Draft Technical Approach for Lake Erie Phosphorus Load-Response Modeling

Submitted to the Science Advisory Board

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1. **PURPOSE AND BACKGROUND**

The Environmental Protection Agency (EPA) Region 5 is co-leading a binational workgroup to develop and implement the Nutrients Annex ("Annex 4") of the 2012 Great Lakes Water Quality Agreement (GLWQA) in accordance with Article 3(b) of the GLWQA. Under Annex 4, the U.S. and Canada (herein referred to as "the Parties") are charged with establishing binational Substance Objectives for phosphorus concentrations, loading targets and allocations for the nearshore and offshore waters of Lake Erie by February 2016. While the Annex applies to all Great Lakes, only Lake Erie has time-bounded commitments, reflecting the Parties' commitment and understanding of the need for prompt action to combat the algae issue there.

Lake Ecosystem Objectives

Pursuant to Article 3(1)(b)(i), the Parties adopted the following Lake Ecosystem Objectives related to nutrients:
1. minimize the extent of hypoxic zones in the Waters of the Great Lakes associated with excessive phosphorus loading, with particular emphasis on Lake Erie;
2. maintain the levels of algal biomass below the level constituting a nuisance condition;
3. maintain algal species consistent with healthy aquatic ecosystems in the nearshore Waters of the Great Lakes;
4. maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the Waters of the Great Lakes;
5. maintain an oligotrophic state, relative algal biomass, and algal species consistent with healthy aquatic ecosystems, in the open waters of Lakes Superior, Michigan, Huron and Ontario; and
6. maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

Substance Objectives and Loading Targets

To achieve the above Lake Ecosystem Objectives, in accordance with Article 3(1)(b)(ii), the Parties are to establish Substance Objectives for phosphorus concentrations for the open waters and nearshore areas of each Great Lake. To achieve these Substance Objectives for phosphorus concentrations, the Parties shall in turn, develop phosphorus loading targets and allocations for each Party for each Great Lake. The 2012 Amendment of the GLWQA carried forward the following Substance Objectives for Total Phosphorus Concentration and Phosphorus Loading Targets to be used on an interim basis for the open Waters of the Great Lakes:

Interim Substance Objectives for Total Phosphorus Concentration in Open Waters (ug/l) (as represented by Spring means)	
Lake Superior	5
Lake Huron	5
Lake Michigan	7
Lake Erie (western basin)	15
Lake Erie (central basin)	10
Lake Erie (eastern basin)	10
Lake Ontario	10

Interim Phosphorus Load Targets (Metric Tonnes Total P Per Year)	
Lake Superior	3400
Lake Michigan	5600
Main Lake Huron	2800
Georgian Bay	600
North Channel	520
Saginaw Bay	440
Lake Erie	11000
Lake Ontario	7000

In summary, the charge to establish phosphorus concentrations and loading targets under the amended GLWQA is two-fold:

    1. for the open Waters of the Great Lakes:
        (a) review the interim Substance Objectives for phosphorus concentrations for each Great Lake to assess adequacy for the purpose of meeting Lake Ecosystem Objectives, and revise as necessary;
        (b) review and update the phosphorus loading targets for each Great Lake; and

(c) determine appropriate phosphorus loading allocations, apportioned by country, necessary to achieve Substance Objectives for phosphorus concentrations for each Great Lake;

2. for the nearshore Waters of the Great Lakes:
(a) develop Substance Objectives for phosphorus concentrations for nearshore waters, including embayments and tributary discharge for each Great Lake; and
(b) establish load reduction targets for priority watersheds that have a significant localized impact on the Waters of the Great Lakes.

The Parties further committed to, by 2018, develop a binational phosphorus reduction strategy and domestic action plans designed to meet the nearshore and open water phosphorus objectives and loading targets for Lake Erie, and subsequently track implementation of the strategies and action plans, and report progress every three years. Whereas under the prior GLWQA the phosphorus objectives and targets remained static, the phosphorus objectives and targets established under Annex 4 may need to be revisited periodically. Ongoing monitoring, evaluation and adaptive management will be critical to track the changes in phosphorus concentrations and loads, in addition to other drivers like hydrology and climate, and the ecological response in the lake.

Approach to Develop Phosphorus Concentrations and Loading Targets

A binational Sub-Committee with representatives from the Great Lakes Executive Committee (GLEC) member organizations at the federal, state/provincial and municipal levels was formed to lead implementation of Annex 4 in 2013. The Annex 4 Sub-Committee established an "Objectives and Targets Development Task Group" to review and update the nutrient objectives and targets needed to achieve the Lake Ecosystem Objectives for Lake Erie, and provide recommendations to the Sub-Committee based on the current state of the science. This Group has engaged scientists from federal and state water quality programs as well as several subject matter experts from academic and other non-government organizations who bring expertise in Lake Erie ecosystem science and modeling, to develop the approach described herein.

During the late 1970s, several eutrophication models were employed to arrive at the 1978 Great Lakes Water Quality Agreement Annex 3 phosphorus concentrations and loading targets for the open waters of the Great Lakes (currently the interim targets in the 2012 GLWQA). The models ranged from quite simple empirical relationships to kinetically complex, process-oriented models, in order of increasing complexity: Vollenweider's empirical total phosphorus (TP) model (all lakes), Chapra's semi-empirical model (all lakes), Thomann's Lake 1 process model (Lake Ontario and Lake Huron), DiToro's process model (Lake Erie), and Bierman's process model (Saginaw Bay). Results of these model applications were documented in the International Joint Commission's Task Group III report (Vallentyne and Thomas, 1978) and in Bierman (1980). During the mid-1980s, an assessment of several models confirmed they had established a good relationship between total phosphorus loading to a lake/basin/embayment and its system-wide average TP and chlorophyll (Chl-a) concentration.

In 2006, in support to a binational review of the Great Lakes Water Quality Agreement, a committee of modelers conducted an examination of data and models used to support the phosphorus target loads relative to the current status of the Lakes. This group found that the models used previously were no longer sufficient to capture the nearshore eutrophication being observed, because of the need for much finer spatial resolution, and because they did not capture the impacts of ecosystem structure and function changes (e.g., Dreissenid impacts) relative to phosphorus processing and eutrophication responses in the lakes (DePinto et al., 2006). Since then, a concerted research, monitoring, and model enhancement effort has been underway to improve upon eutrophication models in Lake Erie. To assist the Parties in developing and applying an approach for establishing new targets under the 2012 GLWQA, Limnotech under contract to Environment Canada convened an Expert Advisory Group to propose an updated approach in light of the new research and modeling in the Lake. Many recommendations from this group were ultimately adopted by the Annex 4 Objectives and Targets Development Task Group and are reflected in the approach described below.

The general approach for establishing new/revised Substance Objectives and loading targets for Lake Erie is as follows:
      1) establish eutrophication response indicators and metrics related to the nutrient Lake Ecosystem Objectives (LEOs);
      2) use multiple models to compute appropriate load-response relationships and attribute these to the eutrophication response indicators of concern;
      3) synthesize and interpret the results of the ensemble of models to derive phosphorus concentrations and loading targets needed to meet the nutrient LEOs, taking into account the bioavailability of various forms of phosphorous, related productivity, seasonality, fisheries productivity requirements, climate change, invasive species and other factors, such as downstream impacts, as necessary;
      4) apply an adaptive management approach in which the phosphorus concentrations and loading targets are revisited periodically.

Prior to applying the models, a common Lake Erie data set will be defined so all models have consistent input data for their analyses (e.g., source of key input variables, time period of calibration and validation periods). Then load alterations that might be analyzed in producing load-response curves would use all of the same inputs but simply adjust the concentration/load of phosphorus in the hydrologic inputs to the system.

Eutrophication Response Indicators
The Annex 4 Objectives and Targets Development Task Group identified the following four Eutrophication Response Indicators (ERIs) of concern for Lake Erie, along with metrics used to model and track them. This involves defining the metric in terms of how it is measured and what spatial and temporal scale will be used.

(1) Overall phytoplankton biomass as represented by chlorophyll a -
- Basin-specific, summer (June-August) average chlorophyll concentration

This is a traditional indicator of lake trophic status (i.e., oligotrophic, mesotrophic, eutrophic).

  (2) Cyanobacteria blooms (including Microcystis sp.) in the Western Basin –
   • Maximum basin-wide cyanobacteria biomass (mass dry weight)
   • Summer total basin-wide cyanobacteria biomass (mass dry weight integrated over summer bloom period)

The first metric gives an indication of the worst condition relative to harmful algal blooms (HAB)s in the Western Basin, while the second factors in the cumulative effects of multiple drivers (loads, hydrology, wind, temperature, etc.) in producing a season-long cumulative production of HABs. The length of the "summer bloom period" referred to in this metric can vary from one scenario to another.

  (3) Hypoxia in hypolimnion of the Central Basin –
   • Number of hypoxic days
   • Average areal extent during summer
   • Average hypolimnion DO concentration during stratified lake conditions

All three of these metrics are quantitatively correlated based on Central Basin monitoring and analysis, but they are different manifestations of the problem. Each has a bearing on the assessment of the impact on the ecosystem (especially fish communities), and on the relative impact of physical conditions and nutrient-algal growth conditions on the indicator.

  (4) *Cladophora* in the nearshore areas of the Eastern Basin –
   • Stored P Content

While beach fouling by sloughed *Cladophora* is arguably the most important metric for *nuisance algae*, there is neither an acceptable monitoring program to measure and report progress, nor a scientifically credible model to relate it to nutrient loads and conditions. There are models that can relate *Cladophora* growth to ambient DRP concentration and models that can estimate nearshore DRP as a function of loads and biophysical dynamics. Linking these models could allow researchers and water quality managers to then relate loads to *Cladophora* growth, but the accumulation of errors across models minimizes the utility as a predictor. Instead, these models will explore the relative impacts of loads recommended for other eutrophication response indicators on *Cladophora* growth potential. DRP will be used as an input to the response curve model, and stored P content as the response measure of *Cladophora* biomass accumulation/growth.

Preliminary List of Models to be Applied
The Annex 4 Objectives and Targets Development Task Group identified a preliminary list of models capable of addressing each of these indicators (Table 1). The ensemble of models proposed to be applied have all been developed to address the current Lake Erie ecosystem structure and function, including the potential to address both nearshore and offshore conditions. The models also represent a range of complexities and assumptions. Each of the proposed

models will be assessed using a set of evaluation criteria to identify the final set of models to be applied. Note that the EPA does not itself own or operate models suitable for this undertaking, and none of the proposed models are currently in the public domain. Nearly all of the proposed models are maintained by individuals at research institutions. Hence, EPA sought assistance from a third-party contractor to coordinate with the various model operators as required to execute the ensemble modeling project, and ensure that the project is executed in a manner consistent with applicable EPA requirements and with generally accepted and approved quality assurance objectives.

Table 1. Models considered for ensemble modeling effort, organized according to capability to address selected ecosystem response indicators.

Model	Response Indicators			
	Overall phytoplankton biomass	**Western basin cyanobacterial blooms**	**Central basin hypoxia**	**Eastern basin Cladophora (nearshore)**
Chapra (TP mass balance model)	X		X	
DePinto (WLEEM 3D linked hydro – sed. transport – advanced eutrophication model)	X (Western)	X	X (provide organic matter load)	
Leon, Yerubandi, & Bocaniov (ELCOM-CAEDYM 3D whole lake hydrodynamic/WQ)	X	X	X	X (boundary conditions)
Zhang (2D - EcoLE)	X	X	X	
Obenour (Probabilistic cyanobacteria model)		X		
Stumpf (bloom severity index)		X		
Yerubandi, McCrimmon (Lam's 9 Box model)	X		X	
Rucinski (1D Central basin hypoxia model)	X (Central)		X	
Auer (Great Lakes *Cladophora* model)				X
Higgins (*Cladophora* growth model)				X

2. MODEL OVERVIEW

The ensemble modeling application project will produce a series of load-response curves for the relationship between phosphorus loading (several different representations, including TP and DRP loading) and eutrophication response indicators, including total chl-a, cyanobacteria blooms, Central Basin hypoxia, and Eastern Basin *Cladophora*.

Each of the models being applied for the Lake Erie ensemble modeling project are briefly described below. The description includes the type of model, a summary of the input and output (including the eutrophication response indicators they model), a brief explanation of the calibration/confirmation process, and supporting documentation.

i. *Chapra TP Model*

The Chapra TP model is a TP mass balance intended to predict annual phosphorus concentrations and corresponding trophic conditions in offshore waters based on external loadings. Trophic conditions are defined as a function of the TP levels (10 – 20 µg P/L is mesotrophic; and <5 µg P/L is ultraoligotrophic). This model is designed to predict average annual phosphorus concentrations in the offshore waters of the Great Lakes as a function of external loading. It is a mass balance model and was developed as an update to the original mass balance model that was used, with other models, to establish phosphorus loading targets for the 1978 Great Lakes Water Quality Agreement (Chapra and Dolan 2012). Prediction of nearshore concentrations and concentrations at more frequent intervals than annual is beyond the intended purpose of the model.

The lakes are divided into a few segments to better resolve horizontal gradients in phosphorus. Concentrations are calculated as a function of time, incorporating the impacts of morphology, water flows, and loadings. In the model the initial concentration in the segment is modified by advection, loading, diffusion rates, and settling velocities. Model outputs include annual estimates (1800-2010) of phosphorus concentrations. The model can be expanded to predict overall Chl-a and Central Basin hypoxia. Chapra and Dolan (2012) provides complete documentation of model equations, assumptions, calibration and validation. Documentation of formal and/or informal assessments of model uncertainty/sensitivity is planned as part of this modeling effort.

ii. *WLEEM*

WLEEM is a three dimensional fine-scale, process-based, linked hydrodynamic-sediment transport-advanced eutrophication model developed for the Western Basin of Lake Erie over the past five years. WLEEM provides a quantitative relationship between loadings of water, sediments, and nutrients to the Western Basin of Lake Erie from all sources and its response in terms of turbidity/sedimentation and total and functional group phytoplankton biomass. The model is documented in several project reports, including:

- LimnoTech. 2013. Development of an Integrated Modeling Approach for Quantifying the GLRI Deposition Metric: Pilot Application to Toledo Harbor. Final Technical Report prepared for U.S. Army Corps of Engineers – Buffalo District under contract to Ecology & Environment, Inc. 125 pp.

- LimnoTech. 2012. Development of a Phosphorus Mass Balance Model for Missisquoi Bay. Prepared for Lake Champlain Basin Program, under Contract to New England Interstate Water Pollution Control Commission (NEI Job Code: 989-003-006, Project Code: L-2010-034). 89 pp. (March 30, 2012).

- LimnoTech. 2010. Development, Calibration, and Application of the Lower Maumee River – Maumee Bay Model. Technical report prepared for the U.S. Army Corps of Engineers, Buffalo District. 113 pp. (December 30, 2010).

- LimnoTech. 2009. Upper Mississippi River – Lake Pepin Water Quality Model Development, Calibration, and Application. Prepared for Minnesota Pollution Control Agency, St. Paul, MN (July, 2009). 305 pp.

The WLEEM operates on a daily time scale and can produce time series outputs and spatial distributions of either total chlorophyll and/or cyanobacteria biomass as a function of loading. It has been initially calibrated to 2005 data and recalibrated/corroborated by application to the 2011-2013 field data, with an emphasis on cyanobacteria biomass data from Bridgeman at the University of Toledo.

The WLEEM utilizes the following model components:
- *Simulating Waves Nearshore* (SWAN) for the wind-wave sub-model;
- *Environmental Fluid Dynamics Code* (EFDC) for the hydrodynamic sub-model;
- *Sandia National Laboratory* (SNL) algorithms for the sediment transport sub-model; and
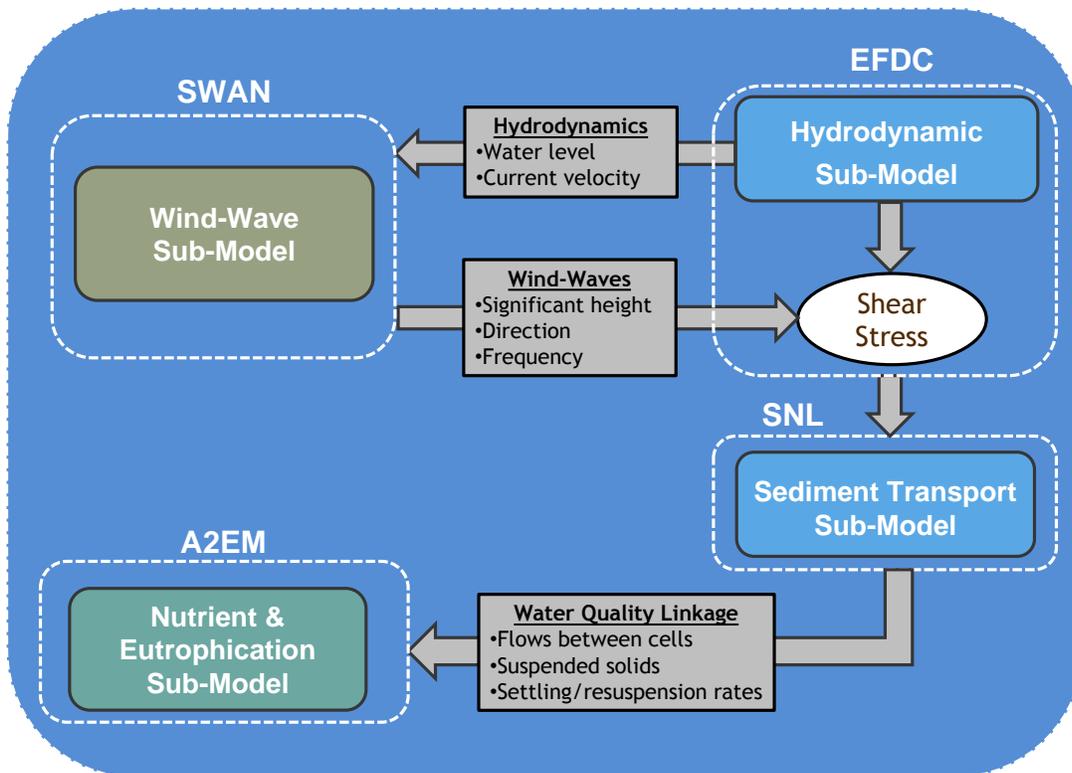- Advanced Aquatic Ecosystem Model (A2EM).

Figure 1: Diagram illustrating how the wind/wave model, hydrodynamic model, sediment transport, and water quality model interact together in WLEEM.

The A2EM (Advanced Aquatic Ecosystem Model) framework was originally developed from the public domain version of RCA computer code, developed and documented by HydroQual (2004). LimnoTech made significant modifications to that public domain code to include such aspects as interactions between solids transport and lower food web dynamics, explicit modeling of growth and associated grazing/nutrient cycling processes associated with zooplankton functional groups, incorporation of a benthic algae growth (e.g., Cladophora sub-model), incorporation of a dreissenid bioenergetics/phytoplankton filtering/nutrient cycling sub-model for multiple age classes of two mussel species, and kinetic adsorption/desorption of orthophosphate to particulate inorganic solids from tributary loads and bottom sediment resuspension.

WLEEM has been calibrated and corroborated by comparisons between model output and observations (state variables, processes) for 2011-2103 using the same set of model coefficients for all three years. Documentation of this corroboration process will be accomplished by reporting model-data comparison statistics for key state variables for all three years. Model confirmation and uncertainty assessment will be accomplished by computing the model-data comparison statistics for the baseline year of 2008 model run using the same coefficients developed in the 2011-2013 corroboration.

iii.   ELCOM-CAEDYM

ELCOM-CAEDYM is a three-dimensional hydrodynamic and biogeochemical model that consists of two coupled models: a three-dimensional hydrodynamic model - the Estuary, Lake and Coastal Ocean Model (ELCOM; Hodges et al., 2000), and a biogeochemical model - the Computational Aquatic Ecosystem Dynamics Model (CAEDYM; Hipsey and Hamilton, 2008). The CAEDYM models the impact of water quality on ecological outcomes in waterbodies. The ELCOM is a Fortran 90 software program that models three-dimensional water dynamics driven by hydrodynamic and thermodynamic parameters (Hipsey et al. 2006; Hodges and Dallimore 2014). The combined ELCOM-CAEDYM model couples hydrodynamics, thermodynamics, and water quality to model biogeochemical processes, primary and secondary production, nutrient and metal cycling, and oxygen concentrations (Liu 2013).

This is a highly complex model with 112 state variables. Model outputs can be used to develop response curves for the ecosystem response indicators related to overall phytoplankton biomass, Western Basin cyanobacterial blooms, and Central Basin hypoxia, and to provide boundary conditions for the Eastern Basin *Cladophora* ERI.

iv. EcoLE (CE-QUAL-W2 model)

The EcoLE model is a two-dimensional hydrodynamic and water quality model for Lake Erie that is based on the CE-QUAL-W2 framework (a model developed by the U.S. Army Corps of Engineers). In the modeling of Lake Erie, it is able to simulate water levels, currents, and thermal stratification. This hydrodynamic model is then combined with submodels that address chemical and biological factors (Figure 2). The biological submodels include phytoplankton, zooplankton, and dreissenid mussels (grazing and excreting nutrients). Phytoplankton include non-diatom edible algae, non-diatom inedible algae, and diatoms. The phytoplankton growth is a function of temperature, light and nutrients. Cladocera and copepods are the primary grazers included in the zooplankton compartment. They feed on the edible algae and diatoms. Mussels are also assumed to feed on phytoplankton (Zhang et al. 2008).
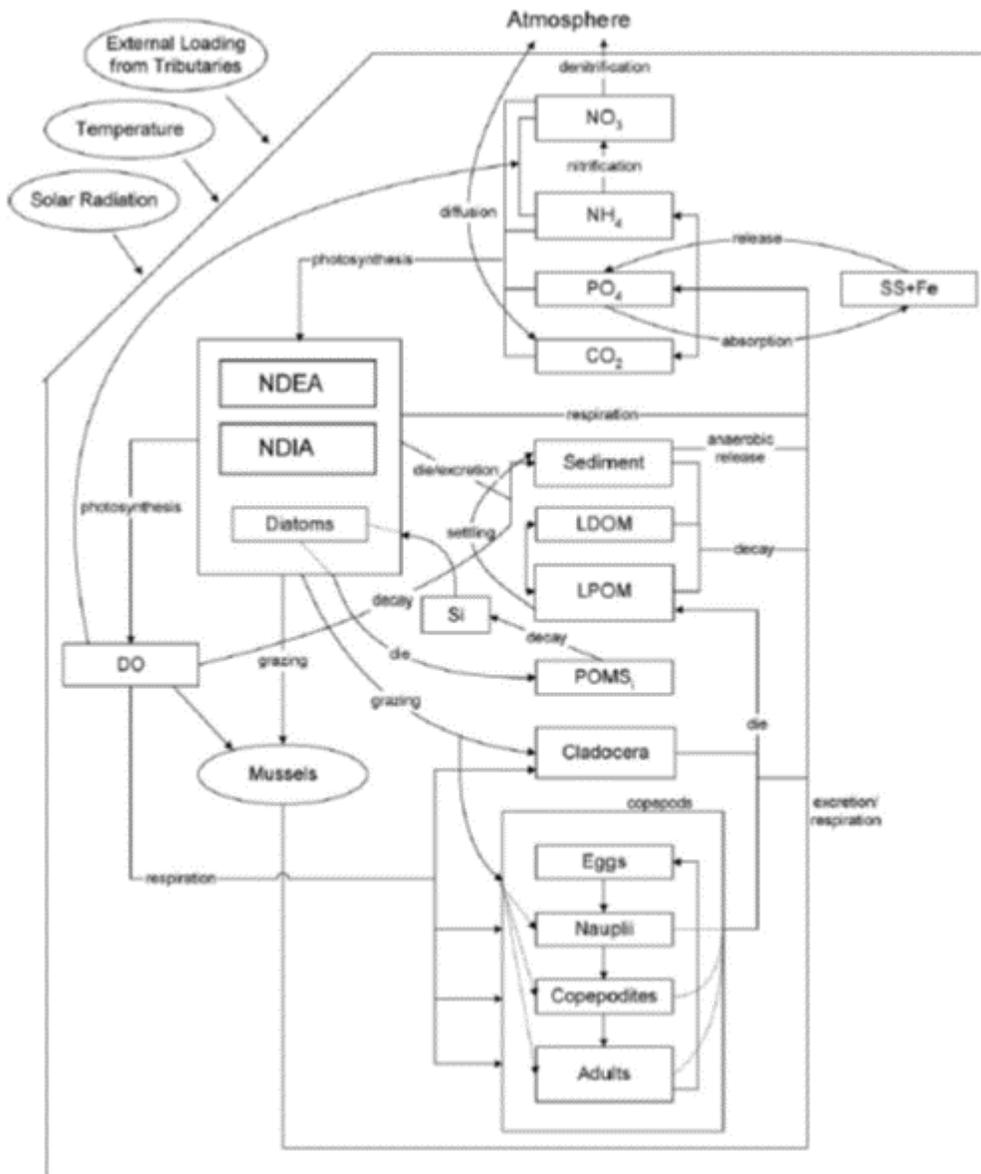

Figure 2: EcoLE chemical and biological structure from Zhang et al. 2008.

11

The model's algal biomass output can be converted to chlorophyll concentrations. The model also dynamically simulates dissolved oxygen in the lake, and has been applied to evaluate the importance of weather and sampling intensity for calculated hypolimnetic oxygen depletion rates in the western-central basin (Conroy et al. 2011). The CE-QUAL-W2 user manual (Cole and Buckak 1995) contains complete model description on model equations, coefficients, driving variables, assumptions and time steps of predictions. Other publications supporting the model's performance include: Boegman 1999; Boegman et al. 2001; Boegman et al. 2008b; Zhang 2006; Zhang et al. 2008; and Zhang et al. 2011.

v. UM/GLERL Probabilistic Cyanobacteria Model

The UM/GLERL (University of Michigan/National Oceanic and Atmospheric Administration [NOAA] Great Lakes Environmental Research Laboratory) cyanobacteria model is a probabilistic, empirical forecasting model developed to relate the size of the Western Basin cyanobacteria bloom to spring phosphorus loading and potential temporal changes in the Lake's susceptibility to large cyanobacteria blooms (Obenour et al, In review).

Model inputs include peak bloom estimates derived from satellite remote sensing and in situ field sampling, monthly Maumee River nutrient concentrations (e.g., TP and DRP), and monthly Maumee River discharges. The nutrient concentration and flow data are used to determine 'effective' spring phosphorus loads, and these loads are related to the cyanobacteria bloom observations.

The deterministic form of the bloom forecasting model is as follows:

$$\hat{z}_i = \begin{cases} \beta_b + \beta_0 + \beta_w W_i + \beta_t T_i & \text{for } \beta_0 + \beta_w W_i + \beta_t T_i > 0 \\ \beta_b & \text{for } \beta_0 + \beta_w W_i + \beta_t T_i < 0 \end{cases} \tag{1}$$

where β_b, β_0, β_w, and β_t are model parameters that predict bloom size, $\hat{z}_i$, in year i, in terms of spring TP load, W_i, and model year, T_i. The parameter β_b is a background bloom level representing the bloom size in years of minimal TP loading. The parameter β_0 is an intercept term, and β_t represents how that intercept changes over time. Parameters β_b and β_0 have units of 1000 MT bloom (dry weight) and β_t has units of (1000 MT bloom)/year. The parameter β_w represents the unit increase in bloom size per unit increase in TP load (MT/mo). The 'time step' of the model is yearly.

Predicted values are related to bloom observations, $z_{i,j}$, through the following two probabilistic expressions:

$$z_{i,j} \sim Gamma[(\hat{z}_i + \gamma_i)^2/\sigma_\epsilon^2, \ (\hat{z}_i + \gamma_i)/\sigma_\epsilon^2] \tag{2}$$

$$z_i \sim Gamma(\hat{z}_i^2/\sigma_\gamma^2, \hat{z}_i/\sigma_\gamma^2) - \hat{z}_i \tag{3}$$

The gamma distributions have shape (g_α) and rate (g_β) parameters (i.e., *Gamma* (g_α, g_β)) such that the mean and variance are g_α/g_β and g_α/g_β^2, respectively. Model prediction errors (γ_i) are drawn from a gamma distribution with variance σ_γ^2; and observation measurement errors are drawn from a gamma distribution with variance σ_ϵ^2. Here, subscript j differentiates between multiple observations of the same bloom, i.e., observations from remote sensing [Stumpf et al., 2012] and from in-lake sampling [Bridgeman et al., 2013].

For each year, spring TP load is determined as a weighted average of January to June ($m = 1$ to 6) monthly loads, based on the following equations:

$$W_i = \frac{1}{\sum \psi_m} \sum_{m=1}^{6} w_{i,m} \psi_m \tag{4}$$

$$\psi_m = \begin{cases} 0 & \text{for } m \leq (\beta_\psi - 1) \\ m + 1 - \beta_\psi & \text{for } (\beta_\psi - 1) < m < \beta_\psi \\ 1 & \text{for } m \geq \beta_\psi \end{cases} \tag{5}$$

where β_ψ, is a weighting parameter.

All model parameters are determined probabilistically, through Bayesian inference, using R and WinBUGs software. Cross validation will be performed to quantify uncertainty and robustness.

vi. NOAA Empirical HABs Forecasting Model

NOAA's Empirical HABs Forecasting Model is a predictive model that relates spring flow from the Maumee or TP load to predict algal bloom magnitude in the Western Basin of Lake Erie (Stumpf et al. 2012). Model outputs can be used to develop response curves for the Western Basin cyanobacteria bloom ERI.

Documentation of model equations, coefficients, driving variables, assumptions, and time step of predictions is available in Stumpf et al, 2012. Bloom severity is updated annually with satellite data. Results also compared to Bridgeman data for stations in western west basin, conducted annually. Satellite confidence is ~25% for post 2011. 2013 comparison suggests that model should be expanded to include July.

vii. Environment Canada 9-Box Eutrophication Model

Environment Canada's 9-Box Eutrophication Model allows for quantitative understanding of eutrophication and related hypoxia in Lake Erie (Lam et al. 1983). It was originally developed at the National Water Research Institute (NWRI) and verified against empirical data in the 1970s. The model was used to demonstrate that phosphorus loading is positively correlated with

sediment oxygen demand rate; however, thermal layers, diffusion processes, and meteorological processes may have significant short-term impacts on hypolimnion anoxia that confound interpretation of changes in phosphorus. The Nine-Box Model thus provides benefit to decision makers by integrating both phosphorus loading and meteorological impacts (Lam et al. 1987a).

The NWRI Nine-Box Model (Lam et al. 1987a) divides Lake Erie into nine boxes: three horizontal basins (west, central and east) and three vertical thermal layers during stratification (epilimnion, mesolimnion, and hypolimnion). Weather factors such as wind, solar radiation, air temperature, and water vapor pressure control the box thicknesses, temperatures, vertical entrainment and diffusion, and interbasin fluxes. These processes affect temperatures and water quality, including DO, and phosphorous. The Nine-Box Model simulates total phosphorus (TP) as two components of soluble reactive phosphorous (SRP) and organic phosphorous (OP) (i.e. TP = SRP + OP) (page 6-3 Lam et al. 1987a).

Some other points of interest for the Nine-Box Model:

- Inputs and outputs are daily and extend from day 1 to 365 for the selected year

- Interbasin transport between Central and Eastern Basins consists of wind driven flow patterns: 1) circulating within epilimnion and mesolimnion; and 2) circulating within mesolimnion and hypolimnion

- Thermal layer thickness and temperatures of each basins are calculated using a 1D thermal model

- Water budget balancing done in epilimnion or hypolimnion, not mesolimnion as it is a thinner layer.

The most recent application of the Nine-Box Model looked at the changes in DO and P pre- and post- zebra mussel arrival in the late 1980's (Lam et al. 2002). The model had been verified and validated for the period before arrival (1967-1982) (Lam et al. 1987a) and then used to simulate for years after arrival: deviation from observed are said to be due to the zebra mussels. The main difference between Lam et al. 1987 and Lam et al. 2002, an increased settling rate from 0.04 to 0.07 m/d.

Besides increased settling of P, it was found that SRP was under-predicted in the spring in the Western Basin, likely due to faster rate of P recycling by Dreissena and the full mixing in the Western Basin. Although it may be ideal to do recalibrations with the most recent data, for the proposed ensemble modelling effort the modelers intend to use the Lam et al. 2002 version as it

is the most recent version of this model. Publications supporting the model's performance include: Lam et al. 1983, Lam et al. 1987a and b, and León et al. 2007.

viii.   One-Dimension Central Basin Hypoxia Model

The Central Basin Hypoxia Model is a one-dimensional model and links hydrodynamics and eutrophication to determine hypolimnion oxygen conditions as a function of phosphorus load and meteorological factors. In addition, the model incorporates light, phytoplankton, zooplankton, and organic carbon. The conceptual model that is the framework for the eutrophication portion of the model that is applied to the Central Basin Hypoxia Model is shown in Figure 3. This model provides decision makers with knowledge of the relationship between phosphorus loading and lake hypoxia, an important negative impact of eutrophication.

The one-dimensional model has been corroborated with data from 1987-2005 for dissolved oxygen (DO), total phosphorus (TP) and chl-a. Response curves of DO (hypolimnion oxygen demand, hypoxia days, hypoxic area, bottom DO) vs TP and DRP have been developed and published, based on the existing calibration (Rucinski et al. 2010, Rucinski et al. 2014).
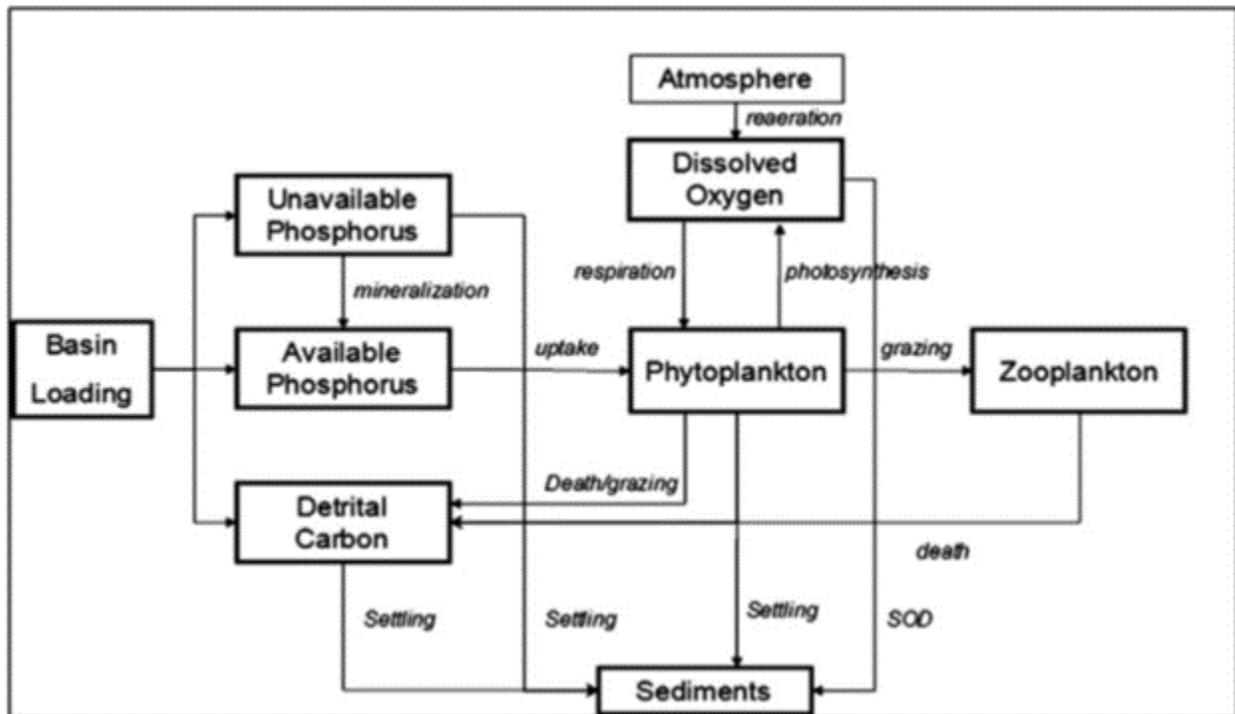

Figure 3. Conceptual framework for the Central Basin Hypoxia Model (from Rucinski et al. 2014).

ix. Great Lakes Cladophora Model

The Great Lakes Cladophora Model (GLCM) accepts environmental forcing conditions (e.g. light and temperature) and specified concentrations of DRP as inputs and generates seasonal time series of Cladophora standing crop, sloughed biomass and production over a gradient of water depths. The GLCM evolves from the framework developed by Canale and Auer (1982), updated to include advances in biokinetic attributes and to add a user-friendly graphical user interface to facilitate use by others. In its application here, and in the spirit of this project's ensemble approach, modeling with the GLCM will draw conceptually from the *Cladophora* Growth Model developed by Higgins et al. (2005) for use on the Great Lakes. Michigan Technological University will be responsible for application of the GLCM in relation to the Cladophora ERI. Michigan Technological University will utilize DRP concentrations at the Central/Eastern Basin boundary provided by the ELCOM-CAEDYM Modelers to determine open lake DRP forcing conditions for the Eastern Basin. Sensitivity analyses will be performed as part of the application of the GLCM for this project as well. Documentation of model equations and calibration can be found in Tomlinson et al. 2010 and Auer et al. 2010.

3. DATA SOURCES

All models being applied for this project will use secondary data (i.e., previously collected, reported, modeled or synthesized data) from Lake Erie for their input, calibration, and evaluation. The data quality objectives and associated criteria for the secondary data used for this project are listed below:

1) Data are from a known and reliable source. The data sources and rationale for data source selection will be documented. Data will be compiled primarily from reliable local, state, federal and peer-reviewed sources.
2) Data are of known quality. The quality of secondary data will be documented using the following criteria:
    a) data were generated under an approved QAPP or other sampling document (references will be documented);
    b) data include quality assurance statements/descriptions/qualifiers and/or associated quality control data that allows evaluation for precision, bias, representativeness, completeness, comparability and/or sensitivity as appropriate;
    c) data come from peer-reviewed publications; and
    d) data quality is limited or unknown, but come from a reliable source (data limitations and the rationale for data source reliability will be documented).
3) Data are appropriate for the intended use. This will be documented using the following criteria:
    a) data satisfy project objectives;
    b) data satisfy evaluation and modeling requirements;

c) data exhibit appropriate characteristics (e.g., quality, quantity, temporal, spatial); and

d) data were generated using appropriate methods.

Primary data sources used to develop, calibrate, and validate the models are listed below. Data from these, or comparable quality, government and academic institutions will be used to run the models. The modeling team will document the sources of the data and report on any assumptions made in order to run the models for the baseline year and for development of load-response curves. Additional model-specific data sources will be documented in the final report.

Phosphorus Loads

- International Joint Commission Annual Reports of annual TP load estimates.
- Published compilations of annual TP load estimates (Fraser 1987; Lesht et al. 1991; Dolan 1993; Dolan and McGunagle 2005)
- U.S. EPA and Environment Canada annual TP load estimates (SOLEC 1994)
- EcoFore TP and DRP data. Methods and sources of these data are described in Dolan and Chapra (2012) and Dolan and McGunagle (2005).

Water Quality Data

- U.S. EPA Permit Compliance System and the Integrated Compliance Information System
- Ontario Ministry of the Environment Industrial Strategy for Abatement database

Tributary Flow Data

- U.S. Geological Survey National Water Information database of daily tributary flow data
- Environment Canada Hydrometric Data database of daily tributary flow data
- National Oceanic and Atmospheric Administration hourly water level measurements at gage stations
- Grand River Conservation Authorities continuous flow data

Tributary Nutrient Data

- U.S. EPA STORET database of annual TP estimates for tributaries
- Provincial Water Quality Monitoring Network database (Ontario Ministry of the Environment) database of annual TP data for tributaries

- Heidelberg University daily (or more frequent) concentrations of suspended solids, TP, DRP, ammonia, and nitrate nutrient concentration data for the rivers
- University of Wisconsin – Green Bay loading estimates from tributaries not directly monitored by Heidelberg University
- University of Waterloo dataset for east basin daily total phosphorus (2001-2002) (Depew et al. 2006).

Meteorological Data

- Environment Canada daily rainfall data
- National Oceanic and Atmospheric Administration hourly (and daily) average atmospheric conditions at meteorological stations including average wind speed and direction, air temperature, relative humidity, air pressure, solar radiation, and cloud cover.

Biological Data

- University of Toledo collected data from 8 nearshore-to-offshore transects with fixed sample stations at 2, 5, 10, and 20+ m to assess nutrient pools of phosphorus, nitrogen, and carbon in the dominant biological (i.e., bacteria, phytoplankton, zooplankton, benthic algae, Dreissenid mussels, dominant infaunal and epifaunal benthos) and physical compartments (i.e., water column, sediments) of Lake Erie.

- U.S. Environmental Protection Agency Lake Erie Trophic Status collaborative project compiled and analyzed data from about 20 published studies with various data collection time frames (Matisoff and Ciborowski 2005).

- University of Waterloo dataset for east basin daily planktonic primary production, chl a, (also underwater light climate) (2001-2002) (Depew et al. 2006).

Lake Bathymetry Data

- National Oceanic and Atmospheric Administration one-meter bathymetry data were compiled as a cooperative effort with the Canadian Hydrographic Service. The seven hundred thousand bathymetric sounding data were collected for more than a century for navigational purposes. Digital sounding data are at standard scales of 1: 100,000 or 1: 50,000.

4. MODEL EVALUATION AND APPLICATION

The modeling process to be followed for all models applied in this project will be based upon guidance provided in U.S. EPA (2009b) "Guidance on the Development, Evaluation, and Application of Environmental Models." Documentation of the model evaluations will include:

- Complete documentation of model equations, coefficients, driving variables, assumptions and time step of predictions
- Documented comparisons between model output and observations (state variables, processes) used in calibration as well as final model evaluation performance values
- Documentation of post-calibration (i.e., validation) testing (e.g., comparison of model performance for observations not used in the calibration)
- Documentation of formal and/or informal assessments of model uncertainty/sensitivity

Each of the proposed models will be assessed against a set of evaluation criteria in order to identify the final set of models to be applied. The models will be evaluated using the following criteria:

- **Predictive and Statistical Validation:** An appropriate measure of correlation or goodness of fit will be used both in the calibration of the model, i.e., setting parameters such that the model most closely matches the empirical data, and in the validation of the model, i.e., evaluation of the degree of agreement of the model with empirical data that were not used to calibrate the model. A correlation suggesting that 50% or greater of the variability in the relationship between the TP or DRP and the ERI(s) is addressed by the model will be acceptable. Lower levels of correlation may be considered acceptable with caveats.

- **Other Validation Considerations:** face validity; comparison to other models; internal validity (repeated use of model yields consistent outputs); extreme condition tests appear reasonable; and interpretation of sensitivity analysis.

- **Usefulness Considerations:** Qualitative consideration of the usefulness of the model for evaluation of phosphorus reduction on ERIs. For example, the amount and availability of data required by the model may impact the utility of the model.

Each of the models selected for the analysis has the purpose of predicting one or more ERIs based on the levels of TP or DRP. Therefore the ability to correctly predict ERIs will be an important consideration in the final model selection. The findings of the model evaluations will be provided in the final technical report.

EPA requested a minimum of six values of loads be used to generate load-response curves for each model for both TP and for DRP. The six loads to be included in the load-response analyses are 125%, 100%, 75%, 50%, 25%, and 0% of the baseline years load, as shown in Table 2. Each of these loading scenarios will use the same hydrology as the baseline year, adjusting the load by

adjusting the tributary/node concentration of phosphorus. The range of loading scenarios include both increases in loading from the baseline year, as well as complete elimination of loadings. Complete elimination of loading (0% of baseline year) is not included as a potential target for load reductions; rather, it addresses the question of the extent to which eutrophication indicators can be reduced, given existing inventories of phosphorus in the water column and sediments. This analysis is expected to be sufficient to compare the response of the models to changes in TP and DRP; to inform an investigation into the cause of differences in model response; and to identify the eutrophication indicators and conditions under which different models are likely to be most useful. Further, the analysis is expected to be achievable within the constrained timeframe available for this analysis.

Table 2. Inputs of TP and DRP Used to Generate Load-Response Curves

Scenario
0% of baseline year TP load
0% of baseline year DRP load
25% of baseline year TP load
25% of baseline year DRP load
50% of baseline year TP load
50% of baseline year DRP load
75% of baseline year TP load
75% of baseline year DRP load
100% of baseline year TP load
100% of baseline year DRP load (baseline)
125% of baseline year TP load
125% of baseline year DRP load

The team of Modelers selected 2008 as the baseline year that will be used by all models included in this study. This year was chosen as a baseline year because: 1) it is the most recent complete inventory of tributary loading data (as published in Dolan & Chapra, 2012); 2) the TP annual load to Lake Erie for 2008 (10,830 metric tons per year) was virtually equal to the existing Great Lakes Water Quality Agreement target load of 11,000 metric tons per year; and 3) the lake exhibited representative metrics for the eutrophication response indicators of concern.

Additional information specific to the individual model applications are noted below.

i. *Chapra TP Model*

In the short term, this model would be used in its present version to develop basin-specific load-response curves for TP and chl-a (Chapra and Dolan, 2012). Chapra will also investigate the feasibility of extending his model framework to relate hypolimnetic oxygen and sediment nutrient release in the Central Basin (Chapra and Canale, 1991) to TP computation.

ii. *WLEEM*

WLEEM will be run for the common baseline year using nutrient and solids loads to the Western Basin from all sources estimated in the same way that Dolan estimated the loads for the EcoFore project. The model will produce spatial and temporal profile outputs of TP, DRP, NO_3, total NH_3, TKN, total phytoplankton biomass (as milligrams carbon per liter and chl-a), functional phytoplankton group biomass (e.g., cyanobacteria), and several ancillary state variables (T, chloride, TSS, and volatile suspended solids, endogenous respiration coefficient, DO). The concentration of all state variable outputs will be expressible as either volumetric concentration in a given three-dimensional model cell or as a depth averaged concentration for every horizontal grid cell. The state variables can also be expressed as a mass of the constituent in a given volume of water, thus facilitating the development of Western Basin mass balances from the model output. These mass balances can be developed on any spatial and temporal basis, including the total mass of cyanobacteria in the Western Basin integrated over the entire growing season. In summary, concentration or mass balance outputs can then be averaged or aggregated over any desired time and space (e.g., basinwide, August average of cyanobacteria chl-a).

The following scenarios will be run with the model using the common baseline year as the 100% scenario (additional scenarios may be run based on suggestions from EPA and Environment Canada):
- Baseline loads and flows and other forcing functions;
- Multiplying TP and DRP loads (by changing concentration) from all tributaries and the Detroit River by 0%, 25%, 50%, 75%, 100%, 125%;
- Multiplying TP and DRP loads (by changing concentration) from only the Maumee River by 0%, 25%, 50%, 75%, 100%, 125%;
- Multiplying TP and DRP loads (by changing concentration) from only the Detroit River by 0%, 25%, 50%, 75%, 100%, 125%;
- Multiplying only DRP loads (by changing concentration) from all tributaries and the Detroit River by 0%, 25%, 50%, 75%, 100%, 125%;
- Multiplying only DRP loads (by changing concentration) from only the Maumee River by 0%, 25%, 50%, 75%, 100%, 125%;
- Baseline with no sediment feedback, either by resuspension or pore water diffusion).

The output from these scenarios will permit the production of a large suite of load-response plots with TP or DRP load (either annual or cumulative over some specified time period, like March-

June) on the x-axis and any one of the state variables on the y-axis (again averaged over any specified time and/or space designation for the Western Basin). The current plan for the y-axes for these load-response curves is the following:

- Chl-a
    - Basin-wide summer (June - August) total chl-a average concentration
- Cyanobacteria
    - Maximum basin-wide cyanobacteria biomass (mass dry weight)
    - Summer total basin-wide cyanobacteria biomass (mass dry weight integrated over summer bloom period (start of bloom to end of bloom))
    - Maumee Bay summer total cyanobacteria biomass (mass dry weight integrated over summer bloom period (start of bloom to end of bloom))

The output will also be used to compute net fluxes (loads) of phosphorus and decomposable organic carbon to the Central Basin by various load management options. This Western Basin to Central Basin daily flux will be used as input to the one-dimensional Central Basin Hypoxia model.

iii. ELCOM-CAEDYM

In the short-term, Environment Canada and Bocaniov will collaborate to undertake the following ELCOM-CAEDYM model application activities:

- Using the common, baseline year selected by the modeling group, assess ELCOM-CAEDYM performance with respect to observed nutrient and phytoplankton concentrations during that year.
- Control experiments with different loading scenarios similar to those suggested for WLEEM.
- Generate Load (TP, DRP) vs Total Chl-a curves
- Generate Load (TP, DRP) vs Cyanobacteria Chl-a
- Generate Load (TP) vs Hypolimnetic oxygen concentration
- Generate Load (TP) vs hypoxia area

iv. EcoLE (CE-QUAL-W2 model)

The short term activities will be first to use input data and forcing functions from the baseline year to simulate the water qualities, and then check the model simulations against total chl-a, cyanobacteria chl-a, and central basin DO for that year. The model will then be used to run different TP and DRP loading scenarios, including 0%, 25%, 50%, 75%, 100%, and 125% of baseline loads. Load-response curves will be generated for total chl-a and cyanobacteria biomass in the Western Basin, and hypoxia area and hypolimnetic oxygen concentration in the central basin.

v. UM/GLERL Probabilistic Cyanobacteria Model

In the short term, the application of the Obenour model will include the following steps:

1. Recalibrate model to 'bioavailable' phosphorus loads. Bioavailable phosphorus loads will be determined by applying 'bioavailable fraction coefficients' to the DRP and non-DRP phosphorus loads from the Maumee River. The coefficients will be initialized based on prior information developed through literature review, and the coefficients will be updated based on bloom model calibration, through Bayesian inference. The revised model will be compared to models using TP and DRP loads only.
2. Incorporate additional remote sensing data products. The bloom forecasting model will be re-calibrated to include any newly available remote sensing data products (such as those derived from SeaWiFs and CZCS satellite imagery) that provide an indication of peak bloom size. A longer calibration dataset will improve our ability to model short and long-term bloom dynamics.
3. Develop load-response curves. The revised model will be run for the common baseline year using nutrient loads from the Maumee River. Scenarios will include multiplying TP and DRP-only loads (by changing concentration) from the Maumee River along a gradient of 10%-150%. The output from these scenarios will permit the production of load-response plots with spring TP or DRP load on the x-axis and peak bloom size on the y-axis.

vi. NOAA Empirical HABs Forecasting Model

In the short term, Stumpf will apply their bloom severity forecasting model to suggest TP and DRP load targets using the Maumee River as the surrogate for the loading of influence in the western basin. First, they will update the model published in Stumpf et al., 2012. Then they will produce load-response curves for the Western Basin cyanobacteria metrics using the revised model. The load-response plots will also provide estimates of uncertainty for the various relationships examined.

vii. Environment Canada 9-Box Eutrophication Model

In the short-term, the Environment Canada 9-Box model will be applied by Environment Canada with the following steps:

- Using the common, baseline year selected by the modeling group, assess 9-Box model performance with respect to observations of eutrophication response indicators for that year.
- Run NWRI vertical temperature model for providing stratification to hypoxia model
- Generate Load (TP, and DRP) vs phosphorous and chl-a response in west, central and east basins
- Generate Load (TP) vs DO concentrations response curves for Central Basin hypolimnion

- Generate Load (TP) vs hypoxia area (NWRI method) of the Central Basin.

viii. 1D Central Basin Hypoxia Model

The 1D Central Basin Hypoxia model can produce a range of hypoxia conditions (any of the selected metrics) for a given load to Lake Erie as a function of a range of observed or hypothesized physical forcing conditions that might affect the duration and magnitude and depth of stratification. The short-term application will use the existing model parameterization and the common, baseline year to develop a series of hypoxia load-response curves for the three metrics. These curves will be driven by the same load reduction scenarios suggested above (applied to both the Western Basin and Central Basin inputs). The load of phosphorus and organic material from the Western Basin to the Central Basin for those scenarios will be computed by WLEEM.

Chl-a load-response curves will be produced using the same series of phosphorus load reduction scenarios. This will provide an input to the overall phytoplankton biomass metric for the Central Basin.

ix. Great Lakes Cladophora Model

The GLCM will be applied to model the change in *Cladophora* standing crop, production and generation of sloughed biomass in a model domain along the north shoreline of the Eastern Basin in response to changes in DRP and TP inputs using various loading scenarios, e.g. 125%, 100%, 75%, 50%, 25%, and 0% of the load for the baseline year. Specifically, this effort will include:
- Adaptation of the GLCM to accommodate the physical features and biokinetic considerations inherent to the Lake Erie application;
- Performance of GLCM sensitivity analyses to facilitate assignment of uncertainty estimates to the P-loading/*Cladophora* response relationship;
- Develop a DRP-based response curve relating *Cladophora* metrics (e.g. standing crop, production and generation of sloughed biomass) to ambient DRP levels;
- Apply, in series, a hydrodynamic framework and the GLCM to develop load-response curves corresponding to various load reductions for,
- DRP concentrations at the Eastern - Central boundary, using boundary DRP values supplied by Annex 4 Workgroup members, e.g. the EC ELCOM-CAEDYM team and;
- TP concentrations at the Eastern - Central boundary, using tributary and point source phosphorus bioavailability coefficients derived for Lake Erie.

5. ANTICIPATED RESULTS

The modeling team has been formed and is currently working to evaluate and apply the models. The modelers will synthesize the results into a report that includes:
- Discussion of the outcomes of the calibration and validation of the models
- An evaluation of the performance of each model with insight as to where the models are likely to be useful and any limits of usefulness that are identified
- Examples of load-response curves and comparisons of the load-response curves and, to the extent the models lead to differing conclusions, a discussion of the differences
- Recommendations from the ensemble modeling approach and how the outputs may be useful for informing decisions
- Key gaps where additional research and development may improve the ensemble modeling approach.

The Annex 4 Subcommittee will vet and interpret the results and prepare recommendations for the Great Lakes Executive Committee (GLEC) in spring 2015. Upon approval from the GLEC co-chairs, EPA and Environment Canada will begin consultation with stakeholders on the updated phosphorus concentrations and loading targets, and seek a full peer review by the Science Advisory Board.

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