Lake Erie's seasonal dissolved oxygen problem: State of the science and approaches to best inform future understanding

A Report by the Steering Committee of the 2021 CIGLR Workshop "*Lake Erie Central Basin Hypoxia: State of the Science Review and Approaches to Track Future Progress*"

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Introduction

In October 2021 the Cooperative Institute for Great Lakes Research (CIGLR) convened a virtual summit to address hypoxia in the central basin of Lake Erie. Forty-one attendees (Appendix I) representing US and Canadian federal, state and provincial agencies, academic partners, and other stakeholder groups reviewed the state of the science and assessed approaches for tracking the future progress of hypoxia extent. This summit was preceded by three webinars focused on: the GLWQA Nutrients Annex subcommittee history and process, current and past monitoring efforts aimed at hypoxia in the lake, and modeling products related to hypoxia. Participants in the summit split into four breakout rooms and discussed questions pertaining to hypoxia in Lake Erie. This report includes a summary of the general themes discussed in the workshops and the resulting set of recommendations.

Seasonal hypolimnetic hypoxia has been a regular occurrence in Lake Erie's central basin since at least the late 1950s (Hawley et al 2006; Scavia et al 2014; Watson et al 2016). The Nutrients Annex of the 2012 Great Lakes Water Quality Agreement (GLWQA) (ECCC and EPA 2012) includes the lake ecosystem objective (LEO): "minimize the extent of hypoxic zones in the Waters of the Great Lakes associated with excess phosphorus loading, with particular emphasis on Lake Erie" [Article 3(1)(b)(i)]. Subsequent modeling work indicated a 40% reduction of annual phosphorus loads to Lake Erie's central basin would be necessary to achieve this LEO (Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee 2015). This recommendation was adopted by the United States and Canada in 2016.

While the GLWQA commits Canada and the US to minimize hypoxic zone extent, it does not prescribe how 'extent' should be evaluated. The Nutrients Annex Objectives and Targets Task Team, created in September 2013 to update Lake Erie phosphorus targets, evaluated three potential hypoxia "Ecosystem Response Indicators" (ERIs):

- Average hypolimnion dissolved oxygen (DO) concentration during August and September
- Average areal extent during summer
- Number of hypoxic days

The Task Team applied several models to quantify phosphorus load and eutrophication response relationships. All models indicated that phosphorus reductions to the central basin would reduce hypoxic conditions (Zhang et al. 2008, Bocaniov et al. 2016; Rucinski et al. 2016; Scavia et al. 2016). Ultimately, the Task Team recommended a target phosphorus load that raise the average August and September hypolimnetic dissolved oxygen concentrations to 2.0 mg/L or higher; models predicted that the total phosphorus reductions would reduce the hypoxic area from an average of 8,790 km^2 (Zhou et al. 2015) to approximately 2,800 km^2 (Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee 2015). However, since establishing a 40% phosphorus reduction target in 2016, there has not been an assessment of whether hypoxic conditions are changing because there is no routine assessment of hypoxic extent or severity to track progress toward this goal. Furthermore, in the time since the targets were set, the direct contemporaneous link between hypoxia and phosphorus inputs has been questioned (Reavie et al. 2016; Del Giudice et al. 2018) as has the stressor-response relationship used to support the hypoxia load targets (Arhonditsis et al. 2018).

Hypoxia is difficult to assess for several reasons: 1) the large size of central basin hypoxic zone presents challenges for obtaining adequate coverage (Xu et al. 2021; Tellier et al. 2022), 2) recent monitoring and modeling indicate that hypoxia tends to establish itself in the nearshore and progress towards the offshore, which differs from what was previously understood (Rowe et al. 2019; Valipour et al. 2021), 3) regular hypoxia occurrence has been reported on the periphery of the central basin, where routine hypoxia monitoring does not occur (Stow et al. in review; Kraus et al. 2013; Xu et al. 2021) and 4) unlike algal bloom extent, hypoxic extent cannot be measured remotely via satellite imagery. Hence, the CIGLR hypoxia summit focused on two main objectives:

1. Evaluate approaches to track progress in reducing hypoxia that is expected to occur in response to management actions underway to meet the updated phosphorus load targets. Reporting should include providing results to support decision making by resource managers and outreach to the stakeholders and general public.
2. Identify data requirements and gaps that should be addressed through enhanced monitoring programs, to make routine assessments of Lake Erie hypoxia possible.

<u>Objective 1 - Summary of approaches for tracking progress in reducing hypoxia</u>

Addressing hypoxia in Lake Erie involves the collaboration of two federal governments, five states, the province of Ontario, and numerous academic and non-governmental organizations. Thus, no single metric for tracking hypoxic extent reduction will be suitable for all involved parties. A key point emphasized in multiple breakout discussions was that the current Lake Erie hypoxia monitoring programs and sampling designs are contingent upon each organization's capacities and programmatic endpoints. Different stakeholders may have greater concerns about certain environmental impacts of hypoxia. Current Lake Erie monitoring is conducted at several spatial and temporal scales (Appendix II, Table 1). For example, several agencies and academic partners deploy stationary buoys equipped with thermistor strings and depth-resolved oxygen sensors that record data at high frequency, often taking several measurements each hour, while other partners rely on synoptic sampling collecting water column profiles along nearshore to offshore transects at weekly to monthly intervals.

With multiple organizations collecting data at differing spatial and temporal frequencies, the diverse ensemble of monitoring approaches poses challenges for data harmonization to conduct coherent assessments. Summit participants also expressed difficulty tracking all currently available products, but acknowledged that multiple groups are actively attempting to create, or contribute to existing central data repositories.

Potential metrics for describing hypoxic extent:

Given the absence of a uniform metric for measuring hypoxic extent, different approaches were discussed during the summit. Participants listed the following potential metrics to be used for reporting and assessment, along with some general comments about each:

- Average hypolimnion DO concentration

    - There are currently 13 established fixed location DO monitoring programs, conducted by several institutions, with varying measurement frequencies (Appendix II, Table 1).
    - The EPA Great Lakes National Program Office (GLNPO) DO monitoring program also includes oxygen depletion rate estimates.
    - Monitoring programs sometimes overlap; where possible, agencies should coordinate efforts.
- Spatial extent
    - There is a need for an operational definition of 'spatial extent' of hypoxia. Without an unambiguous definition, it will be challenging to track measurable progress at reducing hypoxia.
    - The current monitoring programs and (ship-based, logger-based including GLATOS enhancements) provide large quantities of valuable hypoxia data, but the data have not been assembled in a way that the Nutrients Annex can use for a reportable quantitative metric.
- Duration of hypoxic conditions
    - Large hypoxic water masses in the central basin of Lake Erie can persist for months, whereas discrete episodic hypoxia events have shorter timescales (Ruberg et al. 2007; Perello et al. 2017; Jabbari et al. 2019). Accurately estimating duration will require expanded monitoring, both spatially and temporally.

These three metrics: average DO concentration, spatial extent, and duration of hypoxic conditions will most likely be used to assess hypoxic extent in the near-term, as there are baseline data for these parameters that span multiple years. Using all three metrics in parallel, or an integrated measure such as hypoxic volume-days, which captures both extent and duration, is advisable. However, workshop participants also discussed additional indicators that could complement these three metrics. Other potential indicators included:

- Biological indicators of hypoxia
    - The extent of suitable habitat zones for mayflies has decreased in the central basin since at least the 1950s, which may be reflective of effects of hypoxia (Bridgeman et al. 2006)
    - The number of annual localized fish kills resulting from abrupt drops in DO may be used as a metric. A significant fish kill event was reported near Cleveland in 2021.
    - Dreissenids cannot survive in hypoxic water; mass mortality events may be used as an indicator of hypoxia. SUNY Buffalo State is developing image analysis methods for detecting and assessing abundance of dreissenid mussels in different Lake Erie benthoscapes (Karayatev et al. 2018, 2022).
- The number of people directly affected by hypoxic water at drinking intakes
    - Major hypoxia events may happen once or twice per year and can last up to a week or more. Cleveland Water provides water to about 1.45 million people who live in a 640-square mile service area, and can report on drinking water impairments that result from hypoxic events (Ruberg et al. 2008)

- Geochemical indicators of hypoxia
    - In oxygen-depleted water, iron and manganese in lake sediments become more soluble, potentially indicating hypoxia (Edwards et al. 2005; Smith and Matisoff 2008).
    - Molybdenum accumulation in sediments has been used as an indicator for hypoxic bottom water (Boothman and Coiro 2009).
    - Otolith trace element microchemistry can reveal individual fish exposure to hypoxic conditions (Limburg et al. 2015).
    - Greenhouse gasses such as methane and nitrous oxide are produced in reducing environments caused by hypoxia, potentially indicating hypoxia (Salk et al. 2016; Townsend-Small et al. 2016, Fernandez et al. 2020).

S**uitability for both stakeholders and the parties:**
Summit participants acknowledged that the need for hypoxia monitoring or forecasting products will differ depending on interested parties or stakeholders. Reporting and communication frequencies will also differ by organization. For example, progress reporting and condition assessments by Environment and Climate Change Canada and US EPA typically occur every three years under the GLWQA; products with higher communication frequencies such as early warning systems may be more favorable to drinking water stakeholders. The seven Great Lakes Sea Grant programs may be helpful at identifying specific reporting needs for their respective constituencies. Several potentially useful products for stakeholder communication were discussed and are listed below:

- NOAA Experimental Hypoxia Forecast Model
    - While it is easy for government agencies to use and interpret the model, it is less accessible for the general public.
- 3D animations of model outputs and maps
    - Hypoxia communication and education can be challenging because of the physical nature of hypoxia – it cannot be seen. Visual products such as maps or 3D depictions of hypoxic zones may be useful in summarizing how hypoxia has or has not changed in specific locations.
- Social media posts
    - The Cleveland Water Department has a blog that informs users of drinking water quality products.
    - Some weather forecasters are very active on social media and have large followings. They may be better equipped to communicate the hypoxia issue to a greater number of people.

Objective 2 - Data requirements and gaps for assessing hypoxic extent

Hypoxia in Lake Erie occurs at several scales. Large-scale events include the main hypoxic water mass that forms in the deeper central basin, while smaller events may occur with localized effects on habitat and water quality. While widespread hypoxia events are generally well-documented by current monitoring programs, smaller-scale events may go undetected unless they are reported by nearby observers. Hypoxic events of any scale may have detrimental impacts on both human and aquatic health and should therefore be monitored, modeled, and forecasted as accurately as possible. Table 2 (Appendix II) summarizes known modeling products related to central basin hypoxia.

Critical gaps in current monitoring programs, datasets, and models:

- There are multiple biogeochemical processes that reduce DO concentrations, making them natural drivers of hypoxia. The processes interact with each other and have varying timescales (i.e., seasonality); the relative influence of each driver on hypoxic severity remains uncertain. Examples of such drivers include sediment oxygen demand (SOD) and diagenesis, and carbon sources and fate.
    - SOD is a driver of DO depletion, but the source and timescale of the production that drives the SOD is not well understood (Edwards et al 2005).
    - Different models of SOD meet different purposes; some are explicitly linked to carbon diagenesis while others are more phenomenological and relate the process to temperature, DO, or other factors (Bowman and Delfino 1980; Snodgrass 1987; Clevinger et al. 2014).

- There are gaps in the spatial coverage of shipboard and fixed-location sampling. Contemporary Lake Erie central basin monitoring locations are shown in Figure 1. Spatial sampling gaps include:
    - Transient hypoxia, which occurs on the edges of the central/eastern basins, and in the western basin. Spatial coverage within the central basin main hypoxic mass is fairly robust. However, hypoxic conditions at the edges can differ yearly and within years. The spatial and temporal variations of hypoxic water at the margins of the main mass make it more challenging to monitor (Chamberlin et al. 2020). Initially, it was believed that hypoxia would initially impact water in the deepest area of the central basin, which is where GLNPO monitoring stations are located. It has since been discovered that hypoxia in Lake Erie often initially sets up in waters which are deep enough to sustain a thermocline but shallow enough to have a thin hypolimnion, which contains a lower mass of oxygen, thus depletes quickly (Valipour et al. 2021). The existing GLNPO program, by itself, appears to be insufficient to capture the full extent of hypoxia or short-term events.
    - The thickness and position of the hypolimnion was reported to be more dynamic than was previously recognized, as seasonality and SOD greatly affect hypolimnetic thickness. Additionally, the shape of the hypolimnion can be convex or concave at the thermocline due to physical factors such as wind conditions (Smith and Matisoff 2008; Rao et al. 2014). The depth of the thermocline across the central basin can differ by up to 10 meters; thus, the horizontal shape of the thermocline is difficult to describe based on available monitoring data. Characterizing the shape is important for understanding where the thermocline will intersect the bottom close to shore, and for calculations of the rate of hypolimnetic oxygen depletion and measures of hypoxic volume.

- There is uncertainty about the seasonality of hypoxia, especially relating to overwinter conditions that may fuel summer hypoxia (Wilhelm et al. 2014; Reavie et al. 2016). Winter diatom blooms, ice cover, ice phenology, and the timing and duration of stratification all have complex effects on hypoxia onset and severity.
- There is uncertainty as to how climate change will impact the timing, duration, and spatial characteristics of hypoxia in the central basin; changing conditions will have direct effects on all natural drivers of hypoxia (Kalcic et al. 2019).

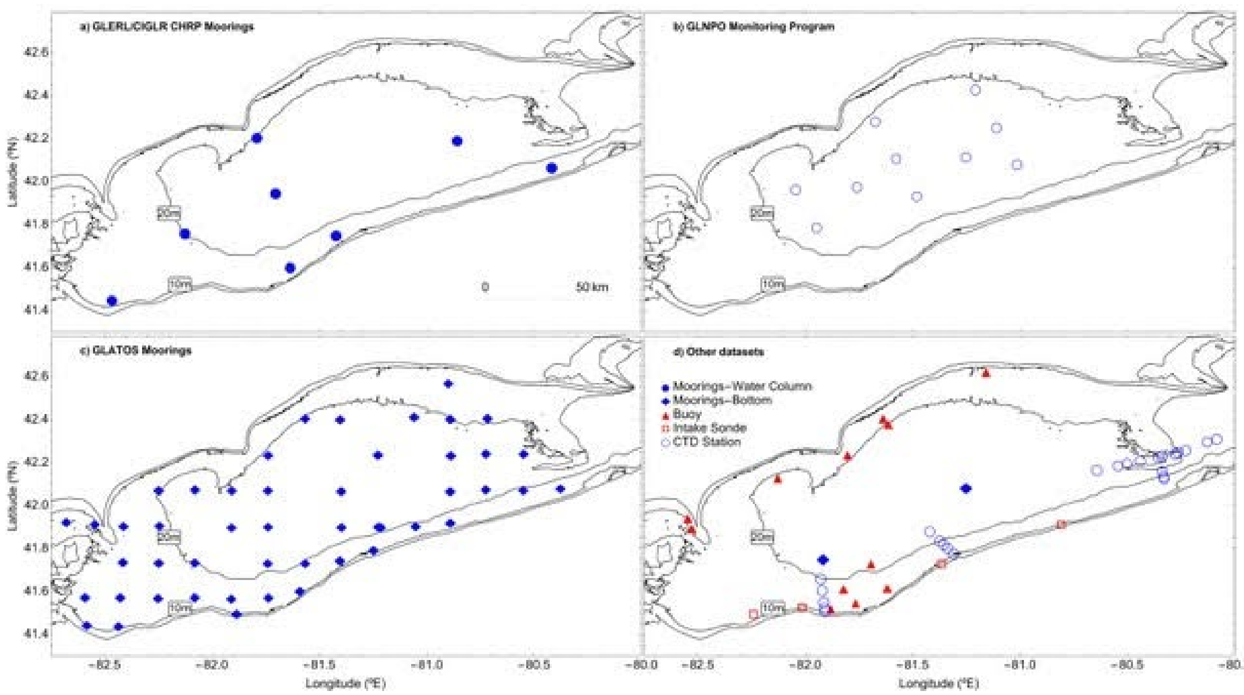

Figure 1 - NOAA Great Lakes Environmental Research Laboratory (GLERL) Coastal Hypoxia Research Program (CHRP) mooring network (a), GLNPO hypoxia network (b), USGS Great Lakes Acoustic Telemetry Observing System (GLATOS) network (c), Cleveland Water and LimnoTech, Great Lakes Observing System (GLOS), OH EPA, PA DEP, Province of Ontario Realtime Limnological System, and Real-Time Aquatic Ecosystem Observation Network (RAEON) (d). Depth contours represent 10 and 20 m. Appendix III includes an expanded descriptions of some of these programs.

Recommendations

The steering committee collated discussion notes from the three webinars, and the CIGLR summit plenaries and breakout discussions, to develop the following recommendations for monitoring, quantifying, tracking and reporting changes in hypoxia. To implement these recommendations, the committee also recommends development of a comprehensive Active Adaptive Management Framework for Lake Erie (Stow et al. 2020), to assess progress toward all commitments of the GLWQA.

Recommendation 1: Support coordinated monitoring via multiple platforms. The monitoring programs (Appendix II, Table 1) were each active through the 2021 field season (with noted disruptions to ship-based sampling programs in 2020 due to the covid-19 pandemic) and are expected to continue into the future. Funding uncertainties, future pandemics and often a lack of coordination among monitoring programs pose challenges to maintaining adequate data collection.

Specific Recommendation 1.1: Sustain four complementary observing platforms to acquire a minimum of five years of data. Our understanding of hypoxia patterns comes mainly from ship-based water column profiles of temperature and dissolved oxygen, which have been collected at a frequency of weeks - months since the 1980s. More recently deployed observing systems, using newer technologies, provide enhanced spatial and temporal resolution and a more complete picture of stratification development and DO depletion through the hypoxic season.

The attendees of the summit emphasized the value of the following types of monitoring data:

- Shipboard CTD and dissolved oxygen profiles. The GLNPO and ECCC DO survey data are particularly valuable as a long-term record, for developing models, and as a benchmark for new observing systems and approaches. Additional stations adjacent to moorings or nearshore loggers between July through October would help in comparing those platforms.
- Transects from nearshore to offshore. Transects are particularly useful for interpolating between CTD profile stations or water column moorings.
- Water-column moorings. The NOAA GLERL-CHRP moorings provide high-frequency data on thermal structure and DO, which is particularly important for quantifying the hypoxic volume and recording high frequency hydrodynamic events that are not captured by shipboard surveys.
- Bottom loggers. DO sensor arrays paired with the GLATOS acoustic telemetry network provide spatial coverage, both near and offshore, that would be important for quantifying hypoxic area and duration.
- Real-time systems may be part of the monitoring suite, but their strength is early warning or to inform field planning, which is not strictly required for quantifying the extent of hypoxia to track change over time.

Specific Recommendation 1.2: Establish and maintain a directory of datasets related to hypoxia. Many agencies and projects have generated hypoxia data for their own scientific purposes. A common directory or database of these combined monitoring data does not exist. Moreover, dissolved oxygen data often have differing dimensions (e.g. CTD casts versus moorings), which makes harmonization difficult; and that the ancillary data differ substantially according to their origin. Therefore, it would be appropriate to maintain a directory of past and ongoing hypoxia observations with links to the data and metadata. Many of those datasets (e.g. those generated by GLOS, OMECP monitoring programs) are already configured for Application Programming Interface-type retrievals that could be updated at more frequent intervals.

Specific Recommendation 1.3: Coordinate hypoxia monitoring efforts annually in advance of field years. Hypoxia monitoring should be coordinated via interagency meetings every year. The directory of hypoxia datasets should be updated annually, and include a map showing the locations for each type of observing system. Over the longer term, the Lake Erie CSMI years should serve as an opportunity to obtain enhanced data coverage and to support sampling or process studies on the drivers and consequences of central basin hypoxia.

Recommendation 2: Develop and implement alternative hypoxia metrics to assess status and trends. The summit produced no consensus metric for tracking hypoxia, however it was clear that all of the proposed metrics would benefit from increased monitoring data (Recommendation 1). Therefore, it will be necessary to assess candidate metrics using appropriate data, and evaluate their usefulness over a period of record. This effort should be accomplished via a working group, under the Nutrients Annex Subcommittee's purview, to ensure that the metrics meet reporting and tracking needs.

Specific Recommendation 2.1: Select the metrics that best serve adaptive management needs. During the summit, participants emphasized the need for specificity on what aspect of hypoxia the Nutrients Annex wishes to track, as some were interested in aggregate measures (e.g., total area, volume) and others were interested in fine-scale quantification (e.g., timing and duration of local events that affect drinking water quality). Also, because there is evidence that DO concentrations of < 4 mg/L may have negative effects on some biota, we encourage using metrics to evaluate this higher concentration in addition to the 2 mg/L level recommended by the Nutrients Annex.

The proposed metrics include:

- Hypoxic area (annual maximum and monthly estimates)
- Hypoxic volume (annual maximum and monthly estimates)
- Area-Days and Volume-Days, aggregated over the season
- Mean hypolimnetic DO during stratification
- Duration of hypoxia at specific locations
- Hypolimnetic DO depletion rate

Additional measures proposed that could be examined by the Nutrients Annex:

- Presence/absence of sensitive benthic fauna (e.g. dreissenid mussels, *Hexagenia* larvae)
- Incidence of high-visibility impacts (e.g. fish kills, drinking water advisories)

- Probabilities of transgressing designated hypoxia thresholds

Specific Recommendation 2.2: Provide design specifications for the proposed metrics. These proposed metrics illustrate the breadth of ways to represent hypoxic extent, but each requires an appropriate monitoring design to ensure adequate representation of the property captured by the metric.

Specific Recommendation 2.3: Calculate and compare alternative metrics for quantifying hypoxic extent. Participants identified this as a high priority as it would directly support the Nutrients Annex Lake Erie Adaptive Management process. A primary aim would be to summarize those metrics over the period of record and assess whether they show similar interannual patterns or reveal novel features. Approaches that explicitly quantify uncertainty will be particularly useful. For each metric it will be necessary to perform a sensitivity analysis to understand the dependence on data collection frequency and location. This evaluation will inform recommendations for future long-term monitoring updates.

Recommendation 3: Develop hypoxia reporting products for both the Nutrients Annex (Annex 4) and the public, including visualizations of patterns over time. Several participants reported the need for information products to report progress toward meeting hypoxia goals. These products would be useful for Lake Erie Adaptive Management needs under Nutrients Annex and would also support existing products including the Lakewide Management Annex (Annex 2) Lake Erie Lakewide Action and Management Plan reports (ECCC and EPA 2021), the Ohio Lake Erie Commission's Ohio Water Monitoring Summary and the Interagency Working Group on Harmful Algal Bloom and Hypoxia Research and Control Act HABHRCA Great Lakes progress reports.

Specific Recommendation 3.1: Draft visualizations of hypoxia metrics for the general public. This communication product should convey the degree to which hypoxia is changing over time by comparing the most recent year to previous years. That communication should include context and background information on the drivers of hypoxia, some of its impacts, and sources of additional information (e.g. GLOS portal, NOAA hypoxia forecast). The design could be facilitated by the Great Lakes Sea Grant programs or similar groups involved in outreach and stakeholder engagement, and the frequency of issuance (annually, every 3 years, every 5 years) would need to be determined.

Specific Recommendation 3.2: Provide hypoxia metrics for the most recent year and period of record, for use by the Nutrients Annex subcommittee. With several years of high-intensity data (Recommendation 1) and quantification and visualization of the metrics (Recommendation 2), it will be necessary for the Nutrients Annex subcommittee to make a determination on which metrics will be used to track response of the lake to nutrient loading.

Recommendation 4: Continue investigating modeling approaches to develop a better understanding of the link between loading and hypoxia. The science of Lake Erie hypoxia has progressed since its linkage to phosphorus loadings and specific phosphorus reduction targets were developed. Newer Lake Erie hypoxia modeling has highlighted the importance of atmospheric conditions and currents to hypoxic conditions, and summit participants emphasized considering what humans living in the Lake Erie basin can and cannot control with respect to hypoxia. There is a need to better understand the role nutrients and plankton biomass play in development of local and basin-wide hypoxia, particularly with respect to climatic and other abiotic drivers.

Specific Recommendation 4.1: Revisit modeling approaches used to link hypoxia to phosphorus loads and identify processes that are most uncertain and require additional investigation. The data and estimates generated through Recommendations 1-3 would provide benchmarks for the development of those models.

Specific Recommendation 4.2: Identify and quantify the sources of both water-column and sediment oxygen demand. Recent reports have indicated that, in contrast with what has been generally believed, central basin oxygen demand may originate from sources besides western basin primary production. To accurately model the link between phosphorus inputs, primary production, and oxygen demand will require studies to clarify the oxygen demand sources.

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Appendix I - Workshop Participants and Agenda with Charge Questions

Steering Committee		
Santina	Wortman	USEPA Great Lakes National Program Office
Elizabeth	Hinchey Malloy	US EPA Great Lakes National Program Office
Jeff	May	US EPA Great Lake National Program Office
Mike	McKay	University of Windsor
Craig	Stow	NOAA GLERL
Casey	Godwin	University of Michigan - CIGLR
Meeting Facilitators		
Paris	Collingsworth	IL-IN Sea Grant, facilitator
Carolyn	Foley	IL-IN Sea Grant, facilitator
Christopher	Winslow	Ohio Sea Grant, facilitator
Theo	Jass	ORISE at EPA GLNPO
Workshop Participants		
Mike	Alexander	Michigan Department of Environment, Great Lakes, Energy
George	Arhonditsis	University of Toronto
Bopi	Biddanda	Grand Valley State University
Ruth	Briland	Ohio EPA
John	Bratton	LimnoTech
Thomas	Bridgeman	University of Toledo
Lyubov	Burlakova	Buffalo State
Justin	Chaffin	The Ohio State University, Stone Lab
Ngan	Diep	Ontario Ministry of Environment and Climate Change
Mary Anne	Evans	USGS
Marjorie	Friedrichs	Virginia Institute of Marine Science
Sandra	George	Environment and Climate Change Canada
Paul	Gledhill	Ohio EPA
Jon	Hortness	USGS
Allison	Hrycik	Buffalo State
Brandon	Jarvis	US EPA, Office of Research and Development
Tom	Johengen	University of Michigan
Katelynn	Johnson	University of Windsor
Chris	Korleski	EPA GLNPO Director
Sandra	Kosek-Sills	Ohio Lake Erie Commission
Richard	Kraus	USGS
Scott	Moegling	Cleveland Water
Amy	Newbold	USEPA Gulf of Mexico Program
Euan	Reavie	University of Minnesota, Duluth
Todd	Redder	LimnoTech
Mark	Rowe	NOAA GLERL
Steve	Ruberg	NOAA GLERL
Lars	Rudstam	Cornell University
Don	Scavia	University of Michigan, retired
Al	Steinman	Grand Valley State University

Josh	Tellier	Michigan Department of Environment, Great Lakes, Energy
Reza	Valipour	Environment and Climate Change Canada
Ed	Verhamme	LimnoTech
Ram	Yerubandi	Environment and Climate Change Canada

<u>Workshop Reporting Support</u>

Erica	Doody	ORISE at EPA GLNPO
Theo	Jass	ORISE at EPA GLNPO

Assessing Hypoxia in Lake Erie

CIGLR Summit October 26, 2021

All times are Central Daylight Time

<u>Pre-Meeting Reminders</u>

All attendees received an email on Oct. 19, 2021 about the meeting that includes:
- A short survey on interest in a special issue of JGLR
- A reminder to watch recordings if you have not already seen them
- A reminder to review Monitoring and Modeling Summary Tables. Add information about how your organization uses other the resources listed, as appropriate (see columns L, M, N in each sheet).

<u>9:30 a.m. Meeting Overview and Introductions</u>

9:30 a.m. Welcome remarks - Greg Dick, CIGLR Director
9:40 a.m. Webinar presentation - Paris Collingsworth and Josh Tellier
10:00 a.m. Review purpose of the workshop
10:10 a.m. Summarize key outcomes from previous webinars on Monitoring & Modeling Data Products
10:20 a.m. Review instructions for the group for breakouts

<u>10:30-11:30 a.m. Breakout Session 1</u>

Each breakout room has the same questions and is organized by a moderator and designated note-taker. All participants can access the notes to help deposit links etc.

<u>Charge questions</u>

● What are the 3-4 current, key sources of monitoring or modeling data that are most critical to organizations who want to know the timing and extent of hypoxia in Lake Erie?
● Where are there overlapping efforts for monitoring or modeling hypoxia in Lake Erie?
● What data gaps exist for monitoring or modeling hypoxia in Lake Erie, currently?
● How can current monitoring and modeling programs be enhanced or modified to streamline data collection and sharing, and fill data gaps?
  o Spatial coverage of shipboard and fixed-location sampling
  o Temporal frequency of observations
  o Data availability and quality standards
  o How can technological advances in observing systems complement long-term monitoring and ongoing datasets?

<u>11:30 a.m. Break</u>

Please stay in the breakout room with your camera and microphone off. If you log out of Zoom, you can re-enter the main room and we will help you rejoin your breakout.

<u>12:15 to 1:45 p.m. Breakout Session 2</u>

Remain in same breakout groups, discuss question prompts and prepare a summary from both sessions.

<u>Charge questions</u>

● What is the status of hypoxia in Lake Erie, as we understand it?

- ○ Which particular locations have the greatest known impacts? Which locations have the greatest uncertainty? (can be informed by data gaps above)
    - ○ Are particular times of year worse?
    - ○ Is monitoring set up to answer this question?
- ● How do we share the information with stakeholders?
    - ○ Which communication products are most helpful, currently, and how are they disseminated (e.g., from agency to agency, from agency to particular stakeholder groups, from agency to public)?
    - ○ Could the most helpful communication products be tweaked to make them more suitable for different audiences (e.g., include both metric and imperial units; allow for an ability to zoom in on different locations; revise with a 0-10-type criterion; add in particular metrics for different groups)?
    - ○ Are there key communications products that do not currently exist but could have a major, positive impact on stakeholders' health and livelihood? Is anyone considering producing those?
- ● Could a routine assessment of hypoxia be done? Which metrics are most appropriate for the data available?
    - ○ Compare these metrics for describing hypoxia, with emphasis on potential biases, compatibility with the GLWQA Objective, and suitability for both stakeholders and the parties.
    - ○ What are the advantages and shortcomings of different metrics? (areal extent, spatial location, volume, average DO concentration, duration of hypoxic conditions, etc.)
    - ○ What are the advantages and challenges of adopting an ensemble of metrics and approaches?
    - ○ What design characteristics should be considered, e.g., transects perpendicular to shore, same stations to historic sampling, frequency of sampling events?
    - ○ How can we incorporate these metrics into communications products?
- ● What can we learn from hypoxia monitoring/modeling programs outside Lake Erie and are there examples that we should follow?

Before leaving breakout room, ensure the group has agreed upon 1-2 highlights for each of the main bullets from the morning and afternoon breakouts.

1:45 p.m. Break

2:00 p.m. Report-Out from Breakouts and General Discussion

Return to main room. Round robin sharing of highlights from each breakout. Further discussion as needed.

By 2:45 p.m.: All participants answer: What are the top 3-5 recommendations for U.S. EPA and ECCC to be able to routinely assess hypoxia? What are the top 3-5 recommendations for sharing information with stakeholders? Individuals answer this via a Google form.

Appendix II – Tables 1 and 2

Table 1. Summary of contemporary monitoring data products for Lake Erie central basin hypoxia as of the time of the summit. Note that there were a few monitoring products mentioned in the summit that are not shown here because they were outside of the Central Basin or did not include measurements of DO or temperature.

Short Product Description	**Location Descriptions**	**Parameters and Coverage (B=bottom only, M=multiple depths, P=profile)**	**Duration**	**Measurement Frequency**	**How it is used to inform management decisions**	**Data Location and Contact**
GLERL-CHRP [1]	8 moorings, 12-24 m depth	Temp and DO (M)	May-Sep, 2017-2021	10 minutes	Used to develop a model that is used for an experimental forecast from NOAA	https://www.ncei.noaa.gov/ craig.stow@noaa.gov (Craig Stow)
GLNPO DO Monitoring Program – Loggers [2]	2 moored loggers, offshore	Temp and DO (B)	Jun-Oct, 2017-2020	1 hour		Email may.jeffrey@epa.gov, data site is under development (Jeff May)
Real-Time Buoys and Sondes with Cleveland Water at GLOS	Four buoys near Cleveland, OH	Temp and DO (M)	May-Nov, 2010-2021	varies, typically hourly, Real-Time	Sensor readouts are integrated into drinking water plant SCADA to give lead time for modifying treatment	https://portal.glos.us; https://glbuoys.glos.us/leash; https://glbuoys.glos.us/leavon; https://glbuoys.glos.us/45176b; https://glbuoys.glos.us/45176; https://glbuoys.glos.us/45164; https://glbuoys.glos.us/45169; https://glbuoys.glos.us/lelorain; https://glbuoys.glos.us/lementor; (Shelby Brunner -GLOS, Scott Moegling-Cleveland Water, Ed Verhamme - LimnoTech)
USGS [3]	GLATOS locations and also the GLNPO stations	Temp and DO (B)	Summer, 2019-2021	10 minutes	Presently used to examine how fish habitat usage changes with respect to DO and temperature	Email rkraus@usgs.gov, data site is under development for sciencebase.gov (Richard Kraus)

Short Product Description	Location Descriptions	Parameters and Coverage (B=bottom only, M=multiple depths, P=profile)	Duration	Measurement Frequency	How it is used to inform management decisions	Data Location and Contact
ECCC – moorings [4]	1 deep station, some Canadian shore buoys	Temp and DO (P)	Summer, 2004-2019	Varies	Enhance and implement Lake Erie ecosystem models for adaptive management	Email: Ram.Yerubandi@ec.gc.ca (Reza Valipour/ Ram Yerubandi)
Province of Ontario Realtime Limnological System Buoys	1 central basin buoy	Temp and DO (M) plus currents and water quality	May-Nov, 2014-2021	30 minutes, Real-Time	Understand linkages between the central basin hypoxia, upwelling, cyanobacterial blooms, north shore water quality and indirectly track changes in the condition of the basin as a result of nutrient management changes or as negatively affected by climate change	http://ontario3.loboviz.com http://ontario4.loboviz.com; Email: Ngan.Diep@ontario.ca (Ngan Diep)
RAEON	1 real-time buoy	Temp (P) and DO (B) and water quality parameters	May-Oct, 2019-2021	10 mins	2 buoys are placed at the Union Water Supply System (UWSS) water intakes to inform of any Hypoxic conditions.	Email: katejohn@uwindsor.ca (Katelynn Johnson)
GLNPO DO Monitoring program – shipboard surveys [2]	10 sampling stations, offshore	Temp and DO (P)	Jun-Oct, 1983-2021	2-3 weeks	This program produces oxygen depletion rate estimates for each year from 1970 to present and might be used to track change	Email: may.jeffrey@epa.gov (Jeff May)
ECCC - Shipboard surveys	Multiple stations throughout the central basin	Temp and DO (P)	Summer, intermittent	Twice per year	Enhance and implement Lake Erie ecosystem models for adaptive management	Email: Ram.Yerubandi@ec.gc.ca (Reza Valipour/ Ram Yerubandi)

Short Product Description	Location Descriptions	Parameters and Coverage (B=bottom only, M=multiple depths, P=profile)	Duration	Measurement Frequency	How it is used to inform management decisions	Data Location and Contact
Ohio EPA transects	Four near- to offshore transects	Temp and DO (P) plus water quality parameters	Summer, 2011-2021	2-4/y	Just monitoring at this point	https://www.epa.ohio.gov/dsw/lakeerie/index#125073721-nearshore-monitoring; Email: paul.gledhill@epa.ohio.gov (Paul Gledhill)
Pennsylvania DEP transect	Transect off Erie PA	Temp and DO (P)	Summer, 2017-?			(James Grazio)
OMECP - Index Reference Stations Program	4 nearshore stations	Temp and DO (M) plus water quality parameters	Spring-Fall, 2019-2021	3-year cycle	Understand linkages between the central basin hypoxia, upwelling, cyanobacterial blooms, north shore water quality and indirectly track changes in the condition of the basin as a result of nutrient management changes or as negatively affected by climate change	https://data.ontario.ca/dataset/water-chemistry-great-lakes-nearshore-areas; Email: Ngan.Diep@ontario.ca (Ngan Diep)
OMECP - Nearshore Assessment Program	Nearshore stations	Temp and DO (P) and water quality parameters	Spring-Fall, 2013-2021	3/year	Understand linkages between the central basin hypoxia, upwelling, cyanobacterial blooms, north shore water quality and indirectly track changes in the condition of the basin as a result of nutrient management changes or as negatively affected by climate change	Email: Ngan.Diep@ontario.ca (Ngan Diep)

[1] NOAA Great Lakes Environmental Research Laboratory; Cooperative Institute for Great Lakes Research, University of Michigan (2020). Physical, chemical, and biological water quality observation data at multiple levels from an array of fixed moorings to support hypoxia research in the central basin of Lake Erie, Great Lakes region collected by National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory and the Cooperative Institute for Great Lakes Research, University of Michigan since 2017. [indicate subset used]. NOAA National Centers for Environmental Information. Dataset. https://doi.org/10.25921/qd27-bj97.

[2] U.S. EPA 2021. Lake Erie Dissolved Oxygen Monitoring Program Technical Report: Dissolved Oxygen and Temperature Profiles for the Open Waters of the Central Basin of Lake Erie during Summer/Fall of 2016. (EPA 950-R-21-004)

[3] Kraus, R. T., C. T. Knight, T. M. Farmer, A. M. Gorman, P. D. Collingsworth, G. J. Warren, P. M. Kocovsky, J. D. Conroy, and Y. Prairie. 2015. Dynamic hypoxic zones in Lake Erie compress fish habitat, altering vulnerability to fishing gears. Canadian Journal of Fisheries and Aquatic Sciences 72:797-806.

[4] Valipour, R., L. F. León, T. Howell, A. Dove, and Y. R. Rao. 2021. Episodic nearshore-offshore exchanges of hypoxic waters along the north shore of Lake Erie. Journal of Great Lakes Research 47:419-436.

Table 2. Model products related to Lake Erie central basin hypoxia as of the time of the summit. Note that not all of these models are operated currently. Some of the models listed here were run to assist in evaluating loading targets, for example, and the capacity to operate them over other timespans is unclear.

Short Description	Duration	Current / Historical	Model Description	Output Parameter Descriptions	How it is used to inform management decisions	Link and Contacts
GLERL Experimental Hypoxia Forecast [5]	May-Oct; 2016-current; nowcast/ forecast, also hindcast	Current	Coupled to FVCOM, tracks DO and reduced substance fluxes. Designed for short-term forecast of spatial patterns and upwelling events.	Temperature, DO, and reduced substances throughout the water column	Currently used by public water systems for anticipating impacts of hypoxia for treatment. Also used by fisheries managers for planning surveys.	https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/hypoxiaWarningSystem.html; Mark Rowe, NOAA GLERL. Note that this model is approaching transition to operations with NOAA's National Centers for Coastal Ocean Science
LEEM [6]	Mar-Oct; 2012-2017; hindcast	Current	3D, coupled to FVCOM with advanced aquatic ecosystem model	Water quality parameters, DO, phytoplankton, zooplankton, Cladophora, dreissenid biomass	Link tributary loads to hypoxia	Todd Redder, Limnotech
TuFLow-AED	Apr-Oct; 2013-current; hindcast	Current	3D coupled model	3D hydrodynamics, DO, Phytoplankton, cladophora		Reza Valipour
ELCOM-CAEDYM	Apr-Oct; 2008-current; hindcast	Historical	3D coupled model	3D Hydrodynamics, DO, phytoplankton groups		Reza Valipour/ Ram Yerubandi
Nine-box model [7]	Annual; 1978-2008; hindcast	Historical		basin average mean hypolimnetic DO	Included in Annex 4 ensemble and used to set targets	Ram Yerubandi

Short Description	Duration	Current / Historical	Model Description	Output Parameter Descriptions	How it is used to inform management decisions	Link and Contacts
ELCOM-CAEDYM [8]	Apr-Oct; 2005-2008; hindcast	Historical	Biophysical model relating hypoxia and eutrophication to P loads	Bottom DO and temperature, yield areal and volumetric extent	Included in Annex 4 ensemble and used to set targets	Serghei Bocaniov
Ruckinski et al 2016 1D Model [9]	1987-2008; hindcast	Historical	1-D model of hydrodynamics and eutrophication, inputs include TP loads	Hypoxic days, hypoxic area, mean hypolimnion DO	Included in Annex 4 ensemble and used to set targets	Daniel Rucinski
EcoLE [10]	1997-1998; hindcast	Historical	Biophysical model relating hypoxia and eutrophication to P loads	Hypoxia area and mean hypolimnetic DO	Included in Annex 4 ensemble and used to set targets	Hongyan Zhang
Xu et al 2021 Geospatial Interpolation [11]	Summer-Fall; 2014-2016; hindcast	Historical	Geospatial interpolation based on data from loggers	Temperature and dissolved oxygen		http://hypoxiamapping.smu.edu/hypoxia/; Paris Collingsworth and Joshua Tellier, Purdue
Habitat Quality Model	Jun-Oct; 1993-2018; hindcast	Historical	3D geospatial interpolation based on logger data, coupled with species-specific bioenergetic models	3D habitat quality (for several different species) in relation to temp and DO		Joshua Tellier

[5] Rowe, M. D., E. J. Anderson, D. Beletsky, C. A. Stow, S. D. Moegling, J. D. Chaffin, J. C. May, P. D. Collingsworth, A. Jabbari, and J. D. Ackerman. 2019. Coastal upwelling influences hypoxia spatial patterns and nearshore dynamics in Lake Erie. Journal of Geophysical Research: Oceans 124:6154-6175.

[6] LimnoTech, 2021. Development, Calibration, & Application of a Lake Erie Ecosystem Model, Final Report, prepared under contract to U.S. Army Corps of Engineers - Buffalo District, March 31, 2021, 141 p., 6 appendices.

[7] Lam, D., Schertzer, W., McCrimmon, R., Charlton, M., Millard, S., 2008. Modeling Phosphorus and Dissolved Oxygen Conditions Pre- and Post-Dreissena Arrival in Lake Erie. In: Munawar, M., Heath, R. (Editors), Checking the Pulse of Lake Erie. Aquatic Ecosystem Health and Management Society, Burlington, Ontario.

[8] Bocaniov, S. A., L. F. Leon, Y. R. Rao, D. J. Schwab, and D. Scavia. 2016. Simulating the effect of nutrient reduction on hypoxia in a large lake (Lake Erie, USA-Canada) with a three-dimensional lake model. Journal of Great Lakes Research 42:1228-1240.

[9] Rucinski, D. K., J. V. DePinto, D. Beletsky, and D. Scavia. 2016. Modeling hypoxia in the central basin of Lake Erie under potential phosphorus load reduction scenarios. Journal of Great Lakes Research 42:1206-1211.

[10] Zhang, H., L. Boegman, D. Scavia, and D. A. Culver. 2016. Spatial distributions of external and internal phosphorus loads in Lake Erie and their impacts on phytoplankton and water quality. Journal of Great Lakes Research 42:1212-1227.

[11] Xu, W., P. D. Collingsworth, R. Kraus, and B. Minsker. 2021. Spatio-temporal analysis of hypoxia in the Central Basin of Lake Erie of North America. Water Resources Research 57, doi: 10.1029/2020wr027676

Appendix III - Near-term planned monitoring and data collection (new and continued)

EPA GLNPO Lake Erie DO Monitoring Program
EPA, with field crew assistance from the USGS Lake Erie Biological Field Station, annually monitors DO concentrations at 10 stations in the central basin of Lake Erie throughout the stratified season. This program continues a time series that was initiated in 1983 to monitor and track hypoxic conditions in response to the phosphorus reduction programs implemented by the 1978 GLWQA. Water column profiles of oxygen and temperature are collected approximately every 3 weeks to determine the duration of hypoxia/anoxia at these locations. Since 2017, two DO loggers are also deployed 1m off the bottom at 2 of the long-term monitoring stations to monitor near-bottom temporal variation in oxygen concentrations during the sampling season. In 2022, EPA, USGS and Buffalo State College will collect surface videos at each station throughout the season to investigate infaunal response/benthoscape delineation over a seasonal cycle of hypoxia in Lake Erie's central basin.

Oxygen Mooring Observation Network (OxyMoorON)- Water Column Moorings (NOAA GLERL)
The OxyMoorON project (formerly CHRP) will collect temperature and DO concentration data in Lake Erie to assess hypolimnetic DO status and trends. Guided by research conducted by GLERL from 2017-2020 with funding from the NOAA Coastal Hypoxia Research Program (CHRP), in 2022 and 2023 NOAA plans to deploy a network of 10 moorings, at locations throughout the central basin, to measure hypoxia development and coverage. Each mooring will be outfitted with 6-8 temperature and DO sensors to monitor changes throughout the water column at 20-minute intervals from May through September.

Great Lakes Acoustic Telemetry Observation System (GLATOS)- Bottom Moorings (USGS)
In conjunction with NOAA's OxyMoorON project, USGS will leverage the Great Lakes Acoustic Telemetry Observation System (GLATOS) in Lake Erie by equipping stations with temperature and DO sensors. GLATOS is a network of passive fish tracking receivers used to support the spatial management and conservation of native and non-native species. These receivers are tended on an annual or semiannual basis and can be equipped with autonomous data loggers to provide water quality information from demersal habitats. USGS has previously accomplished this work on a smaller scale in 2020 and 2021 as documented in the public data release on Sciencebase (2020 data release: https://doi.org/10.5066/P9J9AV9V; 2021 data release: https://doi.org/10.5066/P953FO3I). Ontario, Canada, also deployed data loggers in the eastern basin to contribute to the effort. These data provide the ability to retrospectively analyze temperature and DO for ground-truthing of the hypoxia forecast and for analyses to understand the dynamics of hypoxia in the hypolimnion. For this project, the USGS will augment the current configuration with the deployment of 39 additional DO and temperature data loggers on acoustic telemetry receivers, and through the addition of 4 acoustic telemetry receivers with integrated environmental sensors on selected NOAA observation buoys.

Great Lakes Observing System (GLOS)
GLOS and RAEON now use Autonomous Underwater Vehicles, or gliders to collect high resolution real-time physico-chemical data. The gliders can monitor areas that are difficult to access, and they are capable of covering large areas. Preliminary deployments of buoyancy gliders to document central basin hypoxia have produced encouraging results, but also challenges in terms of operating in a relatively shallow water column, collecting data from within a thin hypolimnion, and fouling by precipitated metals.

Illinois-Indiana Sea Grant (IISG) algorithms and data visualizations
Working with federal partners at EPA, NOAA and USGS, IISG has been developing programs to automate the geospatial analysis and visualization of temperature and DO logger data. Building off a recently published Bayesian geospatial model (Xu et al. 2021), IISG is currently working with data visualization experts at Purdue University to develop a program that will interpolate high-resolution logger data (e.g. data streams from the OXYMORON Moorings described above) into a 3-dimensional visualization product, with the ultimate goal of providing federal partners with an online tool that will help quantify, visualize and report on hypoxia endpoints in Lake Erie.