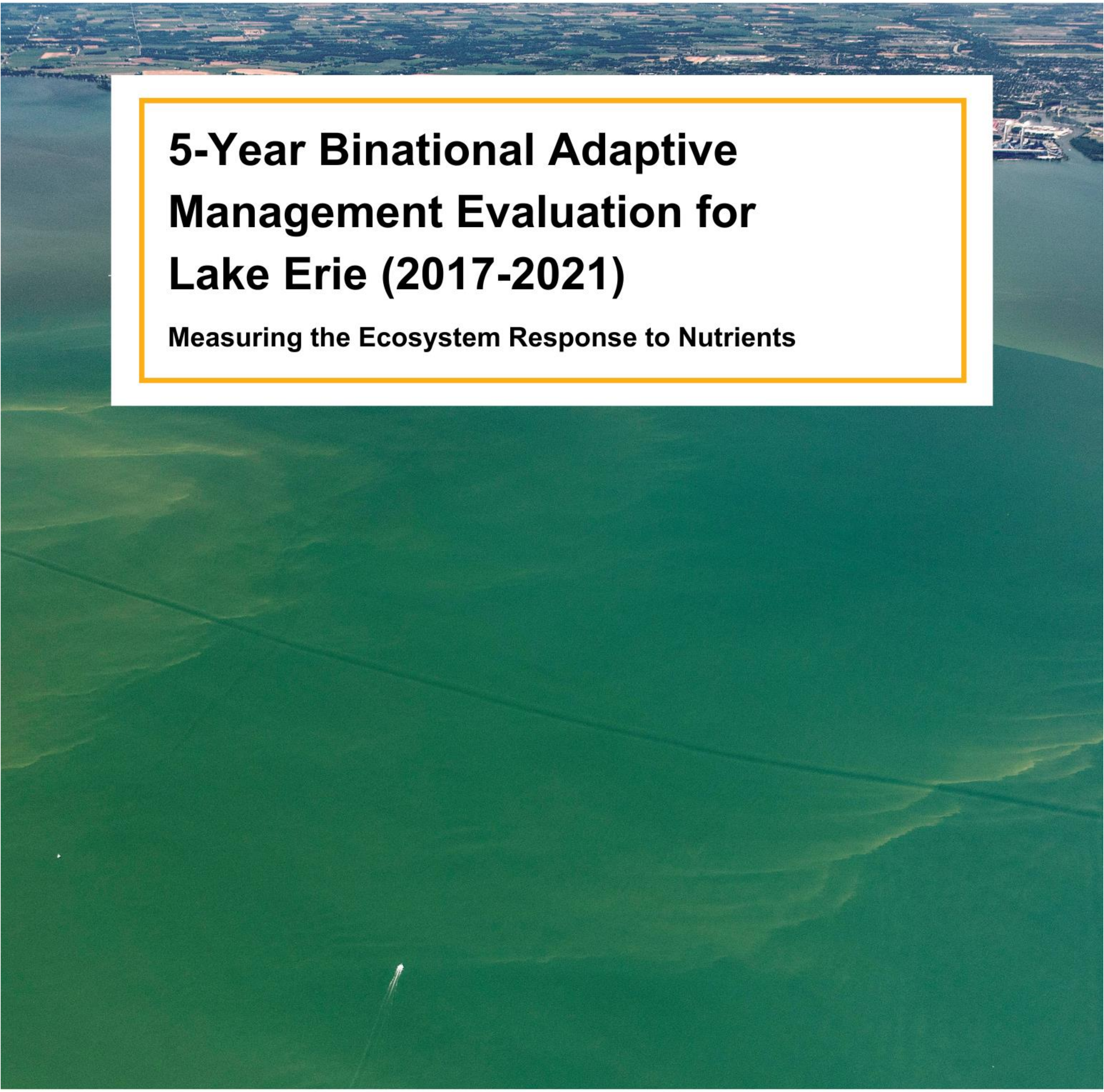
5-Year Binational Adaptive Management Evaluation for Lake Erie (2017-2021)

Measuring the Ecosystem Response to Nutrients



Prepared for:
The Annex 4 Subcommittee

Prepared by:
The Adaptive Management Task Team

With support from General Dynamics Information Technology and LimnoTech

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EXECUTIVE SUMMARY

Under the 2012 Great Lakes Water Quality Agreement (GLWQA), Canada and the United States agreed to use an Adaptive Management (AM) approach for addressing eutrophication issues in Lake Erie. The Binational Annex 4 (Nutrients) Subcommittee committed to conduct an evaluation every 5 years to assess changes in phosphorus loads and progress towards achieving Lake Ecosystem Objectives (LEOs) and make recommendations for improving binational AM efforts.

Table ES-1. Focus of 5-Year Binational AM Evaluation

- Track changes in phosphorus loads to Lake Erie.
- Assess in-lake response of harmful algal blooms (HABs), hypoxia, and *Cladophora* to changes in nutrient loads and measure progress towards achieving LEOs for Lake Erie.
- 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.

This report covers the 5-year period from 2017-2021 and presents the first Binational AM Evaluation conducted since the binational phosphorus reduction targets were adopted by Canada and the United States in 2016 and nutrient management domestic action plans (DAPs) were put in place in 2018. This binational AM effort focuses on assessing phosphorus loading and in-lake response (Table ES-1). These findings inform DAPs and the complementary domestic-led assessments on the effectiveness of watershed-based nutrient management efforts to reduce phosphorus loads to the lake.

The 5-year Evaluation relied on several information sources to assess conditions in Lake Erie, including issue-focused working groups formed to support the Lake Erie Nutrients Annex AM effort. This approach helped ensure that the evaluation benefited from information and expertise available from Canadian and U.S. federal, provincial/state, and local agencies, and academic partners. Key findings and recommendations are summarized for each area of focus below. Additional data and figures can be found in the main report.

Changes in Phosphorus Loads to Lake Erie (2017-2021)

For this evaluation, ECCC and EPA estimated annual and seasonal phosphorus loads using data collected by federal, state, provincial, local agencies, and universities. These data were analyzed to assess changes in phosphorus loads during the 5-year period, considering the three load reduction targets for Lake Erie, which are expressed in terms of reductions from 2008 loads (Table ES-2).

Table ES-2. Binational Phosphorus Load Reduction Targets for Lake Erie

- **To 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:** a 40% reduction in spring total phosphorus (TP) and soluble reactive phosphorus (SRP) loads from the Maumee River in the United States.

- **To maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie:** a 40% reduction in spring TP and SRP loads from the following watersheds where algae is a localized problem: in Canada, Thames River, and Leamington tributaries; and in the United States, Maumee River, River Raisin, Portage River, Toussaint Creek, Sandusky River, and Huron River (Ohio).
- **To minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie:** a 40% reduction in TP entering the western and central basins of Lake Erie—from the United States and from Canada—to achieve an annual load of 6,000 metric tons (MT) to the central basin. This amounts to a reduction from the United States and Canada of 3,316 MT and 212 MT respectively.

- **Target:** A 40% reduction in spring TP and SRP loads from the Maumee River in the United States.

  Maumee River spring (March through July) TP loads ranged from 1,049 to 2,042 MT, exceeding the target load of 860 MT in every year during the 5-year evaluation period (Figure ES-1). Spring SRP loads closely mirrored TP loads, ranging from 216 to 399 MT, and exceeded the target load of 186 MT in every year during the 5-year period. Year-to-year changes in spring TP and SRP loads largely correlated with changes in spring discharge.

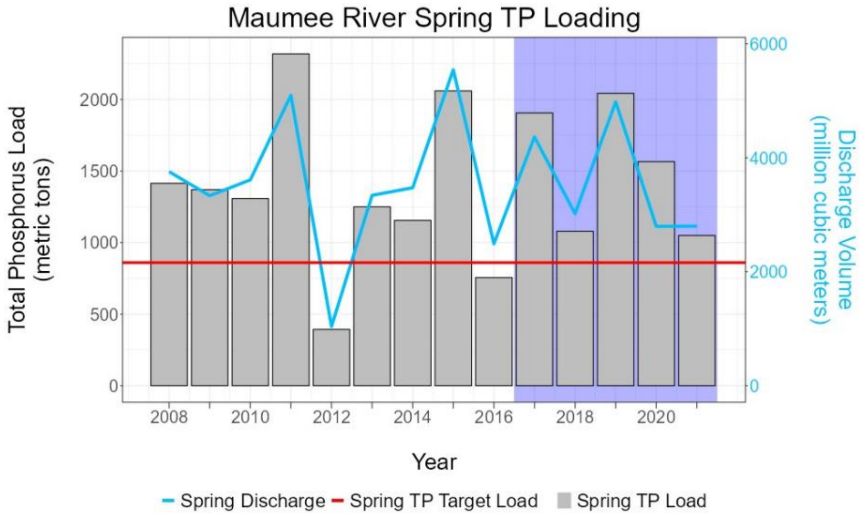

Figure ES 1. Spring total phosphorus load to Lake Erie from the Maumee River for water years 2008 – 2021, including comparison to target load (red line) and total spring discharge (blue line).

- **Target:** A 40% reduction in spring TP and SRP loads from priority watersheds where algae is a localized problem.

  For the two watersheds with the largest average spring (March to July) TP load (Maumee River and Sandusky River), TP and SRP target loads were not met in any year of the 5-year evaluation period. Target loads were met for at least one year in two smaller priority watersheds (Portage

River and River Raisin). Loads largely correlated with spring discharge, with lowest loads occurring in low-discharge years. Limited sampling frequency in some priority watersheds complicated load estimation efforts.

- **Target:** A 40% reduction in TP entering the western and central basins of Lake Erie—from the United States and from Canada—to achieve an annual load of 6,000 metric tons to the central basin.

  The TP annual loading target was not met in any year during the 5-year evaluation period (Figure ES-2). Annual TP load varied from year-to-year and was highly correlated with the discharge from major tributaries. Non-point sources accounted for most of the annual TP load to the central basin.

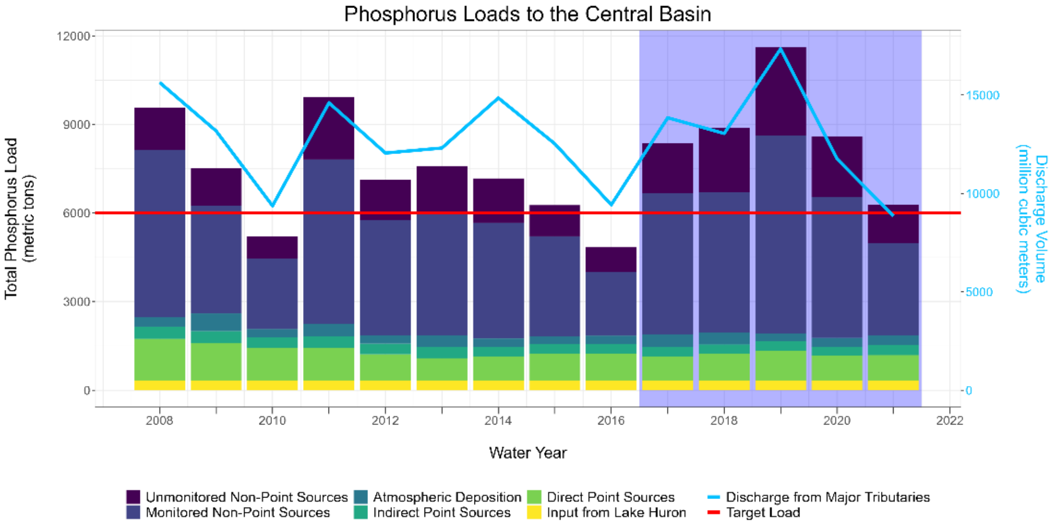

Figure ES 2. Annual total phosphorus load to the central basin of Lake Erie by loading source, including comparison to target load (red line) and total spring discharge (blue line).

In summary, phosphorus load reduction targets were rarely met during the 5-year evaluation period, load reductions were difficult to discern, and loads continue to be largely driven by precipitation (e.g., rain events) and discharge, which is highly variable from year-to-year. These findings are largely expected at this early stage of expanded phosphorus reduction efforts and considering the influence of recent discharge amounts and patterns.

Lake Conditions and Progress Toward Achieving LEOs

The Evaluation considered lake conditions associated with each of the nutrient-related LEOs for Lake Erie (Table ES-3).

Table ES-3. Binational Nutrient-Related Lake Ecosystem Objectives (LEOs) for Lake Erie
• Minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie. • Maintain the levels of algal biomass below the level constituting a nuisance condition, with a focus on benthic macroalgae in the eastern basin of Lake Erie.

- Maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie.
- 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.
- 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.

The evaluation assessed LEOs with defined quantitative objectives, including Interim Substance Objectives from the 2012 GLWQA and eutrophication response indicators (ERIs), where available (hypoxia, cyanobacteria biomass, and trophic condition LEOs). For LEOs without established quantitative objectives (nuisance benthic algae, nearshore algal species), relevant metrics were assessed for evidence of recent change.

- **Trophic Conditions** – Open water spring TP concentrations and summer chlorophyll a concentrations in the western basin were above associated Substance Objectives of 15 µg/L for TP and 3.6 µg/L for chl-a, meaning the waters were in ranges indicative of eutrophic conditions, not the objective of mesotrophic conditions. Open water spring TP concentrations in the central basin were above the Substance Objective, but within a range indicative of mesotrophic conditions. Open water summer chlorophyll a concentrations in the central basin were indicative of oligo-mesotrophic conditions. Open water spring TP concentrations and summer chlorophyll a concentrations in the eastern basin were near the Substance Objectives of 10 µg/L for TP and 2.6 µg/L for chl-a, and, combined, were indicative of oligo-mesotrophic conditions. Overall, concentrations of TP and chl-a were highest and most variable from year-to-year in the western basin, and from 2017 - 2021 all three basins were within the range of values seen in the preceding 15-20 years.
- **Cyanobacteria/HABs** – The western basin algal bloom severity exceeded target levels on the National Oceanic and Atmospheric Administration (NOAA) Bloom Severity Index (SI), where an SI of 2.9 corresponds to the ERI target threshold of 9,600 MT maximum 30-day western basin average cyanobacteria biomass (Figure ES-3). The observed SI ranged from 3 to 8 during the 5-year evaluation period. Blooms in 2017, 2019 and 2021 were moderately severe to severe, and blooms in 2018 and 2020 were mild. Environment and Climate Change Canada (ECCC) bloom severity metrics (i.e., EOLakeWatch, 2022) produced similar findings.

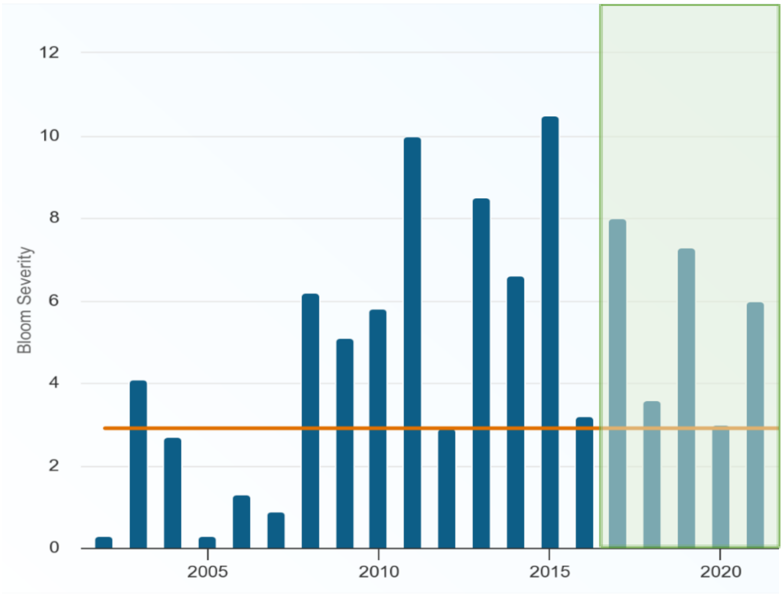

Figure ES 3. Lake Erie bloom severity index (NOAA), 2004 - 2021, highlighting assessment period (green shading; adapted from ErieStat).

- **Hypoxia** – Concentrations of dissolved oxygen in the central basin of Lake Erie exhibited high interannual variability and met the target threshold average August-September hypolimnetic dissolved oxygen concentration (at or above 2 mg/L) in three of the five years in the evaluation period (Figure ES-4).

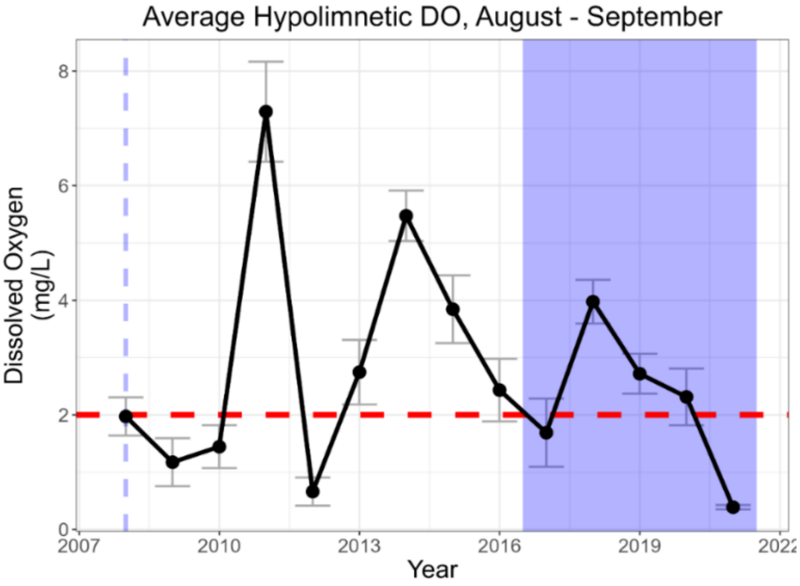

Figure ES 4. Average August-September hypolimnetic DO concentration, 2008 – 2021, highlighting current assessment period (purple shading).

- **Nuisance Algae** – Benthic algae biomass is variable from year-to-year and is often at or above nuisance conditions at shallow sites sampled in the eastern basin, whereas deeper sites (>3m) are generally below nuisance conditions. The large interannual variation makes it difficult to discern trends.

In summary, Lake Erie continues to exhibit eutrophic conditions as indicated by phosphorus and chlorophyll a concentrations as well as continued HABs in the western basin. Phosphorus and chlorophyll a concentrations in the central and eastern basins were relatively stable during the evaluation period and consistent with the associated trophic condition LEO, though central basin hypoxia remains. Nuisance benthic algae continues to be an issue in the eastern basin.

Recommendations for Improving Ability to Assess Progress

As part of the 5-year Evaluation, the AM Task Team reviewed information and binational collaborative efforts conducted under Annex 4 of the GLWQA and developed monitoring, modeling, and research recommendations to support the goals of the next 5-year Evaluation. The overarching recommendations include:

- Conduct more formalized and regularly occurring processes for developing and testing hypotheses of load-response relationships to help identify key uncertainties.
- Coordinate and strategically expand monitoring efforts to improve capacity to:
    - Evaluate lake response to nutrient loading;
    - Develop and refine ecosystem models;
    - Support improvements in existing monitoring technologies and methods;
    - Support development of emerging monitoring technologies and methods; and
    - Identify knowledge gaps and inform research priorities.
- Refine and improve methods and models to better evaluate load and ecosystem response relationships.
- Consider expanding ERIs to improve ability to evaluate progress toward achieving LEOs, accounting for evolving improvements in data coverage and quality.

See 5.2.2 for more details including specific suggestions pertaining to each component of the evaluation (trophic status, hypoxia, etc.).

Conclusion

Beyond interannual variability, there is not a clear change in phosphorus loading to Lake Erie over the 2017-2021 period. As expected from the lack of change in phosphorus loading, the objectives for in-lake conditions have not been achieved. This finding (that both loading targets and in-lake condition objectives have not been achieved) should not be interpreted as a lack of progress, because an observable response in water quality will require significant and sustained reductions in phosphorus loads. There is an expected lag between implementation of best management practices (BMPs) and observable load reductions from watersheds, and the timeframe for this evaluation was relatively short. Notably, many eutrophication indicators analyzed here and in other studies indicate that conditions in the lake have not worsened in recent years. Additionally, the evaluation’s findings are consistent with the broad consensus that phosphorus remains the primary and most manageable driver of HABs and hypoxia in Lake Erie.

This first 5-year Evaluation serves an initial assessment of progress and a baseline against which to track future progress towards our binational goals. Significant efforts are underway in Canada and the United

States to reduce phosphorus loads to Lake Erie, that, when brought to full scale and given time to be effective, are expected to provide benefits of improved Lake Erie water quality and ecosystem health. It is clear that more time will be required to reduce loads and draw down existing, legacy phosphorus from the system and allow the lake to respond and recover. Climate change will continue to affect discharge amounts and patterns into the future, thus a key challenge for meeting load reduction targets will be to reduce phosphorus loads despite discharge variability and trends.

Meanwhile, significant advancements are being made in our understanding of phosphorus load-response relationships. Enhanced monitoring, modeling, and research continues to refine our understanding and help identify areas that will require more study. These include the role nitrogen and other factors play in bloom toxicity, relative contribution of sediment and water column processes to hypoxia, and the significance of loadings from the St. Clair-Detroit River system. This cycle of knowledge creation, information sharing, and collaboration is the backbone of AM, and will ultimately accelerate progress toward achieving Lake Erie nutrient related LEOs.

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ACKNOWLEDGEMENTS

We would like to acknowledge the efforts of the Great Lakes Water Quality Agreement Nutrients Annex Subcommittee's Adaptive Management Task Team, both past and present, for their dedication and contributions to this evaluation. This work was supported by the U.S. Environmental Protection Agency Great Lakes National Program Office as part of General Services Administration (GSA) Contract # GS00Q14OADU116, Task Order # 47QFLA22F0075EPA Scientific and Technical Support for the Great Lakes National Program Office (GLNPO) with General Dynamics Information Technology (GDIT) under the direction of Ken Klewin, U.S. EPA Technical Point of Contact.

Our thanks extend to the Canadian and U.S. scientists and programs referenced in the report. Their monitoring, modeling, and research supplied the necessary data for this evaluation. Many of them also gave valuable input as participants in related workshops and meetings, or through direct feedback during the report's preparation.

1 INTRODUCTION

1.1 BACKGROUND

Over enrichment of nutrients resulting in excess algal growth, or eutrophication, poses significant threats to Lake Erie. Harmful algal blooms (HABs) have increased since the late 1990s, low-oxygen (or hypoxic) events continue to occur in the central basin, and nuisance macroalgae (e.g., *Cladophora*) has frequently fouled beaches and clogged water intakes. Total phosphorus (TP) and soluble reactive phosphorus (SRP) from tributaries has been identified as a main driver for HABs and hypoxia issues and contributes to nuisance macroalgae growth through a series of complex environmental processes.

Under Annex 4 (Nutrients) of the 2012 Great Lakes Water Quality Agreement (GLWQA), Canada and the United States committed to addressing eutrophication in Lake Erie by establishing Lake Ecosystem Objectives (LEOs), phosphorus load reduction targets, phosphorus reduction strategies, and Domestic Action Plans (DAPs) for nutrient management. Canada and the United States agreed to use an Adaptive Management (AM) approach to achieve the LEOs.

A formal binational Adaptive Management Framework (AMF) for nutrients in Lake Erie is overseen by the Annex 4 Subcommittee's AM Task Team. This effort requires the application of monitoring, modeling, and research to evaluate the lake's response to changing phosphorus loads. The primary objective of the AM Task Team is to develop and implement a formal AM process to track progress towards achieving LEOs for Lake Erie.

This report presents the findings of the Binational AM Task Team regarding progress made toward achieving the nutrient related LEOs for Lake Erie. This is the first Binational AM Evaluation to be conducted since nutrient management DAPs were put in place in 2018 and covers the 5-year period from 2017-2021. The report:

- Compiles information regarding nutrient loads (Section 2)
- Compiles information regarding lake conditions and evaluates signs of progress with respect to the following:
  - Trophic Conditions (Section 3.2)
  - Cyanobacteria/HABs (Section 3.3)
  - Algal Community Composition in Nearshore Waters (Section 3.4)
  - Hypoxia (Section 3.5)
  - Nuisance Algae (Section 3.6)
- Describes progress in modeling, research, and collaboration (Section 4)
- Presents recommended priorities for monitoring, modeling, and research to support future binational AM efforts for Lake Erie (Section 5)

The remainder of this section provides information regarding LEOs and binational AM efforts. Sections 2 through 5 of the report present the findings of the 5-year Evaluation and recommended priorities to support future binational AM efforts for Lake Erie.

1.2 GEOGRAPHIC SCOPE

The AM Evaluation is focused on three key issues (HABs, hypoxia, and nuisance algae) and where they occur in each of Lake Erie's three basins (western, central, and eastern) (Figure 1). The Evaluation considers the response of the lake ecosystem to phosphorus loadings from major tributaries and the Huron-Erie corridor, including Lake St. Clair.

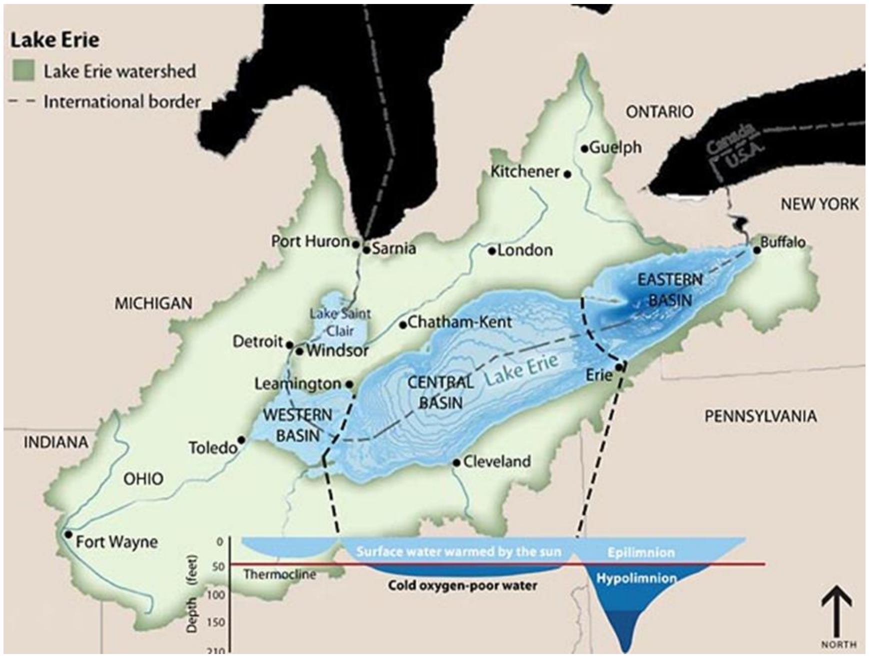

Figure 1. Scope of the Binational Lake Erie Nutrient AMF. Study area illustrates the watershed, location, and bathymetry of each Lake Erie basin and Lake St. Clair (Source: Environment and Climate Change Canada).

1.3 LAKE ECOSYSTEM OBJECTIVES, PHOSPHORUS REDUCTION TARGETS, AND EUTROPHICATION RESPONSE INDICATORS

Under Annex 4 of the 2012 GLWQA, Canada and the United States established LEOs to guide binational nutrient management efforts (Table ES-3).

To support these LEOs, Canada and the United States agreed to establish Substance Objectives, defined in terms of target phosphorus concentrations, for each Great Lake and to develop phosphorus loading targets and allocations, as required, to meet these Substance Objectives. The 2012 GLWQA included interim Substance Objectives for TP concentrations in open waters (i.e., 15 µg/l as represented by Spring means in the Lake Erie western basin, and 10 µg/l as represented by Spring means in the Lake Erie central and eastern basins), and interim phosphorus load targets for each of the Great Lakes.

In 2013, the Annex 4 Subcommittee established the Objectives and Targets Task Team to recommend revisions to existing Substance Objectives and phosphorus load targets for Lake Erie that, if met, would be expected to achieve the LEOs. The Final Report to the Annex 4 Subcommittee recommended phosphorus load targets for meeting the LEOs, expressed in terms of reductions from 2008 loads, and eutrophication response indicators (ERIs) and associated thresholds that could be used to evaluate the response of the lake ecosystem to reduced phosphorus loads. Canada and the United States agreed to the recommended phosphorus load reduction targets in 2016.

The adopted targets focused on reducing spring (March to July) loads of TP and SRP to the western basin from the Maumee River, reducing spring loading of TP and SRP from priority tributaries, and reducing annual loading of TP to the central basin (including both loading directly to the central basin and the load to the western basin, which flows into the central basin). Each of these targets directly addresses a specific LEO and is expected to contribute to other LEOs, including maintaining the desired trophic conditions in the three Lake Erie basins. Table 1 describes the relationships between phosphorus load reduction targets and Lake Erie nutrient related LEOs.

Table 1. Binational Phosphorus Load Reduction Targets and Associated LEOs, ERI, and Intended Outcomes

Phosphorus Load Reduction Target	Associated LEOs, ERI, and Intended Outcomes
A 40% reduction in spring TP and SRP loads from the Maumee River in the United States.	**Primary LEO focus:** To 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 **ERI and target threshold:** Maximum 30-day western basin average cyanobacteria biomass is less than or equal to the bloom biomass observed in 2004 or 2012 (≤9,600 MT) 90% of the time (9 years out of 10). **Intended outcomes, including secondary LEO relationships:** Achieving the load reduction target will reduce cyanobacteria blooms to non-severe levels. It will also contribute to maintaining algal species composition consistent with healthy aquatic habitat in the nearshore waters at the mouth of the Maumee River and the desired trophic status of the western basin.
A 40% reduction in spring TP and SRP loads from the following watersheds where algae is a localized problem: <u>Canada</u>: Thames River and Leamington Tributaries <u>United States</u>: Maumee River, River Raisin, Portage River, Toussaint Creek, Sandusky River and Huron River	**Primary LEO focus:** To maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie **ERI:** Indicator(s)/metric(s) under consideration **Intended outcomes, including secondary LEO relationships:** Achieving the load reduction targets is expected to reduce the frequency and severity of smaller localized cyanobacteria blooms at the mouths of these tributaries. Reduced loads from western basin tributaries will also help reduce frequency and severity of western basin HABs. It will also help maintain desired trophic status across the basins.
A 40% reduction in TP entering the western and central basins of Lake Erie—from the United States and from Canada—to achieve an annual load of 6,000 MT to	**Primary LEO focus:** To minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie **ERI and target threshold:** Average hypolimnetic oxygen level from August to September is at or above 2.0 mg/L. **Intended outcomes, including secondary LEO relationships:** Achieving the load target will sustain average hypolimnetic oxygen levels during August and

the central basin. This amounts to a reduction from the United States and Canada of 3,316 MT and 212 MT respectively.	September at or above 2.0 mg/L, increase dissolved oxygen in surface sediment, and reduce internal phosphorus loading (release of oxygen from sediment) to the central basin. It will also help minimize the extent of hypoxic zones in the central basin, improve the benthic community, help maintain desired trophic status across the basin, maintain/improve fishery habitat, improve quality of source water at drinking water intakes and contribute to maintaining the levels of algal biomass below the level constituting a nuisance condition.

(Sources: Binational.net, 2016; GLWQA Annex 4 Objectives and Targets Task Team, 2015; GLWQA Annex 4 Subcommittee, 2016; and GLWQA Annex 4 Subcommittee, 2019).

1.4 DAPS AND BINATIONAL AM EFFORTS

In 2018, Canada and the United States each released their DAPs which outline localized strategies for meeting the new targets in specific jurisdictions and watersheds. In Canada, the federal government and Province of Ontario developed a joint Canada-Ontario Lake Erie Action Plan (LEAP). 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. 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.

DAPs evaluate progress and adapt actions and initiatives to achieve phosphorus 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 best management practices), apply models to predict future conditions, and engage stakeholders on local and regional scales in actions to reduce phosphorus loads. DAPs are reviewed and updated as appropriate every 5 years.

The binational AM effort operates separately from AM activities conducted domestically; however, both processes are complementary. Achieving Lake Erie LEOs are dependent on 1) domestic phosphorus reduction actions achieving phosphorus reduction; and 2) targeted phosphorus reductions achieving the desired in-lake response. The first is being addressed by the domestic jurisdictions with support from federal agencies, while the second is the focus of the Binational Lake Erie Nutrient AMF.

1.5 BINATIONAL ADAPTIVE MANAGEMENT FRAMEWORK AND IMPLEMENTATION

The Binational Lake Erie Nutrient Adaptive Management Framework (AMF) outlines the binational AM process. The framework includes periodic convening of five technical working groups that were established by the AM Task Team, including three issue-focused working groups (HABs, hypoxia, and nuisance algae), a data and modeling working group, and a loadings working group. According to the AMF, the issue-focused working groups will bring together experts from binational federal, state, and provincial agencies and other participating organizations to inform a Binational AM Evaluation to assess the ecosystem response (Figure 2), and to enhance monitoring plans, prioritize uncertainties, and identify research questions and hypotheses. Working groups will also conduct a topic-focused research inventory and synthesis to identify gaps and recommend research priorities to the AM Task Team.

The AMF specifies that the AM Task Team will conduct a Binational AM Evaluation to assess the ecosystem response. This report documents the first such evaluation and includes information developed by the loadings, HABs, nuisance algae, and data and modeling working groups as well as information produced by a hypoxia workshop in 2021. This organizational structure and function of the Binational Lake Erie AM Evaluation is represented in Figure 2.

In support of Lake Erie Nutrient AM, in general, and the Binational 5-year AM Evaluation, specifically, the following activities have taken place:

- Loadings – The loadings working group estimates annual and seasonal phosphorus loads each year while coordinating with the AM Task Team for reporting and evaluation. This group is comprised of experts from U.S. and Canadian federal governments.
- HABs – The HABs working group comprised of U.S. and Canadian federal, state, and provincial agencies and academic partners developed recommendations for coordinated binational monitoring for HABs in Lake Erie and Lake St. Clair in 2021.
- Hypoxia – In 2021 the Cooperative Institute for Great Lakes Research (CIGLR) hosted a hypoxia summit, where attendees representing federal, provincial, and state agencies, academic partners, and other stakeholder groups reviewed the state of the science and assessed approaches for tracking progress toward reducing hypoxia in Lake Erie. Discussion notes from the summit's webinars and breakout rooms were collated to develop recommendations for monitoring, quantifying, tracking, and reporting changes in hypoxia, which were published in November 2022.
- Nuisance algae – The *Cladophora* working group (formerly the Eastern Basin Task Team) assessed whether current science is sufficient for development of binational phosphorus and *Cladophora* targets in the eastern basin of Lake Erie. The team comprised of subject matter experts and representatives from federal, provincial, and state agencies as well as other institutions involved in work in eastern Lake Erie produced a recommendation report in October 2020.
- Modeling – The data and modeling working group harmonizes the collection and synthesis of data generated through binational monitoring and research programs, and to uses this information to develop and run lake models to assess nutrient input-ecosystem response relationships. The working group is comprised of representatives from government agencies and academia, and other researchers.

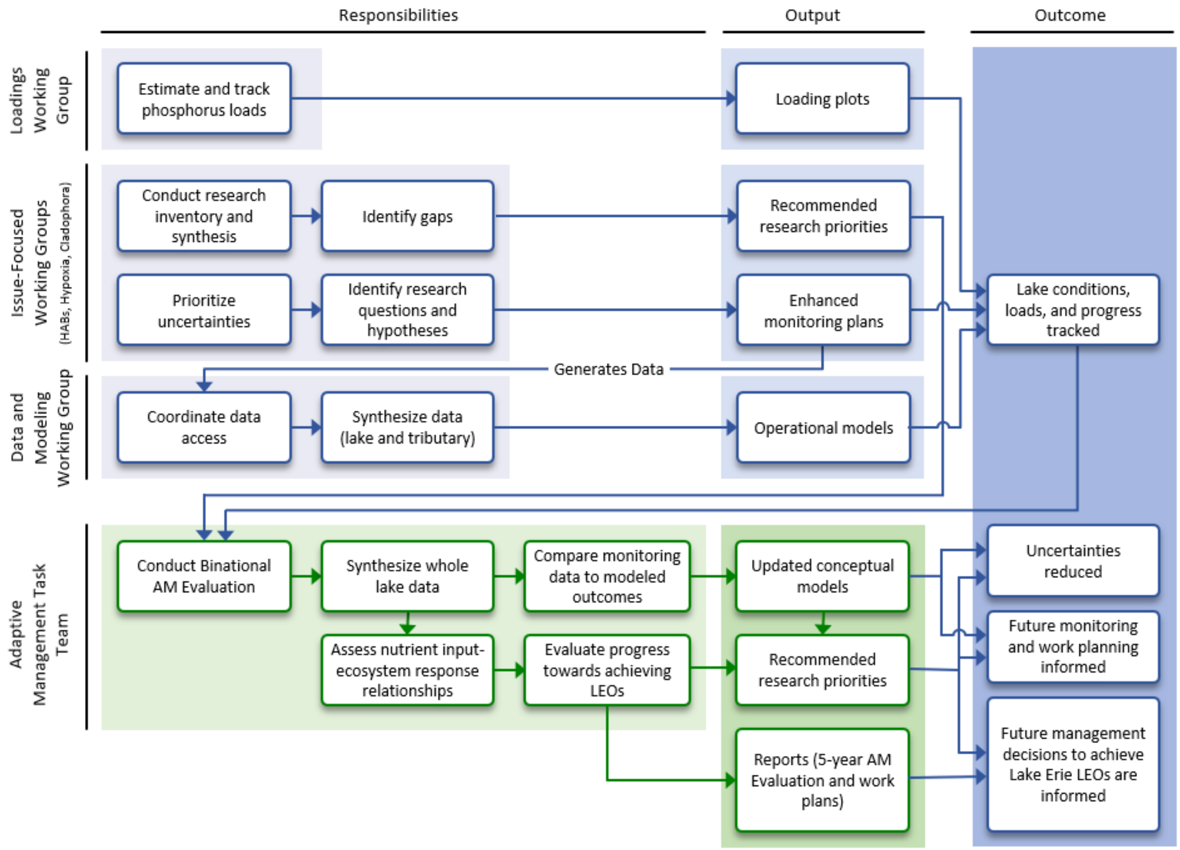

Figure 2. Role of Progress Evaluation in Lake Erie Nutrients AM. 5-year Evaluation activities are highlighted in the green-shaded boxes at the lower left of the diagram.

2 PHOSPHORUS LOADING TO LAKE ERIE

2.1 INTRODUCTION

Three phosphorus load reduction targets were developed by the Annex 4 Objectives and Targets Task Team (2015) and adopted by the Annex 4 Subcommittee in 2016 to achieve GLWQA LEOs: 1) spring TP and SRP load reductions from the Maumee River to address cyanobacteria biomass and associated toxins in the western basin, 2) spring TP and SRP load reductions from priority tributaries with localized algal blooms, and 3) annual TP load reductions to the central basin to minimize the extent of hypoxic zones. A 40% reduction from 2008 loads was adopted based on an extensive binational modeling effort. Evaluating progress towards these reduction target goals requires binational coordination with the federal, state/provincial, and local agencies and universities who collect the data needed to calculate loads across the entire Lake Erie basin. Loading calculations are conducted annually by the Annex 4 loadings working group, which provided the loads used for this evaluation.

2.2 PHOSPHORUS LOADS – STATUS AND TRENDS

2.2.1 Spring Phosphorus Loads to Western Basin from Maumee River

The Maumee River enters the western basin of Lake Erie, with its watershed located in Ohio, Indiana, and Michigan (Figure 3). It is the largest watershed in the Lake Erie basin (17,010 km^2) and the single largest source of phosphorus loading (mean annual TP load of 2,523 metric tons (MT) from 2008 - 2021). Land use in the watershed is dominated by agriculture, and most of its TP load comes from non-point sources (91%[1]), though municipalities (e.g., Toledo, OH and Fort Wayne, IN) and industrial development also contribute point sources (9% of annual TP load).

Figure 3. Map of the Maumee River Watershed. Source: Wikimedia.

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[1] Estimate for both monitored and unmonitored areas of Maumee watershed based on Annex 4 loadings working group calculations.

The large TP and SRP loads and high concentrations flowing from the Maumee River into the western basin fuel algal blooms, and several studies have identified the spring Maumee phosphorus load as the key driver of cyanobacterial biomass in the western basin of Lake Erie (Obenour et al., 2014, Stumpf et al., 2016, Scavia et al., 2016). Based on these findings and a multi-model study (Scavia et al. 2016), the Annex 4 Objectives and Targets Task Team adopted a 40% reduction target from a 2008 baseline, with the expected outcome of limiting cyanobacterial biomass and associated toxins. Significant effort has been directed to the Maumee watershed to reduce phosphorus loads, including DAPs and programs created by U.S. federal agencies (e.g., USDA NRCS 2016b, USEPA et al., 2018) and the states of Ohio (DAP, H2Ohio), Indiana (DAP), and Michigan (DAP, AM Plan).

Phosphorus Load Reduction Target
A 40% reduction in spring TP and SRP loads from the Maumee River in the United States.

Maumee River TP and SRP spring loads measured at the Waterville, OH monitoring location are calculated using data provided by the United States Geological Survey (USGS) and Heidelberg University's National Center for Water Quality Research (NCWQR). Daily loads are computed as the product of daily average discharge at USGS's Waterville, Ohio gage and mean nutrient (TP, SRP) concentration of 1 to 3 samples collected per day by NCWQR autosamplers slightly upstream of the USGS gage. Total spring loads for each water year are calculated by summing the daily loads from March 1 – July 31.

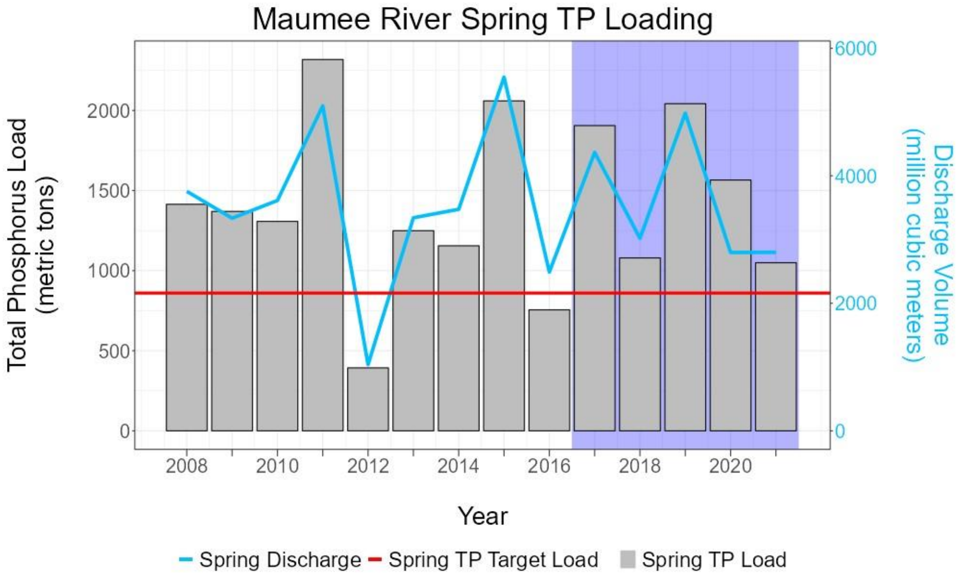

Figure 4. Spring total phosphorus load (grey bars) to Lake Erie from the Maumee River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period.

Maumee River spring TP loads ranged from 1,049 to 2,042 MT (average = 1,528 MT) during the 5-year evaluation period (Figure 44). As in the preceding period, year-to-year changes in spring TP loads largely correlated with changes in spring discharge. The two years with the highest spring TP loads (2017 and 2019) had total discharges over 4,000 million cubic meters, while the two lowest spring TP loads (2018 and 2021) occurred when total discharge was less than 3,000 million cubic meters. The spring TP load target of 860 MT was not met in any year from 2017 to 2021, and since 2008 was only met in the two years with the lowest total spring discharges, 2012 and 2016.

Spring SRP loads closely mirrored TP (Figure 5). Loads ranged from 216 to 399 MT from 2017 to 2021, with an average of 284 MT, and followed changes in spring discharge. The spring SRP target load of 186 MT was not met during the 5-year evaluation period and was last met in 2016.

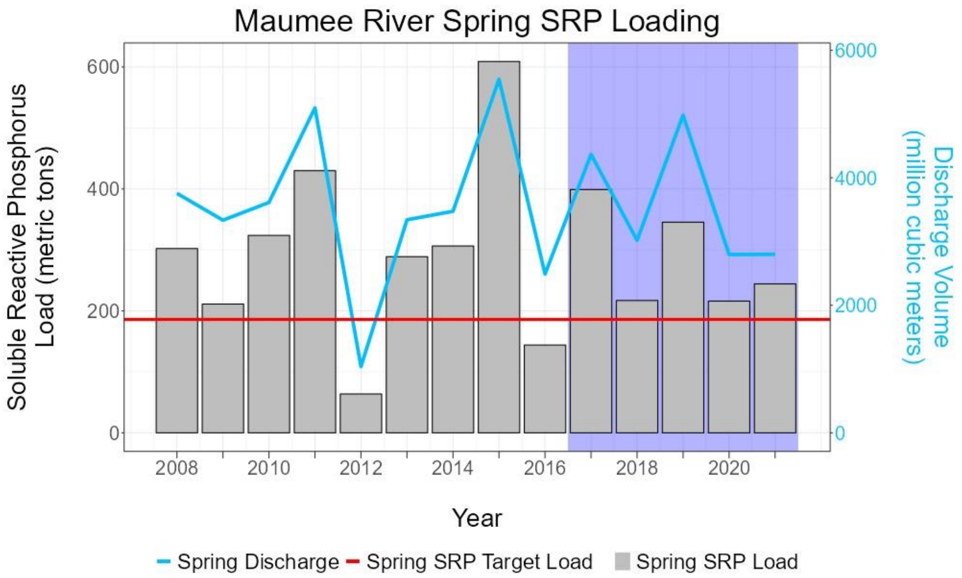

Figure 5. Spring soluble reactive phosphorus load (grey bars) to Lake Erie from the Maumee River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period.

In addition to the specific 40% reduction target adopted in 2016, the Annex 4 Objectives and Targets Task Team recommended that "flow-weighted mean concentrations (FWMC) at tributary mouths should be used as a benchmark to track progress in load reductions." FWMC is calculated by dividing total load by total discharge during the time period of interest, and the 40% load reduction targets correspond to Maumee River FWMC targets of 0.23 mg/L for TP and 0.05 mg/L for SRP. These targets have not been met in any year from 2008 – 2021 (Figures 6 and 7, respectively).

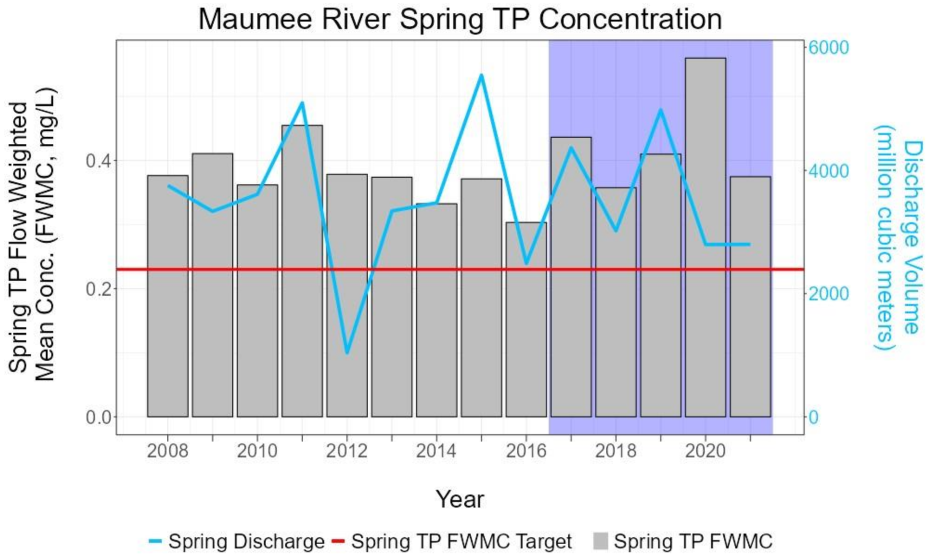

Figure 6. Spring total phosphorus FWMC (grey bars) of the Maumee River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period.

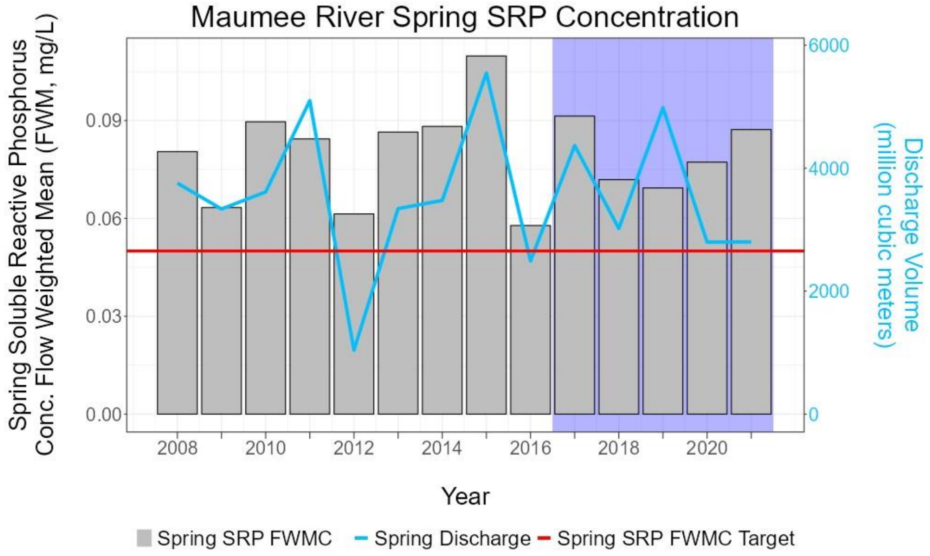

Figure 7. Spring soluble reactive phosphorus FWMC (grey bars) of the Maumee River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period.

In summary, Maumee River spring TP and SRP loads remained above targets during the 5-year evaluation period from 2017 to 2021. Variation in spring loads is closely tied to total spring discharge, with the smallest loads occurring in the driest years. FWMCs also remained above targets for both TP and SRP.

2.2.2 Spring Phosphorus Loads from Priority Tributaries

In addition to identifying the Maumee River as the key driver of the large western basin Lake Erie cyanobacteria blooms, the Objectives and Targets Task Team identified nearshore areas with localized cyanobacteria blooms and adopted 40% spring TP and SRP reduction targets from 2008 for those priority watersheds to reduce the localized blooms. In the United States, these watersheds include the Maumee River (Section 2.2.1), River Raisin, Portage River, Sandusky River, Huron River (Ohio), and Toussaint Creek. In Canada, the Thames River and Leamington area watersheds were identified as priority watersheds. Spring priority tributary load calculations and targets are based on measurements at the monitoring locations, and do not include estimates of loading from areas downstream or adjacent to the monitored watershed areas. Due to limited data collection in 2008 for some tributaries (discussed further below), reduction targets have not yet been established for the Thames, Leamington, Huron (OH), and Toussaint Rivers.

Phosphorus Load Reduction Target
A 40% reduction in spring TP and SRP loads from the following watersheds where algae is a localized problem: United States: Maumee River, River Raisin, Portage River, Toussaint Creek, Sandusky River, and Huron River Canada: Thames River and Leamington Tributaries

Loads for most years in most of the U.S. priority watersheds were calculated as described in Section 2.2.1 for the Maumee River, with discharge data provided by USGS and daily nutrient concentrations provided by Heidelberg University's NCWQR. For U.S. and Canadian tributaries and years for which nutrient concentrations were available but not at a daily sampling frequency, the loads were calculated using the Stratified Beale Ratio Estimator (SBRE; Beale, 1962, Dolan et al., 1981, Tin, 1965) that has been used in prior loading estimates for Lake Erie (Maccoux et al., 2016). In years when limited nutrient concentration measurements were available (e.g., during the COVID-19 pandemic), discharge-based regression was used to calculate loads. For U.S. watersheds not monitored by NCWQR, concentration data were provided by USGS or Ohio Environmental Protection Agency (EPA). Data for Canadian watersheds were collected by Environment and Climate Change Canada (ECCC) and various conservation authorities such as Essex Region Conservation Authority (ERCA) and Lower Thames Valley Conservation Authority (LTVCA) through the Ministry of the Environment, Conservation and Parks (MECP).

Table 2 presents mean spring TP and SRP loads from 2017 to 2021, the number of years during the 5-year evaluation period where load reduction targets were met, and the relative trends (% per year compared to baseline year) in loads and FWMC from 2008 - 2021. It is important to note potential limitations for interpreting changes to the actual loads computed by the Annex 4 loadings working group. First, actual loads are strongly influenced by discharge, and variability in discharge can mask other changes. Additionally, most trend analyses make assumptions about the type of change (e.g., constant linear trend over the time period analyzed) which may not match reality if, for example, implementation of management practices changes over time. Finally, as a result of high year-to-year variability, 10 or more years of data may be needed to discern trends or changes with certainty.

Despite these complications, analyzing changes in loads is important for determining if Lake Erie is responding as expected. For this Evaluation, the Thiel-Sen slope was computed for all available actual loads and FWMCs from 2008 – 2021 and each slope was normalized by the first year's value to determine the percent change per year. This relative index of change can be compared across tributaries, and along with flow-normalized loads for the Maumee River (Section 2.3.1), provides a starting point for evaluating changes to loads that can be repeated and expanded upon in future reports.

Table 2. Spring loading information for priority watersheds.

Watershed	Data Source[1]	Sampling Freq.[1]	Ave. TP Load (MT)	Total Phosphorus				Soluble Reactive Phosphorus			
				Years Met		Trend (%/yr)[2]		Years Met		Trend (%/yr)[2]	
				Load	FWMC	Load	FWMC	Load	FWMC	Load	FWMC
Thames	ECCC	2x/week + precip	169	NT	NT			NT	NT		
Leamington	MECP, ERCA	Biweekly + precip	9	NT	NT			NT	NT		
Huron (OH)	NCWQR	Daily	82	NT	NT			NT	NT		
Maumee	NCWQR	Daily	1,528	0/5	0/5	-1.7%	0.0%	0/5	0/5	-0.2%	+0.4%
Portage	NCWQR	Daily	99	4/5	0/5	+0.6%	+1.5%	3/5	0/5	-0.1%	+0.2%
Raisin	NCWQR	Daily	91	1/5	0/5	-0.4%	+1.6%	NT	NT	+0.4%	+1.7%
Sandusky	NCWQR	Daily	317	0/5	0/5	-0.5%	+0.5%	0/5	0/5	-0.9%	+2.2%
Toussaint		Not monitored									

NT = no target

1. Data sources and typical sampling frequency as of 2023; changes occurred for Thames (2017) and Huron-OH (2018). Toussaint Creek is unmonitored; its load is extrapolated from adjacent watersheds so targets and trends were not evaluated. Biweekly indicates once every two weeks. Precip indicates samples were collected in response to precipitation events in addition to routine sampling.

2. Trends were calculated using the Theil-Sen slope (Sen, 1968) and divided by the 2008 baseline value (2011 for Portage) to give the overall percent increase or decrease per year from 2008 – 2021. Empty trend boxes are due to either missing data or large changes in nutrient sample sizes that limit interpretation of trends. A table with trend p-values table is presented in Appendix 7.2.2.

Of the four spring priority watersheds with data and consistent sampling regimes (Maumee River, Portage River, River Raisin, and Sandusky River), trends were generally small and statistically uncertain for TP and SRP for loads and FWMCs, as indicated by slopes near 0%/year and high p-values. For the two watersheds with the largest average spring TP load (Maumee River 1,528 MT, Sandusky River 317 MT), the 40% reduction load and FWMC targets were not met in any year of the 5-year evaluation period for TP or SRP. In the Portage River watershed, the TP load reduction target effective during the 5-year evaluation period was met in 4 out of 5 years (all but 2019) and the SRP load reduction target was met in 3 out of 5 years (all but 2017 and 2019). The Portage River reduction target uses a baseline of 2011 because that is when NCWQR began daily sampling and 2011 had a similar total spring discharge to 2008 (Ohio Domestic Action Plan, 2020). That also was the year with the highest spring discharge and TP load from 2011 to 2021. The only other case in which an established reduction target was met was the 2021 spring TP load for the River Raisin, which had the second-lowest spring discharge from 2008 – 2021. Notably, none of the FWMC reduction targets were met for spring priority watersheds where they have been established and no tributary had a negative FWMC trend, indicating that when load targets are met during low-discharge springs it is largely due to reduced discharge and not to phosphorus concentrations meeting FWMC reduction targets.

Figures showing estimated loads and discharge by year from 2008 to 2021 have been developed for each priority watershed. Figures for the Maumee River are presented in Section 2.2.1. Figures 8 and 9 for the Thames River and Huron River TP illustrate how changes in sampling frequency have implications for evaluation reduction targets. Figures for all other priority watersheds are included in Appendix 7.2.1.

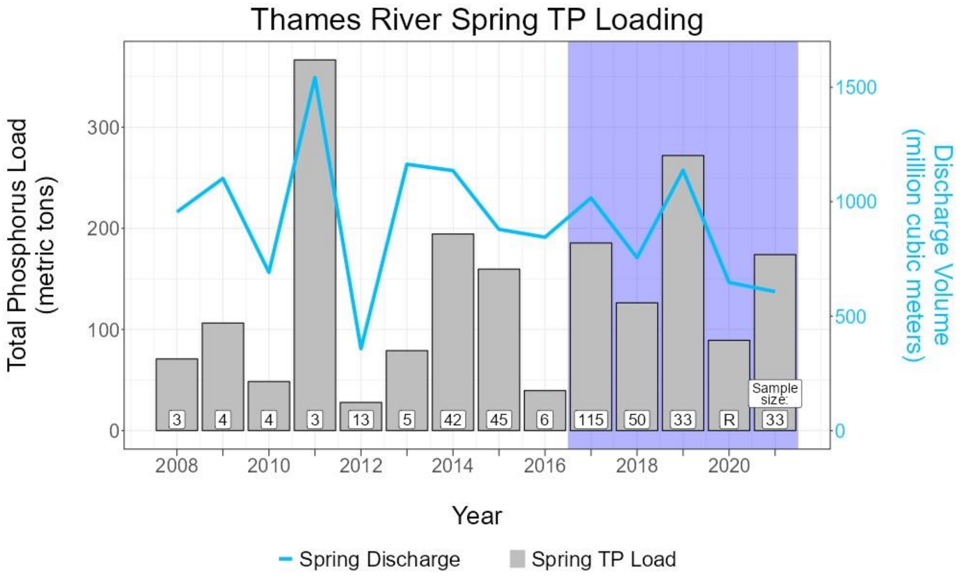

Figure 8. Spring total phosphorus load (grey bars) from the Thames River for water years 2008 – 2021. Blue line total is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring; "R" indicates a discharge-based regression method was used due to limited sampling.

Spring TP loads for the Thames River are highly variable from year-to-year (Figure 8), though changes in sample size over time complicate establishing a load reduction target and interpretation of trends. From 2008 to 2011, only 3 or 4 samples were collected each spring; calculated spring loads are relatively small except for in 2011, which is the largest load during this time period. Small samples sizes are unlikely to adequately capture the load-discharge relationship used as the basis for the SBRE method and may cause inaccurate estimates depending on which specific days were sampled. Comparison of the 2008 discharge and spring load (955 million cubic meters discharge, 71 MT TP) to years with more samples but similar discharge (2015: 879 million cubic meters discharge, 160 MT TP; 2017: 1,017 million cubic meters, 186 MT TP) suggests the spring load estimate for this year is lower than expected, and so a 40% reduction from existing 2008 baseline would be an unrealistically low target. The same pattern is true for the Thames River spring SRP load.

Similar complications arise from changes to sampling size in the Huron River (Ohio) watershed (Figure 9). From 2009 to 2017, nutrient concentrations were measured by Ohio EPA. These samples were not designed for load calculations and spring sample sizes were low in number, ranging from 2 to 19. Starting in 2018, the NCWQR began sampling the Huron River each day for the purpose of nutrient load calculation. Loads after the change in sampling frequency are all higher than all prior years, suggesting that a load reduction based on sampling prior to 2018 would result in an unrealistically low target.

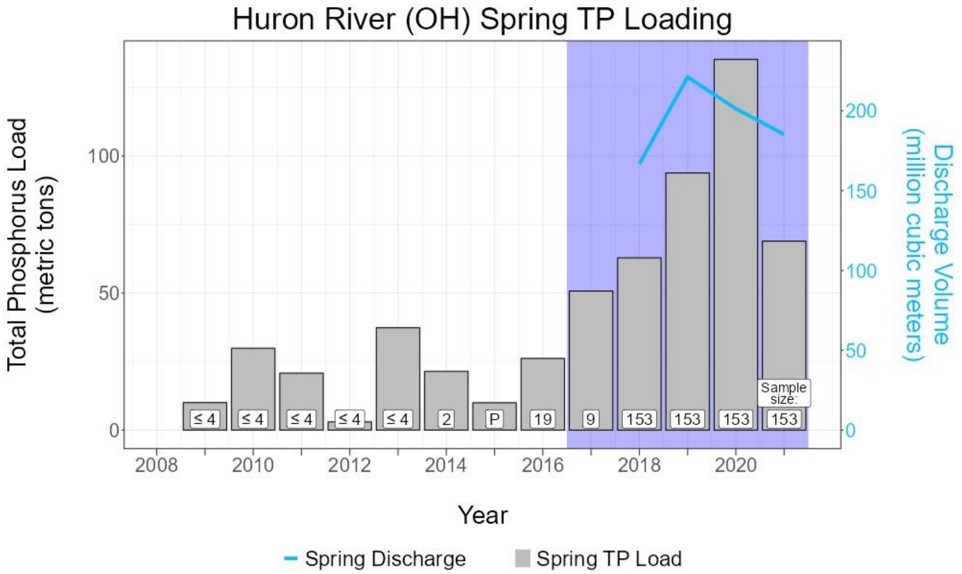

Figure 9. Spring total phosphorus load (grey bars) from the Huron River (Ohio) for water years 2009 – 2021. Blue line total is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring; "P" indicates the annual load was prorated based on the proportion of annual discharge that occurred from March – July due to limited spring sampling. Sample sizes with ≤ indicate maximum possible samples sizes taken from Maccoux et al. (2016), which reported only annual values**.**

2.2.3 Annual Phosphorus Loads to Central Basin

While spring TP and SRP loads from the Maumee River and other priority tributaries were identified by the Annex 4 Objectives and Targets Task Team (2015) for reduction targets to address HABs, annual TP loading to the western and central basins was determined to be a key driver of hypoxia in the central basin. As a result, Annex 4 adopted a 40% reduction target for annual TP from the 2008 baseline to minimize the extent of hypoxic zones. The 40% reduction for hypoxia includes both a total load target of 6,000 MT to the central basin from all sources that feed into the central basin (including inputs from Lake Huron, the atmosphere, and watershed inputs to the Huron-Erie Corridor, western basin, and central basin), as well as 40% reduction targets for individual priority watersheds. These annual TP priority watersheds include the 8 spring TP and SRP priority watersheds (Thames River and Leamington in Canada, and Huron-OH, Maumee, Portage, Raisin, Sandusky, and Toussaint in the United States) as well as four additional watersheds in the United States: the U.S. Detroit River watershed, Vermilion River, Cuyahoga River, and Grand River (Ohio). Annual priority tributary and total central basin load calculations and targets are estimated for the entire watershed (also referred to as "entire complex"), including measured loads at the monitoring locations and downstream and adjacent areas' point and non-point loads.

Phosphorus Load Reduction Target
A 40% reduction in TP entering the western and central basins of Lake Erie—from the United States and from Canada—to achieve an annual load of 6,000 MT to the central basin. This amounts to a reduction from the United States and Canada of 3,316 MT and 212 MT respectively.

The total annual central basin TP load was calculated by summing the component loads (watershed, Lake Huron, and atmospheric inputs). For each individual watershed load, the monitored load at the monitoring location was calculated as described in Sections 2.2.1 and 2.2.2. For unmonitored areas, non-point source loads were calculated using unit area loads (TP load per unit area) from upstream or adjacent monitored areas and added to point source loads in the unmonitored areas.

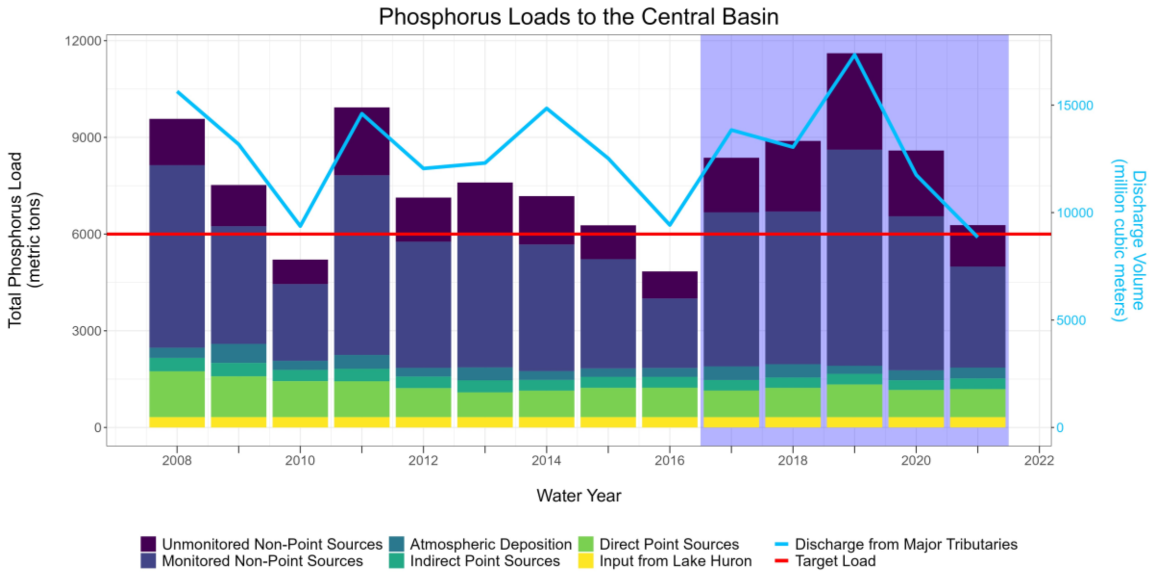

Figure 10. Annual total phosphorus loading to the central basin of Lake Erie. Bar color indicates loading source. Horizontal red line represents the 6,000 MT target, based on a 40% reduction from 2008 baseline. Blue line is total annual discharge from 6 major Lake Erie tributaries.

From 2017 to 2021, the 6,000 MT TP target was not met in any year (Figure 10). The 2021 load of 6,278 MT came closest to meeting the target; this was also the year during the 5-year evaluation period that had the lowest annual discharge from 5 major Lake Erie tributaries at 8,852 million cubic meters. Since 2008, the central basin target was met in two years, 2010 and 2016, which were the only two years besides 2021 with annual major tributary discharge <10,000 million cubic meters. Annual TP load was tightly correlated to the discharge from major tributaries, with a correlation coefficient of 0.85 for 2008 - 2021.

Analysis by source demonstrates the dominance of non-point sources in determining annual TP load to the central basin and year-to-year variability, relative to other sources. Monitored and unmonitored non-point sources accounted for an average of 73% of annual TP loads from 2008 – 2021. Non-point sources ranged from 60% to 84% (2,996 to 9,697 MT) over that period, with lower percentages usually occurring in drier (lower discharge) years and vice versa. Loads from all other sources (point sources, Lake Huron, atmospheric deposition) averaged 27% (range 16 – 40%) and were much more stable from year-to-year (loads varied between 1,748 and 2,597 MT).

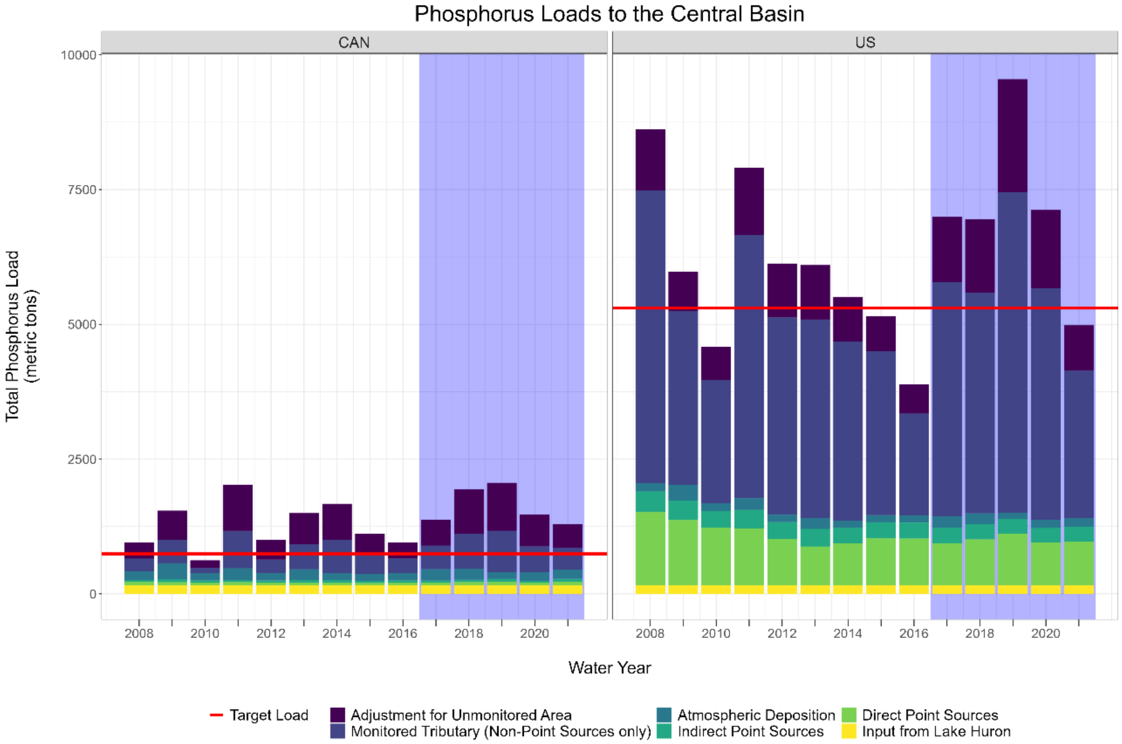

Figure 11. Annual country-specific total phosphorus loading to the central basin of Lake Erie. Bar color indicates loading source. Horizontal red line represents country-specific targets calculated by subtracting reduction specified in each country's DAP from the 2008 load.

Country-specific TP loads to the central basin were also calculated along with reduction targets to illustrate differences in the load magnitude and sources (Figure 11). Lake Huron and atmospheric loads were evenly split between the United States and Canada. Country-specific reduction targets were calculated by subtracting the reduction specified in each country's DAP (3,316 MT for U.S., 212 MT for Canada) from the country-specific 2008 loads. Years with high and low loads were similar between countries, though spatial variability in precipitation (and thus discharge), sampling changes described above, and other factors are expected to create country-specific variability. The U.S. annual TP load to the central basin averaged 6,390 MT from 2008 - 2021, 4.6 times larger than Canada's average load of 1,394 MT. The U.S. load also had a larger contribution of point sources to the total load, averaging 20% compared to 8% for Canada. While no year from 2017 - 2021 met the combined central basin target, the U.S.-specific 40% reduction target was met in 2021 with a load of 4,983 MT. Prior to 2017, the U.S.-specific target was also met in 2010, 2015, and 2016. Three of these years when the U.S.-specific target was met (2010, 2016, 2021) were also the three years with the lowest annual TP load for the Maumee River from 2008 - 2021 (Figure 12). During the period from 2008 – 2021, the Canada-specific target was only met in 2010.

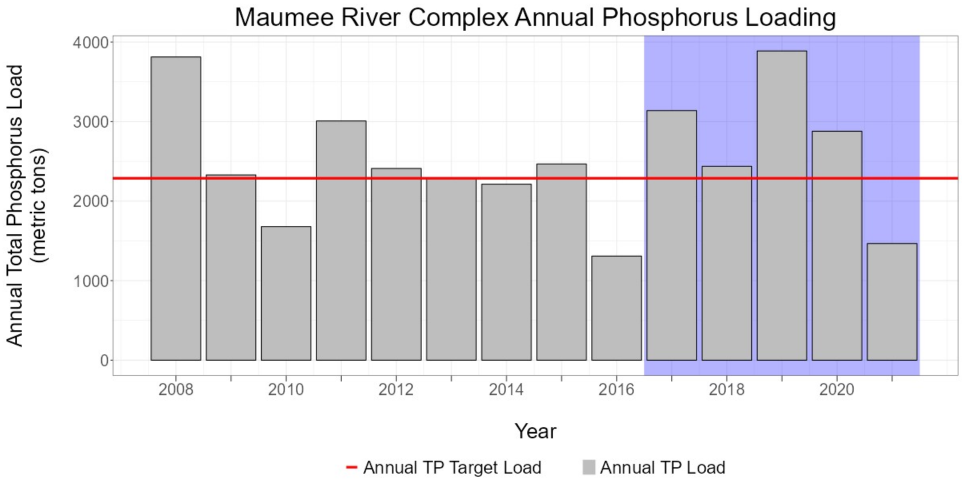

Figure 12. Annual total phosphorus load (grey bars) from the Maumee River watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

To address central basin hypoxia, the Objectives and Targets Task Team identified 12 priority tributaries for TP load reduction, in addition to establishing the combined annual TP target loads for the entire central basin. Table 3 presents mean annual TP loads from 2017 to 2021, the number of years during the 5-year evaluation period where load reduction targets were met, and relative trends in TP load (% per year compared to baseline year as described for spring priority tributaries above). Figures of annual TP load along with TP concentration sample sizes for all tributaries with calculated loads are presented in Appendix 7.2.3. Note that the Detroit River (U.S.) watershed is calculated by summing the loads from the Black (MI), Belle-Pine, Clinton, and Rouge sub-watersheds and direct inputs to the Huron-Erie corridor from the U.S. For this reason, the Detroit River (U.S.) watershed load is not intended to directly represent the inputs at the mouth of the Detroit River.

Table 3. Annual loading information for priority watersheds.

				TP		
Complex (annual)	**Data Source**	**Sampling Freq.**	**Ave. Total Load (MT)**	**# Years Met**	**Trend %/year**	**Trend p-value[4]**
Thames	ECCC	2x/wk + precip	499	No Target		
Leamington[1]	MECP, ERCA	Biweekly + precip	35	No Target		
Cuyahoga	NCWQR	Daily	315	1/5	-2.3%	0.08
Detroit River (U.S.)	USGS	Monthly	848	1/5	-3.0%	0.009
Grand (OH)	USGS	Monthly	266	0/5		

Huron (OH)	NCWQR	Daily	273	0/5		
Maumee	NCWQR	Daily	2,762	1/5	-0.3%	1.0
Portage	NCWQR	Daily	255	1/5	-2.4%	0.32
Raisin[2]	NCWQR	Daily	190	1/5	-0.6%	0.74
Sandusky	NCWQR	Daily	715	2/5	-1.6%	0.32
Vermilion[3]	USGS	Monthly	71	5/5*		
Toussaint		Not Monitored		No Target		

1. Leamington tributary annual loads only available from 2018 – 2021. Biweekly indicates once every two weeks.
2. Michigan calculates and evaluates loads for River Raisin at the monitoring location, while annual values and trends reported in this Evaluation include estimates of loading from downstream and adjacent areas for consistency with Annex 4 methods.
3. There have been large changes in sampling frequency in the Vermilion River, see Figure 15 and text below.
4. P-values used as a conventional statistical measure of evidence against the null hypothesis that the slope is 0.

For priority tributaries that have had relatively consistent sampling from 2008 (Cuyahoga, Detroit, Maumee, Portage, Raisin, and Sandusky rivers), trends varied from -3.0% per year (Detroit) to -0.3% per year (Maumee). However, year-to-year variability for most tributaries was high as is uncertainty in trend slope estimates for most tributaries. The only two tributaries with larger-magnitude trends and smaller p-values were the Detroit River watershed (trend slope = -3.0% per year, p-value = 0.009) and Cuyahoga River (trend slope = -2.3%, p-value = 0.08). Notably, these two tributaries have a relatively high proportion of point sources (Maccoux et al., 2016), though there have been significant efforts to reduce non-point source loading in the Cuyahoga River. The cautions in interpreting trends described above for spring loads also apply for annual loads: changes to load are largely driven by discharge, potentially masking other changes; the slope calculated represents a single, linear rate of change for the entire period, while true changes are likely to be non-constant; and the time period analyzed is shorter than estimates of the length of time needed to detect even large changes (Betanzo et al., 2015).

Similar to spring TP and SRP reduction targets, annual TP load reduction targets were generally not met for the tributaries for which they have been established. Most did not meet targets or met targets in a single year during the 5-year evaluation period from 2017 – 2021. The Sandusky River was the only tributary with high-frequency, consistent sampling from 2008 – 2021 where the reduction target was met in more than one year during the 5-year evaluation period; its reduction target was met in 2020 and 2021.

As observed for spring priority tributary loads, several annual load priority tributaries have had changes in sampling regimes since 2008 that complicate the interpretation of targets and trends. Changes and issues described for spring loads for the Thames, Huron (OH), and Toussaint rivers also apply to annual load sample sizes. The Grand River in Ohio had annual nutrient concentration sample sizes ranging from 1 – 4 samples per year up until 2016 and 11 – 34 samples from 2017 – 2019, and discharge-based regression incorporating prior years of data was used to calculate loads for 2020 and 2021. The 2008 baseline load for the Grand River was 165 MT TP (sample size uncertain); the reduction target was met in all years but 2011 from 2009 – 2016 when sample sizes were low and has not been met in any year from 2017 to 2021 (Figure 13).

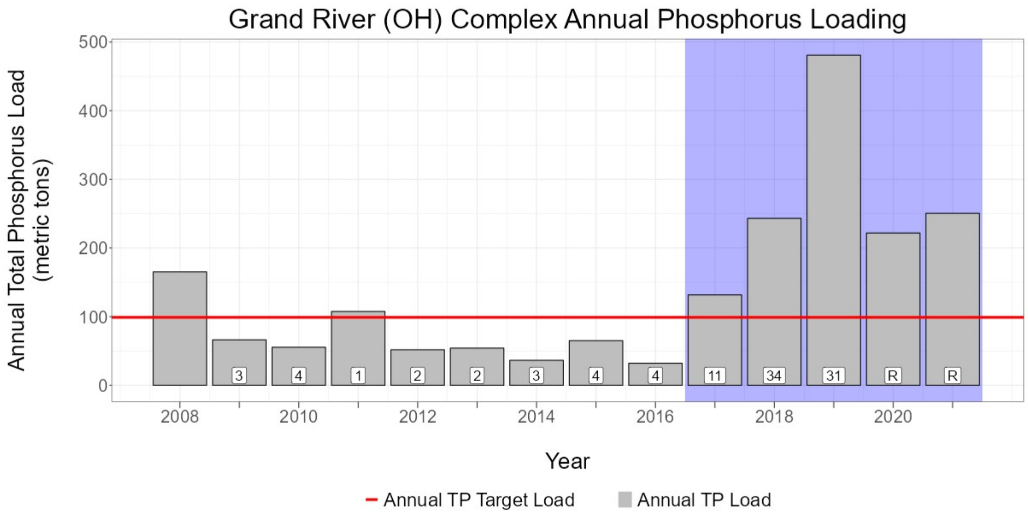

Figure 13. Annual total phosphorus load (grey bars) from the Grand River, Ohio watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

The Vermilion River was monitored by Heidelberg University's NCWQR in 2008 with daily nutrient samples and the resulting load used to establish a 40% reduction target, but from 2009 – 2021 nutrient sampling was conducted by Ohio EPA and USGS with between 4 and 46 samples per year. Years with the highest sample sizes generally have higher annual TP load estimates (Figure 14). The 2008 baseline year has the second-highest annual TP load estimate, and the resulting 40% reduction target was met in all five years from 2017 – 2021.

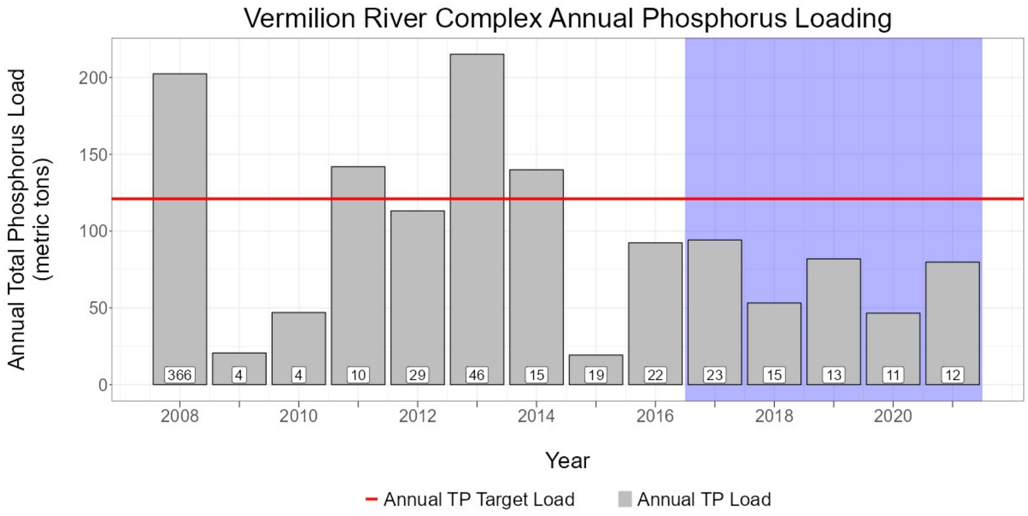

Figure 14. Annual total phosphorus load (grey bars) from the Vermilion River, Ohio watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line

is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

Overall, annual TP reduction targets established to address central basin hypoxia are largely not being met for the entire basin or priority tributaries. The total central basin target was not met during the 5-year evaluation period from 2017 – 2021 and has only been met twice since 2008, during two years with very low discharge. Priority tributary reduction targets were also rarely met where they have been established. For some of the watersheds with targets, and those without, changes in nutrient sampling frequency (or no sampling for unmonitored tributaries) complicate baseline determinations, establishment of reduction targets, and evaluation of trends. Of the watersheds that had consistent sampling, trends in annual TP load from 2008 – 2021 were mostly small and uncertain due to year-to-year variability. Notably, the two watersheds with the strongest evidence for declines (U.S. Detroit River and Cuyahoga) both have high proportions of point sources.

2.3 SUMMARY AND DISCUSSION

2.3.1 Summary of findings and interpretation

Across the three phosphorus loading reduction targets established by the Annex 4 Objectives and Targets Task Team (Maumee spring TP/SRP, priority tributary spring TP/SRP, and priority watershed and total central basin annual TP), most load reduction targets are not being met, and when they are it is usually during low discharge years. FWMC targets were not met in any year for tributaries where they have been established, indicating that even in lower discharge years phosphorus concentrations remain relatively high, and lower discharge rates are largely responsible for cases when load targets are met. The relative magnitude of trends in both loads and FWMCs are generally small and uncertain. The results of this evaluation are consistent with our understanding of controls of nutrient loading to Lake Erie and our expectations based on the degree to which and length of time since management actions have been taken in the watershed.

While extensive efforts to reduce nutrient loading have been completed and are in progress (USDA NRCS 2016b, H2Ohio 2022), several studies have found that multiple management practices will need to be implemented on large (> 60%) proportions of the Lake Erie watershed acreage to significantly reduce phosphorus loads (Scavia et al., 2017; Martin et al., 2021; USDA NRCS 2016a, USDA NRCS 2017). There are expected lags from when BMPs are implemented to when improvements are realized at the lake due to legacy nutrients in fields and streams (Sharpley et al., 2013, Muenich et al., 2016). Lastly, once sufficient BMPs to achieve 40% reductions are implemented, it may take years for changes to be distinguished statistically from natural year-to-year variability (Betanzo et al., 2015; Wellen et al., 2020). These studies and the lack of significant, sustained loading declines documented in this evaluation suggest that continued efforts to reduce nutrient loading are needed, as well as additional time for those practices to take effect and be detectable.

2.3.2 Estimation of Loading Changes Without Influence of Discharge

Discharge drives most of the yearly variability in spring and annual phosphorus loads and changes significantly from year-to-year with precipitation patterns, which makes detecting changes in loads due to other factors such as land-use change or management actions challenging. Flow-normalization is a statistical tool that reduces variability in load estimates and is implemented in the EGRET software developed by the USGS (Hirsch et al. 2023), which integrates daily Weighted Regressions on Time, Discharge, and Season (WRTDS) of nutrient concentrations over the probability distribution of discharge (Choquette et al. 2019). The resulting flow-normalized loads remove most of the daily, annual, and seasonal variability due to flow and are less variable than actual loads, which makes detecting and interpreting trends and changes due to other effects easier.

Rowland et al. (2021) analyzed NCWQR datasets using the EGRET software in three Lake Erie tributaries and provided updated figures for the Maumee River for use in the AM Evaluation. As the single largest load to Lake Erie and the focus of several efforts to reduce nutrient loading, understanding changes to Maumee River loading is crucial to understanding progress towards achieving load reduction targets and LEOs. Annual discharge is highly variable in the Maumee River, with a more than 3x difference in average daily discharge between the lowest and highest years from 1982 – 2021 (Figure 15) and has increased over this time period.

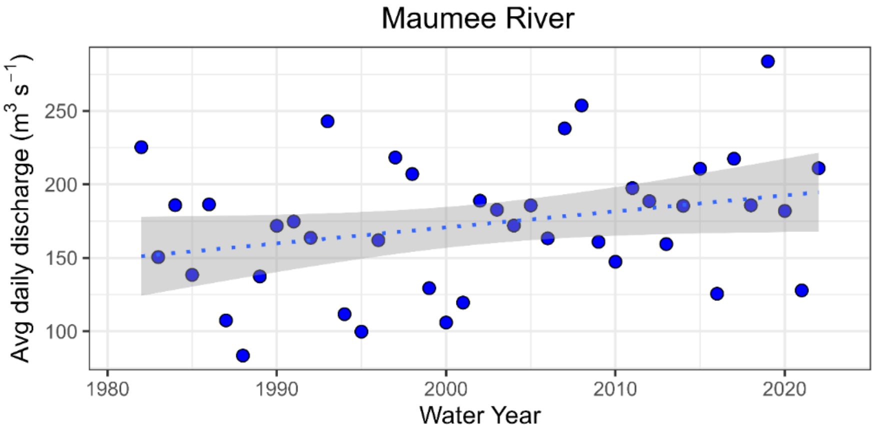

Figure 15. Average daily discharge from 1982 – 2021 for the Maumee River measured at Waterville, OH. Source: F. Rowland, updated from Rowland et al. (2021).

Actual loads of TP for the Maumee River are highly variable and closely follow discharge (Figure 16a). Approximately 77% of the variability in annual TP load is explained by variability in discharge (Rowland et al. (2021) Figure S1). The flow-normalized TP loads (Figure 16a) increased since about 2012 but remain below the peak observed around 1990. Conversely, flow-normalized SRP loads declined since peaking in 2008 but remain nearly 2x higher than the minimum in 1989 (Figure 16b). In addition, flow-normalized loads for different forms of nitrogen measured by NCWQR have all been steady or declined over the past 10 – 20 years (Appendix 7.2.4).

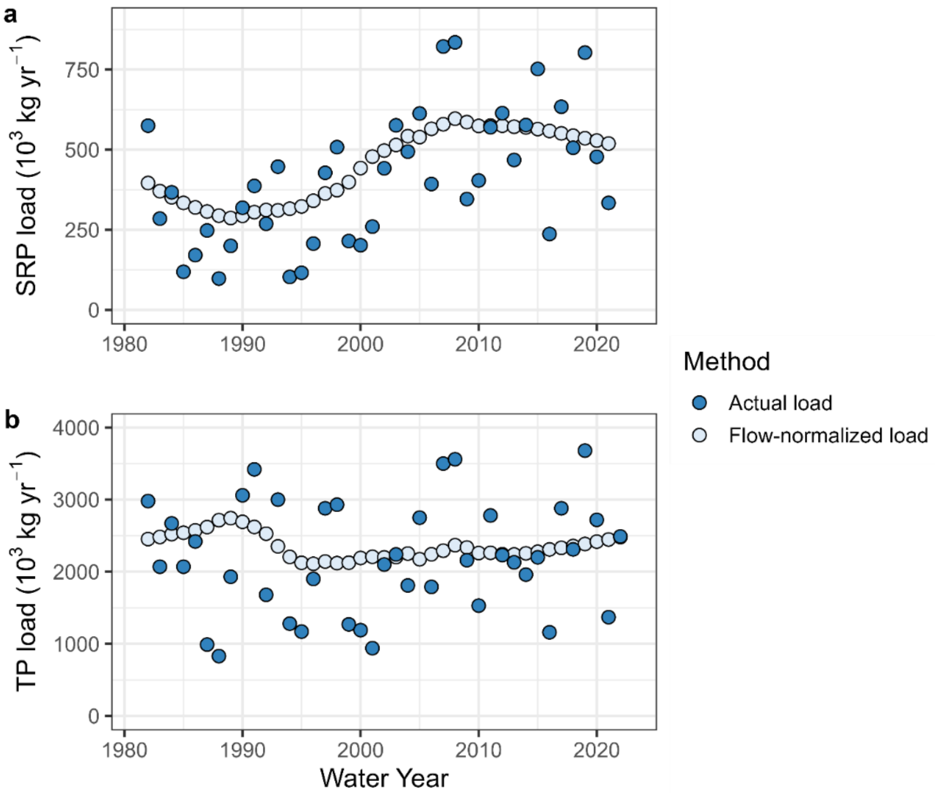

Figure 16. Actual loads (dark blue circles) and flow-normalized load (light blue circles) for total phosphorus (a) and soluble reactive phosphorus (b) for the Maumee River from 1982 – 2021. Source: F. Rowland, updated from Rowland et al. (2021).

The smoothing provided by flow normalization aids interpretation of changes and detection of trends that would otherwise be obscured by year-to-year variability in discharge. While there is little evidence of recent trends in actual loads (Tables 3 and 4), declines in flow-normalized SRP and nitrogen loads suggest that some progress is being made in the Maumee watershed. Declines in flow-normalized SRP are encouraging as this form of phosphorus is highly available to algae and increases in SRP loading have been tied to the resurgence of HABs in the late 1990s and 2000s (Baker et al., 2014, Stow et al., 2015).

Flow-normalized loads can provide indications of relative progress and easier detection of trends, thus, it is important to continue tracking both actual and flow-normalized loads along with flow-weighted mean concentrations (FWMCs) to evaluate progress in reducing nutrient loading. Expanding the regular computation of flow-normalized loads to other priority tributaries (e.g., during the Annex 4 annual loading calculations) has the potential provide additional insight on changes.

2.3.3 Key Areas of Uncertainty

Influence of sampling frequency on load measurement and target and trend analysis - Several tributaries have had changes in nutrient concentration sampling frequencies that are confounded with observed changes in loads or have not been monitored in all years since 2008. For most of these tributaries, nutrient sampling was more limited in early years and increased following the signing of the 2012 GLWQA or the adoption of phosphorus reduction targets in 2016. In these cases, establishing or evaluating load reduction targets and attributing trends to other drivers (as opposed to simply being due to sampling changes) is challenging.

Small sample sizes are unlikely to adequately capture variability in the discharge-concentration relationship and are likely to miss short event windows (such as storms) that have the highest discharge and loading. It is important to note that most of the priority tributaries (including those with the largest loads) currently have frequent sampling (~2x/week or more) and several also have long-term records of measurement. At the scale of the entire central basin annual TP load, 55 – 65% of the annual estimated loads TP between 2017 and 2021 came from sources that can be considered accurately quantified (i.e., point sources and monitored tributary loads for the Thames River and NCWQR sites). Given limited resources for monitoring, it will continue to be important to consider ways to adapt the monitoring strategy to reduce uncertainty.

Lake Huron contribution to the Detroit River load - The Annex 4 loadings working group uses a fixed annual TP load of 321 MT to calculate the contribution of Lake Huron to the Lake Erie load. This value is added to the loads (estimated as described above) from watersheds along the Huron-Erie Corridor to determine the total inputs of the Detroit River to the western basin of Lake Erie. Measuring loads directly near the mouth of the Detroit River is complicated due to the influence of Lake Erie (e.g., seiches can reverse flow) and horizontal flow stratification (i.e., poor mixing within the river). The constant Lake Huron load method is consistent with previous calculation of Lake Erie loads (Maccoux et al., 2016) and is based on the assumptions that phosphorus concentrations of the Lake Huron inflow to the St. Clair River are similar to Lake Huron open water concentrations, and that annual flow is relatively constant.

However, recent research (Burniston et al., 2018; Scavia et al., 2019; Scavia et al., 2020; Scavia et al., 2022; Scavia, 2023) suggests that the Lake Huron and total Detroit River TP loads may be much higher than values calculated with the Annex 4 loadings working group method. Load estimates from Lake Huron based on data collected at the head of the St. Clair River and based on other methods are 3-5x higher than the 321 MT used by the Annex 4 loadings working group. The difference between Lake Huron loads estimated by the Annex 4 loading group and in recent studies is similar in magnitude to the corresponding differences in downstream loads from the Detroit River to Lake Erie (Scavia, 2023). Further analysis to estimate Detroit River loads more accurately, and their influence on HABs and hypoxia in Lake Erie, is ongoing; the results of these studies will be considered in future assessments.

2.3.4 Priorities for Monitoring, Modeling, and Research

The loading estimates calculated annually by the Annex 4 loading working group are based on extensive investments in monitoring by government agencies and other partners. Addressing key data and knowledge gaps could strengthen future evaluations and inform nutrient management efforts in Lake Erie watersheds. Several tributaries had insufficient data collection in 2008 to accurately estimate loads from which to set reduction targets. The 2015 Objectives and Targets Task Team report recommended load reduction targets for priority watersheds be established in the domestic action plans. Alternative methods should be considered to set reduction targets for these priority tributaries to provide a target load against which progress can be evaluated. Relatedly, all priority tributaries need sufficient nutrient concentration sampling to ensure loads can be accurately calculated and to minimize sampling-related changes in load estimates. Uncertainties in the Lake Huron and Detroit River loads should also be examined further. Routinely calculating flow-normalized loads to remove the impact of discharge for all tributaries with sufficient data can provide useful feedback on whether actions in the watershed are having the intended impact.

3 LAKE RESPONSE TO NUTRIENT LOADS

3.1 INTRODUCTION

Nutrient loading from the watershed plays a central role in determining in-lake conditions, along with internal processes such as release of nutrients from sediments and filtering of the water column by invasive dreissenid mussels. Understanding the state of Lake Erie and how it responds to loading requires measuring a wide range of physical, chemical, and biological variables using diverse methods, including ship-based sampling, in-situ sensors, and satellite remote sensing. Monitoring is carried out by federal, state, provincial, and local government agencies as well as universities and other groups. While collectively these activities generate a wealth of data critical to our understanding of Lake Erie, this evaluation limited analysis to data that have been collected using consistent methodology over long time periods, with sufficient spatial coverage to broadly characterize conditions across the lake's basins, and that match the time periods specified by the ERIs.

ECCC's monitoring and surveillance program has existed since the 1960's and collects water quality data from approximately 65 stations on Lake Erie, both nearshore and offshore. During spring and summer surveys, water quality data such as nutrients, contaminants, chlorophyll, major ions (silica), metals and physical parameters are collected. The U.S. EPA Great Lake National Program Office (GLNPO) has conducted monitoring in Lake Erie since 1983 to measure nutrients, metals, water chemistry, physical parameters, dissolved oxygen, chlorophyll, and phytoplankton community structure at 22 stations on Lake Erie during spring and summer surveys. In addition to these long-term monitoring programs, additional data provided and used in this evaluation include remote sensing data on HAB severity from ECCC and NOAA, as well as *Cladophora* biomass at sentinel monitoring sites by ECCC and USGS. These data were compared to ERIs established by the Annex 4 Objectives and Targets Task Team or GLWQA Interim Substance Objectives when possible and assessed for evidence of recent changes compared to historic variability when quantitative objectives have not been established.

3.2 TROPHIC CONDITIONS

The trophic status of the Great Lakes has been a focus of the GLWQA since its signing in 1972 and continues to serve as a key indicator of ecosystem health. Nutrient concentrations, proxies for phytoplankton biomass, and water clarity (i.e., Secchi disk depth) support an understanding of trophic status and facilitate evaluation of how nutrient reductions affect overall productivity.

Lake Ecosystem Objective (LEO 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

Performance measure: Maintain nutrient concentrations at levels that meet basin-specific trophic status objectives for sustaining a healthy and diverse fish community

Trophic status Substance Objectives: Basin-specific open water spring TP concentration, basin-specific open water summer chlorophyll-a concentration

The Annex 4 Objectives and Targets Task Team did not identify a need to revise the existing Interim Substance Objectives for total phosphorus concentrations in open waters, as represented by spring[2] means, which are: 15 µg/L in the western basin and 10 µg/L in both the central and eastern basins. It is anticipated that the targeted phosphorus reductions will result in average spring mean phosphorus concentrations in open waters that will meet the basin-specific trophic status objectives (Annex 4 Objectives and Targets Task Team, 2015). Corresponding target summer chlorophyll-a concentrations were reported in Chapra and Dobson (1981) and have been adopted in State of the Great Lakes reporting as an Interim Substance Objective, with a target of 3.6 µg/L in the western basin and 2.6 µg/L in the central and eastern basins.

3.2.1 Summary of Observations – Trophic Status, 2017-2021

In-lake nutrient concentrations and chlorophyll-a are measured through long-term monitoring programs by both GLNPO and ECCC. Other federal, state, provincial, and academic partners also operate monitoring stations to assess indicators of trophic status but results from those stations are not incorporated into the results discussion below.

Three years of data within the assessment period are available. Open water concentrations of spring total phosphorus and summer surface chlorophyll-a were compared to GLWQA Interim Substance Objectives and ranges indicative of different trophic conditions in Great Lakes waters as reported in Dove and Chapra (2015).

Open water spring concentrations of total phosphorus in the western basin of Lake Erie were above the Substance Objective in all years and were in the range of concentrations associated with eutrophic conditions. Open water spring concentrations of total phosphorus in the central basin were above the Substance Objective in all years and were in the range associated with mesotrophic conditions. Open water spring concentrations of total phosphorus in the eastern basin were close to the Substance Objective in all years and were in the range associated with mesotrophic conditions in all three years (Figure 17).

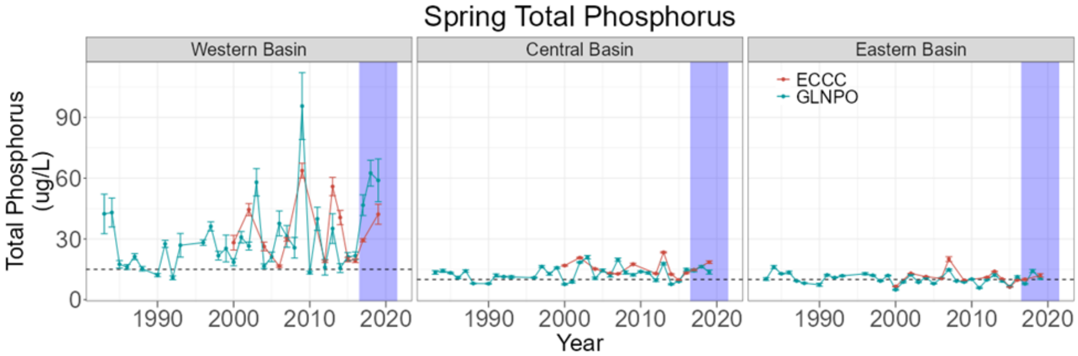

Figure 17. Spring (April to May) average (± SE) total phosphorus concentrations in the western, central, and eastern Lake Erie basins. The dotted line indicates the Interim

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[2] For the Interim Substance Objectives, "spring" is designated as April to May, whereas "spring" for the phosphorus loading targets is defined as March to July.

Substance Objective. 2017 to 2021 is highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

Although there are not designated Substance Objectives for other nutrients, GLNPO and ECCC also measure other nutrients, including SRP, ammonia, nitrates and nitrites, silica, and total Kjeldahl nitrogen. Results from monitoring for those nutrients are provided in Appendix 7.2.5.

Summer surface chlorophyll-a concentrations in the western basin were above the Interim Substance Objective in most samples throughout evaluation period and in the range associated with eutrophic conditions in Great Lakes waters. Summer chlorophyll-a concentrations in the central basin were also generally above the Interim Substance Objective during the evaluation period, and concentrations fell within the range associated with oligo-mesotrophic conditions. Eastern basin summer chlorophyll-a concentrations were generally below the Substance Objective and within the range associated with oligotrophic conditions in all three years (Figure 18).

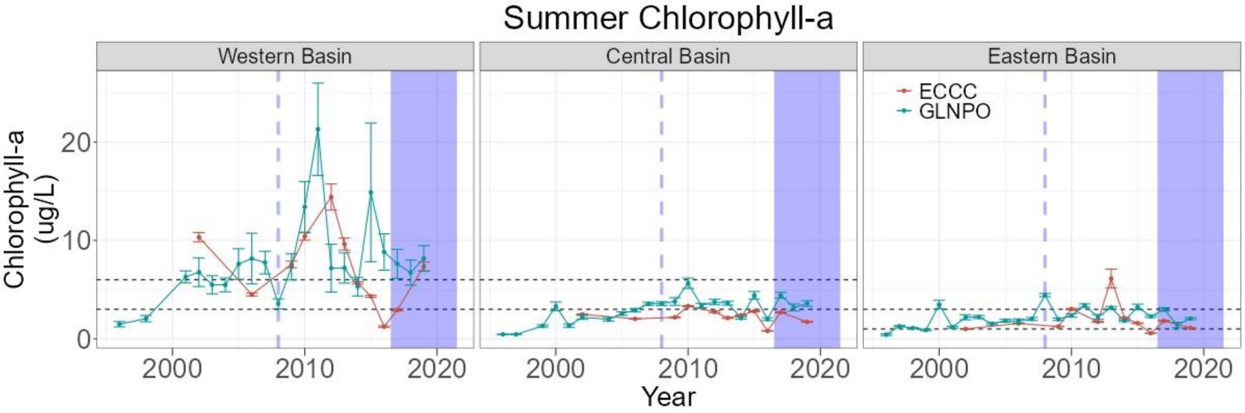

Figure 18. Summer (June to August) average (± SE) chlorophyll-a concentrations in the western, central, and eastern Lake Erie basins. The dotted lines indicate the targeted ranges (Dove and Chapra, 2015) corresponding to trophic status objectives in GLWQA 2012. 2017 to 2021 is highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

Modeling has suggested that the targeted 40% reduction in spring and annual phosphorus loading would maintain trophic status at a level that would not impact the carrying capacity for the fish community, with the potential exception of the central basin (Annex Objectives and Targets Task Team, 2015). These assessments were based on annual open water TP concentrations, not spring concentrations. Because there was not a persistent reduction in load during the assessment period, this evaluation cannot assess how lake trophic conditions respond to load reductions.

3.2.2 Priorities for Monitoring, Modeling, and Research – Trophic Status

Long-term monitoring programs under GLNPO and ECCC have been designed to meet assessment needs laid out in the GLWQA, but beyond these programs there are opportunities to improve consistency in monitoring, which may allow for expanded evaluation of LEOs and/or advances in our understanding of Lake Erie's load-in-lake response relationship. The Lake Erie and Lake St. Clair HABs working group pointed to the importance of developing a consistent approach in their recommendations for monitoring (2021). Additionally, the working group recommended integrated water sampling (as is done by GLNPO and ECCC) at all monitoring locations with select monitoring stations supplemented with surface samples (and potentially other depths).

3.3 CYANOBACTERIA/HARMFUL ALGAL BLOOMS

HABs develop annually in Lake Erie's western basin and can extend into the central basin in late summer. The cyanotoxins produced by the HABs in the western basin threaten human and animal health, while the excessive algal growth itself disrupts food webs, degrades fish and wildlife habitats, reduces spawning areas, limits fish productivity, impedes recreational uses of waterways, and clogs water intakes. Furthermore, the decomposition of algal biomass associated with HABs contributes to hypoxia and "dead zones" that are uninhabitable to fish and aquatic organisms.

Lake Ecosystem Objective (LEO 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 western basin of Lake Erie.

Performance measure: Reduce the occurrence, extent, and frequency of HABs in Lake Erie's western and central basins.

Cyanobacteria/HABs ERI and target threshold: Maximum 30-day western basin average cyanobacteria biomass <9,600 MT

Research and modeling have shown that open water cyanobacteria biomass in the western basin of Lake Erie is largely driven by spring TP and SRP loads from the Maumee River, with other factors like wind, mixing, and temperature affecting the bloom characteristics. Phosphorus loads from other western basin tributaries may also contribute to the bloom, but loads from these tributaries more directly affect nearshore, localized algal blooms.

Although bloom size and toxicity are not inherently linked (e.g., a small bloom can be toxic), general prevention of HABs is considered the most appropriate means to control cyanotoxins as minimizing cyanobacteria biomass can be assumed to reduce the potential for high toxin production (Annex 4 Objectives and Targets Task Team, 2015).

3.3.1 Summary of Observations – Cyanobacteria/HABs, 2017-2021

The Annex 4 Subcommittee uses maximum 30-day western basin cyanobacteria biomass[3] as the ERI to track progress toward the cyanobacteria bloom biomass LEO.

Cyanobacteria biomass is primarily measured through remote sensing. NOAA and ECCC utilize slightly different approaches to characterize the bloom, but both compile daily satellite imagery to measure indicators of algal biomass and validate the satellite measurement with field data. NOAA calculates the Cyanobacteria Index (CI) from the biomass of cyanobacteria, measured by the reflectance at three wavelengths associated with cyanobacterial cells (Wynne et al., 2021), whereas ECCC measures overall chlorophyll-a concentrations and therefore does not distinguish between the type of phytoplankton (Binding et al., 2018).

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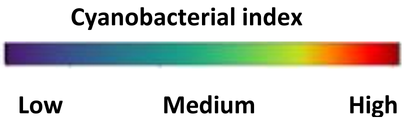
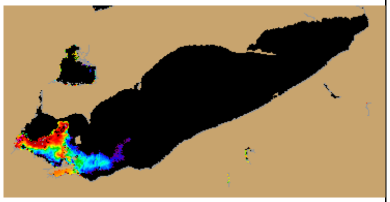
[3] Some other bloom metrics, including those used in the State of the Great Lakes reporting, use areal extent of the bloom rather than bloom biomass, which may result in a different determination of bloom severity.

NOAA calculates the bloom severity index (SI) based on the biomass over the 30-day window with maximum biomass. The ERI threshold of less than 9,600 MT approximately corresponds to an SI of 2.9. An SI above 5 is considered a severe bloom, while blooms over 7 are very severe. Figure 19 summarizes the algal blooms experienced in Lake Erie's western basin from 2017 to 2021. Overall, there was high interannual variability in the severity of the bloom, ranging from 3 to 8 on the bloom SI. Figure 20 presents Lake Erie SI data for 2004-2021. Between 2017 to 2021, the bloom SI target was not met in any year, though the 2020 bloom came close with a SI of 3.



The cyanobacterial bloom biomass, represented as the cyanobacterial index (CI), is calculated from reflectance measurements at wavelengths specifically associated with cyanobacteria blooms, which are collected from satellites (NOAA 2021). The CI on the maps are snapshots from a single day at peak bloom intensity, while the bloom severity index (SI) summarizes the overall severity of the bloom and is based on the biomass over the peak 30 days.

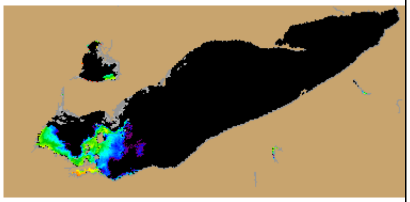
2017



CI from NASA MODIS_Terra & Aqua data collected September 20, 2017.

The 2017 bloom was considered severe with an SI of 8. The bloom peaked in mid-September, with an additional peak in August. Scum covered up to 280 square miles of the western basin during the September peak. There was heavy rainfall in May and late June.

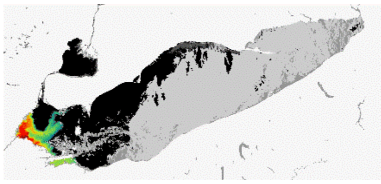
2018



CI from NASA MODIS-Aqua data collected August 11, 2018

The 2018 bloom was mild, with an SI of 3.6. The bloom peaked in August, with a relatively early emergence and ending. Although some scum formation occurred, it was localized and relatively uncommon. Although annual rainfall was in line with long-term averages, rain in May, June, and July was low.

2019



CI from Sentinel 3a data collected August 7, 2019

The 2019 bloom, with an SI of 7.2, was relatively severe. The bloom reached full intensity in August and declined by October. Strong winds in September dispersed and diminished the bloom. Scums were present, but not to the extent observed in 2017.

2020

CI from Sentinel 3a data collected August 22, 2020

The 2020 bloom was mild with an SI of 3 and just slightly over the goal of 2.9. The bloom peaked in the end of August and declined rapidly following strong wind events in September. Although the bloom covered a large area, it was mostly low density with low risk for toxins.

2021

CI from Sentinel 3a data collected September 7, 2021

The 2021 bloom was moderately severe with a 6.0 SI. The bloom peaked in late August/early September, weakened in mid-September, and re-intensified toward the end of September. The bloom covered a large area but had moderate biomass. Spring was relatively dry but July had high rainfall.

Figure 19. Summary of Western Lake Erie bloom conditions from 2017-2021. Grey areas of the lake indicate cloud cover on the image collection date. Note change in image source (MODIS to Sentinel 3a) from 2018 to 2019.

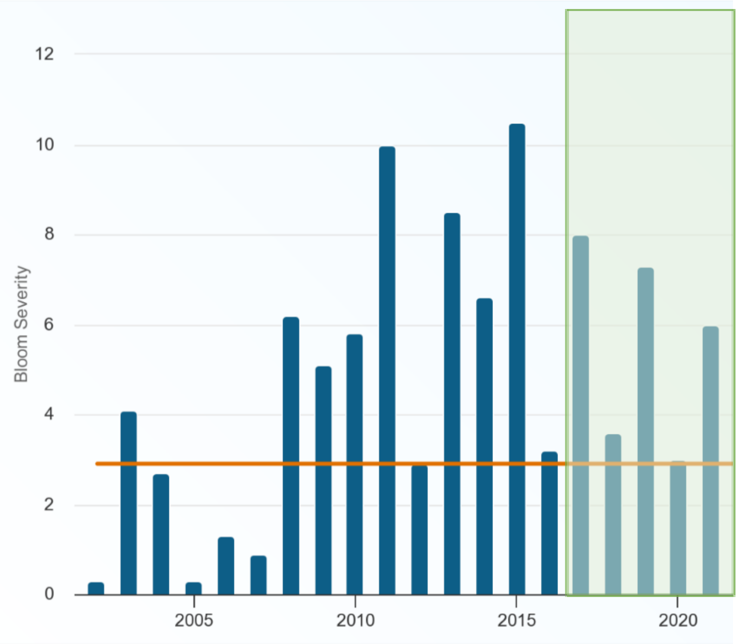


Figure 20. Lake Erie bloom severity index (NOAA), 2004-2021. 2017 to 2021 are highlighted as the current assessment period for the 5-Year Binational AM Evaluation (adapted from ErieStat).

ECCC reports the average and maximum bloom severity between June and October by multiplying the bloom intensity (average chlorophyll concentration within bloom area) and bloom extent (area) (Environment and Climate Change Canada, 2022). While this metric does not directly report on the 30-day maximum ERI, it can provide another view of the bloom biomass. As shown on Figure 21, although calculated differently from NOAA's Bloom SI, the overall characterization of the bloom is quite similar, with 2017 being the most severe bloom, followed by 2019 and 2021. In both severity metrics, 2020 and 2018 were reported as relatively mild blooms.

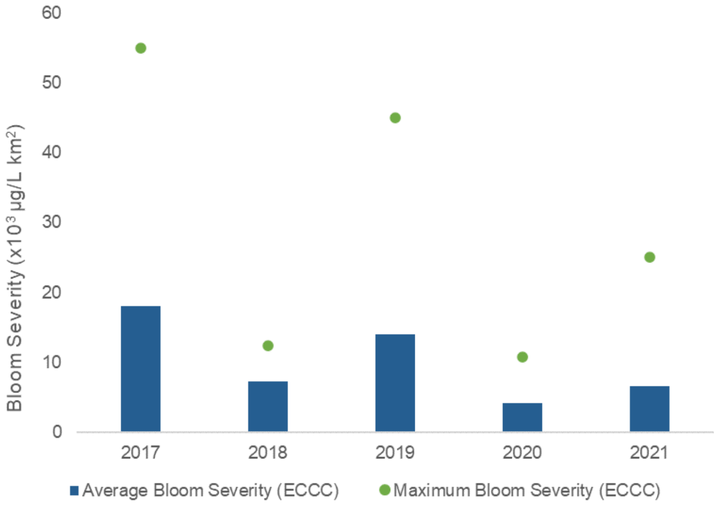


Figure 21. Average and maximum June – October bloom severity (ECCC) for Lake Erie blooms from 2017-2021. (Data from EOLakeWatch, 2022)

An ERI specific to bloom toxicity has not been established. Rather, bloom biomass is used as a proxy to evaluate toxicity, under the broad assumption that a larger bloom may generate more cyanotoxins. Although it is understood that the bloom size and toxicity are not inherently linked, the bloom size may serve as an indicator of toxicity. There are numerous (116) monitoring stations that measure cyanotoxin concentrations (Figure 22), all of which measure the most common class of cyanotoxin, microcystins, but typically do not measure other cyanotoxins or discern between differently structured microcystins (microcystin congeners). Additionally, the methods used to analyze microcystins have been developed to meet program-specific needs by the entities conducting the monitoring and are not standardized or consistently employed across monitoring stations. An assessment of the overall status of cyanotoxins in the western Lake Erie basin – distinct from the cyanobacterial biomass ERI – will require careful consideration of methodological variability to synthesize these disparate data and generate meaningful insights.

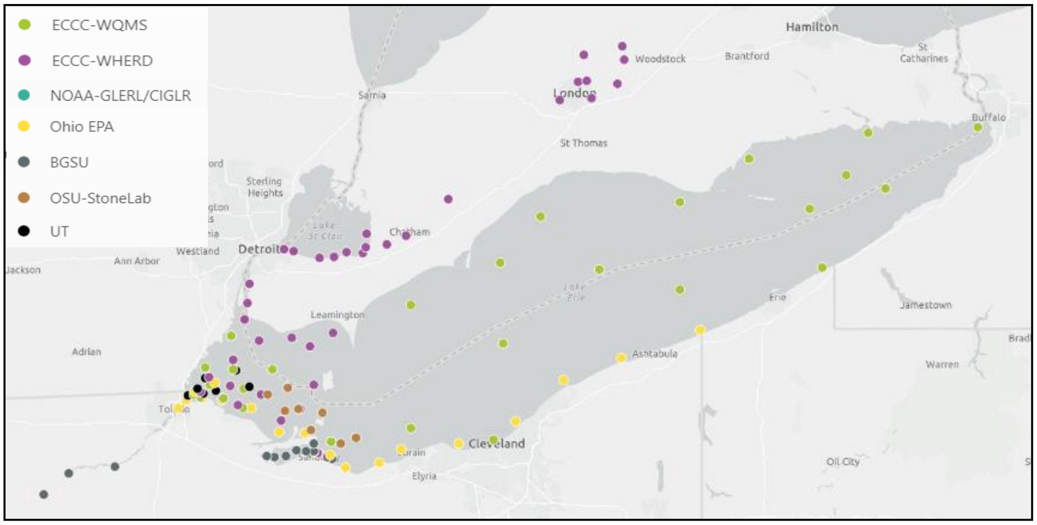


Figure 22. Monitoring stations where cyanotoxins are measured (HABs working group, September 2021).

3.3.2 Interpretation of Observations – Cyanobacteria/HABs, 2017-2021

From 2017 to 2021, HABs in Lake Erie have been variable and have not met the target threshold of <9,600 MT of cyanobacteria biomass, corresponding to a 2.9 bloom severity, in any year. Broadly speaking, improvements in HABs would not be expected, based on the understanding that HABs are driven largely by Maumee River spring phosphorus loads, which similarly have not declined and did not meet the 40% spring TP and SRP reduction targets.

NOAA produces a bloom forecast each year to anticipate the bloom severity. The forecast is based on an ensemble of loading models. Figure 23 shows actual and forecasted bloom severity for the 2017 to 2021 assessment period. NOAA reassesses the approach at the end of each year to make improvements in forecasting capability.

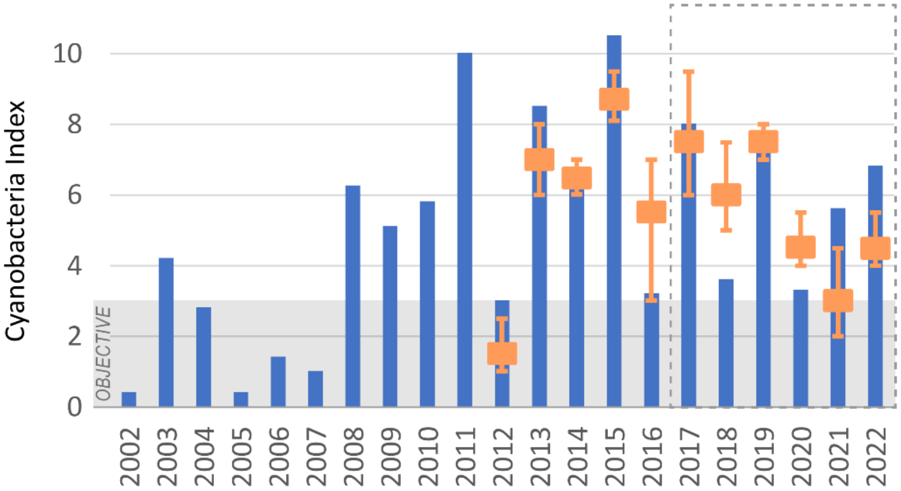


Figure 23. Actual and forecasted bloom severity index (NOAA) from 2002 to 2021. Orange box plots represent forecasted bloom severity and blue bars represent observed severity.2017 to 2021 are highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

Observations regarding loading and bloom severity during the assessment period point to the complexity of the system and the influence of factors like wind and timing of the phosphorus loading. Figure 24 compares Maumee River spring TP and spring SRP to the bloom severity. The expectation of bloom severity changing with spring phosphorus was generally the case from 2017 to 2021, with the interesting exceptions of 2020 and 2021.

In 2020, the Maumee River spring TP load was higher than in 2021 and the spring SRP load was similar (though slightly lower), yet the 2020 bloom was noticeably less severe than in 2021. In 2020, strong September winds (including a day with 40 mph winds) dispersed the bloom and it weakened rapidly after its late August peak (Stumpf et al., 2020). The 2021 bloom similarly weakened following strong winds in September, but re-intensified following a period of calmer winds and warmer waters (Stumpf et al, 2021). Although the Maumee River spring phosphorus load was relatively low in 2021, a disproportionate amount of the load was from July (Maumee spring SRP in July 2021 was the third highest July load recorded since 2008) (Stumpf et al., 2021). 2018 also had a considerably less severe bloom than 2021 despite similar Maumee River spring phosphorus loading. The 2018 Maumee River spring phosphorus loading was disproportionately delivered early in the season (March and April), with very low loading in July (Stumpf et al., 2018).

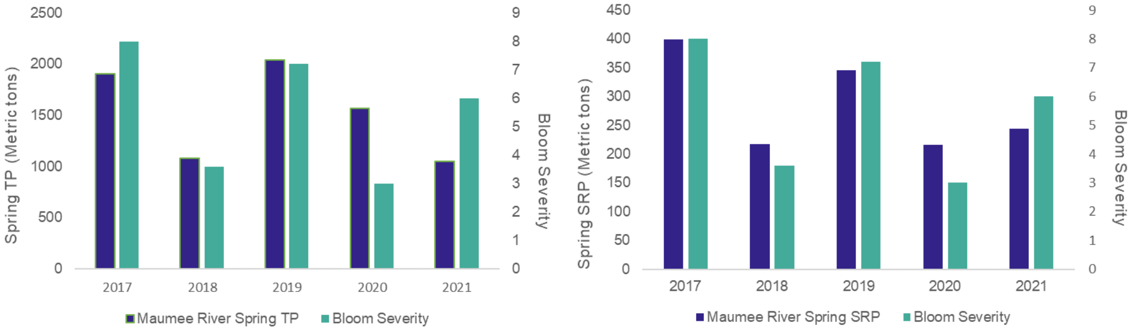


Figure 24. Maumee River spring TP and spring SRP, respectively, plotted with bloom severity (NOAA) on the secondary axis. (Data from ErieStat).

Spring phosphorus load reductions during the 5-year evaluation period have not met targets and have not been extensive or consistent enough to evaluate HABs response to changes in load.

3.3.3 Priorities for Monitoring, Modeling, and Research – Cyanobacteria/HABs

Extensive monitoring, modeling, and research progress has been made, enabling evaluation of GLWQA Annex 4 LEOs and also informing improved AM toward LEO attainment, but filling key data could expand evaluation and advance our understanding of Lake Erie HABs. The HABs working group identified numerous monitoring opportunities to fill priority monitoring gaps, including extending remote sensing analysis to Lake St. Clair, weekly or biweekly monitoring of in-lake nutrient concentrations (including nitrogen species and silica), and a longer in-situ monitoring season with more frequent data collection (Lake Erie and Lake St. Clair Harmful Algal Blooms working group, 2021). The HABs working group further recommended the development of a binational HABs monitoring plan so data gaps can be addressed in a consistent manner (Lake Erie and Lake St. Clair Harmful Algal Blooms working group, 2021).

3.4 ALGAL COMMUNITY COMPOSITION IN NEARSHORE WATERS

Algal community composition and abundance points to the trophic status of the lake. Additionally, assessing the algal community composition may facilitate detecting subtle ecosystem changes (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022).

Lake Ecosystem Objective (LEO 3): Maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie.

Performance measure: Maintain a healthy algal community composition in Lake Erie and Lake St. Clair.
ERI: Indicator(s)/metric(s) under consideration

3.4.1 Summary of Observations – Nearshore Algal Community Composition, 2017-2021

A designated ERI has not yet been established to track progress toward the LEO for algal community composition in nearshore waters, but it is important to consider how the algal community structure may be shifting in response to changes in nutrient inputs. There are over 150 stations in the Lake Erie basin (including Lake St. Clair and some tributaries) where samples are collected to assess algal community composition, most of which (117) analyze samples for a comprehensive count of all algal species. Other samples are analyzed for major algal group distribution or overall phytoplankton biomass. A number of factors make comprehensive assessment of algal community composition difficult (rapid changes in time, spatial patchiness, methodological and taxonomic differences across monitoring programs), and so it is important both to consider the comparability of data used for analysis and also avoid over-interpreting short-term changes. However, consistent sampling (locations, timing, collection/processing methods, etc.) can provide important indications of changing ecosystem conditions.

EPA GLNPO's Biology Monitoring Program collects phytoplankton samples twice a year (April and August) at 20 stations across Lake Erie. This program is the longest taxonomic record of algal community composition for Lake Erie. Findings from the last 20 years of monitoring in the western basin are presented in Figure 25. There is wide variability in community composition by year, but spring is dominated by diatoms while summer tends to be dominated by cyanobacteria. From 2017 – 2021, cyanobacteria accounted for the greatest proportion of phytoplankton in 2017, which was also the year with the highest HAB severity (though samples were not collected in 2020 due to the COVID-19 pandemic). Cyanobacteria in recent years have accounted for a lower proportion of summer phytoplankton than in years prior, but this observation is not necessarily indicative of a persistent shift in community composition and continued evaluation as additional data become available is recommended. These data only represent "snapshots" (i.e., community composition the day the sample was collected) of four years in the 2017 - 2021 evaluation period, and additional data sources and years of data should be analyzed before concluding there has been a recent, large shift in algal community composition.

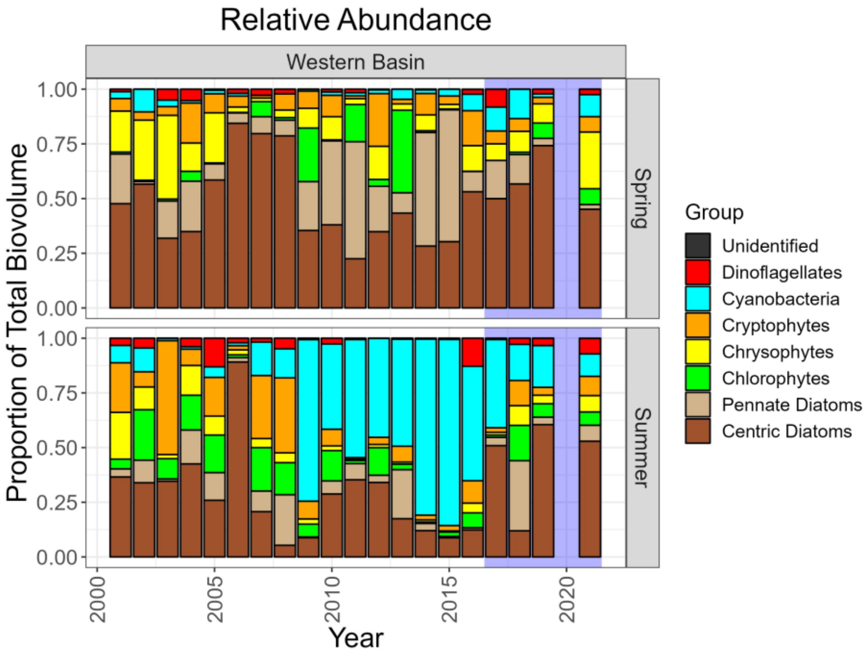


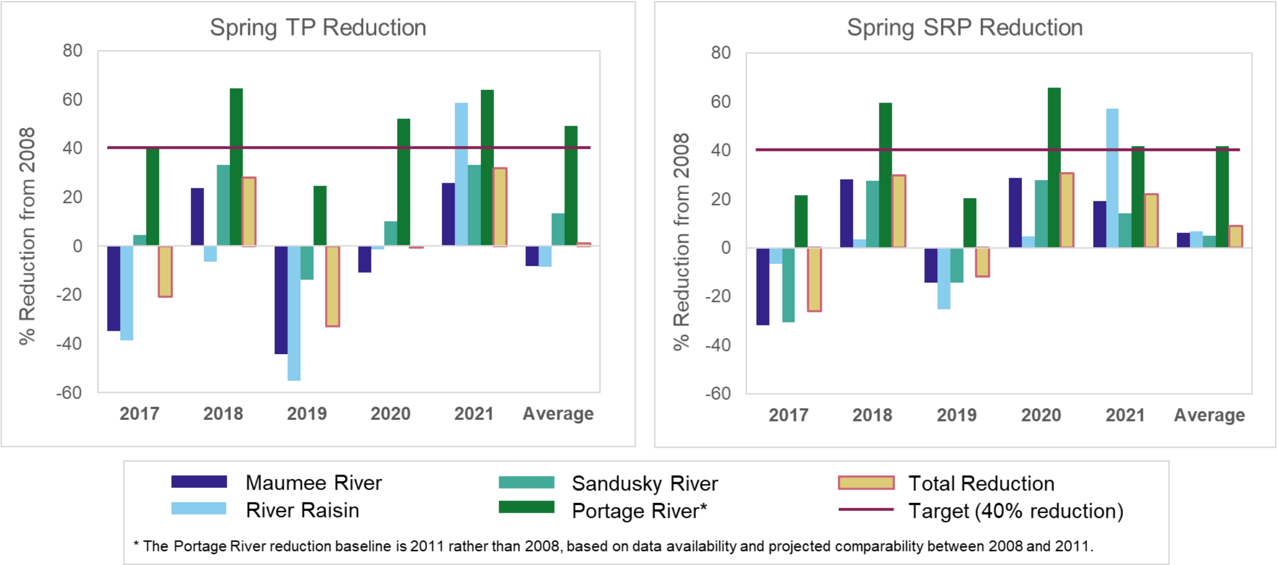
Figure 25. Relative abundance of phytoplankton groups collected in the Western Basin of Lake Erie GLNPO's Great Lakes Biology Monitoring Program. 2017 to 2021 are highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

3.4.2 Interpretation of Observations – Nearshore Algal Community Composition, 2017-2021

Limited data are available for the current assessment period, but the 2022 State of Great Lakes Report identified the status of phytoplankton in Lake Erie as poor with a ten-year deteriorating trend, pointing to the western basin cyanobacteria (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022).

In addition to the open water cyanobacteria bloom discussed in Section 3.3, nearshore, localized cyanobacteria blooms may have a significant impact on nearshore ecosystems and communities. Spring TP and SRP 40% phosphorus load reduction targets were established for priority tributaries to address localized blooms; meeting these reduction targets would in turn be anticipated to have positive impacts on algal community composition.

Generally, phosphorus reduction targets were not attained over the assessment period. Figure 26 shows a summary of spring TP and SRP load reductions for tributaries that have targets. From 2017 to 2021, phosphorus loads from the Portage River were consistently below the baseline[4], including four years that met the TP target and three years that met the SRP target. The only other tributary that met TP and/or SRP targets was the River Raisin for both TP and SRP in 2021. The combined average loads from 2017 to 2021 for the four tributaries with targets decreased by 2.8% and 8.9% for TP and SRP, respectively, from the 2008 baseline. Nutrient-driven changes to algal community composition would likely not be anticipated based on these load changes. Algal community composition is also affected by numerous other factors, including food web composition, climate change, and invasive species.



* The Portage River reduction baseline is 2011 rather than 2008, based on data availability and projected comparability between 2008 and 2011.

Figure 26. Spring TP and SRP reductions, from the 2008 baseline, for the four tributaries that have established spring phosphorus load targets. Because the chart shows phosphorus load reductions, a negative number indicates an increase in phosphorus load. (Data from ErieStat).

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[4] The Portage River baseline is 2011 rather than 2008, based on data availability and projected comparability between 2008 and 2011 (Ohio Domestic Action Plan, 2020).

3.4.3 Priorities for Monitoring, Modeling, and Research – Nearshore Algal Community Composition

EPA GLNPO's Great Lakes Biology Monitoring Program has one of the only long-term basin-wide databases (1983 – present) for Lake Erie. The HABs working group recommended establishing additional long-term monitoring stations using standardized sample collection, processing, and taxonomy (Lake Erie and Lake St. Clair Harmful Algal Blooms Working Group, 2021).

3.5 HYPOXIA

Bottom water hypoxia (defined as dissolved oxygen concentrations < 2 mg/L), develops seasonally in Lake Erie's central basin and has been a regular occurrence since at least the late 1950s. Updated phosphorus load targets were established in 2016 with the goal of reducing the severity of these low oxygen conditions in the central basin.

Lake Ecosystem Objective (LEO 4): Minimize the extent of hypoxic zones associated with excessive phosphorus
Performance measure: Reduce the extent and duration of the hypoxic zone in Lake Erie's central basin **Hypoxia ERI and target threshold:** Average hypolimnion dissolved oxygen (DO) level in the central basin from August to September is at or above 2 mg/L.

Hypoxic zones are colloquially referred to as "dead zones" because the habitat can no longer host many of the organisms that typically live in the cold, bottom waters. Fish may be displaced from preferred habitats or experience direct mortality during hypoxic episodes (Kraus et al. 2015). Organisms with limited or no mobility cannot leave the hypoxic zone and can die from reduced oxygen supply. Public water systems incur additional treatment costs to mitigate undesirable taste and aesthetic problems associated with hypoxic water when it enters drinking water intakes.

Modeling has shown that dissolved oxygen (DO) in Lake Erie's central basin hypolimnion decreases with increasing TP loads, and that the annual TP load to western and central basins is the most appropriate load scale to use to predict hypoxia. However, physical parameters including temperature, wind, currents, and stratification also play key roles in formation of hypoxia, so a range of hypoxia spatial and temporal extent could be expected from a given phosphorus load.

3.5.1 Summary of Observations – Hypoxia, 2017-2021

The Annex 4 Subcommittee identified a number of ERI metrics that would be appropriate to track progress toward the hypoxia LEO but focused on the mean August – September hypolimnetic DO concentration as the metric used for modeling and establishing a phosphorus reduction target, with a target of 2 mg/L.

EPA GLNPO's Lake Erie Dissolved Oxygen Monitoring Program collects water column profiles of DO and temperature from 10 stations in Lake Erie's central basin at approximately 3-week intervals during the stratified season (June – October) each year. Based on these data, the hypoxia threshold was met in three out of the five evaluation years: 2018, 2019, and 2020, as shown on Figure 27. It should be noted that the 2020 survey differed from other years due to COVID-19-associated sampling limitations: five stations (in U.S. water only) were sampled instead of the typical ten stations.

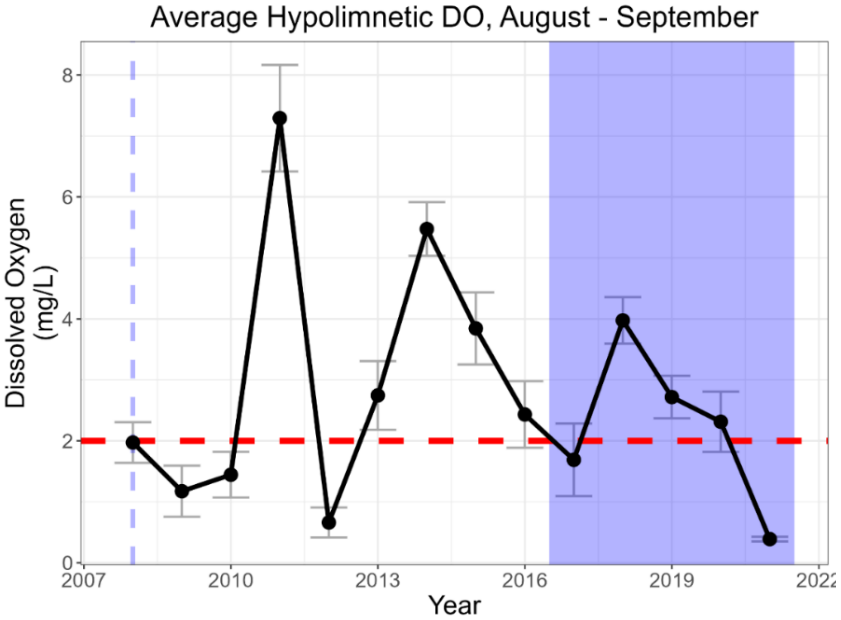

Figure 27. August – September hypolimnetic mean (± SE) DO concentration from GLNPO's Lake Erie Dissolved Oxygen Monitoring Program. The 5-year evaluation period is highlighted.

3.5.2 Interpretation of Observations – Hypoxia, 2017-2021

Concentration of hypolimnetic mean DO in the central basin exhibited annual variability and met the ERI target in three years during the evaluation period despite the annual phosphorus loading target of 6,000 MT not being met. This perhaps unexpected result may be explained by the strong influence that physical factors have on hypoxia, beyond the impact of TP load.

Another complicating factor is that hypoxic conditions are dynamic, varying over different spatial and temporal scales, which requires synoptic monitoring approaches. The GLNPO Lake Erie Dissolved Oxygen Monitoring Program was designed to monitor a relatively homogeneous area of the central basin, intended to reduce spatial variability and aid in the assessment of changes to oxygen depletion rate (the hypoxia metric used in the 1970s and 1980s) over time (Figure 28; Rosa and Burns, 1987). More recent research suggests that hypoxic conditions first develop in nearshore areas where the hypolimnion is thinner and has less oxygen to start with, before extending offshore (Rowe et al., 2019; Valipour et al., 2021). Therefore, it is likely that the data obtained through the annual GLNPO survey do not fully capture the hypoxic conditions in the central basin of Lake Erie.

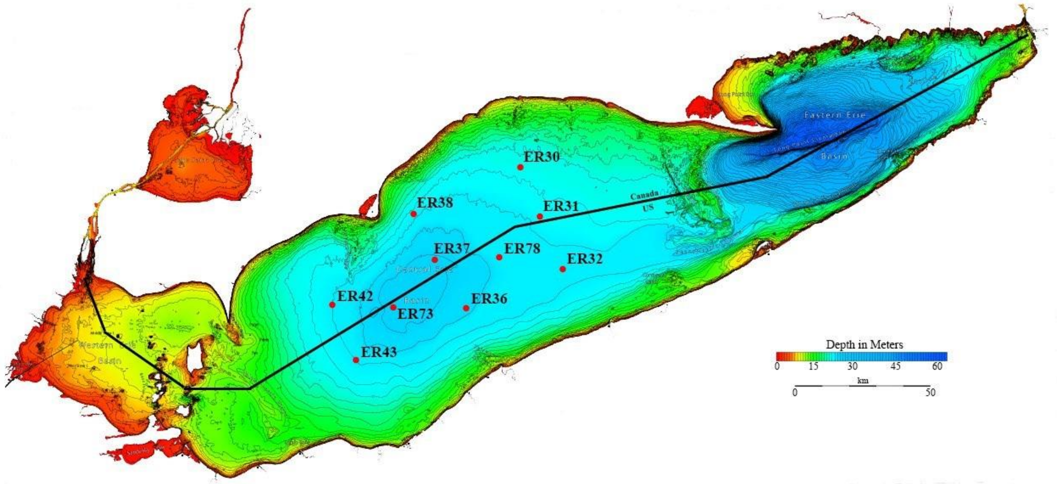

Figure 28. GLNPO Lake Erie Dissolved Oxygen Monitoring Program survey locations, overlaid on bathymetric map of Lake Erie (U.S. EPA, 2023).

3.5.3 Priorities for Monitoring, Modeling, and Research – Hypoxia

There are opportunities to improve the ability to characterize the extent/severity in hypoxia through coordinated monitoring, incorporation of additional hypoxia metrics, and continued development of hypoxia models. Numerous monitoring programs for hypoxia have been initiated in recent years across Lake Erie that provide increasingly substantial coverage of the central basin, but a mechanism to compile these monitoring results has not yet been developed. Additionally, finer-scale events more limited in space and time may be missed with current monitoring programs. Attendees of the October 2021 hypoxia summit recommended sustaining shipboard profiles, nearshore to offshore transects, water-column moorings, and bottom loggers over at least five years, and further recommended coordinating monitoring efforts annually.

It may be appropriate and useful to consider additional hypoxia metrics beyond the average August – September mean DO concentration. The Annex 4 AM Task Team selected this metric, but also identified the average summer hypoxic area and the number of hypoxic days as ERI metrics that could respond to evaluation of LEO attainment. Evaluating additional metrics would be more feasible as increased monitoring data are available, and monitoring efforts could be designed to adequately report on the selected metrics. In addition to the ERI metrics, the hypoxia summit proposed additional metrics, including hypoxic volume and duration of hypoxia at select locations. The summary report from the hypoxia summit emphasized calculating and comparing numerous alternate metrics to understand if they reveal similarities or differences in the assessment of hypoxia trends (Wortman et al., 2022).

Of the three ERIs and associated loading reduction targets developed by the 2015 multi-model effort (Scavia et al. 2016) and Annex 4 Objectives and Targets Task Team recommendations, hypoxia had the largest degree of uncertainty as represented by variability in the load-response relationship of the included models. Recent advances in our understanding of the drivers of hypoxia combined with improved models and expanded data availability present the opportunity to reduce that uncertainty. In turn, the hypoxia summit participants recommended that modeling of the phosphorus load-hypoxia response be revisited and potentially applied to additional metrics to better understand the role of nutrients and algal growth in the development of hypoxic conditions.

3.6 NUISANCE ALGAE

Filamentous green algae grows on hard substrates in all of the Great Lakes. Shoreline fouling by decaying filamentous algae (primarily *Cladophora*) in the summer months was a common phenomenon in the lower Great Lakes as far back as the mid-20th century (Taft and Kishler, 1973). Targeted research in the late 1970s concluded that phosphorus load reductions would reduce nuisance algae growth (Auer and Canale, 1982). In Lake Erie, reports of shoreline fouling began to increase again in the mid-1990s as *Cladophora* reached or exceeded nuisance levels (Howell, 1998). *Cladophora* remains broadly distributed along much of the north shore of the eastern basin of Lake Erie, as well as along offshore shoals with sufficient hard substrate for *Cladophora* attachment (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022). Empirical and anecdotal evidence suggests that recent biomass levels in Lake Erie are comparable to those observed in the 1960s and 1970s when conditions were considered problematic.

With the resurgence of the nearshore algal problem in some areas and with other changes in the ecosystem (caused by invasive species including Dreissenid mussels as well as climate and land use change), *Cladophora* management has become more complex (Higgins et al., 2008; Auer and Bootsma, 2009; McCusker et al., 2023). The lack of a consistent *Cladophora* monitoring framework has been cited in the past as a major impediment to understanding the status and trends of *Cladophora* in the Great Lakes (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022; Ciborowski, 2016). Reductions in phosphorus loading to the western and central basins are expected to reduce open lake phosphorus concentrations in the eastern basin (Annex 4 Objectives and Targets Task Team, 2015). However, at the time the reduction targets were set, it was unclear what the impacts of these reductions would be on nearshore nuisance benthic algal blooms, mostly caused by *Cladophora* in the eastern basin. In addition, it was unknown whether additional reductions in phosphorus loading from sources in Lake Erie's eastern basin were warranted. Hence, in the absence of supporting evidence, Canada and the United States committed to re-evaluate the viability of setting and/or revising science-based numeric algal and phosphorus targets for the eastern basin.

In 2017, a binational *Cladophora* research plan was initiated to coordinate research and monitoring which would support future efforts to develop targets (Ciborowski, 2016). Synthesis of work completed under the research plan revealed a significant degree of complexity between *Cladophora* biomass and potential drivers of Cladophora growth, including SRP, light availability, dreissenids, and substrate (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022; McCusker et al., 2023). In 2020, the Annex 4 Subcommittee formed the Lake Erie eastern basin task team. The team was charged with assessing whether current science is sufficient for development of binational phosphorus load and *Cladophora* targets to meet the GLWQA Annex 4 LEOs for the eastern basin.

The Lake Erie eastern basin task team developed a recommendations report in 2020, which concluded that though important advances in understanding the environmental drivers controlling growth of benthic algae had been made since the 2017 research plan was developed, scientific consensus was that the development of additional phosphorus loading targets for the eastern basin at that time was not supported. The report summarized the available scientific knowledge and described additional research, data collection, data analysis, monitoring and modeling required to assess, develop and, if need be, establish new or revised nutrient targets at a future time to address nuisance *Cladophora* growth in Lake Erie.

Continued research to date has focused on understanding drivers of *Cladophora* growth, including specific interactions of Dreissenid mussels, nutrient loading, and light availability. When *Cladophora* blooms undergo sloughing events, decaying organic matter washes up on beaches, clogs intake pipes, and acts as an incubator for bacteria. Sloughed material exerts significant impacts on the health of human and animal populations, shoreline ecosystems, infrastructure, and recreation and tourism industries. Relationships between *Cladophora* growth and the extent of washup on beaches is not yet well understood.

The Lake Erie eastern basin task team identified two potential ERIs that may be appropriate in tracking progress towards relevant LEOs in the eastern basin:

1) *Cladophora* biomass in nearshore blooms; and
2) *Cladophora* biomass washed up on shorelines and found in water intake pipes.

Although potential ERIs have been identified, specific methods for estimating biomass basin-wide have not been defined. Specific challenges in monitoring *Cladophora* biomass, both in-situ and washed up on shorelines, include improving the accuracy with which areal biomass can be determined with satellite imagery, and the development of sampling / measurement methods and approaches that are robust in the face of spatial and temporal variability. Some progress on in situ assessment has been made while large scale shoreline assessments of washup are lacking.

Prior to the initiation of sentinel site monitoring in 2012, assessment of *Cladophora* in eastern Lake Erie was done on an ad-hoc basis from 1995 to 2010 (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022) as exploratory monitoring and research and in response to regional concerns. Biomass was measured infrequently between 1995 and 2012, apart from a significant effort in 2001 – 2002 comprising the most spatially comprehensive data set for Lake Erie (Environment and Climate Change Canada and U.S. Environmental Protection Agency, 2022). Since 2012, regular assessment of biomass has occurred at 4-5 transects in the vicinity of the Grand River, extending eastward to Port Colborne, Ontario (ON) by ECCC (McCusker et al., 2023). Since 2018, two transects on the US shore have been assessed in the vicinity of Erie, PA and Dunkirk, NY (Przybyla-Kelly et al., 2020a, 2020b).

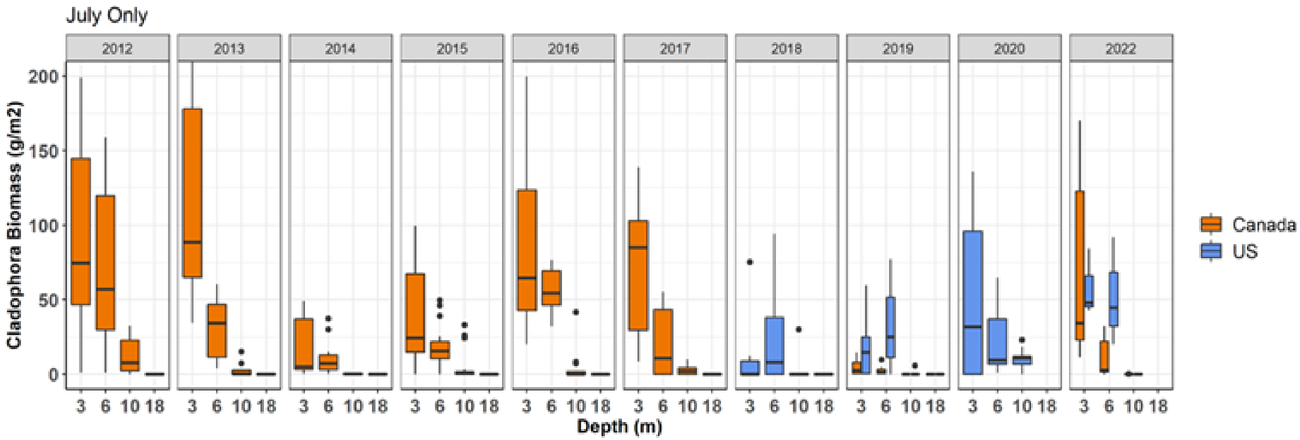

Figure 29. *Cladophora* biomass measurements in Lake Erie, 2012-2022. Contains preliminary data undergoing review (Source: Evans and McCusker, 2022). Black lines indicate median values and boxes extend to 25th and 75th percentiles.

Currently, according to the 2022 State of the Great Lakes Report (Environment and Climate Change Canada and the U.S. Environmental Protection Agency 2022) *Cladophora* assessment, the status of Lake Erie (including the St. Clair-Detroit River Ecosystem) is ‘poor[5]’. The report further notes that:

- Monitoring of 4 - 5 transects between Port Dover, ON and Port Colborne, ON since 2012 demonstrates that biomass is variable from year-to-year but remains at or above nuisance conditions (50 g dry weight / m^2 lakebed); at most shallow sites sampled, whereas deeper sites (>3m) are generally below nuisance conditions;
- Both offshore and nearshore, localized phosphorus concentrations are implicated in high growth;
- There is no indication of trends improving or worsening from 2007-2019 in Lake Erie, owing to a large degree of interannual variation

Canada and the United States continue to conduct sentinel site monitoring (Figure 29). Sentinel site monitoring has been conducted at priority nearshore transects in Lake Erie by ECCC since 2012. Since 2018, the USGS has monitored 8-12 sites in the lower four Great Lakes including 2 in Lake Erie. Efforts are also underway to evaluate the effectiveness of autonomous underwater vehicles (AUV) and remotely operated vehicle (ROV)-mounted optical sensors for determining *Cladophora* biomass and distribution. While these will not be as synoptic as satellite imagery, they yield higher resolution data on Cladophora biomass along with habitat characterization, and will allow for greater spatial coverage than conventional grab sampling methods.

4 LAKE ERIE ECOSYSTEM MODELS, RESEARCH AND COLLABORATION

Continued refinement of models based on research and monitoring allows us to better predict the lake response in each basin to future nutrient management actions, which helps us to optimize those actions for the greatest sustained improvement in the shortest amount of time at the lowest cost. Effective collaboration maximizes advances among a distributed binational set of teams and minimizes duplication, delays, lags, and gaps.

4.1 INTRODUCTION

Since the release of the Annex 4 Subcommittee phosphorus targets for Lake Erie and the supporting information in the binational study and modeling report (Annex 4 Objectives and Targets Task Team, 2015; Battelle, 2016), advances and progress in numerical modeling, lake-related research, and binational collaboration have refined the understanding of the impacts of excess nutrient loading on Lake Erie. At the same time, some research has shown that existing conceptual models for how certain parts of the system operate may be too simple or inaccurate, particularly related to loading from the St. Clair-Detroit River system and associated impacts to Lake Erie. Several areas of scientific progress and collaborative activities since 2016 are described briefly here. Coordinated binational activities will continue to be incorporated through AM to make sure that the latest science is being brought to bear on improving Lake Erie.

4.2 PROGRESS IN MODELING ECOSYSTEM RESPONSE

Research groups in Canada and the United States have continued to improve understanding of Lake Erie via coordinated monitoring and modeling. As monitoring results and experiments refine the description and understanding of nutrient cycling and biological responses at greater resolution, numerical models have been improved to reflect this understanding. The models, in turn, have helped guide where additional monitoring should be conducted and what types of experiments are needed to better constrain model formulations and improve model outputs for nutrient reduction scenario simulations and ecosystem response forecasts.

In-lake bloom processes have been examined as they relate to the influence of nitrogen and other factors on bloom growth and toxicity (Chaffin et al., 2018; Newell et al., 2019; Palagama et al., 2020). Scavia et al. (2016, 2019a, 2019b, 2019c, 2020, 2021, 2022), Bocaniov and Scavia (2018), Bocaniov et al. (2019), and Dagnew et al. (2019) published results of new modeling and monitoring studies that expand understanding of phosphorus loading from the St. Clair-Detroit River system to Lake Erie. Among the findings of these studies was evidence that resuspended sediment carried from Lake Huron to Lake Erie through the St. Clair-Detroit River system may be providing particulate phosphorus loads that have not previously been well documented.

Arhonditsis et al. (2019a and 2019b) reviewed Lake Erie watershed and lake models and monitoring and made recommendations for their use in AM. Burniston et al. (2018) published results of a collaborative binational project to directly measure nutrient loads in the St. Clair-Detroit River system. Liu et al. (2020) synthesized weekly in-lake monitoring data and satellite data collected between 2008 and 2017 with a goal of moving toward HAB toxicity forecasting (Zhou et al., 2023). Anderson et al. (2021a, 2021b) made novel in situ time-series measurements of phosphorus release from central basin sediments in association with the development of bottom-water hypoxia, and others have done studies on nutrient processing in river mouths including Sandusky Bay (Salk et al., 2018; Hampel et al., 2019). This collection of studies has refined conceptual models, modeling frameworks, and management approaches.

4.3 OTHER PROGRESS IN UNDERSTANDING LOAD-RESPONSE RELATIONSHIPS

Watershed models exist for the St. Clair-Detroit River system, Maumee River, Portage River, and Grand River, among others. Mechanistic lake models exist for the western basin (Verhamme et al., 2016), the central basin (Rowe et al., 2019; Bocaniov et al., 2016 and 2020; Valipour et al., 2021), and the eastern basin (Valipour et al., 2016 and 2019) of Lake Erie. LimnoTech completed a new whole-lake model (LimnoTech, 2021). Kuczynski et al. (2020) published an improved *Cladophora* model that incorporates self-shading and other mechanistic enhancements; these refinements were incorporated into LimnoTech's whole-lake model. The new models have been used to develop hypothetical management scenarios and to test the sensitivity of the lake to changes in particular components of the ecosystem or of human drivers and tributary nutrient loads.

NOAA uses satellite images and weather-driven models to prepare twice-weekly bulletins throughout the summer algal bloom season as an operational product. NOAA also produces a pre-season ensemble model forecast and a post-season comparison of HAB model predictions to observed conditions. Coordinated whole-bloom sampling (the "HABs Grab") was done in the western basin in 2018 and 2019 to get intensive spatial measurements of the summer blooms at two different timepoints (Chaffin et al., 2021) to improve process understanding of blooms and to serve as modeling targets (Zhou et al., 2023). The United States and Canada participated jointly in the 2019 sampling event. Planning for future joint sampling events like this is underway, and the approach was adapted into a coordinated pilot winter sampling effort across all five Great Lakes in 2022.

Central basin hypoxia monitoring has been conducted most intensively since the 2014 Cooperative Science and Monitoring Initiative (CSMI) field year by GLNPO (Xu et al., 2021; Tellier et al., 2022). The City of Cleveland has also monitored hypoxia near its water intakes since 2014. These monitoring programs supported a modeling project by CIGLR and NOAA (Rowe et al., 2019), which built on prior research by Scavia et al. (2016), Rucinski et al. (2016), and Del Giudice et al. (2018). The modeling program developed an experimental short-term hypoxia upwelling forecast product to inform drinking water plant operators and other stakeholders, but it was not designed to produce a seasonal forecast. A seasonal forecast would likely require winter and early spring monitoring of diatom biomass in the western basin and central basin, which is not routinely performed before GLNPO's spring surveys in April. Summer stratification would also be an important component of a seasonal prediction, but this is not possible to forecast accurately at a seasonal scale.

Annual summaries of hypoxic area or volume are not produced at present (Stow et al., 2023), although an operational monitoring program, especially with sensors that report in real time rather than after physical recovery of loggers and downloading of data, could produce in-season reports similar to those produced for HABs. An intercomparison study of three mechanistic models from Canadian and U.S. researchers evaluated the performance of the three models in comparison to monitoring data and to each other (Rowe et al., 2003) and found significant variations in simulation results. Fish telemetry data have been used to study fish movement as it relates to the presence of hypoxic water in the basin (Kraus et al., 2023).

Eastern basin macroalgae spatial coverage and biomass are not consistently monitored or reported for the whole basin, although related research and monitoring programs have been conducted or are underway by ECCC (Valipour et al., 2016; McCusker et al., 2023), MECP (Chomicki et al., 2016), Michigan

Tech Research Institute (MTRI; Brooks et al., 2015), and the USGS (Wimmer et al., 2019; Przybyla-Kelly et al., 2020; Depew et al., 2022). The MTRI methodology using remote sensing has been applied retrospectively to create a macroalgae time series at select sites (e.g., Ajax, Ontario), and could be applied annually to produce a summary of the maximum extent of coverage.

4.4 OUTREACH AND COMMUNICATION

Many government and non-governmental organizations provide outreach and education to the Lake Erie community. Agency and academic researchers and managers who work on Lake Erie topics routinely advise these organizations on developments in their disciplines. This allows research advances and products to be shared with potential users and impacted individuals and communities as quickly as possible. Binational coordination and communication through the GLWQA Annex 4 Subcommittee and associated task teams and work groups helps advance the goal of effective technology transfer and improved public awareness.

4.4.1 DAP AM Collaboration

In 2015, Ontario, Michigan, and Ohio formed the Western Basin of Lake Erie Collaborative Agreement, committing to reduce nutrient levels entering the lake by 40% by 2025, compared to 2008 levels. Their 2018 DAPs supported the federal plans and the Annex 4 Lake Erie Binational Phosphorus Reduction Strategy. Examples of updates and communication products associated with these commitments include the updated Ohio 2020 DAP, Michigan’s Adaptive Management Plan to Reduce Phosphorus Loading into Lake Erie (2021), and the Canada-Ontario Lake Erie Action Plan (2018). These plans were prepared in consultation with the Annex 4 Subcommittee and Task Teams, as well as with consideration of comments provided on draft versions from interested individuals and organizations.

4.4.2 Binational and Inter-agency Science Collaboration

Federal, state/provincial, and academic agencies and institutions have collaborated extensively on Lake Erie monitoring, modeling, and research in the last five years, as mentioned above. Coordinated sampling and experiments have been performed in CSMI field years in 2014 and 2019, and planning is underway for 2024. These field-year activities are conducted in response to research priorities and data gaps identified by the binational Lake Erie Partnership Management Committee, which emerge from pressing management challenges.

Centralized reporting of real-time data from the lake and some tributaries, as well as operational model outputs (waves, currents), is coordinated by the Great Lakes Observing System (GLOS). A binational GLOS-affiliated fish telemetry array (15-km grid) that is used for tracking tagged fish in Lake Erie is maintained by the Great Lakes Acoustic Telemetry Observing System (GLATOS; Kraus et al., 2018). Monitoring activities by agencies and institutions are augmented by efforts such as the Lake Erie Volunteer Science Network, a regional binational community of practice organized by the Cleveland Water Alliance that empowers community members to collect, share, and engage with water quality data for the conservation of Lake Erie for the benefit of its residents, visitors, and managers.

4.4.3 Participation in Research Symposia

Federal and state or provincial organizations participate regularly in seminars, workshops, summits, and conferences to hear the latest results from their colleagues and learn about advances in understanding of watershed and lake processes and effective management actions. Ohio Sea Grant organizes an annual *Understanding Algal Blooms: State of the Science Conference* in September, and webinars and public meetings are presented throughout the year by various organizations that play a role communicating Lake Erie science and management to audiences with a range of scientific expertise. Additional examples of recent research symposia with binational participation include the following:

- International Association for Great Lakes Research (IAGLR)
    - IAGLR 64th Annual Conference, virtual, May 17-21, 2021
    - State of Lake Erie Conference, Cleveland, Ohio, March 16-17, 2022
    - Joint Aquatic Sciences Meeting, Grand Rapids, Michigan, May 14-20, 2022
    - IAGLR 66th Annual Conference, Toronto, May 8-12, 2023
- CIGLR Virtual Summit: Lake Erie Central Basin Hypoxia: State of the Science Review and Approaches to Track Future Progress, October 2021
- International Joint Commission (IJC) Nutrients Synthesis Workshop, virtual, October 28-29, 2021
- Great Lakes HABs Collaborative webinars (https://www.glc.org/work/habs)

5 RECOMMENDED PRIORITIES FOR IMPROVING EVALUATION

5.1 INTRODUCTION – KEY AREAS OF FOCUS

This section presents recommended priorities for improving understanding of the response of Lake Erie to nutrient management efforts. In line with the charge of the AM Task Team, these recommendations focus on improving capacity to better predict the effectiveness of nutrient management efforts in achieving nutrient related LEOs, and understanding how the watershed and lake are responding to changing conditions, rather than specific actions to reduce phosphorus loads and/or improve watershed health. Specifically, these recommendations focus on the following objectives:

- Reducing uncertainty to better predict management-loading-response relationships
- Providing information to inform future progress evaluation and review of objectives and targets
- Providing information that would be useful for future DAP refinements/domestic actions

5.2 RECOMMENDED PRIORITIES

Binational AM Evaluations are slated to be conducted every five years, based on the process outlined in the AMF. Evaluations are dependent on prior and ongoing monitoring, modeling, and research efforts. Completing the next round of the evaluation will depend on the continuing refinement of those efforts.

There are numerous opportunities to enhance the ability to assess progress with targeted recommendations for monitoring, modeling, and research. These recommendations were developed by the AM Task Team and are supported by the work of collaborative efforts under Annex 4, specifically, the recommendations from:

- The Loading Calculations Technical Symposium Summary Report (April 2017).
- HABs working group's *Recommendations for Binational Monitoring of Harmful Algal Blooms in Lake St. Clair* (November 2021).
- The 2021 hypoxia summit summary report *Lake Erie's seasonal dissolved oxygen problem: State of the science and approaches to best inform future understanding* (November 2022).
- Lake Erie eastern basin task team's *Recommendations Report: Assessment of Current Science for Development of Binational Targets* (October 2020).
- Data and modeling working group's *Draft Recommendations for the AM Evaluation* (March 2023).

5.2.1 Overarching Recommendations

The following recommendations describe key areas of focus for future work to support AM in Lake Erie:

- Consider expanding ERIs to improve ability to evaluate progress toward achieving LEOs, accounting for evolving improvements in data coverage and quality.
- Refine and improve methods and models to better evaluate load and ecosystem response relationships.
- Conduct more formalized and regularly occurring process for developing and testing hypotheses of loading-ecosystem response relationships to help identify key uncertainties and guide research, monitoring, and modeling efforts.
- Coordinate monitoring efforts to improve comparability of data with a focus on improving capacity to:
    - Evaluate lake response to nutrient loading.
    - Develop and refine ecosystem models.
    - Support improvements in existing monitoring technologies and methods.
    - Support development of emerging monitoring technologies and methods.
    - Identify knowledge gaps and inform research priorities.

5.2.2 Monitoring, Modeling, and Research Recommendations

The Adaptive Management Task Team developed detailed suggestions for implementing monitoring, modeling, and research recommendations. These recommendations are organized by topics presented in the report, and informed by the findings of this evaluation as well as the reports and recommendations produced by the AMTT working groups:

General Recommendations	Detailed Suggestions	Rationale
Trophic Status		
Standardize water sample collection	▪ Integrated samples at all stations to accurately characterize conditions to the thermocline or sediment. ▪ Discrete samples, including at the surface and bottom of the water column, should be collected at select priority locations to capture variability in the water column. ▪ Analysis should consistently include nitrogen species and silica (in addition to phosphorus).	Algal biomass at the surface may not be representative depending on wind conditions. Different monitoring programs have different sampling protocols.
HABs/Cyanobacteria		
Refine existing long-term HABs monitoring programs:		
Extend HABs sampling season	▪ Extend sampling season from April to October to evaluate temporal trends in HABs associated with warming temperatures. ▪ Conduct winter sampling to monitor for cyanotoxins and bioactive metabolites during cooler months.	Climate change poses challenges for capturing spring conditions and the entire bloom season. Winter-early spring diatom blooms and cyanobacterial blooms under ice, and their impact on summer HABs, are areas of uncertainty.
Increase sampling frequency	▪ Increase sampling for cyanotoxins and phosphorus to weekly or biweekly during peak bloom season.	Sampling frequency currently varies between agencies, but increased sampling (especially during peak bloom conditions) will provide increased granularity and ability to assess trends.
Refine/expand sampling and monitoring methods	▪ Assess toxin sampling comparability and trends across monitoring programs. ▪ Include cyanotoxin congeners and other nutrients in regular sampling. ▪ Conduct fluorescence profiles at all monitoring stations to estimate biomass.	Most existing toxin assays conducted do not have a mechanism to account for varying toxicity of microcystin congeners or consider other cyanotoxins, which may be present or emerge with changing

	▪ Continue to calibrate and refine remote sensing technologies. ▪ Use qPCR method to better characterize cyanotoxin strains.	community composition. Information on vertical variability of algae will support remote sensing calibration/validation and refinement of algorithms.
Coordinate HABs monitoring programs to improve comparability:		
Coordinate sampling methods	▪ Integrated sampling at all stations and discrete sampling at selected priority monitoring stations with more depths and/or parameters.	Using consistent methods will allow for integration of data from multiple sources.
Compare remote sensing approaches	▪ Extend remote sensing analysis and reporting across Lake Erie and Lake St. Clair. ▪ Assess and document differences in remote sensing methods and results between different entities working on Lake Erie. ▪ Use hyperspectral flyover imagery when cloud-cover is present.	Different entities use different methods (satellites, retrieval algorithms, areas of analysis) for remote sensing of HABs.
Algal Community Composition		
Continue and expand long-term monitoring stations	▪ Use a combination of algal species identification at a subset of stations and fluorometry monitoring to determine major algal groups at additional stations.	Ability to assess status and trends in algal community composition in Lake Erie's nearshore and open waters requires a long-term, basin-wide program.
Standardize monitoring approach	▪ Develop binational taxonomy guidance to help standardize sample collection and processing. ▪ Standardize instruments (e.g., fluoroprobes) and methods used to expand across the study area.	Algae identification can vary from lab to lab; identification/enumeration is not practical at all stations, but standardized approach can still be used.
Encourage and support development and implementation of emerging monitoring technologies	▪ Use hyperspectral flyovers to identify community composition. ▪ Explore automated taxonomy options.	Incorporating advancing technology may provide enhanced data collection, improve consistency, and alleviate resource constraints.
Hypoxia		
Support and incorporate monitoring from multiple sampling platforms	▪ Utilize multiple observing platforms: shipboard profiles, transects, water column moorings, and bottom loggers. ▪ Develop a hypoxia dataset (DO and temperature) directory (including metadata) to aid in data harmonization. ▪ Coordinate monitoring through interagency meetings before field seasons.	Incorporating data from multiple sources can improve spatial and temporal coverage of ERI assessment.

Consider additional hypoxia metrics	▪ Evaluate potential metrics (including ERI metrics of spatial extent and duration of hypoxic conditions, plus additional metrics such as biological or geochemical indicators of hypoxia) on suitability for AM and feasibility with available data; consider how monitoring improvements can support reporting on additional metrics. ▪ Provide design specifications for proposed metrics to support monitoring design. ▪ Compare hypoxia quantification under different metrics.	The Annex 4 Objectives and Targets Task Team identified three metrics to report on hypoxia but focused on the summer average central basin hypolimnetic DO concentration metric. Additional metrics can provide clearer understanding of progress on reducing hypoxia, though different stakeholders may have different metrics that are most relevant to them.
Nuisance Algae		
Maintain consistent and coordinated sentinel site monitoring	▪ Measure biomass at sites with different light levels relative to biomass. ▪ Select sites with differing community composition of *Cladophora* and associated benthic algae.	A continuous binational data record is needed to improve understanding of interannual variability in *Cladophora* growth and how it is affected by environmental conditions.
Continue investigating biological and physical interactions affecting *Cladophora* growth	▪ Incorporate near-bed and shallow water hydrodynamics and fluxes, connections between tributary loading and light availability. ▪ Quantify phosphorus supply rates from dreissenid mussels for the eastern basin under a variety of conditions, including the role of seston composition in dreissenid diet. ▪ Characterize sources of phytoplankton/seston (offshore vs. nearshore) for consumption by dreissenid. ▪ Investigate the role of microbes and dreissenid mussels in nutrient uptake and organic matter in the remineralization of phosphorus. ▪ Use additional monitoring data to validate dreissenid mussel population dynamic components of ecosystem models.	Additional research, data collection, data analysis, monitoring, and modeling are required to assess and develop nutrient targets to address nuisance *Cladophora* growth in Lake Erie.
Investigate the fate of sloughed benthic algae	▪ Develop methods to better quantify the amount of material that washes onto beaches, and the relationship between washup amount and in-lake growth. ▪ Examine decay rates and transport to determine the importance of these processes to shoreline fouling and phosphorus budgets. ▪ Work with social scientists and health departments to determine what level of washup constitutes nuisance conditions and health risks.	Sloughed material exerts the most significant impacts on the health of human and animal populations/shoreline ecosystems, infrastructure, and recreation and tourism industries. The relationship between *Cladophora* growth and the extent of washup on beaches is not yet well understood.

Encourage development of remote sensing and emerging technologies	▪ Employ remote sensing for improved tracking of biomass and account for turbidity interference to assess validity, reduce uncertainty in models, and link in-lake biomass to shoreline washup and nuisance conditions. ▪ Improve imagery at sentinel sites.	Remote sensing will more effectively and efficiently monitor the spatial and temporal extent of nuisance algae in the eastern basin.
Loadings		
Address sampling changes in priority tributaries:		
Document changes in sampling methods and implications for loading estimates	▪ All evaluations of trends and whether targets are met should recognize tributary-specific changes in sampling that likely impact load estimates, and that uncertainty should be communicated along with evaluations.	Major changes in nutrient concentration sampling have occurred in several priority tributaries since 2008. Loading estimates based on small sample sizes have a higher degree of uncertainty and maybe biased low if days with high discharge and concentration are missed.
Set reduction targets for priority tributaries without targets	▪ Each entity responsible for setting targets for tributaries with insufficient data from 2008 to use as a baseline should continue collecting data to accurately estimate loads and use those data to set evidence-backed reduction targets. This could be done by estimating 2008-equivalent loads from years with similar discharge and sufficient nutrient concentration sampling, or by developing load-discharge relationships to estimate loads in 2008, for example.	Nutrient concentration sampling in some priority tributaries was insufficient in 2008 to accurately estimate loads from which to set reduction targets
Ensure tributary water quality sampling is sufficient to accurately estimate loads:		
Priority tributaries load estimates	▪ Maintain nutrient concentration sampling at current levels or monthly sampling, whichever is greater, along with continuous discharge records. ▪ Conduct additional sampling to capture the range of flow and loading conditions. Tributary-specific sampling regimes should be determined based on 2017 workshop report.	Accurate estimates are needed to evaluate reduction targets, estimate trends, and for in lake models and loading-response curves.
Lake Huron/Detroit River load estimates	▪ Evaluate alternative methods for monitoring and calculating LH/DR loads and, if necessary, settle on a new method. ▪ Evaluate ecosystem models to determine impacts of any updates to LH/DR loads on lake response curves.	Accurate estimates are needed to evaluate reduction targets, estimate trends, and for in lake models and loading-response curves.
Evaluate changes in loading:		

Evaluate loads for evidence of progress in nutrient loss reductions in the watershed	▪ Flow-normalized (WRTDS) loads should be computed annually and trends analyzed for all tributaries with sufficient data.	Nutrient loading is strongly influenced by discharge which can mask other changes and impacts of management actions. Analyzing loads and concentrations with the influence of discharge removed will provide additional and likely earlier insight as to whether progress is being made in the watersheds.
Ecosystem Models & Load-Response Relationships		
Conduct annual model runs:		
Utilize a suite of models to create a robust modeling approach for AM in Lake Erie	▪ Clearly outline what endpoints are being examined in each model to ensure diverse modeling tools with different strengths and weaknesses are available. ▪ Establish modeling criteria to allow for inter-comparisons and connections between models. ▪ Make model code, documentation, inputs, and outputs publicly available to increase repeatability, understanding, and preserve models for future use.	Multiple models are necessary to create a robust modeling approach for AM in Lake Erie
Continue investigating modeling approaches to develop a better understanding of the link between loading and hypoxia	▪ Revisit modeling approaches used to link hypoxia to phosphorus loads and identify processes that are most uncertain and require additional investigation. ▪ Identify and quantify the sources of both water-column and sediment oxygen demand.	Recent reports and modeling indicate that central basin oxygen demand may originate from sources beyond western basin primary production; atmospheric conditions and hydrodynamics may be drivers of hypoxia.
Include additional parameters in monitoring programs to improve understanding of nutrient load-ecosystem response relationship:		
Include nitrogen species and silica in tributary and in-lake monitoring programs	▪ Monitor both phosphorus (TP, SRP) and nitrogen (NO_3+NO_2, NH_3, TKN, TN) species, as well as silica for both in-lake concentrations and tributary loads.	Understand the role of nitrogen species and silica in HABs development
Evaluate internal loading as a driver of algal production and HABs	▪ Measure proxies for internal loading, including temperature and dissolved oxygen profiles, and sample for SRP, TP, NO_3+NO_2, and NH_3 1 m from lakebed.	Internal loading may create a delay in HABs response to external loading reductions.

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7 APPENDICES

7.1 LITERATURE REVIEW – SYNTHESIS OF RECENT (POST-2017) RESEARCH

Introduction

A review of recent literature related to Lake Erie eutrophication is underway including five focus topics: hypoxia, *Cladophora*, nutrient cycling, harmful algal blooms (HABs), and nutrient loads. The review includes primarily recent (post-2017) peer-reviewed publications for Lakes Erie, along with some moderately older (post-2005) key papers and topically-relevant articles from outside the basin or reviews that covered a broader geography, as appropriate. In addition, a few technical reports (e.g., ECCC and USEPA 2017 and 2020), monographs, and abstracts of recent scientific presentations were included where peer-reviewed papers on the topics covered are not available. A total of 115 records reviewed to date are included in the companion annotated table. Not all are cited below, but all are listed alphabetically and classified according to one of more of the five focus topics in the table by “X” marks in the columns following the citation. Additional references are actively being identified.
Short summaries related to recent Lake Erie research on the five focus topics follow, along with a small amount of related research from other parts of the Great Lakes basin or outside the basin. The publications reviewed primarily include scientific research results, but policy and adaptive management elements, as well as specific consideration of factors such as the impacts of climate change are also included. The table contains short entries on key findings, as well as uncertainties and additional research needs, which are also summarized here. Note that the Great Lakes HABs Collaborative also released a HABs knowledge gaps fact sheet in April 2021.

Mechanistic lake models exist for the western Lake Erie basin (Verhamme et al., 2016), the central basin (Rowe et al., 2019; Bocaniov et al., 2020; Valipour et al., 2021), and the eastern basin (Valipour et al., 2016 and 2019). LimnoTech completed a new whole-lake model in early 2021. This whole-lake modeling effort required assembly of a database of load inputs and developed average loads from various data sources and estimations. An ensemble of models was used to determine the appropriate load reduction target of 40% to achieve acceptable hypoxia and HAB conditions in the lake. The newest models will be used in the future to revisit these conclusions, as models integrate data spatially and temporally and incorporate the current state of process understanding in their algorithms.

In 2015, the Annex 4 Objectives and Targets Task Team identified 17 priority research, monitoring, and modeling activities to support management decisions and listed critical overarching topics under a heading of “What we do not know”. The list included questions about phosphorus speciation and bioavailability; the roles of nitrogen, dreissenids and other invasive species, and inter-annual variability in hydrometeorology; and whether a 40% load reduction will be adequate to reduce impacts at local scales for each priority tributary and receiving water area (e.g., Sandusky River/Sandusky Bay). Mohamed et al. (2019) also listed key uncertainties that impact the ability to make good management decisions about Lake Erie restoration.

Hypoxia

Central basin hypoxia monitoring has been conducted most intensively since the 2014 Cooperative Science and Monitoring Initiative (CSMI) field year by the U.S. Environmental Protection Agency – Great Lakes National Program Office (USEPA-GLNPO; Xu et al., 2021; Tellier et al., 2022), although earlier data also exist (Zhou et al., 2013). The City of Cleveland has also monitored hypoxia near their water intakes since 2014. These monitoring programs supported a modeling project by the Cooperative Institute for Great Lakes Research and NOAA (Rowe et al., 2019), which built on prior research by Scavia et al. (2016) and Rucinski et al. (2016). The modeling program developed an experimental short-term forecast product but was not designed to produce a seasonal forecast. A seasonal forecast would likely require winter and early spring monitoring of diatom biomass in the western basin and central basin, which is not routinely performed (Twiss et al., 2012 and 2014). Annual summaries of hypoxic area or volume are not produced at present, although an operational monitoring program, especially with sensors that report in real time rather than after physical recovery and downloading of data, could be used to create such summaries.

Apart from small offshore blooms of *Dolichospermum* in July (Chaffin et al., 2019), the central basin of Lake Erie does not typically experience HABs, but it does host large areas of hypoxic bottom water in summer and early fall. As mentioned under discussion of the western basin, the Detroit River is believed to be the primary source of nutrients that fuel diatom and, to a lesser extent, cyanobacteria blooms that sink into the stratified basin and consume oxygen as they decay. Sediment oxygen demand is also believed to play a role, along with upward fluxes of nutrients from sediment and bottom waters during upwelling events. Direct tributary loads to the central basin are smaller than fluxes from the western basin but may be locally important. A full mechanistic understanding of these processes and movements of nutrients, biomass, and hypoxic water over the spring, summer, and fall has been elusive, but mechanistic and predictive models have recently been developed to simulate these processes, and the resolution of monitoring data has also improved (Rowe et al., 2019; Tellier et al., 2022).

Uncertainty related to net climate change impacts in the coming years on stratification and other hypoxia-related phenomena is an important factor that is aligned with taking an adaptive approach in the management of the system. High ice cover in Lake Erie, which requires sustained low winter temperatures and low winds, has shown no trend over most of the lake from 1973 to 2013, and a slight downward trend along the Ontario shore over the same period (Mason et al., 2016). Anderson (E. Anderson et al., 2021) showed evidence of long-term warming in deep waters of Lake Michigan, which may also be taking place in other lakes, but insufficient data are available to document it as completely. The interaction of phosphorus in the Detroit River plume with spring diatom production and summer cyanobacteria blooms in the central basin is still unclear, as that part of the basin is not well monitored and important interactions occur in early spring when ice is breaking up, and during summer when complex mixing between river plumes takes place. The transfer of biomass and nutrients from the western basin to the central basin is also not well understood or quantified, but this is important as a driver of central basin hypoxia.

Cladophora

The eastern basin of Lake Erie is the deepest, and also possibly the least well understood. Growth and sloughing of excess macroalgae such as *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). Effective ways to reduce nutrient loading to the basin, particularly from Ontario tributaries including the Grand River, suffer from many of the same challenges as the Maumee River watershed such as insufficient understanding of BMP effectiveness and of legacy phosphorus cycling in the system (Hanief and Laursen, 2019; Van Meter et al., 2021). Eastern basin macroalgae spatial coverage and biomass are not consistently monitored or reported for the whole basin, although related research programs have been conducted or are underway by Environment and Climate Change Canada (ECCC; Valipour et al., 2016), MECP (Chomicki et al., 2016), Michigan Tech Research Institute (MTRI; Brooks et al., 2015), and USGS

(Wimmer et al., 2019). The MTRI methodology using remote sensing has been applied retrospectively to create a macroalgae time series at select sites (e.g., Ajax, Ontario), and could be applied annually to produce a summary of the maximum extent of coverage. Kuczynski et al. (2020) published an improved *Cladophora* model that incorporates self-shading and other mechanistic enhancements. Current research on macroalgae-related processes, including extensive field elements, is underway by USGS at stations in Lake Erie, among other locations (Wimmer et al., 2019).

Nutrient Cycling

Anderson (H. Anderson et al., 2021a and 2021b) made novel in situ time-series measurements of phosphorus release from central basin sediments in association with the development of bottom-water hypoxia, and others have done studies on nutrient processing in river mouths including Sandusky Bay (Salk et al., 2018; Hampel et al., 2019). Recent research looked at phosphorus limitation related to lipid binding in Lake Erie (Musial et al., 2021).

Where present in abundance, invasive dreissenid mussels have caused a nearshore shunting and benthification of phosphorus in multiple lakes (Hecky et al., 2004). This suggests that mussels trap and retain phosphorus in nearshore areas and especially around tributaries, thereby increasing benthic nutrient levels in nearshore areas. Over the long-term, mussel densities in the western and central basins have remained low due to unsuitable substrate and hypoxia, while densities in the eastern basin are much higher but peaked in 2002 (Karatayev et al., 2014; Karatayev et al., 2018). Selective feeding by mussels on diatoms versus cyanobacteria has been described by Vanderploeg et al. (2001), but modeling suggests that this is not a major factor in algal bloom intensity (Verhamme et al., 2016). Basin-wide impacts of dreissenid mussels were quantified by Li et al. (2021), and Larson et al. (2020) examined nutrient processing in river mouths around Green Bay.

Harmful Algal Blooms

In-lake bloom processes were examined as they relate to remote sensing (Binding et al., 2019, Soontiens et al., 2019), algal bloom seed stock in sediment (Kitchens et al., 2018), and the influence of nitrogen and other factors on bloom growth and toxicity (Chaffin et al., 2018; Newell et al., 2019; Palagama et al., 2020; Hellweger et al., 2022). Coordinated whole-bloom sampling was done in the western basin in 2018 and 2019 to get two snapshots of the summer blooms (Chaffin et al., 2021). Arhonditsis et al. (2019a and 2019b) reviewed Lake Erie watershed and lake models and monitoring and made recommendations for their use in adaptive management. Liu et al. (2020) synthesized weekly in-lake monitoring data and satellite data collected between 2008 and 2017 with a goal of moving toward HAB toxicity forecasting.

National analyses have shown or predicted increasing algal bloom intensity related to climate change (Chapra et al., 2017), although some analyses have suggested that the apparent increase in blooms, particularly in inland lakes, may be an artifact of more intensive sampling (Hallegraeff et al., 2021; Kraemer et al., 2021; Wilkinson, et al., 2021).

Questions remain about the nature and importance of the phosphorus stored in surface sediment in the western basin between spring loading from the Maumee River and summer bloom initiation and expansion. Cyanotoxin formation mechanisms and environmental controls are also poorly understood. Lastly, the diversity of cyanobacteria in river mouths, as opposed to monospecific blooms in open waters of the basin, is somewhat enigmatic. In particular, the drivers of the consistent and persistent *Planktothrix* bloom in Sandusky Bay have not been determined (Hampel et al., 2019). These consistent blooms were absent from the bay in 2020 and 2021, and seem to have been replaced by new species in

2022, *Aphanizomenon* and *Dolichospermum* (verbal communications, June 2022 HABs Forecast Event). This has been hypothesized to be connected with the time-correlative removal of the Ballville Dam from the Sandusky River (Sasak, 2021), which has resulted in better flushing of the bay, but a causal linkage has not yet been established.

Nutrients Loads

Nonpoint phosphorus from agricultural sources contributes up to 85% of the total load to western Lake Erie (Scavia et al., 2016; Baker et al., 2019) and is the focus of much of the watershed-based research in the region. A research effort led by The Ohio State University brought together an ensemble of watershed SWAT models and the USGS SPARROW model to assess a suite of related watershed management questions and scenarios. The results of this work have been published in several recent articles (Kujawa et a., 2020; Martin et al., 2021; Kast et al., 2021a; Apostel et al., 2021; Evenson et al., 2021). Analysis of 2019 loading data suggested that loads were lower than what would have been expected given the wet spring and high flows (Guo et al., 2021). Other recent field and stream sediment studies have produced results that seem inconsistent with these observations (e.g., Osterholz et al., 2020; Williamson et al., 2021). That is, stream studies show greater fractions of legacy phosphorus in some settings, particularly in upper watershed areas and small streams, than would be expected based on Guo et al. (2021) data and interpretations. Research to reconcile these results continues. Historical emphasis on erosion control and retention of particulate phosphorus on agricultural fields via practices like conservation tillage, cover crops, and buffer strips has been enhanced by new research on soluble phosphorus, which is more mobile and more bioavailable (Scavia et al., 2014). Choquette et al. (2019) reported on statistical methods for handling variability in streamflow for phosphorus loading calculations. In addition to changes in nutrient loads, shifting nutrient ratios have also been identified as potentially important drivers of ecosystem change in Lake Erie (Prater et al., 2017).

Burniston et al. (2018) published results of a collaborative binational project to directly measure nutrient loads in the St. Clair-Detroit River connecting channel. Scavia et al. (2016, 2019a, 2019b, 2019c, 2020), Bocaniov and Scavia (2018), Bocaniov et al. (2019), and Dagnew et al. (2019) published results of new modeling and monitoring studies that inform phosphorus loading from the St. Clair-Detroit River system to Lake Erie. A companion report to the Scavia et al. (2019a) paper was also released in 2019 (Scavia et al. 2019b). Important new research has been published on urban stormwater loads and impacts in the Detroit River (Hu et al., 2019). Monitoring work on the Niagara River (Hill and Dove, 2021) has implications for outflow from Lake Erie’s western basin. Urban wastewater load reductions from the Detroit area are among the largest reductions in the basin since the baseline year of 2008 (see Scavia et al., 2019c). Despite recent research by the University of Michigan and others (Scavia et al., 2019), questions remain about phosphorus loading and processing in southern Lake Huron (i.e., sediment resuspension and advection into the St. Clair River), the Thames River (Ontario), and the St. Clair-Detroit River system.

The Midwest Region chapter of the Fourth National Climate Assessment by the U.S. Global Change Research Program (USGCRP, 2018) highlighted several trends that have the potential to influence phosphorus loading to Lake Erie and ecological impacts in the lake. Several researchers have identified statistical trends of increasing spring rainfall, runoff, and nutrient loading in Lake Erie watersheds (Stow et al., 2019; Williams and King, 2020). Warmer lake temperatures and longer summers with changing weather patterns are expected to produce more toxic algal blooms and more intense hypoxia in Lake Erie (Michalak et al., 2013; Perello et al., 2017; Jankowiak et al., 2019; Jabbari et al., 2021). Some researchers have proposed that shifting baselines may necessitate adjustments to nutrient loading targets even before they are achieved (Baker et al., 2019). Others have pointed out that under scenarios of longer growing seasons and more winter precipitation falling as rain rather than snow, agricultural nutrient losses in spring may decline, partially mitigating other negative climate change impacts on Lake Erie (Culbertson et al., 2016; Kalcic et al., 2019). More rainfall, especially in the spring, may hinder planting and fertilizing due to field conditions that do not allow equipment to access the fields, as was observed in 2019 (Guo et al., 2021). Changes in nutrient release from cover crops during the non-growing season and other impacts on BMP effectiveness of changing climate are not well understood (Cober et al., 2019).

Literature Review Summary

Several of the scientific discoveries and innovations described above have special significance to nutrient management in Lake Erie and its watershed. The results of the natural experiment that took place in 2019 where excess rainfall in the spring resulted in less fertilizer application indicated that legacy phosphorus and lags from the timing of reduced fertilizer application to lake impacts may not be as important in the Maumee Watershed as previously hypothesized (Guo et al., 2021). New understanding of how dynamic hypoxia in the central basin of Lake Erie is, based on new modeling and monitoring (Rowe et al., 2019), suggests that progress toward the goal of reduced hypoxic area or volume based on nutrient reduction may be difficult to measure and track. The integrated pattern of dreissenid mussel presence or absence in the basin may be a reasonable, if unusual, proxy (Karatayev et al., 2018).

Similarly, the dynamic nature of watershed nutrient delivery based on changing climate, farming practices, drainage modifications, and inadequate tracking of BMPs make systematic assessment of positive impacts on water quality difficult to link to interventions. Despite this, innovative ensemble modeling of agricultural watersheds incorporating enhancements for simulating tile drainage and manure management impacts at high resolution is very promising (Martin et al., 2021). A new high-profile paper by Hellweger et al. (2022) indicates continuing concerns about the potential negative impacts on HAB toxicity of phosphorus load reduction without N load reduction, although there is uncertainty about how likely such a scenario is to develop. Finally, new work on field measurements and modeling of benthic interactions among dreissenid mussels, macroalgae, river plumes, and upwelling (Wimmer et al., 2019; Kuczynski et al., 2020; Hui et al., 2021) is reducing uncertainty that will be critical in managing nutrients in eastern Lake Erie, where offshore oligotrophication is also a concern.

7.2 ADDITIONAL TABLES AND FIGURES

LIST OF ADDITIONAL FIGURES

LIST OF ADDITIONAL TABLES

7.2.1 Spring Priority Tributary Figures

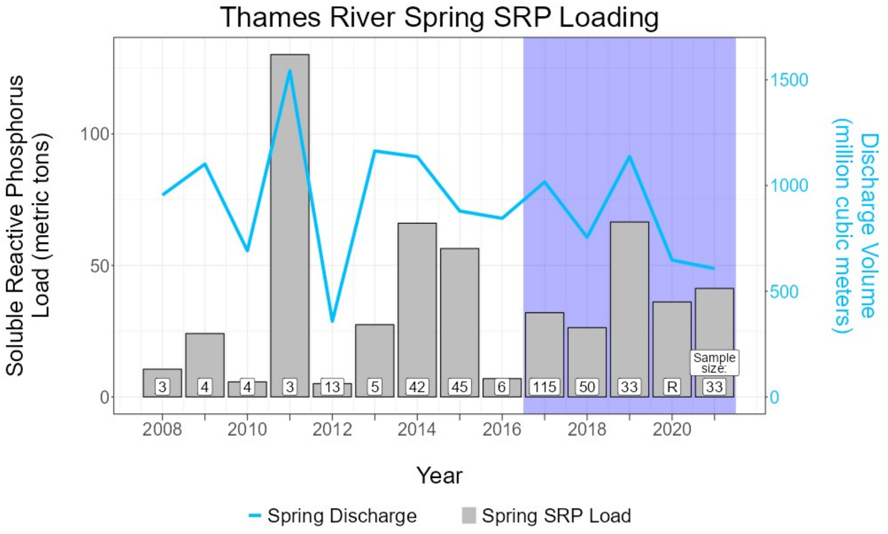

Figure A 1. Spring soluble reactive phosphorus load (grey bars) to Lake Erie from the Thames River for water years 2008 – 2021. Blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring; "R" indicates a discharge-based regression method was used due to limited sampling.

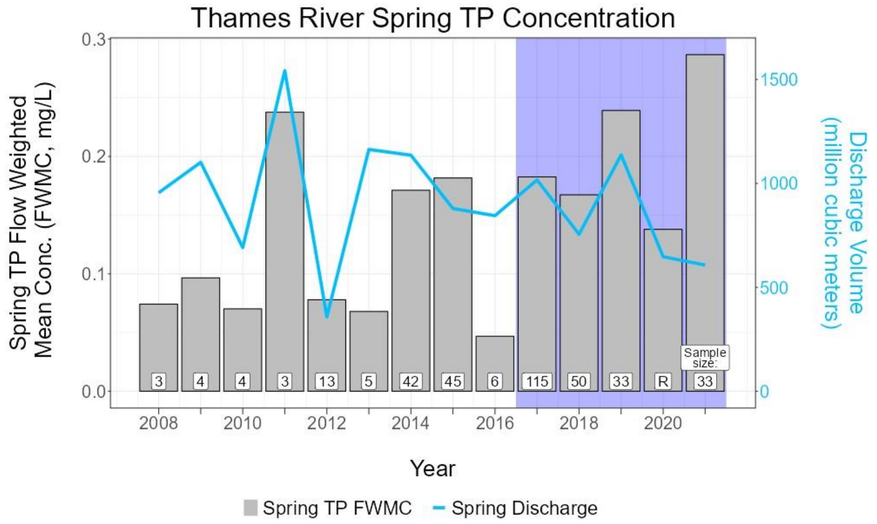

Figure A 2. Spring total phosphorus flow-weighted mean concentration (FWMC; grey bars) to Lake Erie from the Thames River for water years 2008 – 2021. Blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring; "R" indicates a discharge-based regression method was used due to limited sampling.

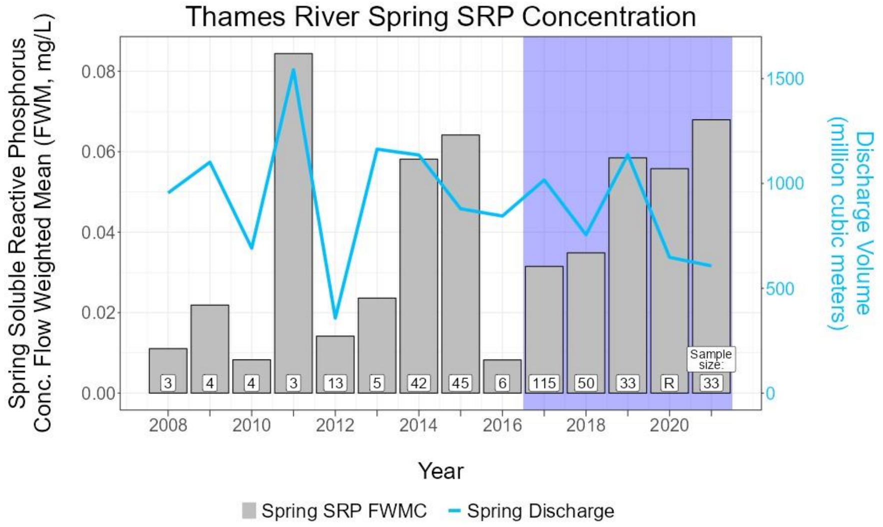

Figure A 3. Spring soluble reactive phosphorus FWMC (grey bars) to Lake Erie from the Thames River for water years 2008 – 2021. Blue line is total spring discharge. Shaded chart area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring; "R" indicates a discharge-based regression method was used due to limited sampling.

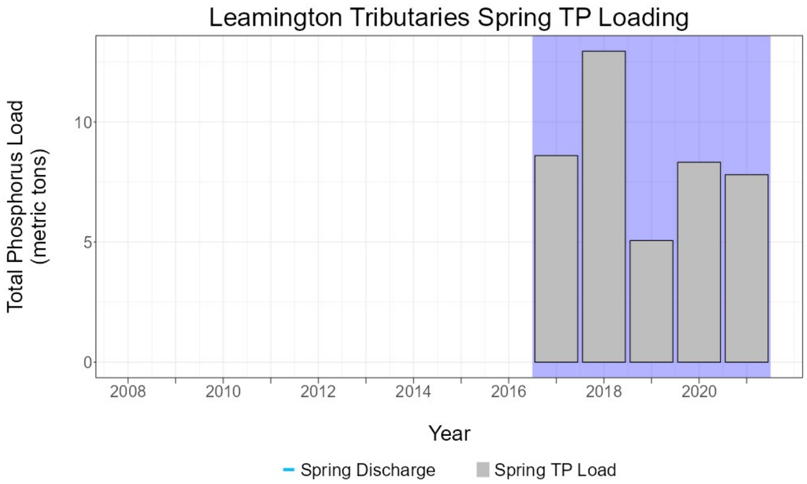

Figure A 4. Spring total phosphorus load (grey bars) to Lake Erie from the Leamington Tributaries for water years 2017 – 2021. Shaded chart area highlights the 2017 – 2021 evaluation period.

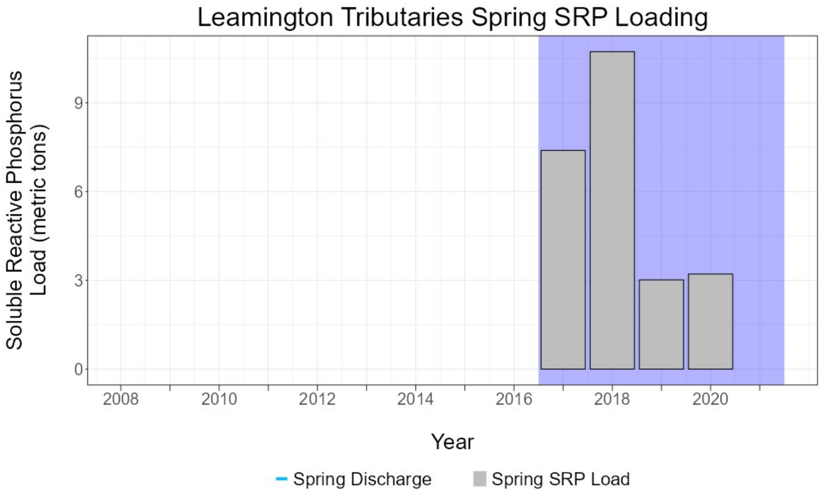

Figure A 5. Spring soluble reactive phosphorus load (grey bars) to Lake Erie from the Leamington Tributaries for water years 2017 – 2021. Shaded chart area highlights the 2017 – 2021 evaluation period.

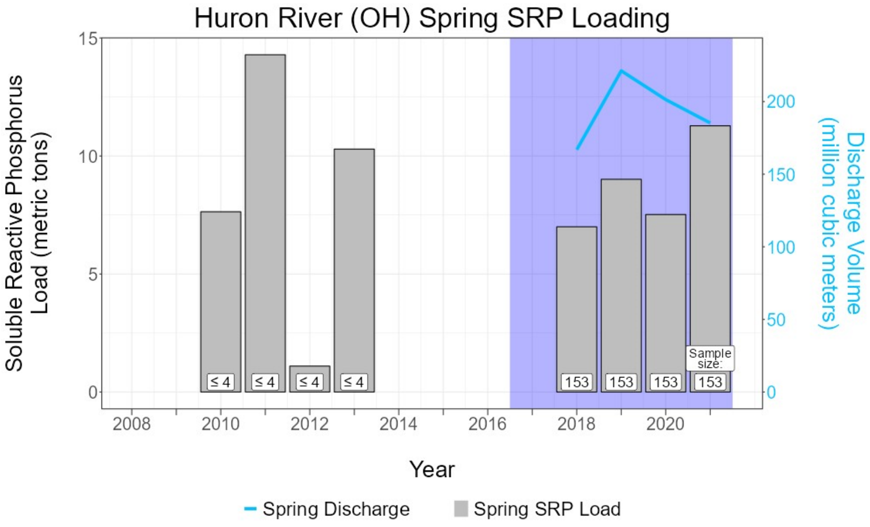

Figure A 6. Spring soluble reactive phosphorus load (grey bars) from the Huron River (Ohio) for water years 2010 – 2021. Blue line total is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring. Sample sizes with ≤ indicate maximum possible samples sizes taken from Maccoux et al. (2016), which reported only annual values**.**

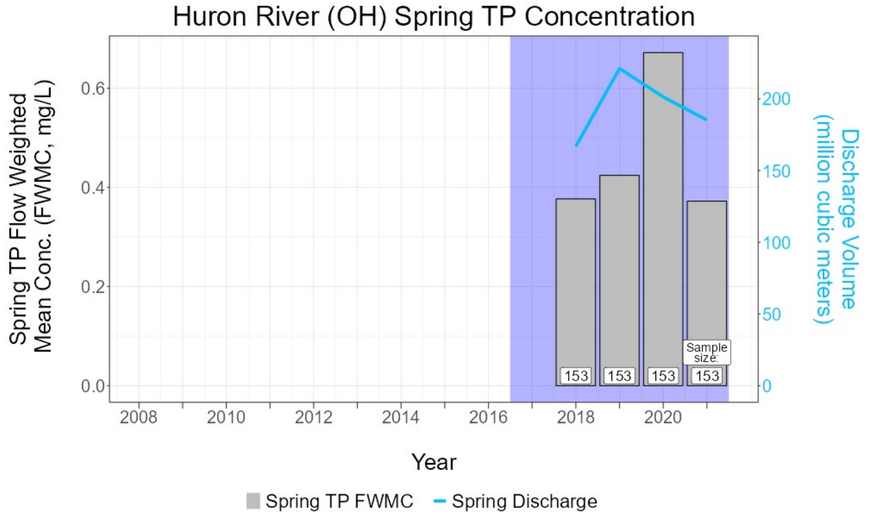

Figure A 7. Spring total phosphorus FWMC (grey bars) from the Huron River (Ohio) for water years 2018 – 2021. Blue line total is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

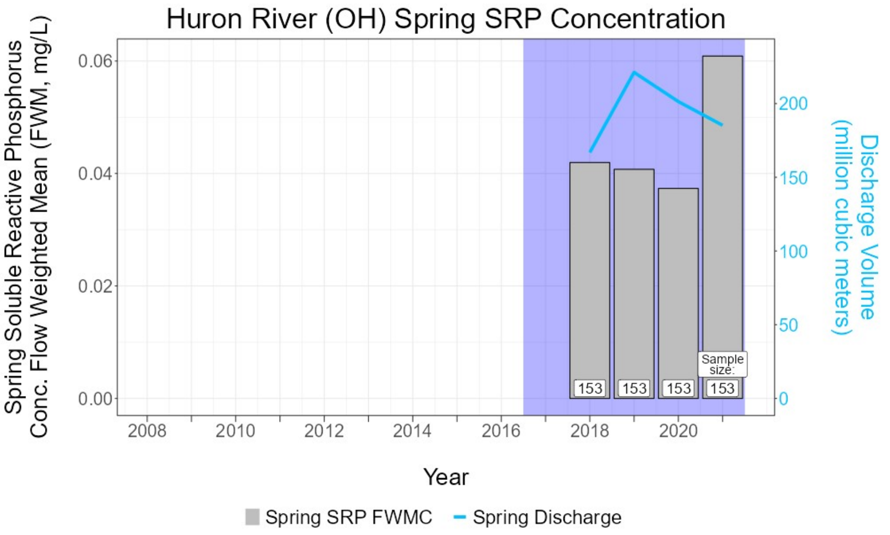

Figure A 8. Spring soluble reactive phosphorus FWMC (grey bars) from the Huron River (Ohio) for water years 2018 – 2021. Blue line total is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

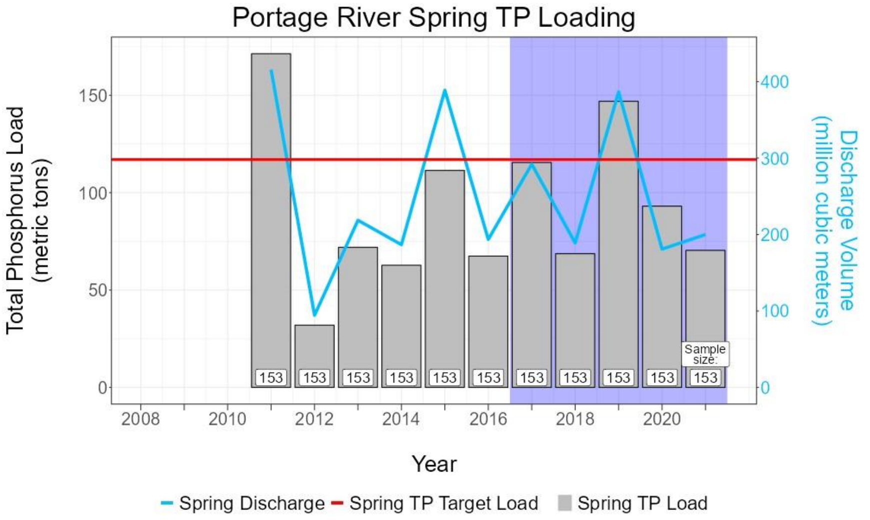

Figure A 9. Spring total phosphorus load (grey bars) from the Portage River for water years 2011 – 2021. Red horizontal line is the target load (40% reduction from 2011 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring.

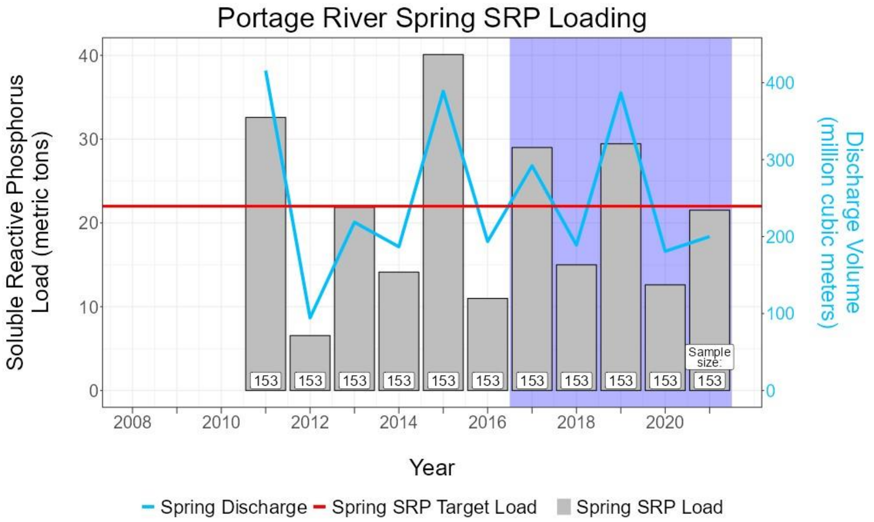

Figure A 10. Spring soluble reactive phosphorus load (grey bars) from the Portage River for water years 2011 – 2021. Red horizontal line is the target load (40% reduction from 2011 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring.

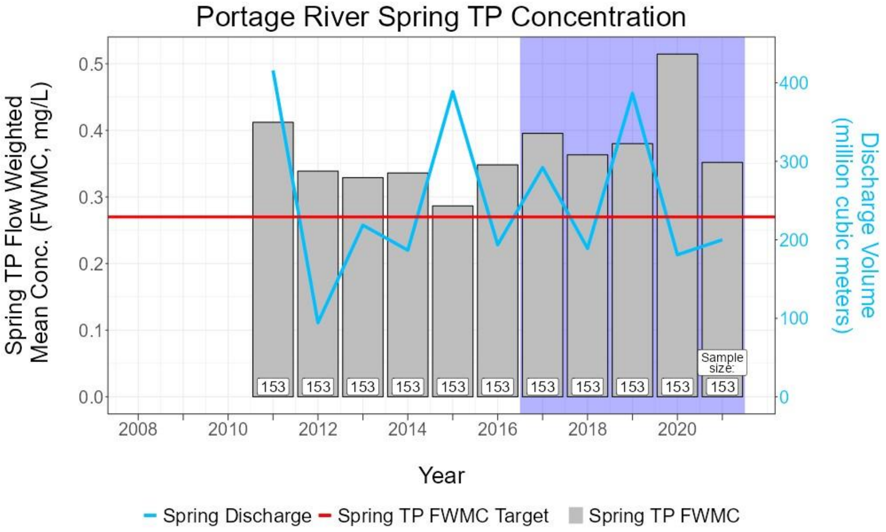

Figure A 11. Spring total phosphorus FWMC (grey bars) from the Portage River for water years 2011 – 2021. Red horizontal line is the target load (40% reduction from 2011 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

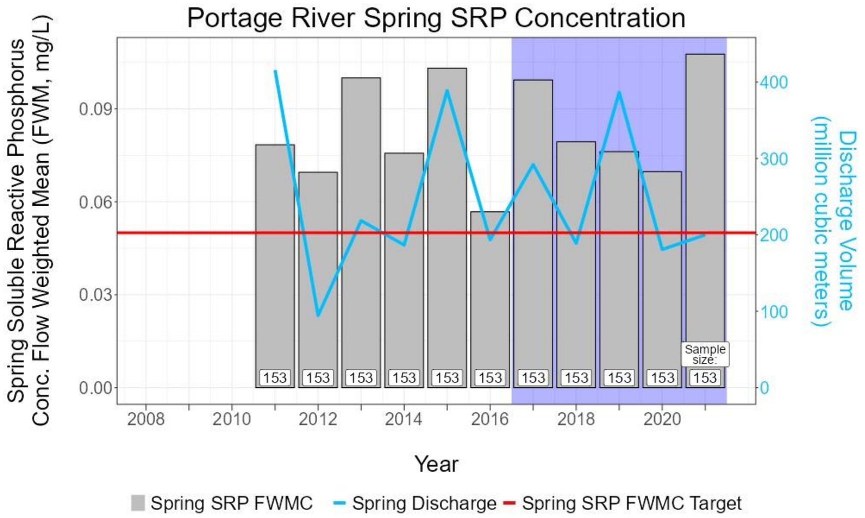

Figure A 12. Spring soluble reactive phosphorus FWMC (grey bars) from the Portage River for water years 2011 – 2021. Red horizontal line is the target load (40% reduction from 2011 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

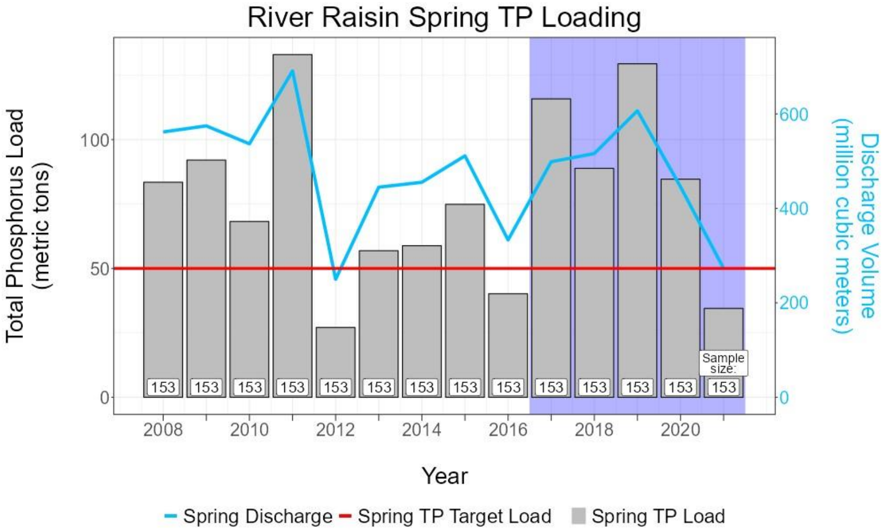

Figure A 13. Spring total phosphorus load (grey bars) from the River Raisin for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring.

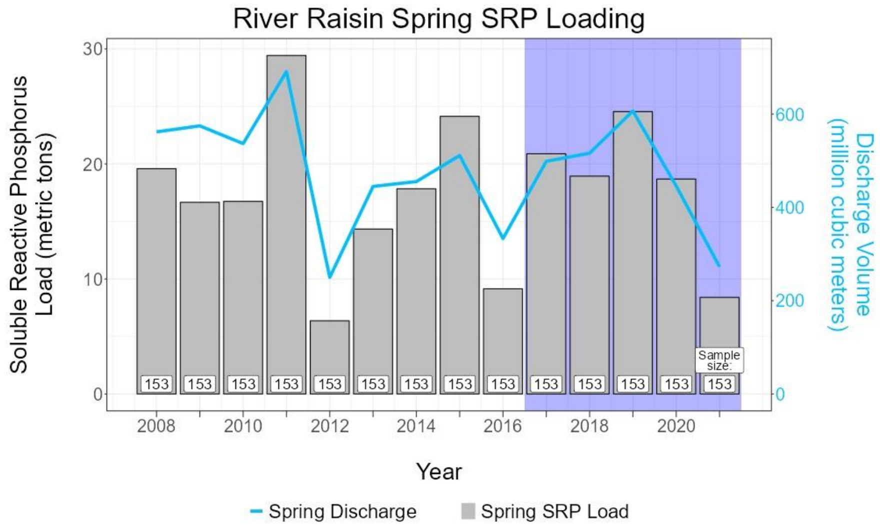

Figure A 14. Spring soluble reactive phosphorus load (grey bars) from the River Raisin for water years 2008 – 2021. Blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring.

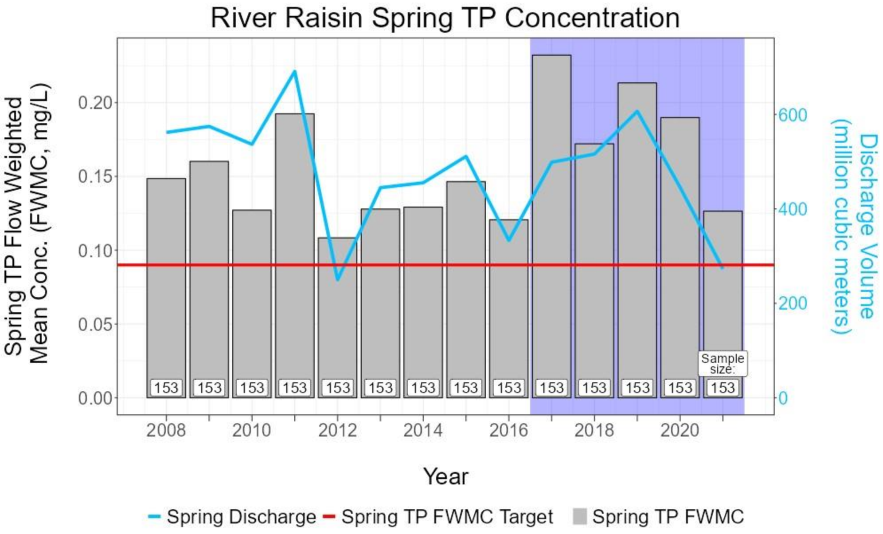

Figure A 15. Spring total phosphorus FWMC (grey bars) from the River Raisin for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

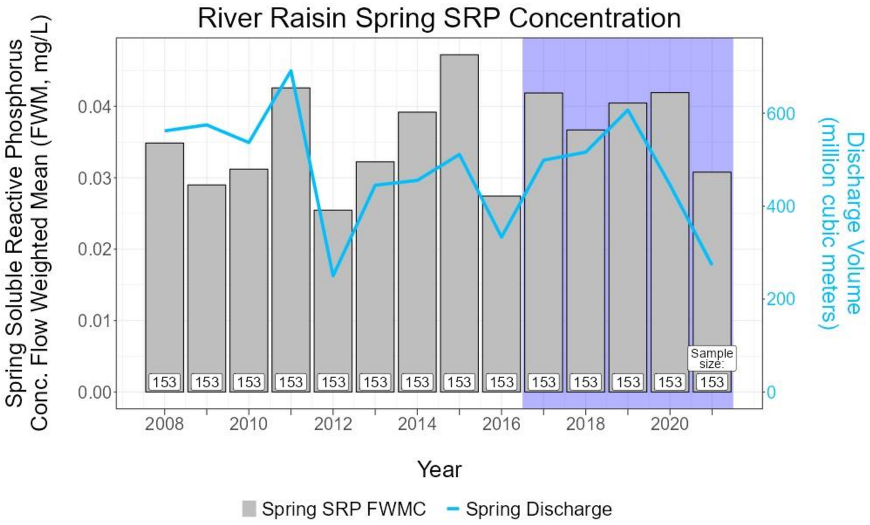

Figure A 16. Spring soluble reactive phosphorus FWMC (grey bars) from the River Raisin for water years 2008 – 2021. Blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

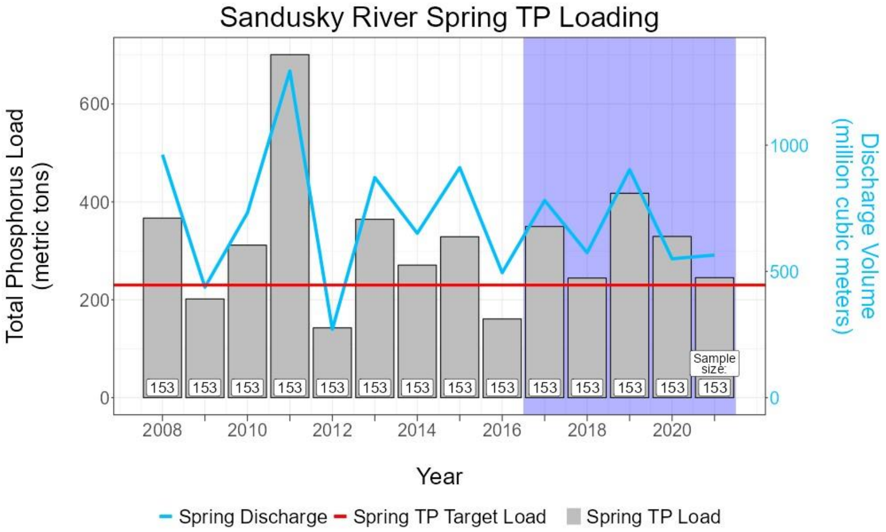

Figure A 17. Spring total phosphorus load (grey bars) from the Sandusky River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring.

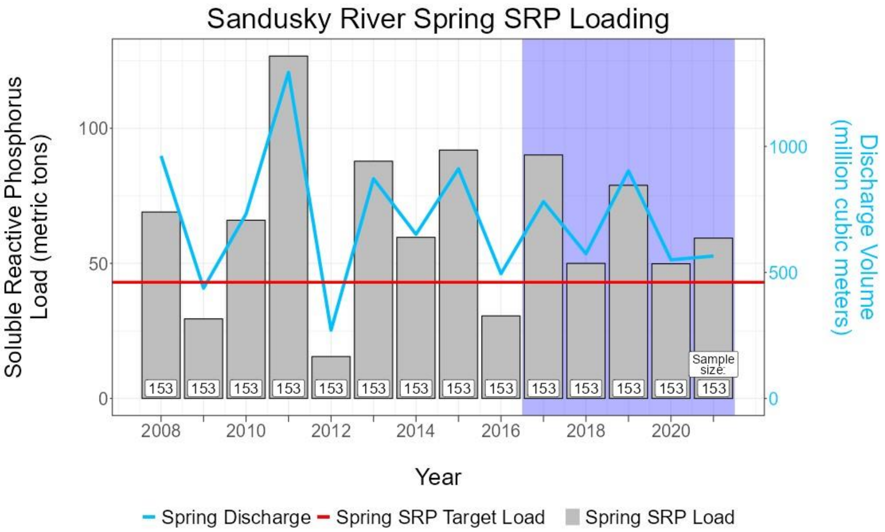

Figure A 18. Spring soluble reactive phosphorus load (grey bars) from the Sandusky River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each spring.

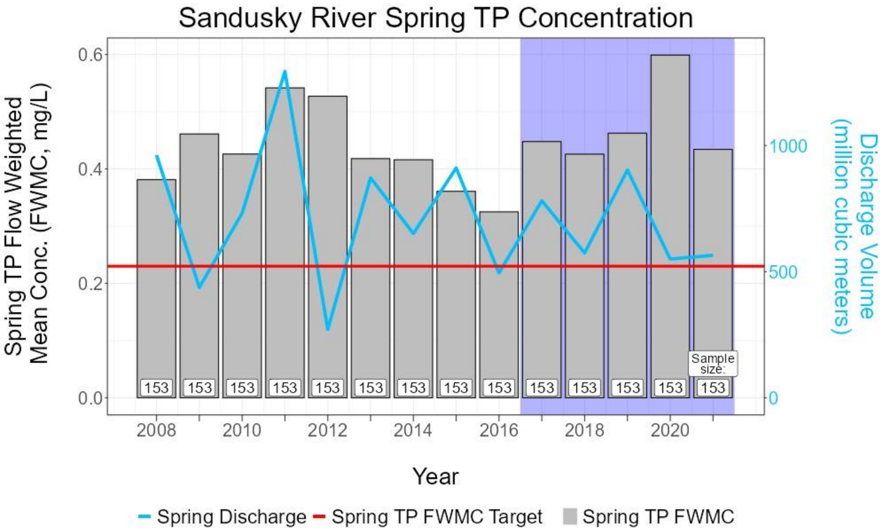

Figure A 19. Spring total phosphorus FWMC (grey bars) from the Sandusky River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

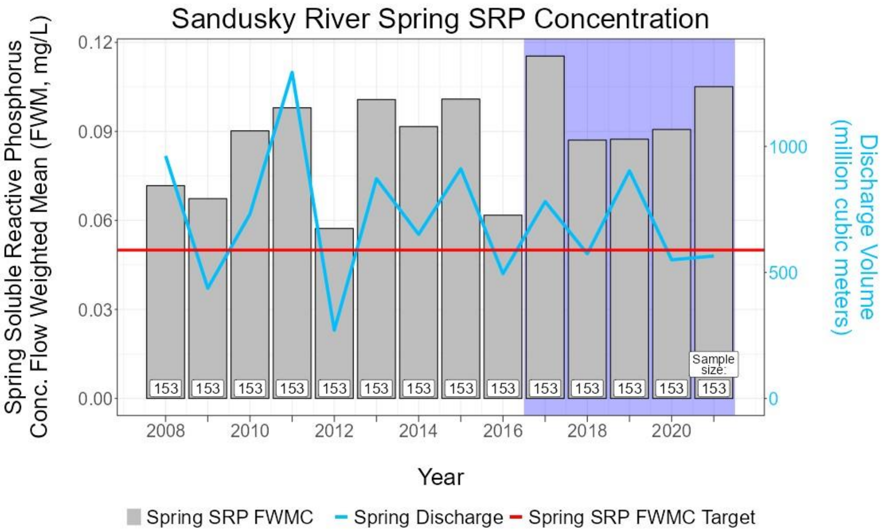

Figure A 20. Spring soluble reactive phosphorus FWMC (grey bars) from the Sandusky River for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline), and blue line is total spring discharge. Shaded blue area highlights the 2017 – 2021 evaluation period. Values in white boxes are the number of nutrient samples (sample size) used for calculation in each spring.

7.2.2 Spring Priority Tributary Loading Trend P-values

Table A 1. Trend p-values (Theil Sen slope) for spring priority tributary loads and flow-weighted mean concentrations (FWMC).

Watershed	**Total Phosphorus**		**Soluble Reactive Phosphorus**	
	Trend p-value		**Trend p-value**	
	Load	**FWMC**	**Load**	**FWMC**
Maumee	0.58	1.0	1.0	0.83
Portage	0.64	0.28	1.0	0.76
Raisin	1.0	0.51	1.0	0.38
Sandusky	0.91	0.74	0.85	0.16

7.2.3 Annual TP Loading Figures

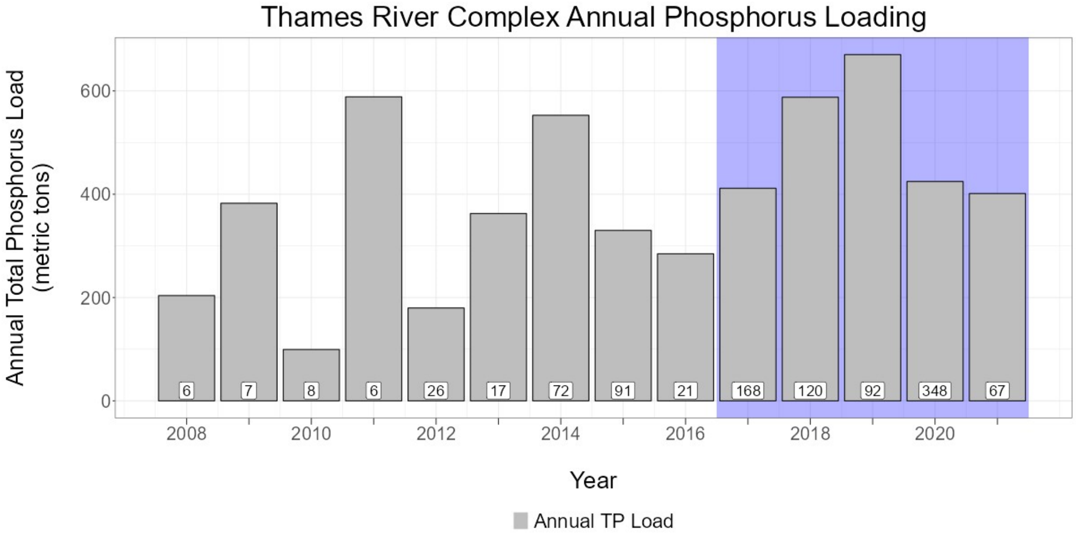

Figure A 21. Annual total phosphorus load (grey bars) from the Thames River watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Shaded chart area highlights the 2017 – 2021 evaluation period.

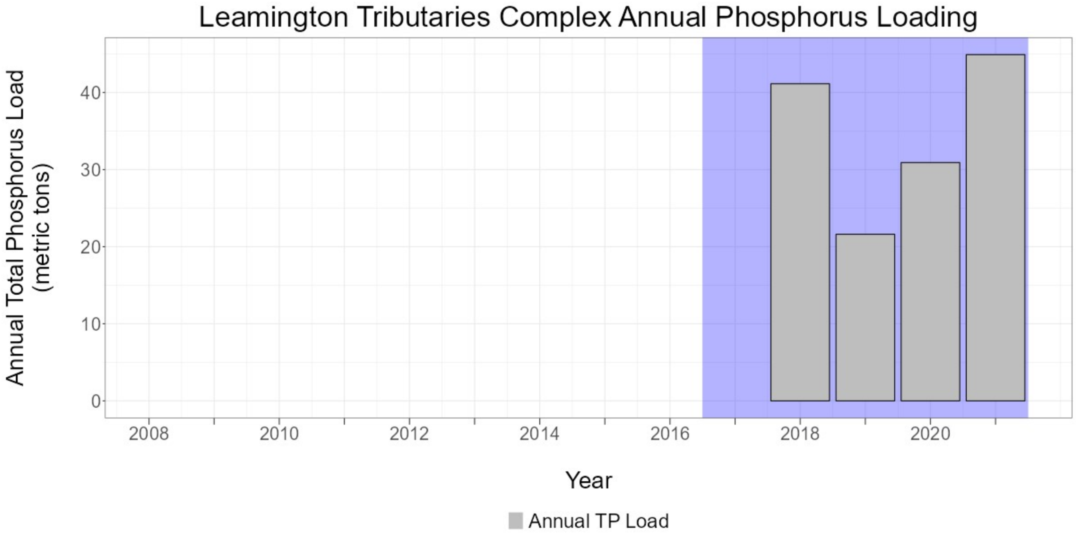

Figure A 22. Annual total phosphorus load (grey bars) from the Leamington watershed for water years 2018 – 2021. Shaded chart area highlights the 2017 – 2021 evaluation period.

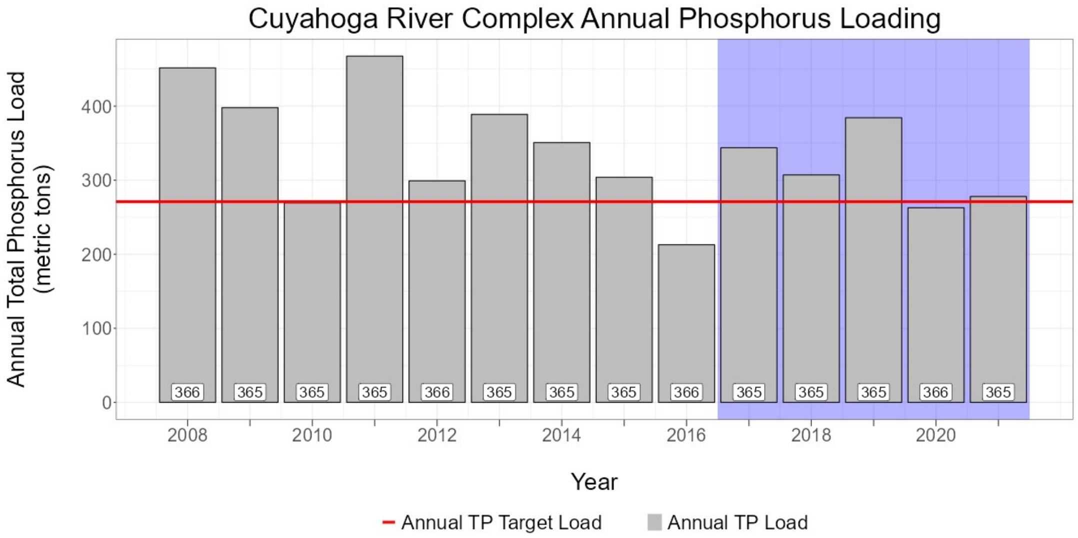

Figure A 23. Annual total phosphorus load (grey bars) from the Cuyahoga River watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

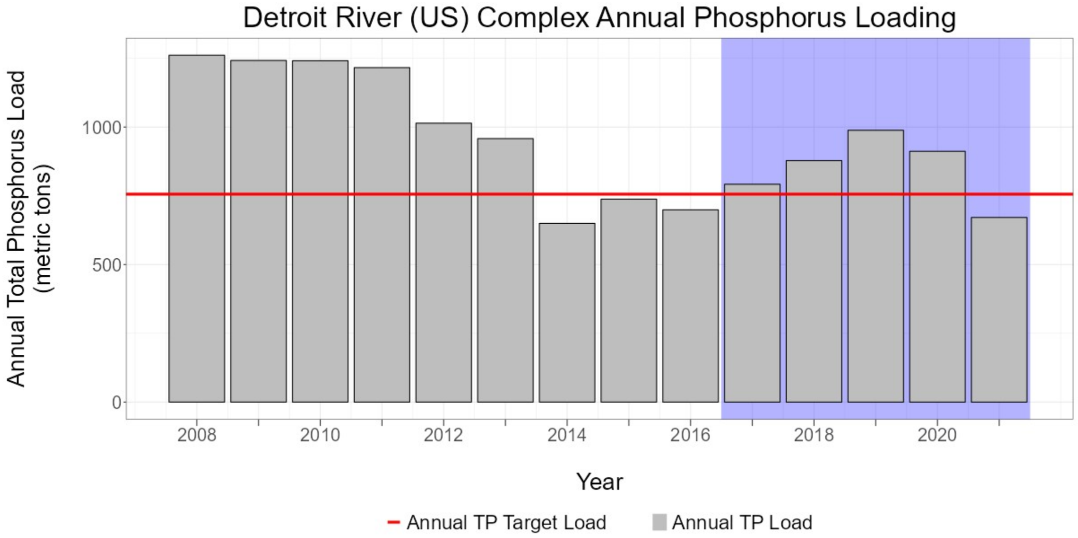

Figure A 24. Annual total phosphorus load (grey bars) from the Detroit River (U.S.) watershed for water years 2008 – 2021. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

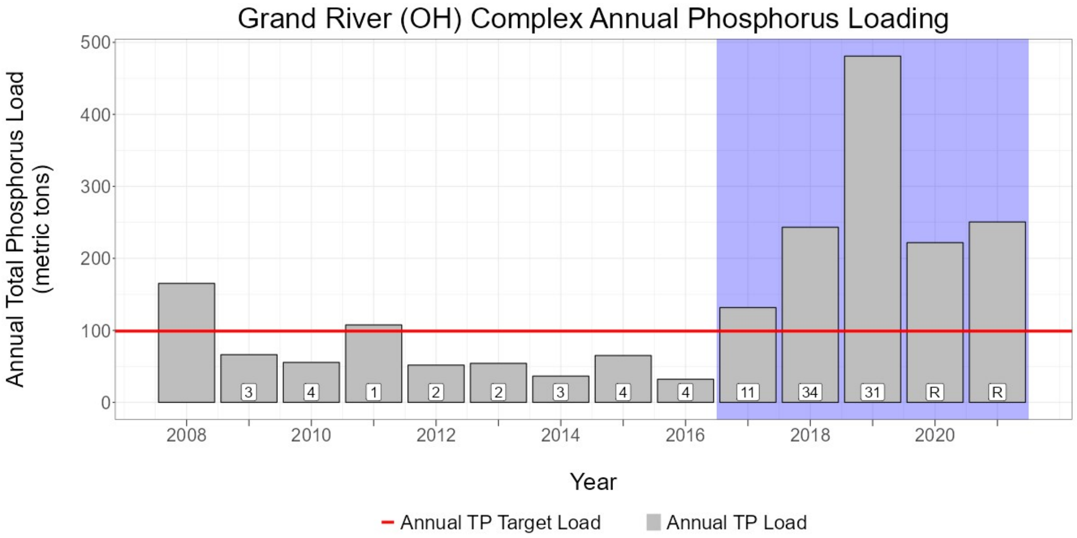

Figure A 25. Annual total phosphorus load (grey bars) from the Grand River, Ohio watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

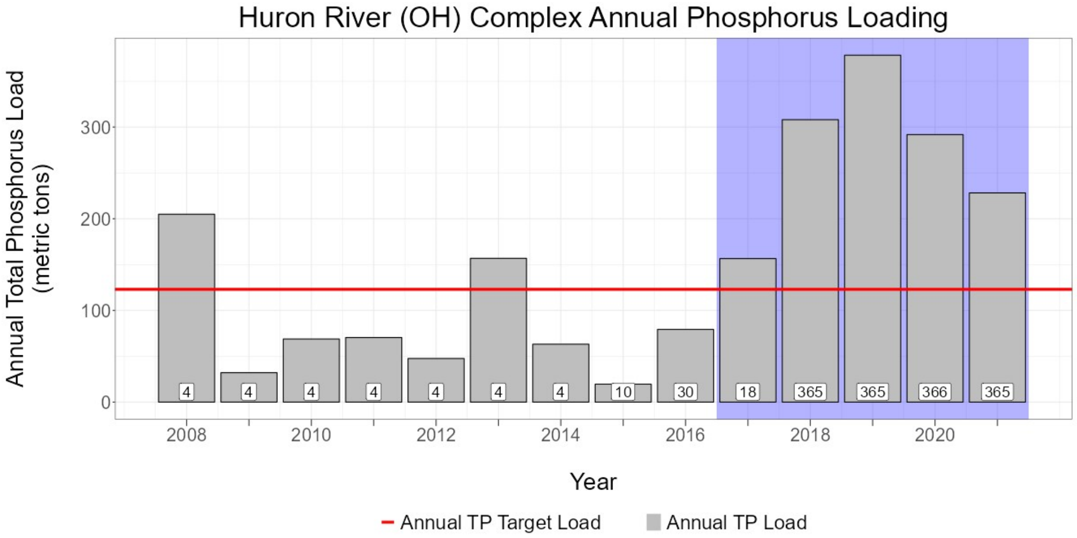

Figure A 26. Annual total phosphorus load (grey bars) from the Huron River, Ohio watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

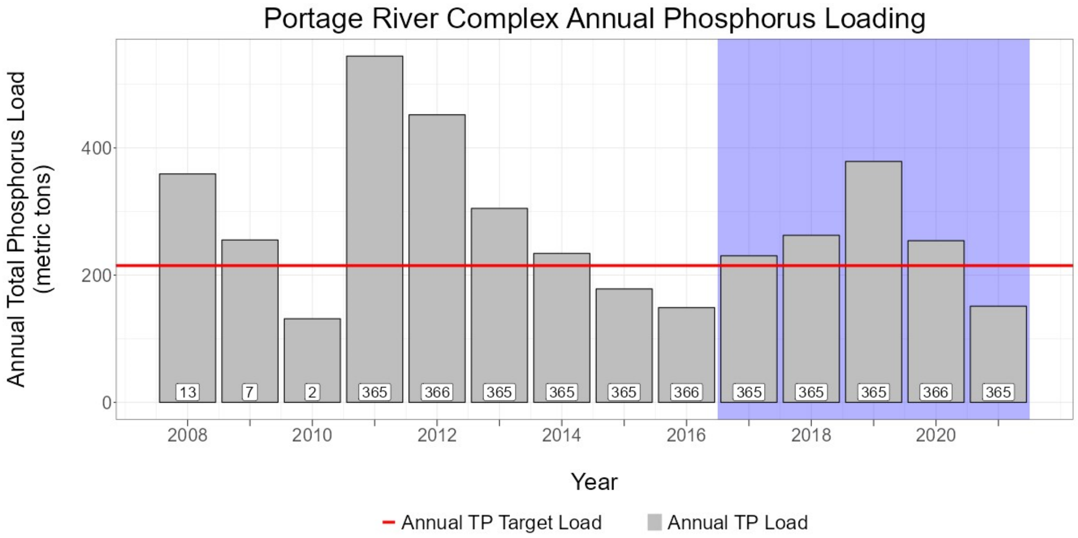

Figure A 27. Annual total phosphorus load (grey bars) from the Portage River watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

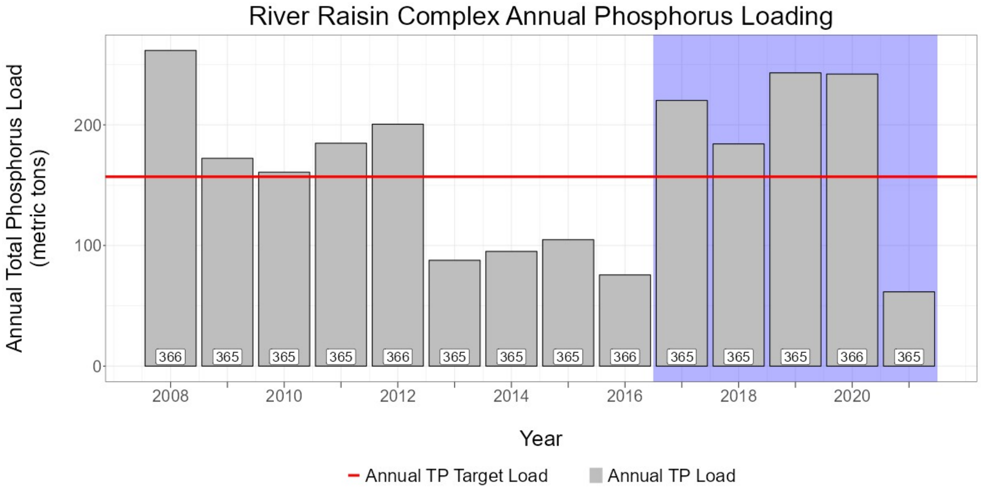

Figure A 28. Annual total phosphorus load (grey bars) from the River Raisin watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period. Note: Calculations done by the Annex 4 loading working group and the state of Michigan use different areas and methods for the River Raisin; as a result annual load values will not match exactly.

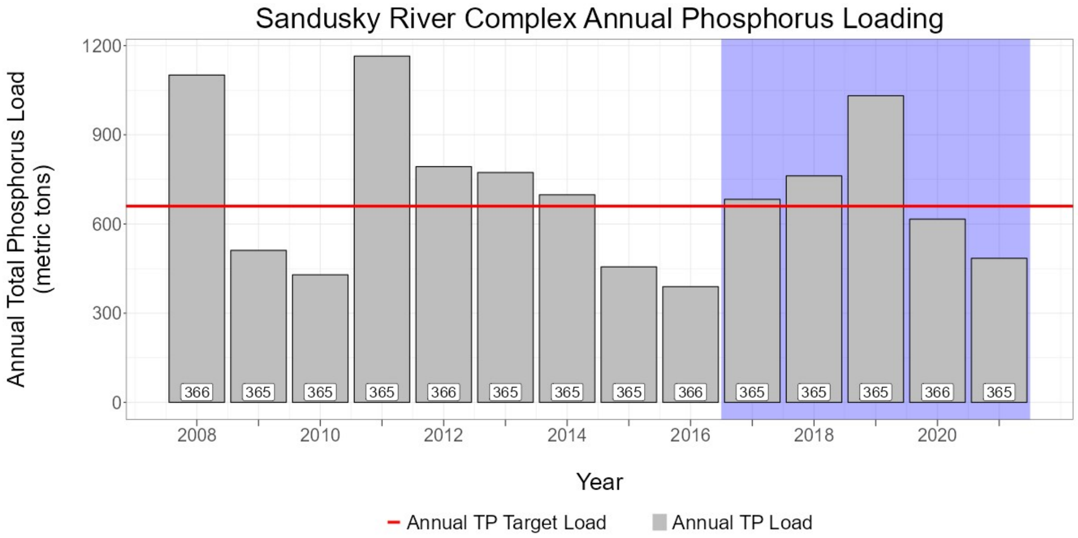

Figure A 29. Annual total phosphorus load (grey bars) from the Sandusky River watershed for water years 2008 – 2021. Values in white boxes are the number of nutrient samples (sample size) used for load calculation in each year. Red horizontal line is the target load (40% reduction from 2008 baseline). Shaded chart area highlights the 2017 – 2021 evaluation period.

7.2.4 WRTDS Nitrogen Loading Figures

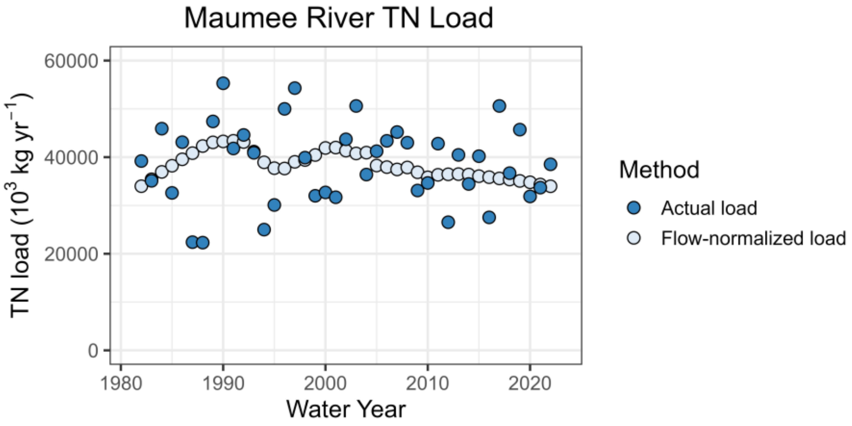

Figure A 30. Actual loads (dark blue circles) and flow-normalized load (light blue circles) for total nitrogen for the Maumee River from 1982 – 2021. Source: F. Rowland, updated from Rowland et al. (2021).

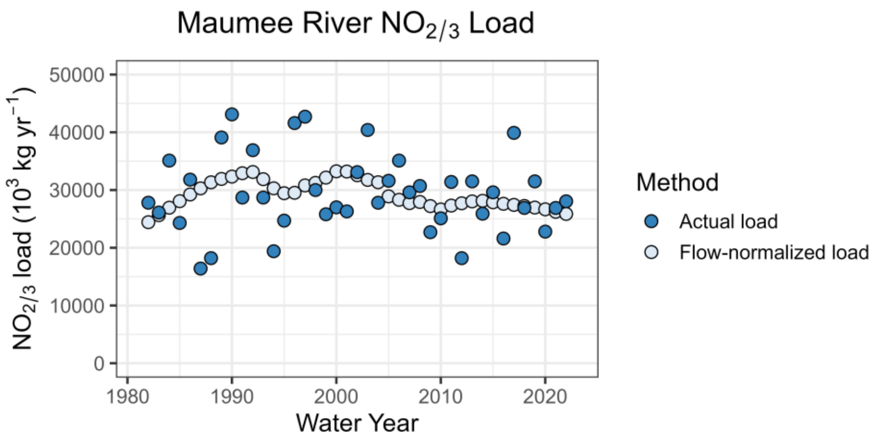

Figure A 31. Actual loads (dark blue circles) and flow-normalized load (light blue circles) for nitrate/nitrite for the Maumee River from 1982 – 2021. Source: F. Rowland, updated from Rowland et al. (2021).

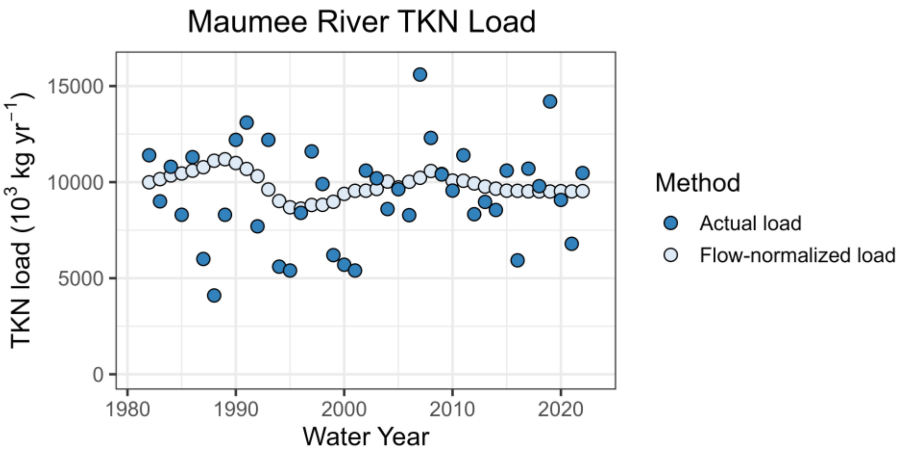

Figure A 32. Actual loads (dark blue circles) and flow-normalized load (light blue circles) for total Kjeldahl nitrogen for the Maumee River from 1982 – 2021. Source: F. Rowland, updated from Rowland et al. (2021).

7.2.5 In-Lake Nutrient Concentration Figures

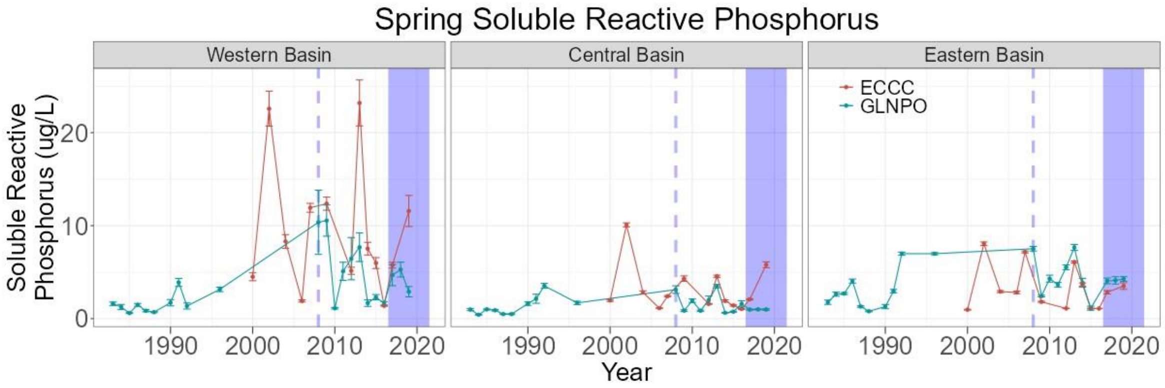

Figure A 33. Spring (April to May) average (± SE) soluble reactive phosphorus concentrations in the western, central, and eastern Lake Erie basins. 2017 to 2021 is highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

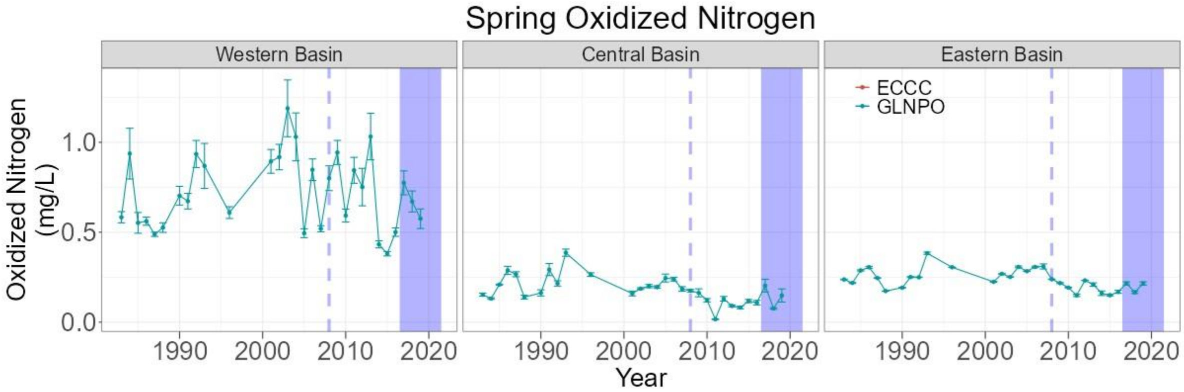

Figure A 34. Spring (April to May) average (± SE) oxidized nitrogen concentrations in the western, central, and eastern Lake Erie basins. 2017 to 2021 is highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

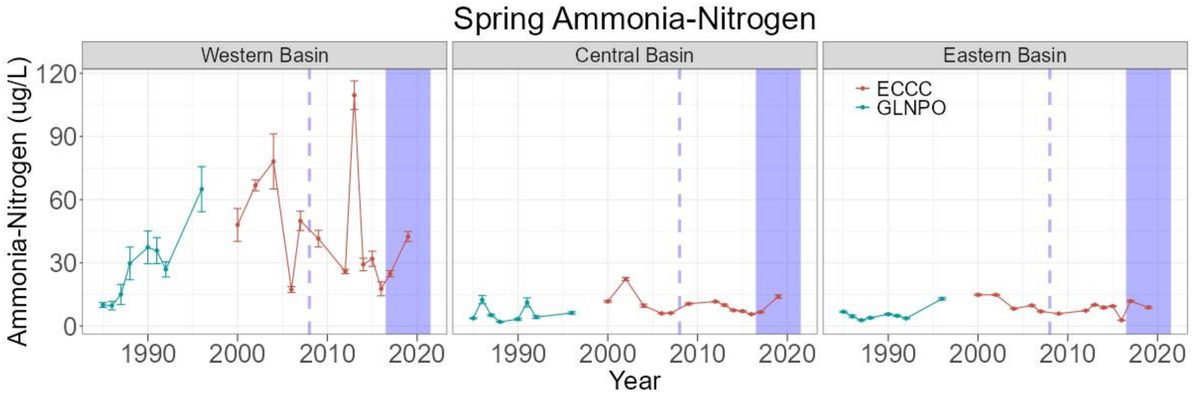

Figure A 35. Spring (April to May) average (± SE) ammonia nitrogen concentrations in the western, central, and eastern Lake Erie basins. 2017 to 2021 is highlighted as the current assessment period for the 5-Year Binational AM Evaluation.

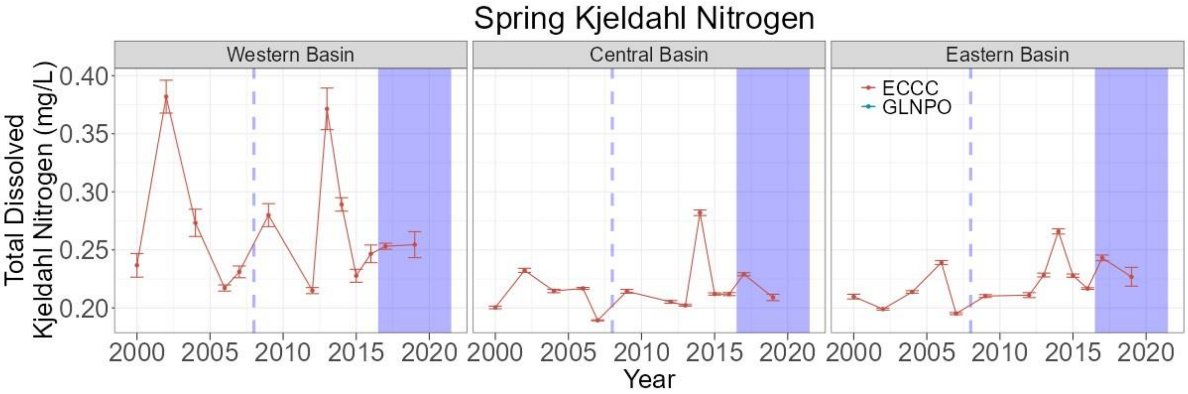

Figure A 36. Spring (April to May) average (± SE) total Kjeldahl nitrogen concentrations in the western, central, and eastern Lake Erie basins. 2017 to 2021 is highlighted as the current assessment period for the 5-Year Binational AM Evaluation.