**Development of a Real-time, Continuous Nutrient Monitoring Network for Western Lake Erie to Address Management of HABS and Hypoxia**

**A. Nutrient Issue**:

Since the 1990s, Lake Erie has been experiencing increased water quality impairment, resulting in significant impairment of the use and enjoyment of this tremendous natural resource. Three key water quality issues have developed, all of which are related to the excessive supply of nutrients into the lake. These impairments include: (1) algal toxins for harmful cyanobacterial blooms (HABS), (2) the size and duration of the hypoxic hypolimnion in the central basin, and (3) the prevalence of *Cladophora* fouling beaches in the eastern basin.In 2011, concentrations of the algal toxin microcystin in the open waters of the Western Basin of Lake Erie (WLE) were 50 times higher than the World Health Organization limit for safe body contact, and 1,200 times higher than the limit for safe drinking water.  In August 2014, the presence of algal toxins in WLE forced the closure of the Toledo, Ohio drinking water treatment plant, affecting water supply to nearly 500,000 people and causing an estimated economic impact from this single event of over 300 million dollars. Since the early 2000s, the hypoxic (low-oxygen) area in the Central Basin of Lake Erie has increased to an average of 4,500 km2, and reaching over 10,000 km2 in more severe years. Hypoxic conditions eliminate benthic food supplies and optimal habitat which subsequently affect the growth and survival of fish species. In 2012, hypoxic conditions were responsible for tens of thousands of dead fish washing up on a 40 km stretch of Lake Erie shoreline. Moreover, hypoxic water poses a significant impact and cost to over a dozen drinking water plants which supply drinking water to over 10 million people. Lastly, *Cladophora,* a filamentous green algae that grows on hard substrates, has been reaching increased nuisance levels since 2000 leading to beach fouling, undesirable odors from decomposing *Cladophora,* clogged industrial intakes and degraded fish habitat.

To combat these growing impairments to ecosystem health and services, the Governments of Canada and the United States formalized revised binational phosphorus reduction targets for Lake Erie under the 2012 Great Lakes Water Quality Agreement (GLWQA). The GLWQA Nutrients Annex Subcommittee developed final target loading recommendations that include: (1) a 40 percent reduction in spring total and soluble reactive phosphorus loads from the Maumee River (U.S.), and (2) a 40 percent reduction in total phosphorus entering the Western Basin and Central Basin of Lake Erie – from the United States and from Canada – to achieve 6000 MT Central Basin load. The GLWQA recommendations were based on meeting established guidelines for what constitutes a healthy and productive ecosystem, including:

1. Minimize the extent of hypoxic zones associated with excessive phosphorus
2. Maintain the levels of algae below the level constituting a nuisance condition
3. Maintain algal species consistent with healthy aquatic ecosystems
4. Maintain cyanobacteria at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health.

Modeling showed that spring loading of phosphorus from the Maumee River is the determining factor controlling the production of cyanobacteria in the open waters of WLE. The GLWQA Nutrients Annex Subcommittee found that to achieve 2012 conditions in the Western Basin in nine out of 10 years, there should be a reduction of 40 percent in spring loads of both total and dissolved phosphorus from the Maumee River, equating to a targeted spring load of 860 metric tons per year of total phosphorus and 186 metric tons per year of soluble reactive phosphorus. No efforts were made establish target loads for nitrogen; however, recent research has emphasized an increasingly important role of nitrogen in regulating both biomass production and toxicity levels within the Lake Erie cyanobacterial community.  The GLWQA Nutrients Annex Subcommittee focused its recommendations on phosphorus loading reductions, not on phosphorus concentrations, in part due to finding that concentrations in the nearshore and open waters vary considerably over space and time, making them very difficult to track in a meaningful way. As a consequence, the GLWQA Nutrients Annex Subcommittee recommended that specific phosphorus concentration objectives not be established for Lake Erie at this time. However, the GLWQA Nutrients Annex Subcommittee estimated that the phosphorus concentrations expected to result from the recommended phosphorus load reductions should reach 12 and 6 µgP/L in the western and central basins, respectively. Interim GLWQA objective target concentrations were 15 and 10 µg/L.

**To determine progress toward meeting the new phosphorus loading targets and verifying the response in the lake, active surveillance of ambient concentrations within the lake is essential. Phosphorus concentrations can be highly variable in time and space, obscuring long-term trends if monitoring frequency is insufficient to discern signal from noise. Deployment of continuous *in situ* monitoring sensors to provide nearly continuous data would be a critical component of the Adaptive Management planning strategy that is currently under development by the Annex 4 (nutrients) subcommittee. We focus on the western basin of Lake Erie since 90% of the lake’s total loading occurs to this basin.**

The proposed Action Plan will take advantage of six years of initial development of a real-time continuous water quality monitoring network for WLE, and over $300K in annual funding support through the EPA Great Lakes Restoration Initiative (GLRI). The Nutrient Sensor Challenge (NSC) provides us with the opportunity to improve upon the existing system reliability, efficiency, and cost of operation. The proposed NOC nitrate and phosphate analyzers are approximately one-half the purchase price of the current nutrient sensor technologies that we are using on the buoy system. Moreover, the operational cost of each deployment will be approximately one-tenth the current cost due to the ability of the end user to make their own reagents versus having to buy proprietary pre-made cartridges. Based on performance during the initial Alliance for Coastal Technologies Nutrient Sensor Verification we also believe that analytical capabilities of the NOC analyzers will result in improved reliability, range of detection, and reduced service cycles. Lastly, the NOC analyzers are able to collect all generated waste internally, and will eliminate our need to maintain external, add-on containment systems, which has proven difficult in the harsh Lake environment.

**B. Team:**

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Dr. Johengen is a Research Scientist with CIGLR-University of Michigan and will serve as the project lead and coordinate all activities of the participating parties. He has over 25 years of experience at nutrient monitoring in the Great Lakes and related research experience on HABS and Hypoxia. He has been a co-PI on the development of the current WLE monitoring network. He is the Chief Scientist for the Alliance for Coastal Technologies and led the initial nutrient sensor verification.

Steve Ruberg is the head of the Observing Systems and Advanced Technologies branch at NOAA-GLERL. He co-led the development of the Lake Erie monitoring network and leads GLERL’s Realtime Coastal Observing Network. He will oversee any required federal support, including vessel support, IT personnel to ensure the maintenance and operation of the network, and oversee funding support provided by the Great Lakes Restoration Initiative.

Russ Miller is a systems engineer with CIGLR-University of Michigan. He is the chief engineer responsible for maintaining the buoy systems and data communications. He will participate in monthly servicing of the monitoring network and ensure continuity of the data streams to NOAA-GLERL and GLOS networks. He will work with NOC to build out the required data processing to incorporate the new sensors into the existing network. He will help implement real-time QA/QC checks on all sensor systems.

Craig Stow is a physical scientist at NOAA-GLERL with over 25 years of experience in pollutant behavior in aquatic ecosystems, ecological modeling and forecasting, uncertainty analysis, and Bayesian inference. He serves as a representative to the GLWQA Annex 4 Nutrient subcommittee and can support statistical analysis of in-lake and tributary loading nutrient data for the project, and facilitate communication pathways for results to binational representatives of the IJC and GLWQA advisory boards.

Hongyan Zhang is a biophysical modeler with CIGLR-University of Michigan. She has been developing a mass balance biophysical model coupling FVCOM hydrodynamics with nutrients, phytoplankton, and zooplankton for Lake Erie to help forecast ecosystem responses to nutrient reduction management strategies. She will use the continuous nutrient monitoring data to investigate the dominant biophysical processes relevant to the nutrient and HAB dynamics at fine spatial-temporal scales, conduct model skill assessment, and conduct data assimilation in short-term event based simulations of HAB response to sudden nutrient inputs.

Kelli Paige is the Executive Director of the GLOS IOOS Regional Association. She has over 10 years of experience working through GLOS on serving data and data products to the research and management communities within the Great Lakes. She will support the integration of the real-time monitoring data into the GLOS data portal and facilitate data archiving and dissemination to a broad range of researchers and managers.

Alex Beaton is a research engineer and technologist based at National Oceanography Centre (NOC), Southampton, UK. He has been heavily involved in the development of NOC’s lab-on-chip sensor platform for the last 8 years. During this time he has planned and conducted several sensor deployments in a diverse range of environments. He will lead the delivery of sensors from NOC, work with CIGLR engineers to interface the sensors with the buoy infrastructure and provide support for deployment and maintenance of the sensors.

Allison Schaap is a research engineer at NOC with 8 years’ experience developing environmental sensors using microfluidic technology. She will facilitate delivery of the NOC sensors, provide protocols for deployment, and offer support for maintenance and deployment.

**C. Current Monitoring:**

Currently, NOAA-GLERL and CIGLR operate a network of four continuous monitoring buoys in Western Lake Erie (WLE) under funding support of the GLRI. Buoys are deployed from May through October and serviced on an approximate monthly basis. Real-time data are served to a NOAA-GLERL data portal and passed by FTP to the GLOS data portal. (<https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/>) (<http://habs.glos.us>).

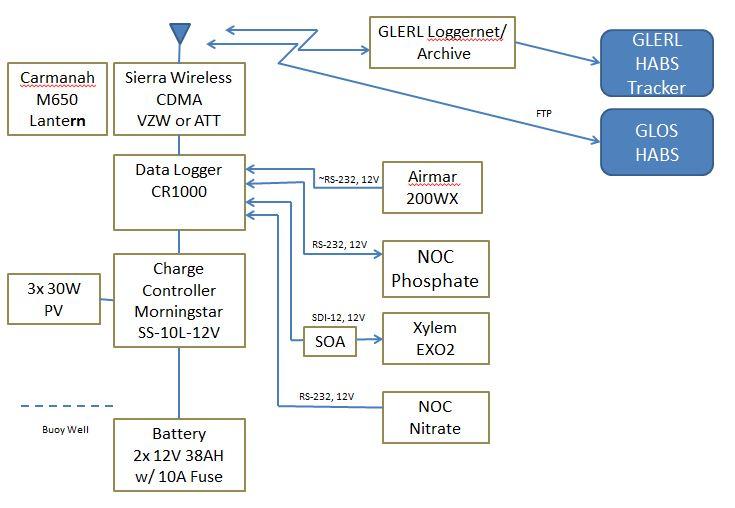
Additionally, GLERL and CIGLR operate a weekly vessel-based monitoring program in WLE biweekly from May to June, and weekly from July to mid-October. The monitoring program generates complete water quality information on nutrients, HABs, and toxin levels. The laboratory data provides independent ground-truthing of in-situ nutrient analyzers and other multi-parameter sondes.

**D. Sensors and monitoring:**

* **Two NOC Phosphate analyzers and two NOC Nitrate analyzers** will be placed on existing buoys at WE2 and WE4. The sensors are miniaturized, wet chemical analyzers, utilizing lab-on-chip technology. Each sensor with integrated reagent packs (total max height: 600 mm, total diameter: 200 mm) will be mounted to the buoys via custom removable clamps.
* **Power** will be supplied via a solar-charged battery system on the buoy. Each sensor requires an average of 1.8 W (Phosphate) and 1 W (Nitrate) when conducting half-hourly measurements.
* **4-6 week service interval:** The sensors will be deployed with cartridge-based reagent packs which will contain enough reagent volume for 6-weeks of half-hourly measurements. Reagents packs can be replaced in the field when visiting the buoys for maintenance. Inlet filters on the sensors will also be changed as part of the 6-weekly service routine. The sensors themselves will remain on the buoys for the full deployment period. Service may occur every four weeks if mussel fouling becomes heavy.
* **On-board standards and calibration check with each sample.** Each sensor will be deployed with onboard calibration standards. Each individual sensor measurement will be accompanied by a measurement of one of these onboard standards, thus eliminating issues associated with sensor drift. A pre-deployment bench-top calibration check will be conducted at 4 nutrient levels to assess response linearity and detection range. Calibration standards will be independently confirmed using standard automated methods on a Seal AA3.
* **Comparative field grab sampling program**: bi-weekly sampling will be conducted in May and June, increasing to weekly from July to October as part of existing NOAA-GLERL and CIGLR HABS monitoring program.
* **Data telemetered, near-realtime to GLERL HABS website:** NOC Phosphate and Nitrate sensors will output live timestamped concentration data via RS232, which will be telemetered via buoy cellular data modems to GLERL for archiving and web display and passed by FTP to the GLOS data portal. In addition, data will be stored on each individual sensor unit.

**E. Data:**

Standard sensor interfaces (RS232) are used to integrate NOC Phosphate and Nitrate sensors into each buoy system. In addition to the nutrient sensors, the buoy operates a meteorological package and a multi-parameter EXO2 sonde which generates water quality data on algal biomass, pH, DO, CDOM, turbidity, conductivity and temperature. A GLERL Linux processor retrieves data hourly from buoys using Loggernet and archives data securely in the lab. Real-time data plots are created from a PostgreSQL database server running at GLERL. Data are transferred to the GLOS HABs Data portal by FTP. The data are also stored on individual buoys (see system configuration below).



2. QA/QC:

We are in the process of trying to implement IOOS QARTOD QC tests with PostgreSQL on a real-time basis. In addition the following protocols will be established:

* **On-board standard validation:** The NOC Nitrate and Phosphate sensors are wet chemical analyzers that are routinely deployed with onboard calibration standards. Every sensor measurement is accompanied by a measurement of an onboard standard, meaning that sensor drift is corrected automatically throughout the deployment. The accuracy of the sensor is dependent on the accuracy and stability of the onboard standards. Reagent and standard packs will be changed every 6 weeks when the buoys are visited for maintenance, and subsamples of the onboard standards will be collected both before and after the deployment of each reagent/standard pack. These subsamples will be analyzed using a Seal AA3, allowing us to monitor accuracy of standards and monitor any standard drift during the deployment (considered highly unlikely during a 6-week period, as standards are preserved by spiking with chloroform).
* **Weekly (and initially bi-weekly) nutrient sampling** at the buoy locations will be conducted in order to quality-check the sensor measurements. Samples will be filtered (0.2 µm) on site and frozen prior to analysis (Seal Analytical AA3) using standard (EPA method citations) automated wet chemistry methods.
* Sensor data will be additionally quality checked by **analyzing the precision of the onboard standard** **measurements** after each deployment. This data is not part of the telemetered data packet, but will be downloaded from the sensors during 6-weekly maintenance, and will provide an indication of sensor precision.

3. Data Sharing:

The nutrient data generated from this monitoring network will be deposited with the digital repository of GLOS to ensure that the research and management communities have long-term access to the data beyond the end of the project. The integrated data management plan proposed leverages capabilities of GLOS and its contract staff. GLOS will make the research data from this project available to the broader scientific research community by automated download or upon request. Preliminary research results may also be presented at scientific meetings over the course of the project, and shared with the GLWQA Nutrient Subcommittee, technical advisors to the IJC, and NOAA program managers. The research data from this project will be supplied to GLOS or other appropriate repositories (e.g., NOAA National Centers for Environmental Information) before the end of the project so that any issues surrounding the usability of the data can be resolved with project team leads. Given the importance of this project to decisions that drinking water quality and ecosystem health, every effort will be made to disseminate results as quickly and effectively as possible, including through educational outreach and media venues such as the annual seasonal HABs forecast media event for Lake Erie and at meetings of the Annex 4 nutrient subcommittee. The GLOS HABs data server is Open Geospatial compliant.

Additionally, the Phosphate and Nitrogen data will be publicly observable through the GLERL HAB HABs and Hypoxia real-time monitoring database. For preservation, data will be stored in accordance with prevailing standards and practice. A master copy of each digital file (i.e., research data files, documentation, and other related files) will be placed in Archival Storage, with several copies stored with partner organizations at designated locations and synchronized with the master, as appropriate.

4. Metadata:

NOC Nitrate and Phosphate sensor data files have a header containing the following information:

* Sensor serial number
* Firmware version
* Time and date of sensor deployment
* Onboard data processing configuration
* Concentration of onboard standard

Additional metadata will include results of the analysis of onboard standards (before and after deployment) and quality flags for each measurement.

Project staff at GLOS, supported by LimnoTech metadata experts, will create substantive metadata in compliance with the most relevant standards for each data type. The XML standard provides for the tagging of content, which facilitates preservation and enables flexibility in display. These types of metadata will be produced and archived:

* *Study-Level Metadata Record*. A summary record will be created for inclusion in searchable online catalogs. This record will be indexed with common keyword thesaurus terms to enhance data discovery.
* *Data Citation with Digital Object Identifier (DOI)*. A standard citation will be provided to facilitate attribution. The DOI provides permanent identification for the data and ensures that they will always be found at the URL specified.
* *Variable-Level Documentation*. Where appropriate, data will be tagged with variable-level information in correct formats for inclusion in databases, which allow users to identify relevant variables and studies of interest.
* *Technical Documentation*. The variable-level files described above will serve as the foundation for the technical documentation that will accompany field/lab data and model outputs.
* *Related Publications*. Publications based on the data will be shared with archives as they become available to provide two-way linkages between data and publications.

**F. Analytics and Interpretation:**

To test the quality of the continuous in situ nutrient data it will be analyzed against discrete reference samples collected during our weekly monitoring program to assess accuracy, response range, and stability. We will conduct additional analysis of percent completion of expected data to assess instrument performance reliability. Any operational improvements or required maintenance or modifications of system components will be documented and reviewed by the project team at the end of the deployment period.

The acquired data will be used in conjunction with daily tributary input data, collected by Heidelberg University, in several modeling/analytical approaches. These combined data will enable us to use a mass-balance biophysical model to investigate how much riverine nutrient loads can directly affect the nutrient concentrations in the lake water column and evaluate what other major processes are affecting nutrient concentrations. The continuous nutrient monitoring data will support model skill assessment and verification, and support event-based model forecasts to explore how HABs may respond to sudden nutrient inputs resulting from river pulses or internal resuspension events. These processes will have a critical impact in the overall time-response of the lake ecosystem to management based nutrient load reductions within the watershed. We will also use these data to help discern seasonal and annual water quality trends and evaluate alternative causal pathways in response to changes in nutrient inputs that occur as a result of nutrient load reductions. We will use approaches including Bayesian networks and dynamic linear models, which facilitate uncertainty quantification, to rigorously differentiate signal from noise among observations that are likely to exhibit high spatiotemporal variance.

**G. Communication and Use:**

Developed by the Great Lakes Observing System (GLOS), the HABs Data Portal provides timely and optimized access to critical monitoring data to help inform management decisions that are affected by the presence of HABs, as well as making this information available to the general public. The HABs Portal serves data from a variety of data providers including federal government, local water treatment utility, and university monitoring programs. The HABs Portal data currently include turbidity, chlorophyll, water temperature, dissolved oxygen, pH, etc. but no nutrient data. The data and documentation from the proposed monitoring network will enrich the dataset, and will be submitted to repositories or end users in recommended formats, including ASCII, tab-delimited or space-delimited (for use with Excel), or common geospatial and animation formats. Documentation will be provided as PDF.

Data and data analysis results from the project will be shared with the GLWQA Nutrient Subcommittee, technical advisors to the IJC, and NOAA program managers. This information can improve management decisions in two areas: 1) Often high phosphorus concentration in the water will be followed by high algal biomass, thus during HAB season, in-situ real time measurement of phosphorus concentration is of timely importance for short-term predictions of changes in HAB abundance. Current short-term forecast of HAB treats algal cells as non-living particles, HAB distribution over short period of time highly depends on physical water movement. Thus, the real time phosphorus concentration may serve as an indicator for HAB biomass changes given the positive correlation between phosphorus concentration and algal biomass in Lake Erie. In addition, we will seek opportunity to show the data on Lake Erie Harmful Algal Blooms Bulletin (<https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/bulletin.html>), as an additional HAB indicator. Lake Erie Harmful Algal Blooms Bulletin that provides bi-weekly forecasts for HABs in Lake Erie and has been widely used by stakeholders and lake managers. 2) Real-time phosphorus concentrations also provide data to understand and assess the effectiveness of nutrient reduction programs occurring throughout the watershed.