator: presence of invader; eDNA evidence; Threat map - Overlap threat on SAR distribution; Variance pattern; lab studies potential pathogens	Data Sources: Department of Fisheries and Oceans monitoring; NGO and Citizen monitoring; Agency or Academic study; fish sampling program	Novel detection
Suspected Threat 2 - Fish pathogen	fish die-off				first observation
One suspected threat identified: Wetland loss /coastal habitat loss (thermal/nutrient/water level change)/biological habitat loss	vegetation map (GLAHF);				
Biological - UNKNOWN					
Unknown Threat 4 - AIS synergies.	As we gain more species and the climate changes it may lead to greater probability of new invasives and new synergies				
Unknown Threat 1 - unsuspected invasive species	Food web disruption (eg baitfish explosion or collapse) and habitat disruption (eg mussels)	Glansis watch list	habitat requirments for each invasive species (prioritize from Glansis list based on likely harm, habitat match)	monitor at probable points of entry, citizen alerts	first observation
Unknown Threat 2- crossover pathogens	Humans to/from other organisms	Is this proven to be possible?	Research needed to verify possibility and under what conditions for specified organsims	may need protocols and targeted surveillance	coordination needed between monitoring and health agencies with public communications a high priority
Unknown Threat 3 - toxin bioaccumulation in the food web					
Unknown Threat 5 - stressors interaction (e.g., climate and nutrient)					

ORDERED SYNTHESIS OF THREATS FROM 12/17/2020 WORKSHOP		RISK KNOWLEDGE		DETECTION / MONITORING / ANALYSIS	
		PREPARE FOR THREAT & STRESSOR IDENT.	**IDENTIFY THREATS & STRESSORS**	**DETERMINE PRESENCE OF THREAT & STRESSOR**	**DECISION FOR TAKING ACTION**
Threat Description (one word or short phrase)	**Example of Stressor Resulting from Threat**	**Foresight**	**Risk Knowledge & Understanding**	**Detection Mechanisms**	**Analysis**
CHEMICAL - KNOWN					
Mercury	fish contamination/human health; stress to bird reproduction; mobilization with water level & climate changes	Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
Microcystins/cyanobacterial toxins		"	"	"	"
PFOS and PFAS#		"	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life , potential source regions	"	"
Chlorinated furans		"	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life	"	"
DDT/PCBs (POPs *)		"	"	Trends, apply toxicity thresholds (e.g., fish consumption advisories)	"
Dioxins		"	"	Add to monitoring program schedules, TEQ evaluations, trends	"
HOCs		"	"	Add to monitoring program schedules, develop toxicity threshold, trends	"
Hydrophobic organic contaminants *		"	"	"	"
Metals * (Se, Cd, As, advise looking them as a whole, susceptible to redox change, link to hypoxia)		"	"	"	"
Oils *		Mussel Watch Program Data, Sediment Monitoring	"	Add to water (or Mussel) monitoring program schedules, effects threshold, trends	"
PAHs		Mussel Watch Program Data, Sediment Monitoring, IADN	"	"	trends, toxicity threshold, relational database development with biochemical metrics, physiological distubances
Pesticides *		Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	"	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
Estradiols		"	"	Add to water (or Mussel) monitoring program schedules, effects threshold, trends	"
CHEMICAL - SUSPECTED					
PFOS and PFAS#		Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life , potential source regions	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
rubber (tire) preservatives		Non-targeted studies, alternate system studies (Tacoma)	Spatiaotemporal trend reports, literature toxicity assessments for multiple species, aquatic and atmopsheric half-life	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
Antibiotics/antibiotic resistance genes		Ample medical studies	Possibility of spread from WWTP to nat. env.	Genomic approach; see Antimicrobial Resistance and Bacteriophages: An Overlooked Intersection in Water Disinfection: Trends in Microbiology (recent Jan 23 2021 review: DOI:https://doi.org/10.1016/j.tim.2020.12.011).	
Microcystins/cyanobacterial toxins#					
Brominated diphenylethers (PBDEs) and their replacements (HBCDD, organophosphate flame retardants)		Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life , potential source regions	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
Fluoride	IQ decrease, Neurological, Reproductive/Beha	China studies vs. Safe Dental Premiss	Decrease in caries in fluoridated/nonflurodated Contries	Decrease in IQ	Masked in Population
Microplastics and their chemicals					
Toxigenic harmful algal species (diatoms)	human and animal toxicity; costly water treatment; expoensive impacts of water supply shut down	not specific to GL; some marine toxigenic species could be harbingers	well known occurence; little know about what triggers toxin expression	remote sensing (satellite); buoys; modelling (e.g. Lake Erie) forecast	observed toxin thresholds; correlation with phycocyanin pigment
Triclosan and other disinfectants (increased use due to COVID)					
carbazoles		Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
Chemical mixtures *	Overall Impacts on Population morbidity /mortality	Some work on 1 to 3 compounds	Masked impact in population	Ministry of Natural Resource Fish comsumption Guideline Global	Tipping point will be masked in the averages of population
Chlorinated carbazoles		Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life	Add to monitoring program schedules, develop toxicity threshold, trends	trends, toxicity threshold, relational database development with biochemical metrics
Chlorinated paraffins		Effective, quantitative measurement,	archived from US and CA tissue monitoirng archives	Add to monitoring program schedules, develop toxicity threshold, trends	"
Chloromethoxyphenols		Historical data from US monitoring programs (GLFMSP, GLSSP, IADN, Mussel Watch), Canadian Programs (Herring Gull Program, Fish and Sediment monitoring)	Spatiaotemporal trend reports, literature toxicity assessments, aquatic and atmopsheric half-life	"	"
Proteomic signatures themselves		Proteome development for indicator species (lake trout)	baseline of "healthy proteome" variances	identify key proteins indicators of healthy vs. non- healthy indicator species and potential links to stressor	"
CHEMICAL - UNKNOWN					
current monitoring programs (nontargeted approaches); Learn how scientists look for new contaminants in long- term monitoring programs for tributary waters and fish. EPA, EC, USGS, some NOAA programs. Fairly advanced way for early detection of chemical threats.		baseline, current/historic spatiotemporal signatures	GLNPO, NOAA Mussel Watch, Herring Gull Program	Spatiotemporal trends of non-monitored* chemicals	Spatiotemporal/ foodweb/ chemical charateristic evaluations
biomarkers of oxidation (ROS)					
genomic surveys (change in structure)		baseline, bioindicator genome development	Process oriented data base resources	Perturbation to process	Process to condition evaluation
proteomic surveys (change in signatures)		"	"	"	"
transcriptome survey (change in activity)		baseline, bioindicator transcriptome development	"	"	"

ORDERED SYNTHESIS OF THREATS FROM 12/17/2020 WORKSHOP		**RISK KNOWLEDGE**		**DETECTION / MONITORING / ANALYSIS**	
		PREPARE FOR THREAT & STRESSOR IDENT.	**IDENTIFY THREATS & STRESSORS**	**DETERMINE PRESENCE OF THREAT & STRESSOR**	**DECISION FOR TAKING ACTION**
Threat Description (one word or short phrase)	**Example of Stressor Resulting from Threat**	**Foresight**	**Risk Knowledge & Understanding**	**Detection Mechanisms**	**Analysis**
CLIMATE CHANGE - KNOWNS					
increased water temperature	hypoxia → internal nutrient loading	scenarios	response indicators (DO, TP concentrations)	Monitoring Programs NOAA; EPA; ECCC	physical attributes that suggest vulnerability to impact
	habitat "squeeze"	fish habitat models; TEK	limnological processes	monitoring (temp & DO); stratification depth	TEK
	thermal shock for fish	TEK	physiological understanding		TEK
increased water & air temperatures	loss of ice cover	model predictions (CMIP6) (uncertinty high)	threat maps	raw meteorological data	going beyond natural variation
	change in lake stratificaiton				
		model predictions	response indicators (DO, TP concentrations)	Data sources (various)	physical attributes that suggest vulnerability to impact
Increased precipitation amounts (water supply changes)	change in thermal habitat supply	model predicitons	maps and time series (air and water temps)	agency data	variance patterns / thresholds
	changes in tributary flows (high and flow)	model predicitons	maps and time series	agency data	variance patterns
	levels and flows changes	model - net basin supply predictions	precip levels and patterns	agency monitoring	
	subsequent changes to coastal and riverine habitats			citizen observations	
	flooding leading to nutrient load delivery and then algal blooms/hypoxia. Not just in obvious places (L. Erie) but also elsewhere e.g., L. Superior per Sterner et al. 2019	bloom forecasting e.g., NOAA models	Risk knowledge and to prepare includes better flood forecasting/floodplain maps, need to restore some wetlands and maybe even have forecasting tools that combine weather patterns with risk of floods that farmers can have access to so that they do not apply fertilizers immediately preceding a big rain event.		
Increased pptn intensity	increased runoff → beach pathogens	scenarios	response indicators	Monitoring Programs (agency)	physical attributes that suggest vulnerability to impact
	change in water levels				
forest fires	denuded watersheds and runoff	model prediction	beyon natural range of variation	agency monitoring program	likelihood and severity
Water level change / Change in Water Balance	water level extremes	Models; TEK	physical limnology / climate models / hydrology	Water level monitoring	trends
	evaporative processes				
EXTREME EVENTS - I THINK IT SHOULD BE UNKNOWN					
note: nutrient group will likely address this as well	algal bloom frequency	model and scenarios; TEK	Threat maps; SOGL indicators	Climate data (?), but response data lacking; GLOS instrumentation; water intake facilities; academic; studies; agency; Remote sensing	Change in underlying variance patterns; Presence / absence
	water quality degradation	model; historical data;	Historical examples / data;	monitoring (ongoing)	concentration levels; regulatory standards;
CLIMATE CHANGE - SUSPECTED					
biotic community shifts	changes in trophic structure / habitat shifts / habitat usage	bayesian analysis, modelling horizon scan	maps changing distributions		
Storm frequency & intensity	Erosion	Models ; TEK	geomorphologic processes	Site specific surveys; Remote sensing / imagery; Meterological forecasting ; Real time Monitoring	Trend analysis
Storm frequency & intensity	Resuspension	Models; TEK	geomorphologic processes	Meterological forcasting	
Storm frequency & intensity	Wave damage	Models; TEK	physical limnology	Meterological forcasting; Real time monitoring	
Mass human migration	increase pressure from human/behavioural	Demographic models	Quantitative social science	Census data	Trend analysis
erosion	reduced ice as protective barrier	model predictions	threat map	Monitoring programs (satellite imagery)	physical attributes that suggest vulernability to impact
	higher water levels	model predictions	threat map	data sources	water level criterion
runoff & nutrient changes	harmful algal blooms / cladophora? Water clarity	model - runoff predictions (unsure re nutrients)	maps of HAB frequency / variation and turbidity plumes (water clarity changes)	bloom, turbidity remote sensing = effects on endpoints (auqatic vegetation, fish distirbutions)	
CLIMATE CHANGE - UNKNOWNS					
MOVE TO UNKNOWNS: changes to wind patterns	changes to coastal habitats / suitability				
climate interactions with other stressor types		scenarios (e.g. war games)	plausible futures	ongoing monitoring	first detection; change in variance patterns;
global pandemic side effects	change in emissions? Less migration / interaction with CC effects				
etc. volcanic eruption	cooling / cloud cover change				
meteor strike	local destruction, creation of dust cloud				
acidification	chnages to habitat / species mortality and distn				
volcanic eruptions, geo engineering, population increase (migration) to the basin increased urbanization in pristine basins like Superior					
climate surprises	unpredicted events with unknown implicataion	scenarios	plausible futures	identification and mapping of drivers	tipping points
EXTREME EVENTS - I THINK IT SHOULD BE UNKNOWN					

ORDERED SYNTHESIS OF THREATS FROM 12/17/2020 WORKSHOP		RISK KNOWLEDGE		DETECTION / MONITORING / ANALYSIS	
		PREPARE FOR THREAT & STRESSOR IDENT.	IDENTIFY THREATS & STRESSORS	DETERMINE PRESENCE OF THREAT & STRESSOR	DECISION FOR TAKING ACTION
Threat Description (one word or short phrase)	**Example of Stressor Resulting from Threat**	**ForesightRisk Knowledge & Understanding**		**Detection MechanismsAnalysis**	
NUTRIENTS - KNOWN					
Agricultural P and N runoff from fertilizer/manure; shoreline urbanization and climate drivers too	HABs, hypoxia, excess macroalgae; changing nutrient ratios; impacts on vulnerable habitats with restricted circulation, long residence times, proximity to agricultural watershed tributary mouths, upwelling zones, urban areas, stratification-prone areas; examples: Green Bay, Apostle Islands, Georgian Bay, Saginaw Bay, L. St. Clair, L. Erie basins, Bay of Quinte; drowned river mouth systems (Muskegon Lake)	Watershed loading estimates, sources and speciation of P, in-lake responses; HABs bulletin (Erie), hypoxia alerts (Erie)	Determine acceptable loads and necessary BMPs to meet loads where they are excessive. Set up monitoring network and data management.	In situ watershed and lake water quality monitoring; satellite imaging; agricultural land use change analysis; crop production, fertilizer use, and livestock tracking	Unacceptable risk point in approaching exceedance of tipping points in loading drivers or lake response
Releases from CAFOs	HABs, hypoxia, excess macroalgae, pathogens	Map CAFOs and track changes; challenges in different jurisdictions and with operations below permit requirement cutoff	Monitor new or expanded meat packing plant locations, optimize monitoring programs to detect CAFO impacts, develop data management system with automated analysis.	In situ watershed and lake water quality monitoring; satellite imaging; geospatial livestock tracking and CAFO permit tracking; CAFO monitoring; microbial source tracking markers	Unacceptable risk point in approaching exceedance of tipping points in CAFO abundance, density, collective impact, river and lake response, and MST markers
Disruption of ecological network by invasives	Mussels disrupt nutrient transport, drive benthification, increased light penetration, macroalgae growth, offshore oligotrophication	Open lake monitoring (LIMNOS, GUARDIAN), CSMI cycle monitoring, benthic sampling and sled/video/sidescan surveys	Develop and expand systems for early detection and vector control	Monitoring of mussel occurrence and abundance, phytoplankton, prey fish, piscivores, and macroalgae; field experiments; long-term study sites and transects to collect time-series data.	Unacceptable risk point in approaching exceedance of tipping points in invasives presence, abundance, or impacts
Aging infrastructure (leaks, failures)	HABs, hypoxia, excess macroalgae, pathogens	Map and monitor outfalls; track progress on mitigation plans; track beach closures	Determine time horizons for major system failures in the event of deferred maintenance or upgrades (sewer collapse, bankruptcy, etc.); monitor the state of the largest systems	Review asset management plans for major Great Lakes cities and assess frequency/magnitude of CSO releases and dry-weather flow; track investments in system repairs and upgrades.	Unacceptable risk point in approaching exceedance of tipping points in infrastructure age, state, operational control, or finances
Modified precip patterns and hydrology	HABs, hypoxia, excess macroalgae, pathogens from pulsed loading (floods, esp. L. Superior)	Collect and analyze rainfall/snowfall and streamflow data, analyze storm statistics	Determine system tipping points by modeling and empirical analysis; assess states of systems relative to tipping points	Preciptation and streamflow monitoring networks	Unacceptable risk point in approaching exceedance of tipping points in runoff management capacity and infrastructure (pumps, dams, levees, erosion control)
Warming and shifting seasonality	Intensified HABs, stratification/hypoxia, more crop uptake from longer growing season and flatter hydrograph with smaller spring load and little snowmelt	Collect and analyze air, tributary, and lake temperature data (3D), soil moisture, snow cover, annual hydrograph changes, baseflow	Determine critical rates of change or thresholds beyond which substantial changes in stressor response are likely; assess system status relative to these	Temperature monitoring networks (wrather stations, stream gages, buoys, thermistor strings in lakes)	Unacceptable risk point in approaching exceedance of temperature tipping points in drivers or response
Internal loading (hypoxic release from sediments and upwelling/overturn)	Release of P, S, Mn, H2S feeds HABs and impacts drinking water; possible fish kill and bird kill impacts (L. Erie, 2012: https://www.huffpost.com/entry/lake-erie- dead-fish-birds-_n_1860723)	Monitor hypoxic extent, stratification, D.O., and dissolved nutrients, metals, and gases; track drinking water quality events	Determine critical rates of change or thresholds beyond which substantial changes in stressor response are likely; assess system status relative to these	In-lake sensors and raw water quality reports from drinking water plants	Unacceptable risk point in approaching exceedance of tipping points in concentrations or response
NUTRIENTS - SUSPECTED					
Nutrients other than P impacting occurrence, species, biomass, and toxicity	Nutrients other than P (including N) for occurrence, species, biomass, and toxicity--silica, iron, speciation, tracers (chloride), calcium decline, sulphur (may want to differentiate Ca declines in the water column vs potential increase in the watershed/ditches due to lime application to bind P).	Monitor major chemical species in lake basins and perform field studies, lab studies, and biogeochemical modleing to understand rates of change and thresholds	Determine thresholds for impacts of changes in major chemical species in lake basins and monitor to assess state relative to thresholds	Research projects; no monitoring programs specific to nutrient components of this driver	Unacceptable risk point in approaching exceedance of tipping points (too high or too low) in concentrations or ratios of drivers or response; possible actions unclear
Epizootics (e.g., avian botulism)	Linked to mussel-cladophora-sloughing-decay-microbes-gobie grazing-bird ingestion-death; example of Sleeping Bear Dunes loon and diving bird deaths (e.g., Kenow et al., JGLR, 2018)	Integrate fish kill and bird kill reporting systems with water quality monitoring programs; perform process understanding experiments to understand complex food web linkages	Determine critical rates of change or thresholds beyond which substantial changes in stressor response are likely; assess system status relative to these	USGS, FWS, MECP, etc. monitoring and event response	Reports of bird/fish deaths above background levels; linking to specific drivers can be tricky
Large-scale sediment disturbance (in-lake and in-watershed, Duluth flood and consequences)	Large sediment plumes or areas of resuspension in lakes due to extreme weather and subsequent HABs; possible recurrence in years following floods	Monitor weather data and satellite images for extreme events; develop rapid response capability to make field measurements during events	Determine critical magnitude beyond which substantial changes in stressor response are likely; monitor the multi-year impacts of events	Remote sensing community reports	Possible actions are limited, unless within-season loading can be adjusted
Nutrient loading from shoreline erosion during high water and storms	Greatest impacts likely in shallow embayments with exposure to large fetch and containing nutrient-rich shoreline deposits	Map areas of potential shoreline impacts and perform field experimenst to determine relative magnitude of inputs and effects	Determine critical rates of change or thresholds beyond which substantial changes in stressor response are likely; assess system status relative to these	Research projects; no monitoring programs specific to nutrient components of this driver	Possible actions are limited, unless shoreline protection can be implemented to reduce erosion, but other negative impacts of that
New invaders or expanding ranges	Pattern of local scale occurrence and then expansion	Continue to update GLANSIS and fund monitroing programs, including watch list development and range expansion mapping (e.g., mussels in L. Superior); link to vectors and drivers	Deploy existing best detection technology (eDNA, eRNA) in critical locations and determine critical thresholds for detection and abundance	ANS task force reports and associated monitoring programs	Action is only appropriate if control technologies exist (pesticides, herbicides, netting, integrated pest management)
Expansion of agriculture to the north with warming climate	Increased eutrophication of existing northern bays (Saginaw Bay, Green Bay, Georgian Bay) and appearance of worsening symptoms in less impacted bays (e.g., Grand Traverse, Chequamegon)	Monitor growing season zone changes, movement of northern or southern limit of crops, impacts of new, intensified or changing crop mixes on water quality	Determine critical percentage of agricultural development of expanding use watersheds, or critical crop types and rotations with associated nutrient loads	Track agricultural conversion in transitional watersheds (approximately 43-45 degrees N latitude)	Determine unacceptable risk point in approaching exceedance of tipping points in terms of agricultural acres or percentage of transitional watersheds
Expansion of net pen aquaculture	Localized eutrophication effects in the upper Great Lakes	Monitor number of operations, species, locations, and associated water quality	Determine carrying capacity of net pen sites using numerical models; monitor status of net pen deployment	Number of pens and of fish in them	If ecosystem impacts are detected, reduce scale of net pens or adjust locations
NUTRIENTS - UNKNOWN					
Extreme climate change impacts on lakes (year-round stratification, extreme events, winter change, non- linear change or trends)	Substantially expanded spatial extent and duration of HABs/hypoxia, positive feedback from internal loading, death of benthic organisms over large areas, common fish kills, collapse of fisheries, widespread impacts on source water quality for drinking water	Assess whether current monitoring programs and analyses are sufficient to detect incremental or catastrohpic changes in Great Lakes nutrient loading and ecosystem responses driven by climate change	Study past events and data to reconstruct critical thresholds; use numerical models to extrapolate to future conditions	Regular regional climate assessments, researchers who work in sentinel locations (Lake Erie, Green Bay, Saginaw Bay)	Unacceptable risk points in approaching exceedance of multiple tipping points in drivers and responses
Major episodic nutrient spills from failed infrastructure or industry	HABs and hypoxia, although possibly short-lived depending on frequency	Optimize or establish monitoring programs to detect events; model linkages with eutrophication phenomena	Study past events and data to reconstruct critical thresholds	Event-by-event reporting	Occurrence of events beyond a certain magnitude as reported by news media or others (e.g., Waterkeepers)
Inundation of shoreline district/major WWTP	HABs and hypoxia, although possibly short-lived depending on frequency	Assess shoreline areas of potential impact and state of mitigation or protection plans	Study past events and data to reconstruct critical thresholds; use numerical models to extrapolate to probabilistic future conditions	Event-by-event reporting	Occurrence of events as reported by news media
Mass CAFO lagoon failures from extreme rainfall events	HABs and hypoxia, although possibly short-lived depending on frequency	Develop approach to tracking lagoon integrity and capacity, as well as post-event assessment by aerial surveys or other means	Determine sensitivity of ecosystems to lgoon failure impacts and model impacts for spill response preparation	Event-by-event reporting; CAFO permit reporting; NGO monitoring	Forecast of exceedance of volume threshold for release
Widespread septic system failures due to rising water tables	HABs and hypoxia; would require long-term investment in upgrades and possible rural housing relocations	Consolidate information from county health departments and septic system contractors; monitor E. coli in streams	Monitor groundwater elevations and determine critical regions where septic systems are already failing or at risk	County and state/provincial health department studies and reporting; groundwater level data	Forecast of exceedance of septic failure threshold and potential public health crisis
Impacts of new industries (greenhouse expansion, new manufacturing with high-nutrient effluent)	HABs and hypoxia, although impacts likely managed by permitting	Watch trends in industry changes (new construction, market shifts, cross-boundary expansion, large-scale plant expansion) based on innovation, incentives, regulations, or consumer demand	Monitor impacts in other geographies to determine how impacts may be manifested in the Great Lakes	Reporting by permitting agencies, economic indicators, news reporting; no regular monitoring program in place	Unacceptable risk points in approaching exceedance of localized loading tipping points in driver

APPENDIX B – Experts Workshop Report (under separate cover)