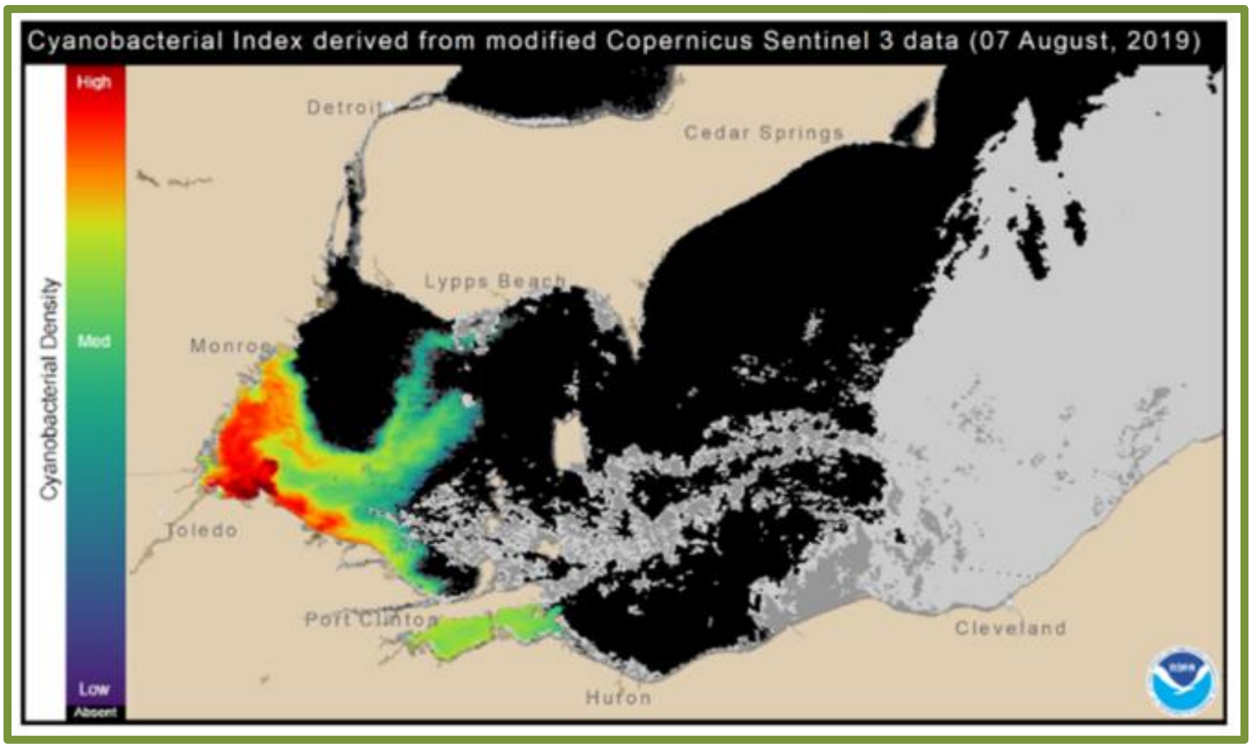
USE OF MODELING APPROACHES TO AFFECT NUTRIENT MANAGEMENT THROUGH ADAPTIVE MANAGEMENT



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On the cover: Cyanobacterial index from modified Copernicus Sentinel 3 data collected August 7, 2019. Grey indicates clouds or missing data. Source: Lake Erie Harmful Algal Bloom Bulletin, 08 August, 2019, Bulletin 12, NOAA - Great Lakes Environmental Research Laboratory.

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1.0 Summary

This report presents the findings and recommendations of the project, Use of Modeling Approaches to Affect Nutrient Management through Adaptive Management, led by the International Joint Commission (IJC) Great Lakes Science Advisory Board-Research Coordination Committee (SAB-RCC). This project grew from the demand to advance the agenda of Annex 4 of the Great Lakes Water Quality Agreement (GLWQA) to solve the priority water quality issue of eutrophication and harmful algal blooms in the western and central basins of Lake Erie. The objective of the project was to compile and synthesize the current state-of-the-science on watershed and lake modeling that has been used to set binational targets for nutrients and as the basis for establishing domestic action plans to tackle the Lake Erie eutrophication problem. This report fulfills the gap relevant to Annex 4 on how to maximize the value of modeling, research, and monitoring to support decision-making in the face of uncertainty and to adapt as a scientific learning process.

The IJC contracted services of the University of Toronto's Ecological Modeling Laboratory to advance the research and management focused on Lake Erie, through the integration of mathematical watershed and lake modeling with adaptive management. Project outcomes are available in the technical report, *Development of an Integrated Modelling Framework to Guide Adaptive Management Implementation in Lake Erie* (Appendix I). This technical report is summarized and synthesized in the following IJC SAB-RCC report to provide advices on using modeling in an adaptive management framework to assess outcomes of management actions to reduce nutrient loading.

Based on the findings, the SAB-RCC makes the following recommendations.
The technical recommendations include to:

- Maintain the multi-model approach, but enhance modeling effectiveness by:
    - Coordinating better with other models in covering multitude of scenarios.
    - Continuously incorporating new data upon availability.
    - Improving quantification of key ecological processes.
    - Reducing uncertainty in model forecasting.
- Establish an integrated system of watershed and lake models which:
    - Includes ecological response indicators.
    - Is consistent in temporal and spatial scales between watershed and lake models.
    - Incorporates sediment transport including erosion and deposition.
- Improve models by:
    - Enhancing and designing monitoring programs based on appropriate metrics and scales to measure changes in nutrient loading and ecological response.
    - Identifying a suite of appropriate metrics and evaluate model performance at multiple scales of resolution.
    - Calibrating and evaluating watershed models at finer temporal and spatial scales to better assess the role of episodic events and land-use practices.
    - Improving watershed models' capability in evaluating and estimating management actions required to meet new loading reduction targets.

- Enhancing capability in accounting for the role of legacy phosphorus in driving algal blooms and toxicity levels of harmful algal blooms.
- Considering additional watershed models that may better capture urban areas.
- Enhancing predictive capability by improving the understanding of key phytoplankton growth processes, internal nutrient sources, the role of nitrogen, interactions between phytoplankton and *Cladophora* growth, role of dreissenids in nutrient cycling and availability, and zooplankton interactions and connection to upper food web.

The institutional recommendations include to:

- Define Lake Erie's eutrophication problem using the Great Lakes nutrient adaptive management (GLNAM) Framework. This involves using an integrated watershed and lake modeling approach on a long-term basis. This would also involve setting up an arrangement to institutionalize the Framework with collaboration across government agencies and jurisdictions.
- Use the GLNAM Framework to inform coordinated planning and implementation of Lake Erie's watershed/lake modeling and nutrient reduction management. This would including identifying key players currently participating in implementing GLNAM Framework, identifying gaps and unmet needs that must be addressed to further advance the GLNAM Framework, and providing status reports on progress achieved.
- Establish and integrate monitoring programs as part of the GLNAM Framework on a long-term continuous basis and evaluate results to learn and adjust research, modeling, and management decisions.
- Update models on a regular basis with principles underlying an adaptive management approach to reduce uncertainty and better representation of an improved understanding of ecological dynamics.
- Institutionalize the GLNAM Framework by establishing the GLWQA as the binational authority to implement GLNAM Framework through Nutrients Annex 4, including identification of agency and institutional partners as well as programs which are responsible for the development and carrying out the GLNAM Framework. These partners/programs should have identified experts, resources, and stakeholders with an established cycle of adaptive management to advance model improvement and to reduce uncertainty in the decision making process.
- Identify and establish funding streams to support the GLNAM Framework through existing and/or new authorizations and appropriations.
- Establish justification for the GLNAM Framework, as a key element in maintaining GLNAM Framework on a long-term and sustainable basis, by quantifying benefits of healthy ecosystem services and providing justification for investment in institutionalizing the GLNAM Framework.

2.0 Overview of Issues

The International Joint Commission (IJC), in its role to encourage cooperation in the management and protection of boundary waters in Canada and the United States, is responsible for assessing progress to restore and protect Great Lakes waters, guided by the Great Lakes Water Quality Agreement (GLWQA or Agreement). The Great Lakes Science Advisory Board Research Coordination Committee (SAB-RCC), under the auspices of the IJC, provides research and scientific advice to the IJC related to the identification, evaluation and resolution of emerging water quality issues in the Great Lakes Basin ecosystem. The SAB-RCC also compiles and synthesizes research activities and findings pertinent to the GLWQA.

Under the amended 2012 GLWQA, Nutrients Annex 4 (one of 10 Agreement annexes) was established to advance scientific research and related guidance on how to approach solving the priority water quality issue of eutrophication, with an initial focus on the western and central basins of Lake Erie. To advance the agenda of Annex 4, the IJC SAB-RCC undertook the project to: 1) compile and synthesize the current state-of-the-science on watershed and lake modeling related to the Lake Erie eutrophication problem; and 2) provide advice on using modeling in an adaptive management framework to assess outcomes of management actions to reduce nutrient loading.

Lake Erie is the shallowest of the five Great Lakes, characterized by productive waters and a valuable fishery. A particular benefit of the lake is the safe drinking water provided to 11 million people. The shallow depth coupled with intensive land use in its watershed make the lake susceptible to eutrophication problems, including harmful algal blooms (HABs) and hypoxia (low dissolved oxygen), which can threaten drinking water supplies. HABs and hypoxia are symptoms of excessive nutrient loading (phosphorus (P) and nitrogen (N)), driving a high level of algal production or eutrophication.

The problem of eutrophication is not new to the Great Lakes; solving problems caused by nutrient loading has been identified as a priority issue under the GLWQA since its inception in 1972. In addition to HABs and hypoxia, eutrophic conditions can affect drinking water taste and odor, and decaying organic matter deposits from *Cladophora* (filamentous algae) gather along the beaches. While phosphorus loading has been identified as the major stressor causing excessive algal production, nitrogen has been also implicated in triggering HAB toxicity. Other stressors identified as exacerbating eutrophication problems include climate change and invasive species.

To reduce eutrophication symptoms, the 1978 amendments to the GLWQA established phosphorus load targets for each of the Great Lakes. Management actions to meet these targets were directed primarily at point sources, such as sewage treatment plants and industrial outfalls. Point source nutrient control was considered successful with observed decreases in eutrophication symptoms. Eutrophication problems, however, reemerged in Lake Erie in the early-2000s, as well as in other locations around the Great Lakes. Since the 1970s, the source of nutrient loading problems has gradually shifted from point to nonpoint sources, including agricultural and urban runoff – posing new management challenges.

3.0 A New Era of Binational Policy and Management to Protect and Restore the Great Lakes

Under the 2012 GLWQA, the IJC is charged with providing recommendations on a triennial basis to guide the Canadian and United States federal governments in meeting Agreement objectives. As reported in the first Triennial Assessment of Progress under the 2012 GLWQA (IJC 2017), the water quality of Lake Erie was assessed as "unacceptable" given the persistence of eutrophication impacts of HABs in the western, hypoxia in the central, and *Cladophora* in the nearshore of the east basins of the lake. To mitigate eutrophication, policy and management tools continue to be developed, including Nutrients Annex 4 guided by the principle of adaptive management, presented under Article 2.4.b of the GLWQA (Canadian and U.S. Governments, 2012, p. 6).

> **Great Lakes Water Quality Agreement Article 2.4.b: Principles and Approaches**
>
> "Adaptive management – implementing a systematic process by which the Parties assess effectiveness of actions and adjust future actions to achieve the objectives of this Agreement, as outcomes and ecosystem processes become better understood."

Binational commitments (agreed to by the United States and Canada) established under the 2012 GLWQA Nutrients Annex 4 include the following (Binational.net, accessed March 2019):

- By 2016, develop binational substance objectives for phosphorus concentrations, loading targets, and loading allocations for Lake Erie.
- By 2018, develop binational phosphorus reduction strategies and domestic action plans to meet the objectives for phosphorus concentrations and loading targets in Lake Erie.
- Assess, develop and implement programs to reduce phosphorus loadings from urban, rural, industrial and agricultural sources. This will include proven best management practices, along with new approaches and technologies.
- Identify priority watersheds that contribute significantly to local algae development, and develop and implement management plans to achieve phosphorus load reduction targets and controls.
- Undertake and share research, monitoring and modeling necessary to establish, report on and assess the management of phosphorus and other nutrients and improve understanding of relevant issues associated with nutrients and excessive algal blooms.

An important milestone achieved under the 2012 GLWQA Nutrients Annex 4 is a binational agreement to reduce phosphorus loads by 40 percent. The GLWQA Nutrients Annex 4 subcommittee was set up in 2013 to develop updated phosphorus targets to achieve six Lake Ecosystem Objectives specified in the Annex (Canadian and U.S. Governments, 2012, p. 31). A working group was formed to develop new targets. The group used nine existing water quality models, operating on differing spatiotemporal scales, to predict changes in three endpoints (HABs, hypoxia, *Cladophora*) under differing phosphorus loading scenarios. The updated targets were proposed in 2015 and finalized in 2016. The final report on the new nutrient target loads was submitted to the US Environmental Protection Agency in 2017 (Binational.net, accessed March 2019). In conjunction with Annex 4, the 2012 GLWQA calls for an adaptive management approach under the GLWQA Science Annex 10 to serve "as a framework for organizing science to provide and

GLWQA Nutrients Annex 4: Lake Ecosystem Objectives

1. Minimize the extent of hypoxic zones in the waters of the Great Lakes associated with excessive phosphorus loading, with particular emphasis on Lake Erie;
2. Maintain the levels of algal biomass below the level constituting a nuisance condition;
3. Maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the Great Lakes;
4. Maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the waters of the Great Lakes;
5. Maintain an oligotrophic state, relative algal biomass, and algal species consistent with healthy aquatic ecosystems, in the open waters of Lakes Superior, Michigan, Huron and Ontario; and
6. Maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

monitor the effect of science-based management options" towards improving Great Lakes water quality (Canadian and US Governments, 2012, p. 53). In implementing an adaptive approach, a premium is placed on learning in an iterative process whereby the outcomes of research and science-based, ecosystem management provide new information to update the next round of program execution to address ongoing ecosystem issues.

Integral to the commitments of the Canadian and U.S. governments under the 2012 GLWQA Nutrients Annex 4 and Annex 10 are the Domestic Action Plans (DAPs) (Binational.net, accessed March 2019). The DAPs require development and implementation of strategies to achieve the 40 percent phosphorus reduction goal for Lake Erie. The Canadian and U.S. DAPs finalized in February 2018 have identified actions for phosphorus reduction and partners to implement them, with performance measures to evaluate progress. The DAPs must integrate an adaptive management approach as agreed upon by the governments of Canada and the United States in the 2017-2019 Great Lakes Binational Priorities for Science and Action (Binational.net, accessed April 25, 2019); thus providing the platform for revision of each DAP every five years, starting in 2023.

4.0 Use of Modeling Approaches to Affect Nutrient Management through Adaptive Management

A variety of mathematical models have been developed for Lake Erie to evaluate the relationships between watershed physical geography, land use patterns and sources of phosphorus loading to better understand ecological interactions and processes. The IJC recognizes the importance of modeling to advance our understanding of the relationship between phosphorus loading and eutrophication, and the ecological response of the lakes. This improved understanding would help the Nutrients Annex 4 subcommittee to develop updated phosphorus targets with more scientific data and less uncertainty. The modeling would also provide the basis to affect nutrient management through adaptive management.

To this end, the IJC SAB-RCC established the project, Great Lakes Nutrient Adaptive Management (GLNAM), implemented primarily with the technical expertise provided by contracted services of University of Toronto's Ecological Modeling Laboratory. The project was guided by four objectives to assess the current state of modeling of Lake Erie and its watershed and integrating adaptive management as part of the approach. Outcomes from the contracted project are available in the technical report titled, *Development of an Integrated Modelling Framework to Guide Adaptive Management Implementation in Lake Erie* (Appendix I).

This final report on the overall GLNAM project is a product of the IJC SAB-RCC work group to synthesize and summarize the contracted project work, featuring findings and highlights. This report also presents recommendations for next steps on using modeling approaches through adaptive management to affect ecosystem management addressing nutrient loading and related

The IJC SAB RCC project was guided by the following objectives:

- Conduct an inventory of current or recent modeling activities that are potentially capable to integrate the outcomes of management actions for Lake Erie, including watershed land use practices, ecosystem health, human health, and socio-economic outcomes.
- Meet the need of integrating adaptive management approach called by the 2012 amended GLWQA to move forward effectively on the Great Lakes water quality issue regarding phosphorus loading and its relationship to eutrophication and ecosystem health.
- Address how adaptive management and environmental modeling can be integrated as an approach that will ultimately be used to identify the levers needed to pull in effecting ecosystem management.
- Provide advice on how progress towards phosphorus reduction goals can be measured and communicated in an adaptive management framework.

eutrophication problems in Lake Erie.

5.0 Making Management Decisions under Uncertainty

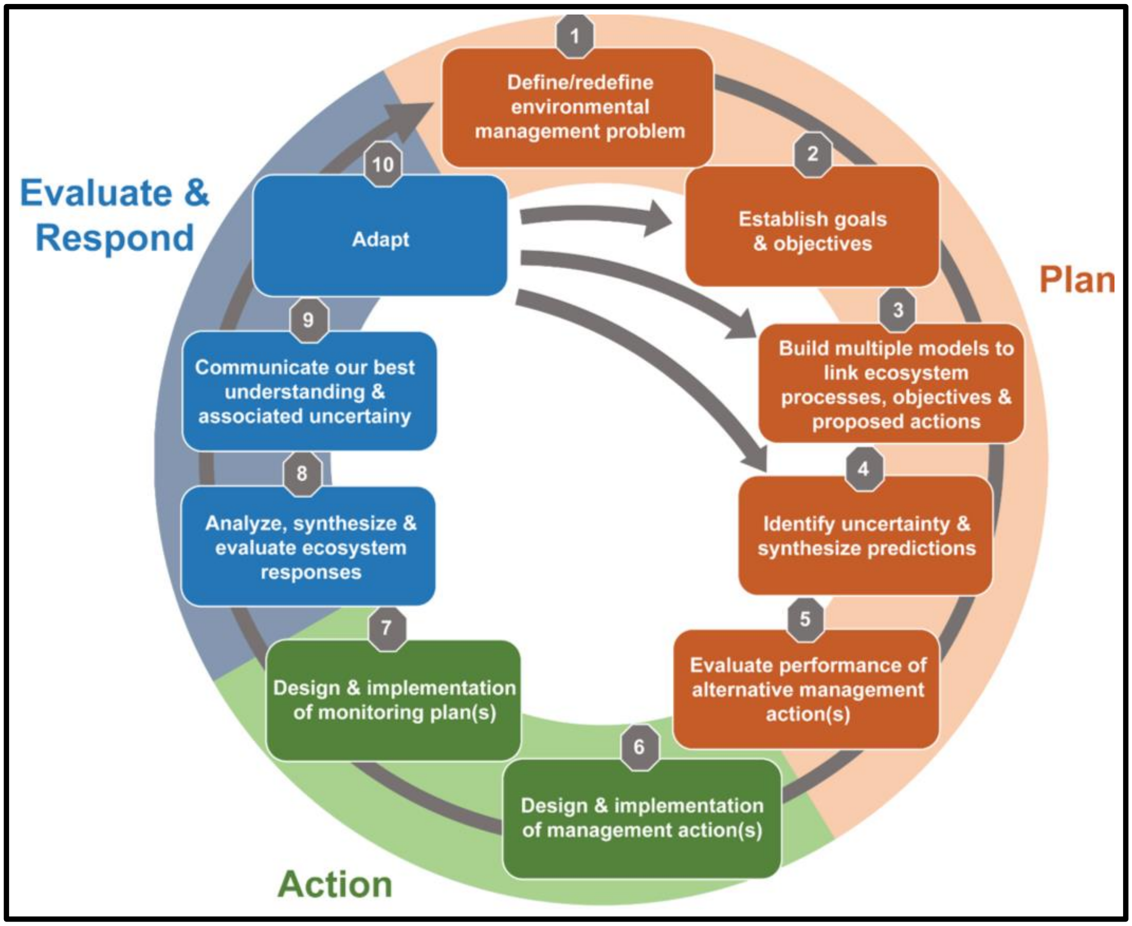
A challenge addressed by coupling environmental modeling with adaptive management

The fundamental purpose of modeling relationships between nutrient loading and the ecological response of Lake Erie is to generate sufficient information to continually improve decision making on management actions to mitigate eutrophication problems. The decision-making process determines a suite of research and management practices to reduce nutrient loading. For example, a group of scientists, resource managers and policy makers are determining the changes needed in agricultural practices to reduce nutrient runoff by 40 percent, as established under the Nutrients Annex 4 of the 2012 GLWQA. In making these decisions the intent is to maximize the best possible outcomes by decreasing the intensity and scope of HABs and limiting dissolved oxygen depletion in the lake.

Uncertainty, however, is inherent in environmental decision making and affects the likelihood that the desired outcomes actually occur, coupled with the eventual consequences (costs and benefits) derived from different outcomes. Uncertainty stems from how well the models represent the chemical, physical and biological processes (e.g., underlying eutrophication) as well as model inputs, such as precipitation or fertilizer application. A significant force driving uncertainty is the occurrence of unexpected events, such as extreme precipitation causing excessive nutrient runoff. Given the ubiquitous uncertainty surrounding the study of environmental systems, the GLNAM approach is built on the premise that modeling needs to be conducted iteratively in conjunction with an adaptive management approach. The GLNAM approach is essential to advance model improvement and thereby reduce uncertainty in the decision-making process. With each iteration, model outcomes are compared to observations and the models are updated to incorporate new information. This updating process helps us to better understand the complexity of different stressors causing eutrophication (e.g., nutrient loading, precipitation, climate change, invasive species), which should lead to improved decision making.

The iterative updating process of adaptive management formalizes a *learn-by-doing* approach in addressing nutrient loading as a primary driver of eutrophication. As an outcome of the GLNAM project that is put forth in the technical report and illustrated in Figure 1, "Adaptive management offers flexibility in making decisions in the face of uncertainty as scientific learning progressively advances from research, monitoring, and impartial evaluation of the past and ongoing management actions" (Arhonditsis et al., 2019a).

Figure 1: The iterative monitoring-modelling-assessment cycles of adaptive management to reduce environmental uncertainty. In Lake Erie, we evaluate steps 4 and 5 in order to design steps 6 and 7 (Arhonditsis, et al., 2019a).



6.0 The Great Lakes Nutrient Adaptive Management Project

6.1 Improving models' predictability and uncertainty to advance nutrient management through adaptive management

6.1.1 Rationale

The overarching goal of the IJC GLNAM project is to develop a process of applying environmental modeling to inform science-based management decisions, through an adaptive management approach. In so doing, there is a need to track progress through regular review of the models to improve our understanding of the relationship between phosphorus loading and Lake Erie's ecological responses. Each of these models has different strengths and weaknesses, including predictive capacities.

GLNAM Project Objectives

a) Establish a better understanding of how ecological interactions in the Great Lakes are affected by the surrounding watershed physiography, land use, and modeling P/N loading;

b) Learn more about the mechanisms underlying ecosystem function (e.g., eutrophic conditions focused on the scope and intensity of algal blooms coupled the toxicity (cyanobacteria) of harmful algal blooms); and

c) Predict the response of lake/tributary systems to reductions in nutrient loading.

In the practice of reliable ecological forecasting, it must be recognized that "there is no true model of an ecological system" (Scavia, et al., 2016), given the uncertainty inherent in each individual model. The underlying rationale for the GLNAM approach is to address the reality that uncertainty does exist in ecological forecasting upon which management decisions are based. Adaptive implementation (or *learning-by-doing*) is often considered the only defensible environmental management strategy, as it promotes an iterative implementation process to deal with the uncertainty of ecological forecasts and to mitigate the impact of inefficient management plans. "Environmental modeling is one of the pillars of the adaptive management process" (Appendix I), whereby the initial forecasts of management actions are augmented with post-implementation monitoring and the resulting integration of monitoring and modeling provides the basis for revised management actions.

6.1.2 Approach

The core of the GLNAM project was based on a technical analysis of recent environmental modeling work, as conducted by Arhonditsis and his team (Appendix I; Arhonditsis, et al., 2019a, b), with a focus in the following areas:

- A literature review to ensure a comprehensive understanding of the major causal linkages underlying phosphorus loading and eutrophication in Lake Erie.

- An inventory of models including watershed and lake models used to represent relationships between phosphorus loading, eutrophication and underlying ecological processes.
- Performance assessment of these models regarding their strengths and weaknesses to establish a roadmap for the GLWQA Nutrients Annex 4 to set priorities for model improvement.
- An evaluation of the model forecasting capability and the likelihood of mitigating eutrophication based on changes in agricultural management practices to reduce phosphorus loading in the watershed.
- Identification of knowledge gaps in determining monitoring assessment objectives on which to base relevant performance indicators can be used in measuring progress.

> "Consistent with the scientific process of progressive learning, the present study aimed to assist the next iteration of the modeling framework by impartially identifying strengths and weaknesses of the existing models and pinpointing essential structural augmentations and research and monitoring priorities in order to integrate watershed and aquatic ecosystem processes."
> (Appendix I, p. 52)

6.1.3 An operational ensemble framework to link adaptive management into the process of learning-by-doing

In recognizing the existence of uncertainty in environmental modeling, a multiple modeling approach was used to not only help quantify uncertainty, but also increase knowledge and understanding of underlying ecological processes (Arhonditsis et al., 2019a).

To advance a multi-modeling approach, the following methodological steps were taken:

- Identify the conceptual or structural differences of existing models to determine the diversity that collectively characterized the multi-model ensemble.
- Determine the most suitable calibration/validation domain and resolution to evaluate model performance in time and space.
- Establish an optimal weighting scheme for individual models when integrating their corresponding predictions.

The purpose of taking a multi-modeling based predictive approach that is coupled with the iterative approach of adaptive management is to progressively improve management decisions by reducing uncertainty in the management of nutrient loading affecting eutrophication in Lake Erie and the other Great Lakes.

6.1.4 Project workshop

This project also employed a workshop involving the project management and technical teams. Through presentations and facilitated dialogue, a common understanding was established among project participants on the project methodology, preliminary findings, and future priorities in the application of environmental modeling and adaptive management to nutrient reduction in the western basin of Lake Erie. The following questions/issues were explored during the workshop:

- What are we learning about watershed and lake models and the potential of environmental modeling in nutrient management through the adaptive management process?
- What is the role of adaptive management in planned phosphorus reductions?
- What are the gaps in our current set of watershed and lake models that need to be addressed to better inform nutrient management?
- What are priority data and knowledge gaps/weaknesses in model performance that need to be addressed?
- What are the results/answers from recent modeling efforts of the ecological relationships in Lake Erie?
- Finding the path to having a robust set of watershed and lake models that can be regularly updated and used to inform nutrient management in the Great Lakes.
- How do we approach building an institutional framework for collaboratively applying these models on a regular cycle coupled within an adaptive management approach?

6.1.5 Project report

To document the proceedings of the GLNAM project, a comprehensive report was prepared for submission to the IJC under the direction of the IJC SAB-RCC co-chairs with input provided by the GLNAM workgroup members. Highlighted are findings presented in the technical report (Appendix I) as well technical and institutional recommendations based on outcomes generated throughout the conduct of this project.

6.2 Findings of model evaluation and integration of adaptive management

This section is directly based on findings from the GLNAM project technical report, *Development of an Integrated Modeling Framework to Guide Adaptive Management Implementation in Lake Erie* (Appendix I).

6.2.1 Overview

To address the persistent eutrophication problem in Lake Erie, a diverse set of watershed and lake models have been developed to improve our understanding of processes causing eutrophication primarily driven by nutrient (P and N) loading. The models are also used to make predictions to support management decisions on nutrient reduction needed to mitigate eutrophication. The performance of these models was evaluated in the context of an adaptive management approach to improve future modeling efforts, particularly to reduce model uncertainty. Project findings (presented in Appendix I), provide detailed guidance to improve modeling strategies through the iterative monitoring-modeling-assessment cycles of adaptive management. As noted in the report (p. 52), “Consistent with the scientific process of progressive learning, the present study aimed to assist the next iteration of the modelling framework by impartially identifying strengths and weaknesses of the existing models and pinpointing essential structural augmentations and research/monitoring priorities in order to integrate watershed and aquatic ecosystem processes.”

6.2.2 A multi-model ensemble is essential to address uncertainty for ecosystem modeling and related management decisions

A variety of mathematical models have been developed for Lake Erie based on a range of conceptual and methodological foundations, each with respective advantages and disadvantages. Modeling efforts to date have significantly advanced our understanding of the processes causing eutrophication in Lake Erie involving factors such as watershed physical geography, land use patterns, phosphorus loading, as well as the response to management actions to reduce phosphorus loading. Not only does this understanding need to be further advanced, but it is also necessary to evaluate the uncertainties inherent in modeling watershed and lake ecosystems and related management decisions.

To justify the inclusion of a model in a multi-model ensemble approach, the following methodological steps are recommended:

- Identify conceptual and structural differences of existing models to determine diversity collectively characterizing the multi-model ensemble.
- Determine the most suitable standards (e.g., calibration/validation domain and spatial/temporal resolution) for evaluating model performance to justify inclusion of a model in the ensemble.
- Distinguish among the different sources of uncertainty and how this should be interpreted in making management decisions.
- Establish an optimal scheme to assign weights to individual models.

Inventory of multi-model ensemble for the Lake Erie

A wide range of data driven and process-based models spanning the entire complexity spectrum were deployed.

- The two empirical models are the UM (University of Michigan) /GLERL (Great Lakes Environmental Research Laboratory) Western Basin HAB model and NOAA Western Basin HAB model.
- The six process-based models are Total Phosphorus Mass Balance Model (TPMB), 1-Dimensional Central Basin Hypoxia Model (1D-CBH), Ecological model of Lake Erie (EcoLE), Western Basin Lake Erie Ecosystem Model (WLEEM), the Estuary and Lake Computer Model-Computational Aquatic Ecosystem.

6.2.3 Watershed modeling using the soil and water assessment tool (SWAT)

To quantify the relative importance of the mechanisms that determine phosphorus loading in the Maumee River watershed, five independent applications of the Soil and Water Assessment Tool (SWAT) (Arnold *et al.,* 1998), a process-based, watershed modeling framework, have been conducted. The use of independent assessments has facilitated a range of expert-

The SWAT model is a watershed model basing its predictive capacity on a wide array of physical, chemical, and biological processes that can drive downstream flow and nutrient export (loading conditions). It was found in the course of the project that the applications of SWAT modeling coalesced in their projections and identified higher total phosphorus loading rates from the northwestern and southern parts of the Maumee River watershed, as was as tendency for higher dissolved reactive phosphorus export rates at the predominantly agricultural central area.

based decisions to run the models, capturing some of the uncertainty in model-based estimation. The SWAT models performed well for aggregated flow and phosphorus loading (i.e., single downstream station, evaluated monthly) but were not evaluated at finer spatial or temporal scales. The models were also used to evaluate high-risk areas for phosphorus export and agreed in their assessment; the ground-truthing for this exercise, however, was limited. This strategy is useful in capturing some of the uncertainties needed to improve our understanding of the role of watershed attributes and function in phosphorus loading. However, analyses examining potential best management practices (BMPs) in the watershed have not provided strong evidence that the updated phosphorus loading targets—40 percent reduction from 2008 loads, which is 860 metric ton of total phosphorus (TP)—will be achieved.

6.2.4 Future needs to improve SWAT modeling

Technical analysis indicates that current modeling work in the Maumee River watershed could be strengthened by addressing the following:

- Evaluate nutrient loading predictions with a finer temporal/spatial resolution to include:
    - Integrating the impact of episodic/extreme precipitation events that can lead to surface runoff that carries increased nutrient loads and presumably modulate the water quality conditions downstream, and
    - Expanding ground-truthing based on a broader scale of multiple sites across the Maumee River watershed to consider factors such as fertilizer/manure application rates or spatial drainage of soils.
- Provide predictions regarding the long-term achievability of the phosphorus loading targets through the application of best management practices, such as fertilizer reduction, tillage replacement, land use conversion, and wetland/buffer restoration. Recommended methodological next steps:
    - Recalibrate the existing SWAT applications to consider both baseline and event-flow conditions (e.g., extreme precipitation) and daily nutrient concentration (not loading) variability in multiple locations rather than from a single downstream site.
    - Integrate legacy phosphorus as a factor in predicting phosphorus loading into the modeling process to account for the phosphorus accumulation in the sediments.
    - Integrate capacity to reproduce the critical hydrological and transformation mechanisms modulating the dissolved reactive phosphorus (DRP) in the Lake Erie basin (e.g., simulation of channel routing and urban BMP scenarios).
    - Improve our understanding of the watershed processes associated with the nitrogen cycle, given the relatively high level of total nitrogen in the dissolved phase that can be transported by both overland and subsurface flow paths.
- Detailed land use information and land management practices are needed for applying such a model at a larger scale.

6.2.5 SPARROW models (Spatially Referenced Regressions on Watershed attributes)

The Spatially Referenced Regressions On Watershed attributes (SPARROW; Smith et al., 1997) is considered an empirical model that is data-driven. It is not meant to be used as a predictive tool, but rather as an investigative and environmental auditing tool to depict basin-specific rather than broad-scale regional, nutrient loading conditions. Empirical, SPARROW-like models can offer complementary benefits to the process-based SWAT models. Such models validate spatial delineation of nutrient "hot spots" and clarify the export rates of nutrients from different land use types (e.g., the fate of fertilizers exported from fields to streams). They can also be used in conjunction with process-based models, such as SWAT, in the Maumee River watershed to serve in narrowing the uncertainty of processes/fluxes parameterized by the process-based models. Very importantly, models in the empirical family can assist in increasing the number of addressed research questions, recognizing that the model will only be as good as the available data.

6.2.6 Lake modeling of ecological relationships of Lake Erie

Modeling of Lake Erie has closely followed the recommended methodological protocol for developing models intended to support management decisions. Performance of the lake models used to update the phosphorus targets was consistent with what is broadly reported in the peer-reviewed literature. An identified issue of concern is that, given the complexity of existing models of Lake Erie, there needs to be more attention focused on the quantification of uncertainty.

In a comparison of model outputs to observations, physical processes (temperature and dissolved oxygen variability) were generally well captured by the models, with relatively good performance. This was less so with chemical and biological variables, as evidenced by decreased performance in nutrient predictions and further decreased performance for phytoplankton and zooplankton abundance. Another issue identified related to performance involves model resolution. Historically, the individual lake models have been evaluated at fairly course spatial and temporal scales (lake basin, seasonal). This has been considered justified because decision making was done at the aggregate scale. In contrast, models for this project were evaluated at finer scales (e.g., specific locations on a given day), consistent with the scale of model prediction, finding modest predictive ability for the lake responses of particular interest.

Also examined was the ability of existing lake models of Lake Erie's central basin to predict hypoxia response to phosphorus load reduction that may be limited due to a lack of information about key sediment processes. The inattention to seasonal considerations in the models was also examined, since research has documented high algal blooms under the ice in the west basin and high algal productivity across Lake Erie during the winter. High winter phytoplankton productivity concomitant with low zooplanktonic and bacterial productivity has led to hypotheses that summer hypoxia in Lake Erie's hypolimnion is due to algal blooms that occurred months earlier in the lake and not linked to summertime HABs that are constrained physically to the epilimnion (Wilhelm et al., 2013; Reavie et al., 2016). Similarly, the ability to predict *Cladophora* response in the eastern basin is limited by lack of knowledge on factors driving *Cladophora* growth (note that the inability to predict *Cladophora* was recognized in the GLWQA Nutrients Annex 4 report, resulting in the deferral of phosphorus target development of *Cladophora* control. Also, the models could not predict fishery response, particularly in the eastern basin, to nutrient load reduction. Concern over offshore productivity decline is addressed in another IJC workgroup project (IJC SPC Workgroup, 2019).

6.2.7 Research priorities identified for the next iteration of lake modeling

The following research and modeling needs are identified to further reduce predictive uncertainty in lake models related to the ecological response, to phosphorus loading, such as HABs, and the extent/duration of hypoxia and *Cladophora*:

- Develop model scale assessment based on a finer resolution in time and space, but maximum or average conditions are needed to inform management decision and target setting.
- Improve understanding of factors affecting phytoplankton ecology, such as the extent to which phytoplankton growth depends on internal nutrient sources (such as excreted material from dreissenids or zooplankton, internal P loading from sediments), role of nitrogen, linkages of dreissenids-nutrient-algae, and phytoplankton-zooplankton interactions, especially in the near shore zone.
- Improve understanding of the factors triggering HAB formation and toxicity. Although the roles of different forms and bioavailability of phosphorus (e.g., dissolved reactive and particulate fractions of TP loads) have considered and evaluated during the initial setting of HAB related load targets, further improvement in understanding of factors triggering HAB formation and toxicity is needed.
- Investigate the role of meteorological conditions, such as warmer temperatures and calmer summer conditions.
- Investigate the potential relationship between nitrogen and toxin-producing *Microcystis* coupled with the increasing *Microcystis* seed colonies.
- Strengthen predictions on the extent and duration of hypoxia and *Cladophora* growth by expanding our knowledge on sediment diagenesis processes.
- Establish a high-resolution monitoring of the nearshore zone to provide critical information regarding the causal linkages between the abiotic conditions (e.g., soluble reactive phosphorus (SRP), light, temperature) and the internal phosphorus content and sloughing rates in *Cladophora* mats.
- Evaluate the roles of winter diatom growth for summer hypoxia in the central basin.

6.2.8 Making the case for an adaptive management approach in conjunction with watershed and lake modeling to affect ecosystem management

Adaptive implementation, referred to as *learning-by-doing*, is often considered the only defensible environmental management strategy because it promotes an iterative implementation process to deal with the uncertainty of ecological forecasts and to address the impact of inefficient management plans. As discussed in the technical report, environmental models are one of the pillars of the adaptive management process, whereby the initial forecasts of management actions are augmented with post-implementation monitoring, and the resulting integration of monitoring and modeling provides the basis for revised management actions and research (Arhonditsis, et al., 2019b).

The framework of adaptive management (Fig. 2) offers a structure for an iterative approach to reducing uncertainty inherent in predictions related to ecological responses to phosphorus loading, such as eutrophication, and related management decisions (e.g., achievability of nutrient loading targets, alleviation of hypoxia, and likelihood to control *Cladophora* growth). The iterative process of *monitoring-modeling-assessment* can reduce the uncertainty of the initial forecasts of management actions by updating the forecasts using lessons learned from post implementation monitoring data and assessments (Fig. 1).

Key issues to consider in implementing an adaptive management approach for nutrient management in Lake Erie include:

- *Determining model resolution and monitoring program:* Fundamental to implementing an adaptive management approach is the determination of appropriate modeling metrics and scales of expression along with the design of a monitoring program to track progress on the environmental response of Lake Erie in both time and space.
- *Archiving relevant data:* Develop systematic records for variables representing direct causal factors related to eutrophication (e.g., phosphorus content in *Cladophora* tissues, characterization of organic matter and phosphorus bound to sediments).
- *Documenting socioeconomic benefits:* Develop a rigorous framework that quantifies the socio-economic benefits gained from an ecosystem that is well-functioning and healthy. This strategy provides incentive for continued investments in research and management needed in the protection of Great Lakes ecosystems and water quality for future generations.

7.0 Recommendations

To ensure an effective, long-term research and management approach to address eutrophication issues in Lake Erie and the other Great Lakes, the IJC SAB-RCC proposes the following recommendations:

7.1 Technical recommendations

To advance environmental modeling in supporting nutrient management of Lake Erie, the next steps should focus on “augmenting” the existing models rather than “reinventing the wheel” by building new models. Key to this process is to design augmentations that will effectively complement and improve the existing models.

- Ensemble modeling:
  - Maintain and improve the ensemble character of modeling and continue research to better coordinate the diversity of watershed and lake models in Lake Erie.
  - Use the diversity of models in the ensemble approach to better understand and quantify key processes in the lake and watershed.
  - In taking an ensemble approach, efforts should be made to quantify and reduce uncertainty in ecological forecasting in response to nutrient loading/concentration and other drivers.
- Couple lake and watershed models:
  - Establish an integrated system of watershed and lake models with ecological response indicators.

    - Establish/maintain consistency between the temporal/spatial scales of the watershed models with that of the lake models to serve as boundary condition inputs to the lake models.
    - Incorporate sediment transport along with erosion and deposition in the watershed and lake models.
- Monitoring Program: Design a monitoring program based upon appropriate metrics and scales to measure changes in nutrient loading and the ecological response.
- Improved evaluation of model performance: Identify a suite of appropriate skill metrics and evaluate model performance at multiple scales of resolution.
- Ground-truthing: Further ground-truthing of the watershed models should include the following:
    - Model calibration and evaluation at finer temporal/spatial scales to better assess the role of episodic events (e.g., extreme precipitation/flow) and land use practices;
    - A directed evaluation of the management actions (BMPs) that will be necessary to achieve the new loading targets, including an assessment of associated uncertainties;
    - Increased attention to the role of legacy phosphorus bounded to the soil in the watersheds and sediment in the lakes in driving algal blooms and toxicity levels of HABs; and
    - Consideration of additional watershed models that may better capture urban areas.
- Predictive ability: To improve predictive ability, future lake modeling efforts should include an improved understanding of key phytoplankton growth processes, internal nutrient sources, the role of nitrogen, interactions between phytoplankton and Cladophora growth, role of dreissenids in nutrient cycling and availability, and zooplankton interactions and connection to upper food web.

7.2 Institutional recommendations

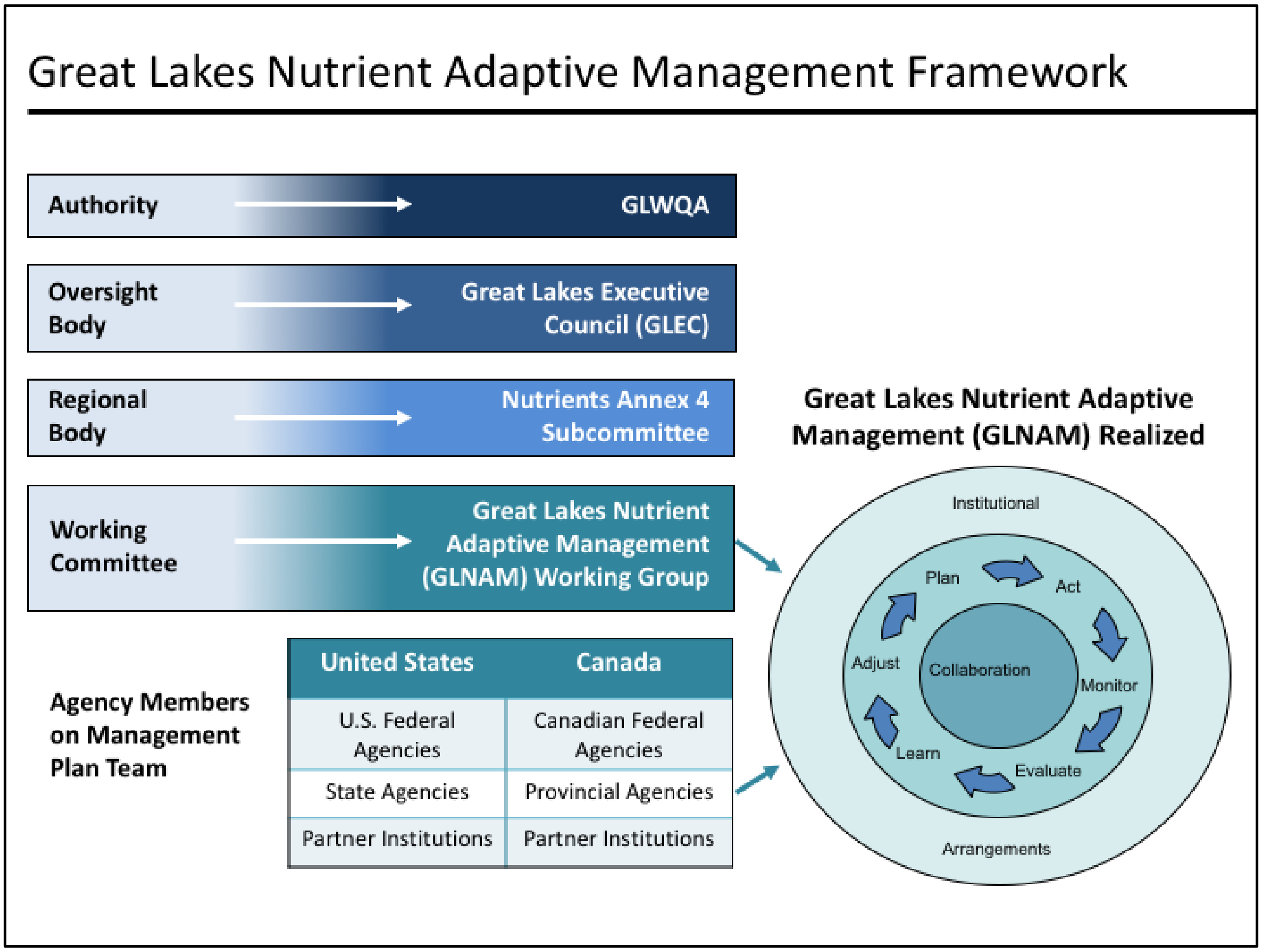
The core principles of the GLNAM Framework serve as the basis for the following institutional recommendations. The GLNAM Framework is driven by an iterative process of research and management activities revolving around the phases: plan-act-monitor-evaluate-learn-adjust. As envisioned under the 2012 GLWQA, the intent of the iterative approach of adaptive management is to reduce uncertainty in the process of limiting nutrient loading to levels necessary for mitigating eutrophication in Lake Erie as well as the other Great Lakes. The following recommendations are proposed by the IJC SAB-RCC as the next steps to institutionalize a GLNAM Framework as illustrated in Fig. 2:

- Define Lake Erie's eutrophication problem(s) aligning with a GLNAM Framework to provide the rationale for institutionalizing a framework based on collaboration across government agencies and jurisdictional lines.
- Develop consensus-based goals in support of the GLNAM Framework as a long-term, sustainable institutional arrangement.
- Integrate watershed and lake modeling (discussed above under technical recommendations) as part of the GLNAM Framework:

- Frame the “correct” questions and testable hypotheses (linked to the aforementioned problem) in the development and implementation of models to better understand the ecological processes underlying eutrophication and to support nutrient reduction management.
  - Establish a common awareness and understanding among researchers, resource managers, and a broad spectrum of stakeholders of the linkages between adaptive management and watershed/lake modeling as part of the GLNAM Framework.
- Use the GLNAM Framework to inform coordinated planning and implementation of Lake Erie’s watershed/ecosystem modeling and nutrient reduction management; as part of this coordinated effort, address the following:
  - Identify key players currently participating in the GLNAM Framework in Lake Erie and use this information to identify gaps and unmet needs that must be addressed to further advance the GLNAM Framework.
  - Provide a status report on the progress achieved thus far in the development and implementation of a GLNAM Framework.
- Establish/integrate a monitoring program as part of the GLNAM Framework on a long-term continuous basis and evaluate results to learn and adjust research, modeling and management decisions.
- Update models on a regular basis (characteristic of adaptive management approach) to reduce uncertainty and better represent an improved understanding of the ecological dynamics.
  - Diagnose models with “post audit process” (research, test, sensitivity analysis, recalibrate) and reapply to determine how model performance and management decisions can be improved (e.g., reevaluate target loads).
- Raise awareness for the following principles underlying an adaptive management approach:
  - Integration of testable questions/hypotheses that serve as key drivers to a GLNAM Framework;
  - Collaboration among stakeholders as a key element of adaptive management to ensure long-term sustainability guided by the GLWQA;
  - Communication, outreach and engagement with stakeholders as critical drivers in building and maintaining spheres of influence in support of a GLNAM Framework; including stakeholder engagement plays a role in identifying research/management priorities under the GLNAM Framework;
  - Consideration of the GLNAM approach as a learning process from which we should expect surprises (e.g., dreissenids, cyanobacteria, climate change);
  - Management actions under the GLNAM Framework should be recognized as experiments that provide the opportunity for learning, given the inherent uncertainty associated with modeling and decision making. It is also important to track such actions and make data available publicly to enhance iterative learning.
- Institutional and governance considerations for the GLNAM Framework:
  - Establish the GLWQA as the binational authority to institutionalize the GLNAM Framework through Nutrients Annex 4 to facilitate implementation.

- Identify agency and institutional partners as well as programs responsible for the development and conduct of a GLNAM Framework:
    - Lead federal agencies: U.S. Environmental Protection Agency (EPA) and Environment Canada Climate Change (ECCC)
    - Supporting Canadian and US federal agencies: US Department of Agriculture Natural Resource Conservation Service (NRCS), US Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA); Canadian Department of Fisheries and Oceans
    - Supporting state and provincial agencies: Ohio EPA, Pennsylvania Department of Environmental Protection, New York Department of Environmental Conservation, Indiana Department of Natural Resources, Michigan Department of Natural Resources
    - Partner institutions: International Joint Commission (IJC), academia, private sector
    - Reporting programs: Domestic Action Plans (DAPs), and GLWQA triennial reporting
  - Identify experts, resources and stakeholders needed to effectively meet identified adaptive management goals and objectives on a long-term basis.
  - Establish a cycle of adaptive management (annual modeling and assessment; annually or every 5-10 years (to be determined) to advance model improvement and to reduce uncertainty in the decision-making process on nutrient management.
- Identify and establish funding streams to support the GLNAM Framework through existing and/or new authorizations and appropriations. Among the funding streams identified to date are the IJC-International Watershed Initiative, USGS monitoring programs, NOAA granting programs (ECOHAB, Sea Grant, etc.) and NOAA research and development laboratories' base funding, Harmful Algal Bloom Hypoxia and Control Act (HABHRCA), Great Lakes Restoration Initiative (GLRI), Lakewide Management Programs (LAMPs), and state natural resource and environmental protection programs of the Great Lakes region.
- Establish justification for the GLNAM Framework: Quantify benefits of healthy ecosystem services, providing justification for investment in institutionalizing the GLNAM Framework. This is considered key in maintaining GLNAM Framework on a long-term, sustainable basis that is necessary to advance nutrient management on eutrophication related problems. Case in point: the cost of nutrient loading reduction in Lake Erie should not be disconnected from the economic value of the ecosystem services provided by the lake.

Figure 2: The Great Lakes Nutrient Adaptive Management (GLNAM) Framework as recommended to guide the development and conduct of an adaptive management approach revolving around the phases: Plan-Act-Monitor-Evaluate-Learn-Adjust.



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9.0 Appendix

I. Development of an Integrated Modelling Framework to Guide Adaptive Management Implementation in Lake Erie. Final contract report prepared for the International Joint Commission by George Arhonditsis, Department of Physical and Environmental Sciences, Ecological Modeling Laboratory, University of Toronto, Scarborough, Ontario, Canada.