Binational Lake Erie Nutrient Adaptive Management Framework

2023

Prepared for:
The Annex 4 Subcommittee

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Executive Summary

Lake Erie is adversely impacted by harmful algal blooms (HABs), hypoxia (low-oxygen zones), and excess growth of nuisance macroalgae (*Cladophora)*. The major driver of these effects is excess phosphorus inputs, primarily from nonpoint sources. Natural resource managers, environmental agencies, and researchers are working to understand these complex phenomena and implement effective management actions to improve the Lake Erie ecosystem. While upgrades to wastewater treatment plants and/or changes to their operations over the years have led to significant reductions of phosphorus from point sources, reducing total phosphorus (TP) and dissolved reactive phosphorus (DRP) loads from agricultural runoff and other non-point sources is more challenging, and therefore is the focus of current and future management actions.

Under Annex 4 (Nutrients) of the 2012 *Great Lakes Water Quality Agreement* (GLWQA), Canada and the United States (the Parties) adopted phosphorus reduction targets in 2016. The targets are to reduce inputs of phosphorus to the western and central basins of Lake Erie by 40% from 2008 baseline levels to help achieve GLWQA Annex 4 Lake Ecosystem Objectives (LEOs) for HABs, hypoxic zones, and nuisance algae.

The Parties recognize that updates or adjustments to nutrient reduction strategies and actions may be warranted by the emergence of new science and knowledge. The Parties have agreed to use an adaptive management (AM) approach to understand the outcomes of actions taken, and to inform future actions necessary to achieve the 40% phosphorus reduction target. The AM approach recognizes uncertainties inherent in the management of complex social and environmental systems and seeks to reduce these uncertainties over time through active hypothesis testing and collaborative learning.

Many of the building blocks for a binational Lake Erie nutrient AM approach are currently in place. Lake monitoring, modeling, and research already in place are improving understanding and predictions of how the lake ecosystem will respond to nutrient reductions. The Binational Lake Erie Nutrient Adaptive Management Framework (AMF) builds on these efforts while aiming to systematically reduce uncertainties, improve information available to decision makers, and further guide management actions toward achievement of the Lake Erie LEOs.

Achieving Lake Erie LEOs are dependent on 1) management actions achieving desired phosphorus reductions and 2) phosphorus reductions achieving the desired in-lake response. The Binational Lake Erie Nutrient AMF is structured to oversee the latter point, focusing on how the ecosystem is responding to changes in nutrient loads. The purpose of the Binational Lake Erie Nutrient AMF is to provide a roadmap to assess three key issues: 1) HABs; 2) Hypoxia; and 3) *Cladophora*, and whether progress is being made towards achieving LEOs related to each of these issues.

Each country's Domestic Action Plans are rooted in adaptive management, as well. Water quality managers are responsible for evaluating the progress made by on-the-ground actions toward achieving phosphorus reduction targets, and to adapt management actions where necessary. Communication between the binational and domestic AM processes is vital to understand how on-the-ground action is affecting phosphorus loading and the resulting in-lake response.

As it may be several years before we see measurable results in the lake, the Binational Lake Erie Nutrient AMF is intended to support long term continued evaluations of progress. Improving the understanding of the relationships between nutrient reduction and ecosystem response will help the Parties make progressively better-informed and effective nutrient management decisions.

The Annex 4 Subcommittee established an Adaptive Management (AM) Task Team to provide coordinated guidance on the AM approach and its implementation in order to monitor outcomes of management actions and track progress towards achieving LEOs for Lake Erie. The AM Task Team is responsible for implementing the Binational Lake Erie Nutrient AMF and will engage five technical working groups and communicate findings. These include three issue-focused working groups on HABs, hypoxia, and *Cladophora;* a data and modeling working group; and a loadings working group.

Evaluations under the Binational Lake Erie Nutrient AMF will occur every 5 years to review progress toward achieving LEOs (e.g., based on data analysis and scenario modeling). Each 5-year binational evaluation will be scheduled to occur in the year prior to the 5-year renewal cycle of the DAPs, so that jurisdictions can consider evaluation findings as they update their management strategies. The evaluation findings and recommendations will also inform the 3-year binational priorities for science and action, the Lake Erie Lakewide Action and Management Plan (LAMP), and the 5-year Cooperative Science and Monitoring Initiative priorities.

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Acronyms and Abbreviations

AM	Adaptive Management
AMF	Adaptive Management Framework
Annex 4	Nutrients Annex of 2012 Great Lakes Water Quality Agreement
BMP	Best Management Practice
DAP	Domestic Action Plan
DRP	Dissolved Reactive Phosphorus (also called Soluble Reactive Phosphorus, SRP)
ECCC	Environment and Climate Change Canada
EPA	Environmental Protection Agency (U.S)
ERI	Eutrophication Response Indicator
FWMC	Flow-Weighted Mean Concentration
GLC	Great Lakes Commission
GLWQA	Great Lakes Water Quality Agreement
HAB	Harmful Algal Bloom
LEO	Lake Ecosystem Objective
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration (U.S.)
P	Phosphorus
SRP	Soluble Reactive Phosphorus (also called Dissolved Reactive Phosphorus, DRP)
TP	Total Phosphorus
USACE	U.S. Army Corps of Engineers

1 Preface

1.1 Background

Over enrichment of nutrients resulting in excessive algal growth (eutrophication) in Lake Erie and Lake St. Clair, poses significant threats to the ecosystem and human health. Harmful algal blooms (HABs) in nearshore areas have increased significantly since the late 1990s. The current understanding of the system is that HABs primarily develop due to high levels of total phosphorus (TP) and dissolved reactive phosphorus (DRP) delivered from major tributaries. Other impacts to the ecosystem resulting from excessive nutrients include depletion of oxygen (hypoxia) that reduces available fish and macroinvertebrate habitat in the lake's central basin, and excessive growth of nuisance macroalgae (*Cladophora*) that foul beaches and clog water intakes, primarily in the eastern basin. While it is more difficult to link nuisance macroalgae to specific nutrient levels, excessive nutrient availability is associated with algal growth. A combination of complex factors, including urban and agricultural intensification, climate change, loss of wetlands, invasive species, and phosphorus resuspension from lake bottom sediments are potentially intensifying eutrophication. Increasing temperatures are creating longer and more suitable algal growing seasons, and more spring rainfall is delivering high nutrient loads right at the beginning of those seasons.

Under Annex 4 (Nutrients) of the 2012 *Great Lakes Water Quality Agreement* (GLWQA), Canada and the United States. committed to addressing the negative effects of eutrophication in Lake Erie by establishing Lake Ecosystem Objectives (LEOs), phosphorus load reduction targets and allocations by country, and phosphorus reduction strategies and domestic action plans. The GLWQA describes six LEOs related to nutrients. In order to achieve these, Canada and the United States set binational phosphorus reduction targets for Lake Erie and developed a Binational Phosphorus Reduction Strategy. The two countries, member States, and the Province of Ontario developed domestic action plans (DAPs) that outline actions for meeting phosphorus load reduction targets in their respective jurisdictions.

In 2015, the Annex 4 Objectives and Targets Task Team used an ensemble modeling approach to recommend revised phosphorus reduction targets for Lake Erie. In recognition of the inherent uncertainties, the Task Team strongly endorsed the adoption of a carefully designed adaptive management (AM) process to track the response of the system, evaluate the effectiveness of management efforts, and update management recommendations as we learn more about the processes underlying the system response. The Annex 4 Subcommittee's Objectives and Targets Task Team evolved into the AM Task Team in 2018 to oversee the development and implementation of a formal Binational Lake Erie Nutrient Adaptive Management Framework (AMF).

Through the GLWQA, Canada and the United States committed to a science-based approach to address LEOs related to nutrients in Lake Erie, and to use AM as a framework to achieve them. This Binational Lake Erie Nutrient AMF was developed by the GLWQA Annex 4 Subcommittee's AM Task Team to provide coordinated guidance on the AM approach and its implementation in order to track progress towards achieving LEOs for Lake Erie.

1.2 Adaptive Management

AM is a learning-based management framework that recognizes the uncertainties inherent in the management of complex social and environmental systems and seeks to reduce these uncertainties over time through active hypothesis testing and collaborative learning. AM recognizes and incorporates uncertainty and complexity in management actions. AM encourages decision makers to consider a range of potential future outcomes and design management strategies that can be adjusted over time in an iterative and collaborative process (Hasselman, 2017; Scarlett, 2013; USEPA, 2010; Williams et al., 2009).

Active AM includes hypotheses development, modeling, monitoring and research to reduce uncertainty and increase confidence in the ability to predict the outcomes of management decisions and actions (Hasselman, 2017; Williams et al., 2009). AM also involves explicit processes to encourage active collaboration and incorporation of multiple, well-informed stakeholder perspectives in framing, evaluating, and adapting management decisions and actions (Hasselman, 2017; Scarlett, 2013; Williams et al., 2009). AM has been used in other major ecosystems to support management actions including Chesapeake Bay, Sacramento-San Joaquin River Delta, and the Everglades (Chesapeake Bay Program, 2021; Delta Stewardship Council, 2021; USACE, 2021).

The AM cycle can be defined in different ways to address different contexts. For the purpose of this Binational Lake Erie Nutrient AMF, the AM cycle is defined by the following steps (Figure 1):

1. **Set goals:** Frame the problem and identify goals in terms of ecosystem outcomes that reflect broader societal values (i.e. LEOs, eutrophication response indicators (ERIs), P reduction targets).
2. **Plan:** Develop plans for monitoring, and other intentional processes that support AM (e.g., modeling, research synthesis, hypothesis development, prioritization of uncertainties, stakeholder engagement, and communication).
3. **Implement:** Implement AM activities and processes identified under Step 2.
4. **Monitor:** Monitor AM implementation progress and collect data to assess environmental conditions and ecosystem responses, help isolate impacts of management actions from natural variability in the system and improve understanding of relevant social behaviors and natural processes.
5. **Synthesize:** Synthesize monitoring data, compare monitoring data to predicted/modeled outcomes, review conceptual models and emerging research to assess potential sources of divergence in predicted and observed outcomes, and refine key uncertainties.
6. **Evaluate:** Convene decision-makers, scientists, and stakeholders to review monitoring data and progress towards ecosystem goals, refine syntheses (data, modeling, and research), and develop and communicate recommendations for modified research priorities, model and hypothesis refinements, adjustments to monitoring programs, and revisions of ecosystem goals.

Figure 1. Steps of the Binational Lake Erie Nutrient AM Cycle

7. **Make Decisions and Adapt:** Review recommendations and make decisions regarding adaptation of action plans and goals to improve understanding and more effectively reach desired ecosystem states.

Active engagement of decision-makers, scientists, and other stakeholders and communication of actions and progress toward ecosystem goals occur throughout the AM cycle.

1.3 Purpose and Audience

The purpose of the Binational Lake Erie Nutrient AMF is to provide a roadmap of the AM approach and its implementation to assess HABs, hypoxia, and *Cladophora* issues in Lake Erie, and whether progress is being made toward achieving related LEOs. This includes how the AM Task Team will coordinate the corresponding modeling, research and monitoring necessary to undertake the assessment. The intended audience for the Binational Lake Erie Nutrient AMF is the Annex 4 Subcommittee, AM Task Team and supporting working groups, as well as domestic agencies responsible for implementing nutrient reduction strategies and domestic action plans.

1.4 Geographic Scope

The AM approach is focused on the in-lake response of the three key issues (HABs, hypoxia, and *Cladophora*), where they occur in each of Lake Erie's three basins (western, central, and eastern) and Lake St. Clair, and considers nutrient inputs from major tributaries and the Huron-Erie corridor (Figure 2).

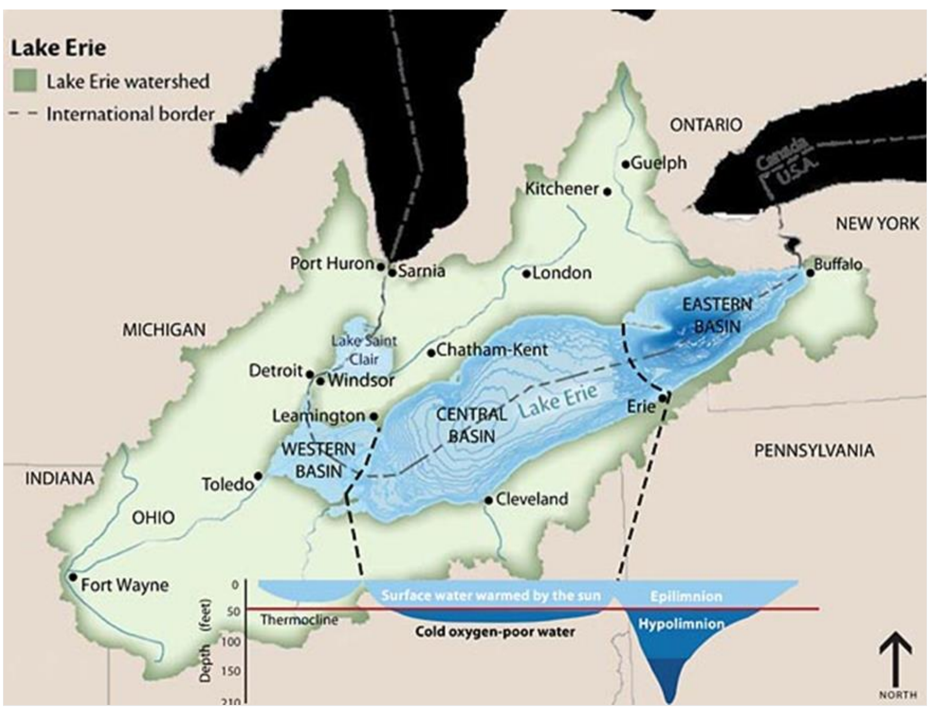

Figure 2. Geographic scope of the Binational Lake Erie Nutrient AMF. Study area illustrates the watershed, location and bathymetry of each Lake Erie Basin and Lake St. Clair (Source: Environment and Climate Change Canada).

2 Introduction

This section reviews the eutrophication issues in Lake Erie and the activities to date to address them, including development of LEOs and implementation of binational and domestic nutrient management actions.

2.1 Lake Erie Eutrophication Issues

A combination of physical characteristics (shallow and warm) and surrounding land use (urban and agricultural) make Lake Erie the most susceptible of the Great Lakes to eutrophication. While algae are an essential component of Lake Erie's ecosystem, excess phosphorus loading resulting in eutrophication in Lake Erie has prompted significant threats to the environment. These threats include harmful blooms of toxin-producing cyanobacteria (blue-green algae), hypoxia caused by the decomposition of dead algae in bottom waters, and excess growth of nuisance algae (*Cladophora*). This section provides a high-level overview of the current state of knowledge of these environmental phenomena.

2.1.1 Harmful Algal Blooms

Harmful algal blooms (HABs) in Lake Erie and Lake St. Clair occur regularly and are dominated by cyanobacteria (blue-green algae), a type of bacteria that can produce blooms containing toxins (e.g., microcystin) with the potential to harm humans and wildlife. HABs in Lake Erie and Lake St. Clair have increased significantly since the late-1990s, primarily due to high levels of total phosphorus (TP) and dissolved reactive phosphorus (DRP) delivered from major tributaries, complicated by climate change, invasive species, and other factors. Severe HABs that form between late July and early October are the primary eutrophication issue in the western basin of Lake Erie. In addition, smaller localized HABs form in nearshore areas of the western basin and Lake St. Clair. Much of the phosphorus load that drives HABs is delivered during large spring storm events as nutrient-heavy runoff travels from tributaries to the lake.

The current understanding is that western basin HABs are primarily driven by spring phosphorus loads from the Maumee River, a major tributary to Lake Erie that runs through highly productive agricultural land. Through active adaptive management, management actions to control TP and DRP are expected to reduce the biomass of the HABs. Furthermore, it is expected that lower overall biomass of HABs will also reduce potential for HAB toxin occurrence in the lake, including at drinking water intakes and recreational beaches.

Remote sensing, multiple models, and daily monitoring are used to predict and track the formation and movement of HABs during the summer months. However, despite improvements to monitoring technology and research advancements, uncertainties still exist regarding causes and impacts of the blooms. For example, questions remain about variations in bloom toxicity, the role of nitrogen in mediating algal growth and toxin production, and magnitude of algae response to changes in loads.

2.1.2 Hypoxia

Hypoxia is a low oxygen zone that is created in the cold bottom layer of the lake when organic matter decomposes, most often when stratified water conditions exist. Some of the hypoxia observed in Lake Erie is a natural phenomenon; however, since the early 2000s, the hypoxic area in the central basin of Lake Erie has increased to about 4,500 km² on average, with the largest hypoxic event covering 8,800 km² occurring in 2012 (GLWQA Annex 4 Subcommittee, 2019).

The central basin harbors large areas of hypoxic bottom water in summer and early fall. Nutrients from western and central basin tributaries fuel spring diatom blooms and summer cyanobacteria blooms, which occasionally extend into the central basin. During the summer when the lake is stratified the decomposition of dead algae uses up the dissolved oxygen in central basin bottom waters. In turn, the resident aquatic organisms become stressed or die, or move elsewhere in the lake.

Our understanding about the spatial and temporal drivers of hypoxia is somewhat limited. Research to date indicates that inter-annual variability in the extent of hypoxic water is controlled more strongly by physical factors affecting stratification than by changes in nutrient loading from year to year (Rucinski et al., 2016), but reducing nutrient loading in the lake is still necessary to reduce the average area of hypoxia over time. Unlike HABs, for which real-time bloom monitoring and reporting has been operationalized using satellites, observations of hypoxia are dependent on in-situ instruments and individual profiling measurements. Comprehensive analyses to map the occurrence and duration of hypoxic conditions using a combination of ship-based observations, data from buoys and bottom sensors are not performed routinely.

2.1.3 Nuisance algae

Cladophora, a macroalgae that can form nuisance amounts of colonies, is a green alga naturally found in low densities along the Lake Erie coastline. *Cladophora* production is the highest and potentially the greatest nuisance where water is clear, nutrient-enriched, and has hard substrate to which the algae can attach. Excess *Cladophora* can clog industrial water intakes, foul beaches, degrade fish habitat, encourage the growth of bacteria, and may create an environment conducive to the development of botulism. Excessive nuisance algae growth can also contribute to localized hypoxia when it decomposes.

Nuisance algae is primarily an issue in the eastern basin due to increased light penetration in the water column caused by filter feeding of invasive mussels. It is hypothesized that water clarity and nearshore nutrient supply in the eastern basin is augmented by phosphorus brought to the surface by wind-driven upwelling, combining to drive excess growth of *Cladophora*.

Like hypoxia, management of *Cladophora* in the eastern basin is complicated by human and natural drivers, such as local and distant sources of nutrient input and summer wind conditions. Growth and sloughing of excess *Cladophora* are widespread in nearshore areas of the eastern basin, but the interplay of river loading, shading by river plume turbidity, upwelling of nutrients, and macroalgae-mussel interactions are areas of active research (Kuczynski et al., 2020). In-situ monitoring of *Cladophora* requires tools such as divers, underwater cameras, autonomous underwater vehicles, sondes, etc. Remote sensing tools to map *Cladophora* are being explored.

2.2 Lake Erie Nutrient Management

Under Annex 4 of the GLWQA, Canada and the United States address eutrophication in Lake Erie using a combination of binational and domestic actions. Actions are implemented under the Binational Phosphorus Reduction Strategy and Domestic Action Plans (DAPs) in order to achieve binational phosphorus reduction targets and the desired ecosystem state described by the LEOs. This Binational Lake Erie Nutrient AMF describes the process by which progress towards achieving targets and LEOs will be tracked and evaluated.

2.2.1 Lake Ecosystem Objectives and Eutrophication Response Indicators

Under Annex 4 of the 2012 GLWQA, Canada and the United States adopted the following LEOs related to nutrients (Great Lakes Water Quality Agreement, 2012):

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
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

In 2015, the Annex 4 Objectives and Targets Task Team developed ERIs to evaluate effects of phosphorus loading reductions and track progress towards achieving LEOs. Table 1 summarizes the recommended ERIs.

Table 1. Summary of Recommended Eutrophication Response Indicators for Lake Erie (Source: GLWQA Annex 4 Objectives and Targets Task Team, 2015).

Eutrophication Response Indicator	Metric	Quantitative Benchmark
Overall trophic status	Basin-specific, spring TP concentration (μg/l).	Interim substance objectives outlined in GLWQA for TP concentration in open waters (as represented by spring means)[1]: • 10 μg/l central basin • 10 μg/l eastern basin • 15 μg/l western basin
Cyanobacteria blooms in the western basin	Maximum 30-day western basin cyanobacteria biomass (metric tons (MT))	Reduce algae to non-severe levels (less than 9,600 MT), such as those experienced in 2012, 90% of the time

Hypoxia in hypolimnion of the central basin	Average hypolimnion dissolved oxygen (DO) concentration during August and September	Maintain DO levels at or above 2 mg/L in the hypolimnion during the August to September period
Cladophora in the nearshore areas of the eastern basin[2]	TBD	

[1] Revised P concentration objectives for open waters have not been recommended at this time
[2] Scientific consensus does not support the development of additional phosphorus loading or Cladophora targets for the eastern basin at this time (Lake Erie Eastern Basin Task Team, 2020)

2.2.2 Phosphorus Load Reduction Targets

In 2015, the GLWQA Annex 4 Objectives and Targets Task Team recommended revisions to the phosphorus loading targets for Lake Erie using a suite of models to evaluate phosphorus load and eutrophication response relationships (GLWQA Annex 4 Objectives and Targets Task Team, 2015). Canada and the United States adopted the revised phosphorus reduction targets in February 2016 (Binational.net, 2016). Table 2 summarizes the binational phosphorus load reduction targets and the LEOs they address (LEO 1, 3, & 4). LEOs 2 and 6 refer to *Cladophora* targets, which have not been established at this time and LEO 5 is not specific to Lake Erie and therefore not considered under the Binational Lake Erie Nutrient AMF.

Table 2. Binational Phosphorus Load Reduction Targets for Lake Erie (Source: Binational.net, 2016; GLWQA Annex 4 Objectives and Targets Task Team, 2015; GLWQA Annex 4 Subcommittee, 2016; and GLWQA Annex 4 Subcommittee, 2019).

Lake Ecosystem Objective	Phosphorus Load Reduction Target
Minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie	40% reduction from 2008 levels in total phosphorus (TP) entering the western and central basins of Lake Erie, from Canada and the U.S., to achieve an annual load of 6,000 MT to the central basin, which equates to reductions from Canada and the U.S. of 212 MT and 3,316 MT, respectively.
Maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the central and western basins of Lake Erie	40% reduction from 2008 levels in spring (March to July) TP and dissolved reactive phosphorus (DRP) loads from the following watersheds where algae is a localized problem: in Canada, Thames River and Leamington Tributaries; and in the U.S., Maumee River, River Raisin, Portage River, Toussaint Creek, Sandusky River and Huron River.
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 western basin of Lake Erie	40% reduction from 2008 levels in spring (March to July) TP and DRP loads from the Maumee River in the U.S.

The Objectives and Targets Task Team concluded that there was insufficient scientific understanding in 2015 to quantify the relationship between phosphorus loads and *Cladophora* levels in the nearshore areas of the eastern basin (GLWQA Annex 4 Objectives and Targets Task Team, 2015). The Annex 4 Subcommittee therefore recommended that a target for the eastern basin be established after additional research is completed (GLWQA Annex 4 Subcommittee, 2016). In 2020, the Lake Erie Eastern Basin Task Team concluded that although important advances in understanding the environmental drivers controlling growth of benthic algae have been made in the last several years, scientific consensus does not support the development of additional phosphorus loading or *Cladophora* targets for the eastern basin at this time. This position was subsequently endorsed by the Annex 4 Subcommittee and agreed to by the Parties.

The Objectives and Targets Task Team recognized several sources of uncertainty intrinsic in the approach used to set targets, including the lack of data regarding bioavailable phosphorus loads and the role of nitrogen loads, dreissenids and other invasive species, and inter-annual hydrometeorology in nutrient load-ecosystem response relationships (GLWQA Annex 4 Objectives and Targets Task Team, 2015).

2.2.3 Binational Phosphorus Reduction Strategy

In 2019, the GLWQA Annex 4 Subcommittee released a Binational Phosphorus Reduction Strategy describing the framework for binational cooperation under the GLWQA Nutrients Annex towards the achievement of the binational phosphorus reduction targets. The Binational Phosphorus Reduction Strategy also includes commitments to engage stakeholders on local and regional scales and describes how progress will be tracked using an AM approach (GLWQA Annex 4 Subcommittee, 2019).

In addition, the document described binational priorities for research and monitoring, including: enhancing in-lake monitoring of algae and hypoxic conditions and conducting research on the factors contributing to these conditions; conducting research on factors driving toxicity in harmful algal blooms, including the role of nitrogen; and applying ecosystem models to improve ability to predict future ecosystem conditions (GLWQA Annex 4 Subcommittee, 2019).

2.2.4 Domestic Action Plans (DAPs)

In 2018, both Canada and the United States released DAPs which outline localized strategies for meeting the new targets in specific jurisdictions and watersheds (Binational.net, 2018). In Canada, the federal government and Province of Ontario developed a joint Canada-Ontario Lake Erie Action Plan (LEAP) (ECCC and Ontario Ministry of the Environment and Climate Change, 2018). In the United States, initial phosphorus load reduction allocations were developed for four states: Indiana, Michigan, Pennsylvania and Ohio. The U.S. federal government and states of Ohio, Michigan, Pennsylvania and Indiana have developed DAPs (USEPA et al., 2018). New York State is participating in the U.S. DAP and is committed to the development of a Lake Erie watershed plan and implementation of a tributary monitoring/modeling program that supports the broader goals of the DAP (USEPA et al., 2018). Each DAP focuses on strategies and actions that address the phosphorus sources and loads and unique environmental and socio-economic contexts associated with the jurisdiction as well as the different roles of federal, provincial/state and municipal/local governments. The Appendix (Table 7) presents a synthesis of strategies and actions included in the DAPs.

DAPs evaluate progress and adapt actions and initiatives to achieve phosphorous reduction targets. DAPs also include strategies to: improve monitoring of phosphorus loads in tributaries and watersheds; invest in research to improve knowledge and understanding of the effectiveness of phosphorus management activities (e.g., agricultural BMPs); apply models to predict future conditions; and engage stakeholders on local and regional scales in actions to reduce phosphorus loads (Binational.net, 2018; GLWQA Annex 4 Subcommittee, 2019). DAPs are reviewed and updated as appropriate every 5 years.

3 Binational Lake Erie Nutrient Adaptive Management Framework

This section outlines how the Binational Lake Erie Nutrient AMF governs binational efforts to measure progress towards achieving LEOs and ERIs for HABs, hypoxia, and *Cladophora* issues in Lake Erie. It distinguishes the scope of the binational AM process in relation to domestic processes and presents core elements of the Binational Lake Erie Nutrient AMF and its implementation. The framework outlined herein may be adapted over time as more information is gained regarding the effectiveness of this approach for guiding binational efforts to achieve the Lake Erie LEOs.

3.1 Overview

Canada and the United States have agreed to use an AM approach for nutrient management in Lake Erie. The Parties recognize that nutrient reduction strategies and actions may need to change over time based on new knowledge. It also provides the rationale for the development of coordinated monitoring, modeling and research to improve knowledge and support decision making. Many of the building blocks for an AM process are already in place. This framework incorporates existing components and provides a structure to ensure that they are utilized to support AM.

This Binational Lake Erie Nutrient AMF takes an active AM approach and explicitly incorporates hypothesis development and research, modeling, and monitoring to prioritize and systematically reduce uncertainties, improve information available to decision makers, and support progressively more effective management actions over time. The effort balances reacting too quickly to indicators that nutrient reductions are not effective, and reacting too slowly when monitoring results indicate that adjustments need to be made or when consensus is evolving around new understanding of important processes.

3.1.1 Scope in Relation to Domestic Actions

The binational AM effort is distinct and complementary to AM activities conducted under domestic action plans (DAPs). The achievement of LEOs in Lake Erie revolves around: 1) the effectiveness of domestic phosphorus reduction strategies to achieve phosphorus reduction targets, and 2) the in-lake response to the targeted phosphorus reductions. The first of these is addressed by the DAP processes, while the second is the focus of the Binational Lake Erie Nutrient AMF. Table 3 describes the focus of the binational and domestic processes.

Table 3. Distinction between the focus of the binational and domestic adaptive management processes.

AM Process	Question	Focus
Domestic Action Plans and AM Processes	Will on-the-ground actions achieve phosphorus reduction targets?	• Watershed actions to achieve phosphorus reduction targets • Evaluate management strategies and actions and adapt to achieve phosphorus reduction targets, if necessary • Adaptation decisions are incorporated in revised DAPs
Binational Lake Erie Nutrient AMF	How is the lake responding to changes in phosphorous loads?	• Monitoring, modeling, and research to track changes to nutrient loads and the in-lake response of HABs, hypoxia, and *Cladophora* • Improve understanding of the relationship between nutrient reductions and LEOs • Integrate information from domestic and binational processes to evaluate ecosystem response to tributary loads • Provide evidence-based research, modeling and monitoring recommendations to the Annex 4 Subcommittee

The Binational Lake Erie Nutrient AMF is complementary to the AM activities being conducted domestically. Both processes generally follow the 7 steps in the AM cycle described in Section 1; however, the binational and domestic processes operate separately and are all at different steps along the cycle. Some domestic jurisdictions have their own separate AM guidance documents (e.g., Michigan's Lake Erie Adaptive Management Plan; Canada and Ontario's AM Task Team implements AM under the Lake Erie Action Plan). Communication between the distinct binational and domestic AM processes is vital to understand how on-the-ground action is affecting phosphorus loading and the resulting in-lake response. The two processes include the exchange of information at certain steps of the AM cycle, such as during the "synthesize" (e.g., monitoring tributary data) and the "evaluation" (e.g., evaluating progress and making recommendations) steps. Information generated through the binational AM effort will inform domestic strategies and actions. Figure 3 illustrates how the binational and domestic AM processes follow the steps of the AM cycle in parallel, and the relationships between the two processes.

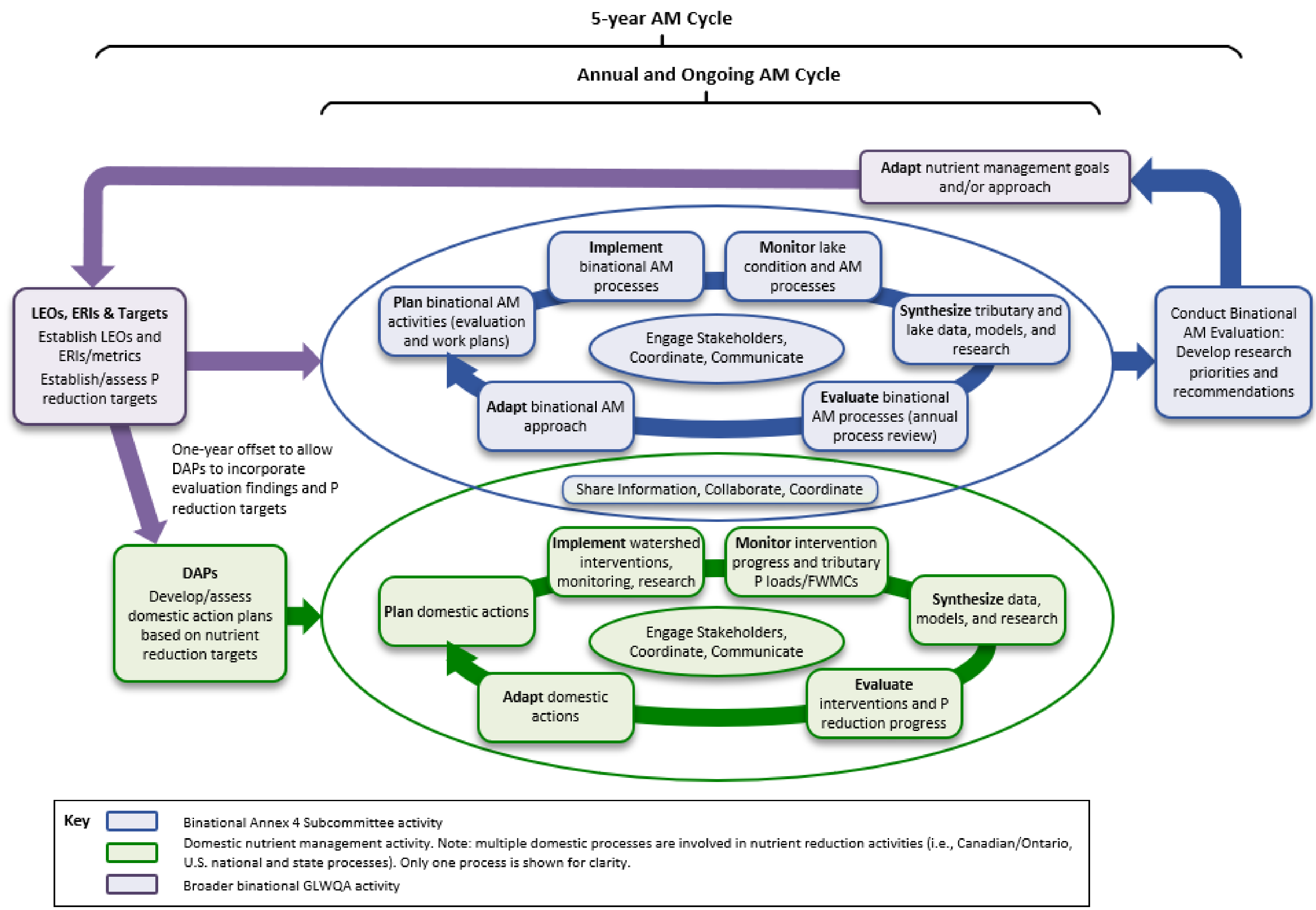

Figure 3. Binational and Domestic Adaptive Management Processes within the Binational Adaptive Management Cycle.

3.1.2 Framework Elements

Each step of the AM cycle (Figure 3) includes both technical and process elements needed to bridge information with evaluation processes to track progress and inform future management action, monitoring, modeling, and research priorities. Technical elements include lake monitoring and modeling, data management, and associated research activities to better understand nutrient input-ecosystem response relationships to reduce uncertainties. Process elements are the ways in which technical elements will be carried out, including engaging working groups to support the development of the 5-year Binational AM Evaluation.

3.2 Technical Elements

The binational AM effort is focused on assessing progress being made toward achieving LEOs; therefore, the Binational Lake Erie Nutrient AMF technical elements focus on the evaluation of the lake itself. Technical elements and their associated focus/objective are listed in Table 4.

Table 4. Binational Lake Erie Nutrient AMF Technical Elements and their focus.

Technical Elements	Focus/Objective
1. Lake monitoring	• Monitor response of HABs, hypoxia, and *Cladophora* to changes in nutrient inputs
2. Data management and access	• Coordinate data availability across organizations
3. Data analysis and synthesis	• Synthesize data and assess progress towards achieving LEOs and tracking changes in nutrient loads • Identify key uncertainties and research questions
4. Operational lake modeling	• Model nutrient-response relationships and reduce uncertainties over time • Develop and refine predictive capabilities
5. Decision support	• Evaluation of monitoring and modeling information provides rationale for evidence-based recommendations to the Annex 4 Subcommittee to inform DAPs and the binational P reduction strategy

These technical elements incorporate existing operational management programs, including modeling, monitoring and research activities conducted by federal, provincial, and state government agencies, academics, NGOs, contractors, and others to track the lake response to changing nutrient loads (Figure 4). Monitoring the in-lake response of HABs, hypoxia, and *Cladophora* will enable tracking of progress towards achieving LEOs, will provide important data to facilitate analysis of ecosystem trends, and will provide inputs for model development and validation. Evaluation of monitoring data and model outputs will be vital for research, modeling, and monitoring recommendations to the Annex 4 Subcommittee to support evidence-based decision making.

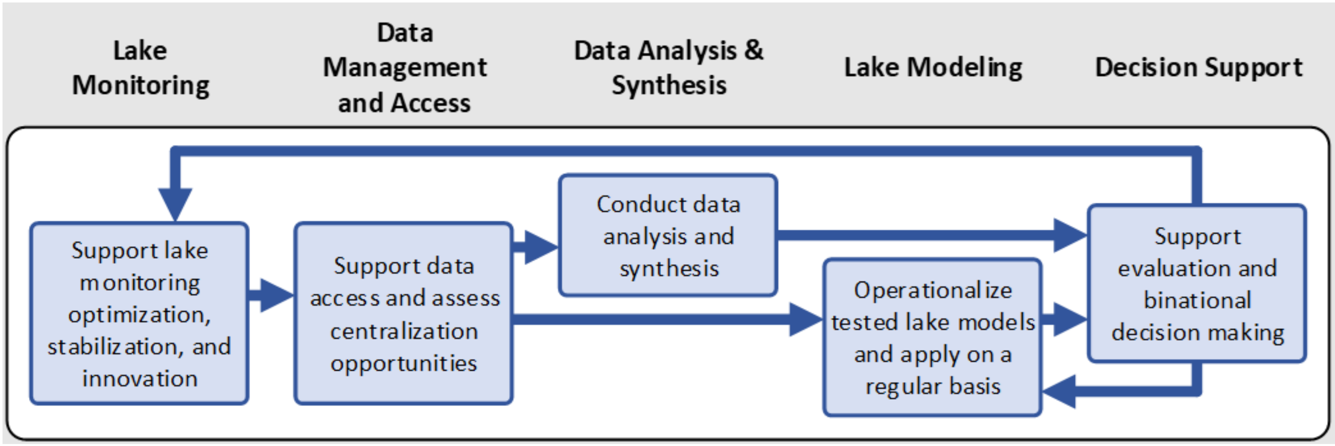

Figure 4. Schematic diagram of technical elements (top row) of the Binational Lake Erie Nutrient AMF.

3.2.1 Lake and Tributary Monitoring

The AM Task Team will leverage existing in-lake monitoring activities, many of which are conducted and/or funded by federal, state, and provincial agencies, to evaluate HABs, hypoxia, and *Cladophora*. This will involve assessing the sufficiency of current lake monitoring programs to assess LEOs and developing monitoring recommendations for each key issue (HABs, hypoxia, and *Cladophora*). In-lake monitoring activities include long term programs at sentinel sites and shorter-term research projects. Tributary load monitoring to the lake will also be used to evaluate and model phosphorus load and ecosystem response relationships. This will occur through direct monitoring (approximately one third of tributaries representing 80% of volume or mass of P input are currently monitored) and model simulation.

3.2.2 Data Management and Access

Monitoring programs create extensive amounts of data that require effective management in terms of quality, compatibility, accessibility, and storage. Individual agencies collect and manage their data in different ways, and data are made available at different times. Furthermore, use of different sampling methods and analytical procedures can limit direct comparisons of different data sources. The AM Task Team will consider options for standardizing and coordinating data access to support adaptive management activities.

3.2.3 Data Analysis and Synthesis

The AM Task Team will synthesize and analyze monitoring data to assess progress toward achieving LEOs and to track changes in phosphorus loads. Analyses will complement those that are already conducted by the Annex 4 Subcommittee agencies and supporting organizations that regularly compile status assessments of Lake Erie (e.g., State of the Great Lakes reporting, triennial Progress Report of the Parties, and the annual Annex 4 Lake Erie loading calculations).

3.2.4 Lake Modeling

The AM Task Team will help coordinate current modeling approaches (e.g., ECCC's whole-lake model, LimnoTech's western basin and whole-lake models) and support model enhancement, development and validation using new data collected through monitoring initiatives. The AM Task Team will oversee the use of operational lake models to evaluate relationships between phosphorus loads and in-lake responses, which will help reduce uncertainty over time. The AM Task Team will support binational prioritization of needs for model development, operation, maintenance, and enhancement.

3.2.5 Decision Support

The Binational Lake Erie Nutrient AMF technical elements described above all contribute to decision support by providing information on the state and trends of the lake system, as well as the ability to evaluate potential future conditions on different climate conditions and load reduction and characteristic regimes. Decision support provides feedback to lake modelers regarding scenarios to be evaluated over multiple rounds of activity, and to lake monitoring programs regarding locations, frequencies, and parameters of data collection needed to support modeling and decision-making. The AM Task Team will track the state of Lake Erie and its response to changing nutrient loads and conditions in order to assess whether progress is being made towards achieving LEOs and to inform future DAPs.

3.3 Process Elements

The Binational Lake Erie Nutrient AMF process elements describe the manner in which the technical elements will be carried out. Process elements and their associated focus/objective are listed in Table 5.

Table 5. Binational Lake Erie Nutrient AMF Process Elements and their focus.

Process Elements	Focus/Objective
1. Technical working groups	Five technical working groups under the AM Task Team: • Three issue-focused working groups (HABs, hypoxia, *Cladophora*): ○ Recommend binational monitoring, modeling and research priorities ○ Conduct topic-focused research inventory and synthesis • Data and modeling working group: ○ Coordinate data access ○ Conduct data analysis and synthesis (lake and tributary) ○ Enhance existing operational lake models • Loadings working group ○ Estimates annual and seasonal phosphorus loads each year ○ Coordinates with the AM Task Team for reporting and evaluation
2. Research synthesis	• Synthesize whole lake research to support the AM evaluation • Develop and refine conceptual models to reduce uncertainties • Identify knowledge gaps and recommend research priorities
3. Binational AM Evaluation	• Design and convene evaluation process • Work planning • Synthesize and assess information generated from technical working groups and loadings group • Periodic review of AM process (AM evaluation every 5-years)

	• Develop recommendations on research, modeling and monitoring priorities
4. Coordination and communication	• Coordinate with domestic processes and Annex 4 • Progress reporting • Communicate recommendations

3.3.1 Technical Working Groups

The Binational Lake Erie Nutrient AMF includes five technical working groups. Three issue-focused working groups are dedicated to the primary eutrophication issues (HABs, hypoxia, and *Cladophora*), one data and modeling working group, and one loadings working group. These working groups will report directly to the AM Task Team. The issue-focused working groups will enhance monitoring plans, prioritize uncertainties, and identify research questions and hypotheses. They will also conduct a topic-focused research inventory and synthesis to identify gaps and recommend research priorities. The loadings group estimates annual and seasonal phosphorus loads each year and coordinates with the AM Task Team for reporting and evaluation. The data and modeling working group will amalgamate data generated through binational monitoring and research programs and use this information to enhance existing operational lake models.

The AM Task Team oversees this work, which includes: establishing working groups where they do not already exist; considering proposed research, modeling, and monitoring recommendations to support the Binational AM Evaluation; supporting coordination and information sharing among workgroups; and communicating progress towards achieving LEOs. Any recommendations from the working groups would be taken into consideration by the AM Task Team during preparation of the final Binational AM Evaluation report.

3.3.2 Research Synthesis

The research inventory and synthesis conducted by the issue-focused working groups will allow the AM Task Team to synthesize whole lake research to prioritize and systematically reduce uncertainties regarding nutrient load-ecological response relationships. Each issue-focused working group will be responsible for tracking and synthesizing research relevant to their issue area. With working group support, the AM Task Team will help organize this information and seek consensus on ecosystem processes and critical knowledge gaps. This will support the Binational AM Evaluation, where the AM Task Team will recommend research priorities that will inform future modeling and monitoring.

3.3.3 Binational AM Evaluation

Implementation of the Binational AM Evaluation is integral to the success of the AM process and will occur every five years. The AM Task Team will design and convene the evaluation processes, support work planning, and synthesize information generated from the technical working groups to report on ERIs and assess progress towards achieving LEOs. The AM Task Team will provide input to all technical elements to ensure that monitoring, modeling, research synthesis, and decision support activities are aligned with evaluation priorities (e.g., hypothesis testing, uncertainty analysis, assessing ERIs). The 5-year evaluation of progress will occur one year before the DAPs expire to allow domestic jurisdictions to consider evaluation findings and recommendations as they update the DAPs. The purpose of the Binational AM Evaluation is to:

1. Assess the in-lake response of HABs, hypoxia, and *Cladophora* to changes in nutrient loads and measure progress towards achieving LEOs for Lake Erie.
2. Track changes in phosphorus (P) loads to Lake Erie.
3. Provide evidence-based recommendations to the Annex 4 Subcommittee regarding research, modeling, and monitoring activities that would improve our ability to assess progress over time.

3.3.4 Coordination and Communication

The coordination and communication element of the Binational Lake Erie Nutrient AMF focuses on the exchange of information and coordination with domestic processes (AM and DAPs) and the broader GLWQA binational collaboration process. In consultation with the Annex 4 Subcommittee co-chairs, this may include AM Task Team members contributing to progress reports and other communication products (e.g., Lake Erie Lakewide Action and Management Plan and Annual Reports), and participating in GLWQA events (e.g., Great Lakes Public Forum) and other Subcommittees (e.g., Science Annex).

In addition, communication and coordination will include the development of materials and participation in activities designed specifically to support the Binational Lake Erie AM process. These will include engagement processes involving the exchange of information to communicate progress and receive input across a spectrum of AM activities, including plans and processes, evaluation, and development of research, modeling, and monitoring priorities and AM recommendations. Five-year reporting will include the results of the Binational AM Evaluation.

4 Implementation

Due to the unique binational partnership and diverse stakeholders supporting the Lake Erie AM process, the organizational structure is likely to evolve over time to reflect lessons learned and potential changes in technical focus and shifting agency roles and commitments.

4.1 Organizational Framework

4.1.1 Roles and Responsibilities

The GLWQA Annex 4 Subcommittee's AM Task Team will be responsible for implementing the Binational Lake Erie Nutrient AMF. The AM Task Team will oversee the activities of the technical working groups. The AM Task Team will implement the Binational AM Evaluation and coordination and communication process elements. Technical elements will be implemented by working groups reporting to the AM Task Team. The AM Task Team may decide to dissolve and/or establish new working groups (in addition to the five identified under Section 3.3) to support these activities.

The AM Task Team will also be responsible for communicating findings and recommendations to the Annex 4 Subcommittee. Recommendations for management action and research, monitoring and modeling priorities will be for consideration by the Annex 4 subcommittee and intended to help inform future work.

The Annex 4 Subcommittee will be responsible for directing and overseeing the work of the AM Task Team. Technical working groups will be responsible for compiling and managing monitoring data and for tracking and synthesizing research relevant to their topic area. The data and modeling working group will be responsible for data analysis and synthesis, and operational modeling. Each working group will be made up of experts from binational federal, state, and provincial agencies and other participating organizations and will contribute to the development of the AM Task Team work plans and progress reports. The AM Task Team will coordinate with working group co-leads to implement communication and implementation activities. Figure 5 illustrates the roles and responsibilities and outputs of the technical working groups and the AM Task Team.

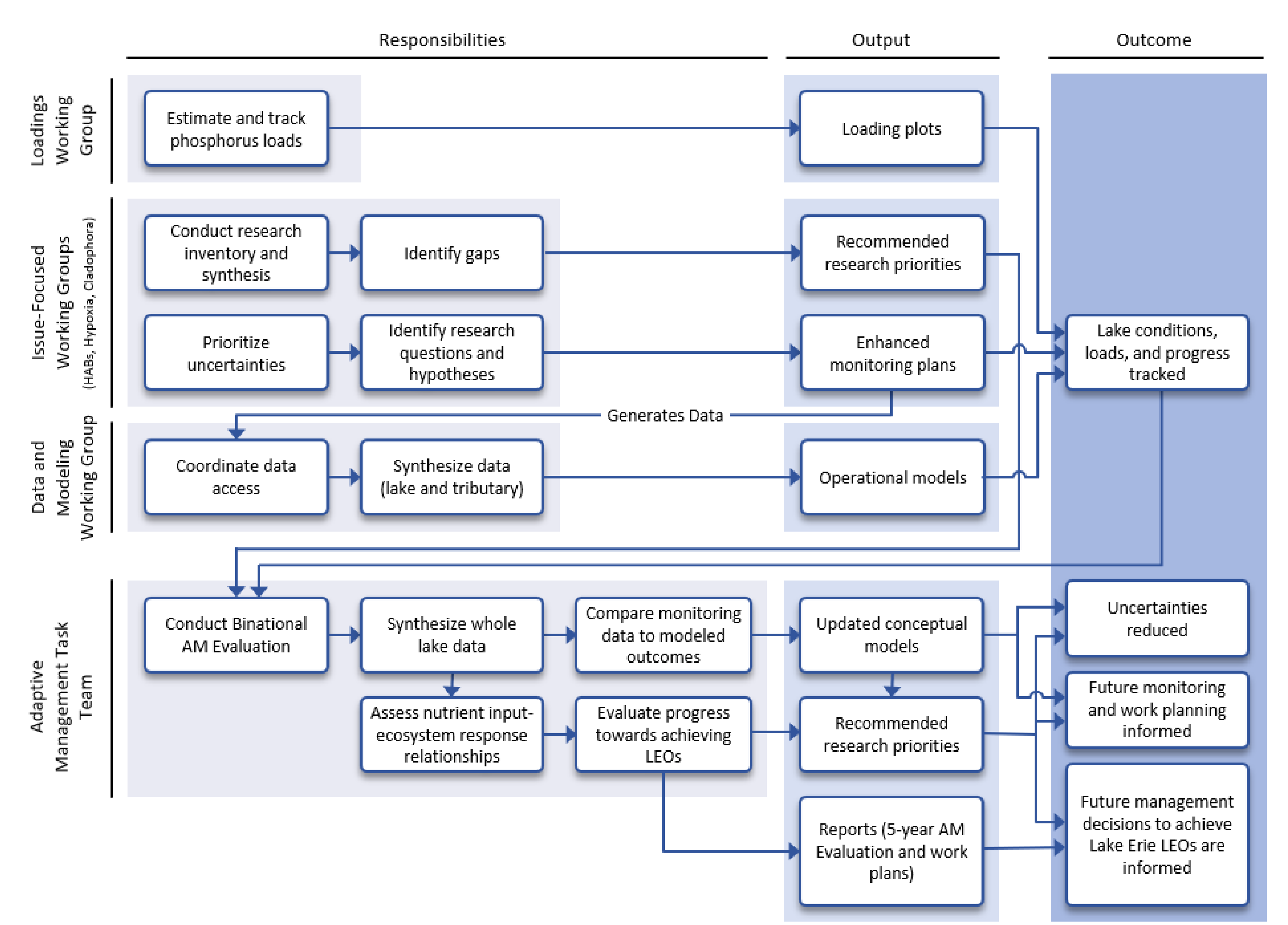

Figure 5. Conceptual diagram of the implementation of the Binational Lake Erie Nutrient Adaptive Management Framework, including key roles and responsibilities, outputs, and outcomes.

4.1.2 Work Plans and Progress Reporting

The AM Task Team, with support from technical working groups, will develop a 5-year strategic work plan. They will also report on progress on a 5-year cycle (Table 6). Work plans will address management of research synthesis, AM-focused evaluation processes, communication and engagement activities, and development and maintenance of the infrastructure required to support the AM process. Every 5 years, the AM Task Team will provide a report to the Annex 4 Subcommittee on progress towards LEOs, and recommendations to improve effectiveness of the AM process.

4.1.3 Resource Requirements

The implementation of the Binational Lake Erie Nutrient AMF will be supported as necessary by representatives of government agencies that participate in the Annex 4 Subcommittee and partner organizations. Participating agencies will determine whether existing staff and resources are sufficient or if additional resources, including contract support, will be required to support the Binational Lake Erie Nutrient AMF.

4.2 Timeline and Integration

The Annex 4 Subcommittee's AM Task Team will develop 5-year work plans and conduct the 5-year Binational AM Evaluation. Table 6 summarizes the activities to be conducted by the AM Task Team to implement the binational Lake Erie Nutrient AMF.

Table 6. Summary of Binational Lake Erie Nutrient AMF Activities and Timelines.

Activity and Frequency	Topics Covered
Planning	
Every 5 years ▪ Lake Erie AM Task Team 5-year plan	▪ Lake monitoring and data management plan ▪ Data analysis and synthesis ▪ Operational modeling and scenarios/forecasting ▪ Research synthesis and conceptual models ▪ Communications and engagements ▪ Binational coordination ▪ Binational Lake Erie AM Evaluation ▪ Implementation infrastructure and resources
Assessing and Reporting	
Annual and more frequent ▪ Issue-focused meetings or workshops ▪ Reporting and discussing activities and findings, such as the Lake Erie LAMP annual report, and public webinars.	▪ AM activities status ▪ Phosphorus load, flow-weighted mean concentrations, and flux status and trends ▪ Algal blooms and hypoxia status, predictions, and trends ▪ Review of progress toward achieving ERIs/LEOs ▪ Technical topics
Binational Lake Erie AM Evaluation	
Every 5 years ▪ Binational Lake Erie AM Evaluation	▪ Changes in phosphorus loads to Lake Erie ▪ In-lake response of HABs, hypoxia, and *Cladophora* to changes in nutrients loads ▪ Progress towards achieving LEOs for Lake Erie ▪ Recommended research, modeling, and monitoring priorities

In addition, through the Annex 4 Subcommittee, the AM Task Team will participate in broader binational public reporting and engagement activities. This will include, for example, contributing information to the Lake Erie Lakewide Action and Management Plan, Great Lakes Binational Priorities for Science and Action, Binational Nutrient Strategy, Progress Report of the Parties, and State of the Great Lakes Report. Engagement activities may include, for example, participation in research conferences and other fora.

The 5-year binational evaluation will be scheduled to occur with sufficient time to allow domestic jurisdictions to incorporate evaluation findings and recommendations in DAP updates (approximately one year in advance). The 5-year binational AM-focused evaluation will inform development of binational priorities for science and actions, and related binational initiatives such as the Lake Erie Lakewide Action and Management Plan. Figure 6 shows the proposed timeline for the 5-year AM-focused evaluation and relationships between 5-year and annual reviews, DAP updates, and these binational science and management planning activities.

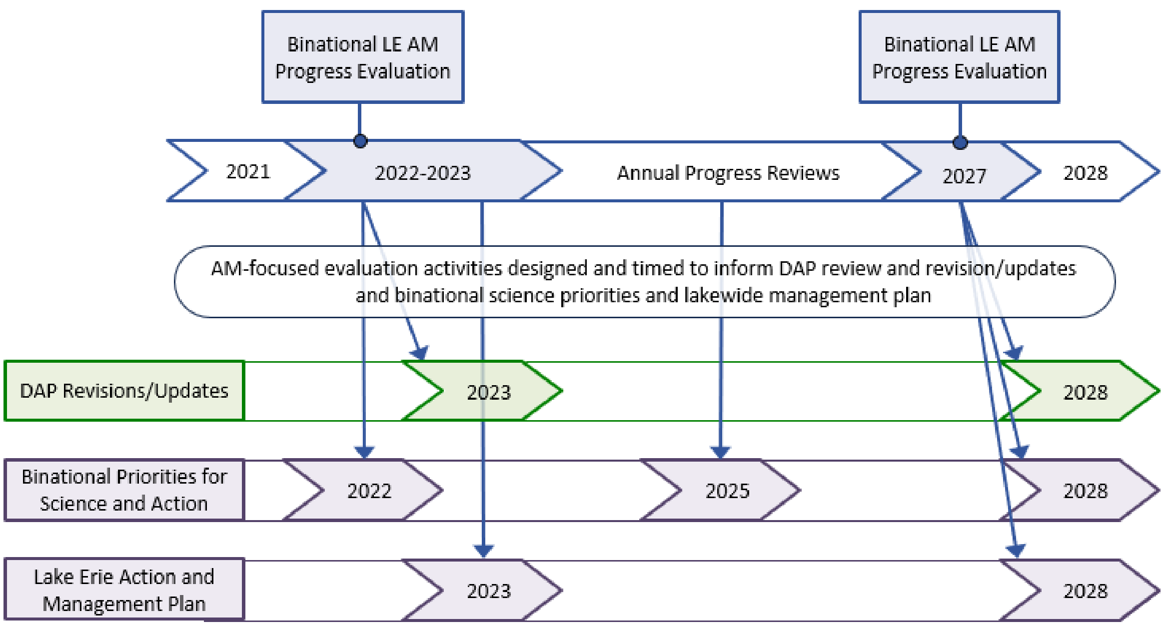

Figure 6. Integrated timeline showing relationships between binational Lake Erie AM-focused evaluation activities, DAP revisions/updates, binational science priorities and Lake Erie LAMP.

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5 Appendix

Table 7. Phosphorus Load Reduction Strategies and Associated Actions Included in DAPs (Source: GLWQA Annex 4 Subcommittee, 2019).

Strategy	Associated Actions
Reduce Phosphorus Loadings from Agricultural Sources	▪ Continue to encourage farmers to adopt on-farm best management practices (BMPs), emphasizing a “systems approach” (combinations of management practices) to comprehensively address concerns at the farm scale. ▪ Adopt 4R’s Nutrient Stewardship Certification or similar programs. ▪ Avoid nutrient applications on frozen or snow-covered ground. ▪ Implement and enforce fertilizer and manure application requirements where they apply. ▪ Prevent agricultural runoff by improving soil health and managing drainage systems to hold back or delay delivery of runoff though the use of saturated buffers, constructed wetlands or other drainage water management techniques. ▪ Reduce the impact of discharges from greenhouses on Lake Erie.
Reduce Phosphorus Loadings from Municipal Sources	▪ Optimize wastewater infrastructure. ▪ Encourage investments in green infrastructure and low impact development. ▪ Identify and correct failing home sewage treatment systems. ▪ Investigate water quality trading as a potential tool for managing phosphorus.
Support Watershed Based Planning and Restoration Efforts	▪ Develop or refine local watershed plans to meet the phosphorus reduction goals for the lake. ▪ Target watershed restoration efforts to areas most prone to phosphorus losses, including reducing legacy phosphorus in soils and sediments. ▪ Restore natural hydrology and ecological buffers to intercept nutrient runoff.
Coordinate Science, Research and Monitoring	▪ Enhance in-lake monitoring of algae and hypoxic conditions and conduct research on the factors contributing to these conditions. ▪ Improve monitoring of phosphorus loads in tributaries and watersheds. ▪ Invest in research and demonstration initiatives to improve knowledge and understanding of the effectiveness of BMPs, particularly BMPs to control soluble reactive phosphorus. ▪ Conduct research on factors driving toxicity in harmful algal blooms, including the role of nitrogen. ▪ Apply ecosystem models to improve our ability to predict future ecosystem conditions
Enhance Communication and Outreach	▪ Engage stakeholders on local and regional scales to increase the understanding of water quality condition and management challenges, nearshore and beach health, and best management practices and policies.