EPA-SAB-16-xxx

The Honorable Gina McCarthy
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460

Subject: SAB Review of Lake Erie Nutrient Load Reduction Models and Targets

Dear Administrator McCarthy:

The enclosed report provides the SAB's consensus advice and recommendations on the development of nutrient-load reduction targets for Lake Erie. At the EPA's request, the SAB has reviewed the modeling efforts used to develop the nutrient-load reduction targets for Lake Erie and provides advice on an adaptive management approach to implementing nutrient reduction goals.

EPA Region 5 is co-leading a binational workgroup established under the Great Lakes Water Quality Agreement to develop phosphorus load-reduction targets, strategies and action plans for Lake Erie. In December 2014, the EPA received early advice from the SAB on a modeling approach to develop the phosphorus-reduction targets. A binational workgroup of scientists then used a suite of models to generate a series of load-response curves to simulate the impact of phosphorus loads on eutrophication indicators in Lake Erie. The load-response curves were used by the Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team (Task Team) to identify phosphorus reductions needed to meet indicator thresholds associated with desired ecological conditions. Two documents were submitted to the SAB for review: (1) a report titled *Annex 4 Ensemble Modeling Report (May 2016 Peer Review Draft) and* (2) a report titled *Recommended Phosphorus Loading Targets for Lake Erie, Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee (May 11, 2015)*.

The SAB was asked to respond to six charge questions that focused on: (1) the adequacy of the evaluation of the models used to develop load-response curves; (2) whether the recommended phosphorus load-reduction targets are based on the best available information; (3) whether scientifically sound phosphorus load reductions can be developed to address growth of a nuisance algae, *Cladophora*; (4) whether nitrogen control, in addition to phosphorus, is warranted in Lake Erie; (5) recommended approaches to assess progress in reducing loadings of phosphorus; and (6) recommendations for an adaptive management approach to implement nutrient reduction goals for Lake Erie.

The SAB commends the EPA for its efforts to determine whether the models used to evaluate the impact of phosphorus loads to Lake Erie meet standards that provide confidence in the accuracy and reliability of results. The models used for the simulations are limited by the data available for calibration and validation, and this affects the ability to rigorously evaluate model quality. The models were applied and evaluated independently by the binational workgroup, not as part of an ensemble approach, and some of the models were accepted for use despite deficiencies relative to the model evaluation criteria. The SAB's major comments and recommendations are as follows:

- The models used by the binational workgroup are not of equal reliability. Assessment of the response to phosphorus loads could be improved by more heavily weighting load-response curves generated by the models deemed most reliable. Given the limitations of some of the models evaluated, the suite of models considered should be reduced. The SAB suggests selecting a single process-based model for predicting the impact of nutrient-load reduction. The Western Lake Erie Ecosystem Model could be further developed for this purpose.

- The SAB agrees that the 40% reduction in total phosphorus load to the Western and Central Basins of Lake Erie recommended by the Task Team will improve Lake Erie water quality and reduce harmful algal blooms. However, even with this reduction, blooms are still likely to occur relatively frequently, perhaps even routinely, in the western arm of the western basin in Maumee Bay. Ultimately, greater load reductions may be necessary to achieve the desired thresholds in the eutrophication-response indicators. Attenuation of hypoxia has a higher degree of uncertainty. Continued lake and tributary monitoring and research will be needed to support the adaptive management program and the models used to simulate load reductions.

- Scientifically sound phosphorus load reduction recommendations to reduce *Cladophora* growth in the Eastern Basin of Lake Erie cannot be developed at this time. The SAB finds that there is insufficient information available to understand and weigh the relative importance of environmental factors that might have causal links to *Cladophora* growth. The Great Lakes *Cladophora* Model can be used to evaluate *Cladophora* occurrence and provide initial predictions of *Cladophora* biomass. However, knowledge gaps must be filled before phosphorus load-reduction recommendations to reduce *Cladophora* growth can be developed with an adequate level of certainty and scientific confidence.

- There is mounting evidence that nitrogen control, as well as phosphorus control, is needed to reduce eutrophication in Lake Erie. In order to evaluate the importance of nitrogen control in Lake Erie, research should be conducted to answer a number of key questions and understand important relationships. These are identified in the attached report.

- Tracking flow-weighted mean concentrations of phosphorus in Lake Erie tributaries, as recommended by the Task Team, is a useful approach for measuring progress in load reduction. This approach accounts for variability in hydrology. However, the SAB recommends that all available tributary monitoring data (discharge, flow, concentrations and loads) and multiple assessment approaches be reviewed and used to evaluate efforts to reduce nutrient loadings. The SAB also recommends that the uncertainty in values derived using flow-weighted or flow-adjusted assessment approaches be explicitly quantified and presented, and that detailed information on the implementation of phosphorus reduction strategies be collected to help explain patterns observed in the future.

- The SAB strongly endorses development of an adaptive management program to implement and evaluate nutrient reduction goals for Lake Erie and recommends that the EPA formally appoint a standing committee to develop and coordinate the program. The program should test alternative hypotheses and conceptual models that can be used to adjust management operations and guide future monitoring and modeling efforts. The SAB's report contains a number of potential hypotheses and accompanying research, monitoring, and modeling tasks that focus on nutrient-load reduction and management of harmful algae blooms and hypoxia. The adaptive management program should include long-term monitoring and eutrophication models to make annual predictions of eutrophication response indicators.

The SAB appreciates the opportunity to provide the EPA with advice on this important subject. We look forward to receiving the agency's response.

Sincerely,

Enclosure

NOTICE

U.S. Environmental Protection Agency
Science Advisory Board
Lake Erie Phosphorus Objectives Review Panel

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Acronyms and Abbreviations

ANAMMOX	Anaerobic Ammonium Oxidation
BMP	Best Management Practice
CAEDYM	Computational Aquatic Ecosystem Dynamics Model
cm	Centimeter
DRP	Dissolved Reactive Phosphorus
DOC	Dissolved Organic Carbon
DNRA	Dissimilatory Nitrate Reduction
EcoLE	Ecological Model of Lake Erie
ELCOM	Estuary, Lake and Coastal Ocean Model
ELCOM	Estuary and Lake Computer Model
ERI	Eutrophication Response Indicator
FAC	Flow Adjusted Concentration
FWMC	Flow weighted Mean Concentration
GLCM	Great Lakes Cladophora Model
GLWQA	Great Lakes Water Quality Agreement
HAB	Harmful Algae Bloom
MT	Metric Ton
M	Meter
µg	Microgram
mg/L	Milligrams Per Liter
N	Nitrogen
NO_2	Nitrite
NO_3	Nitrate
P	Phosphorus
POC	Particulate Organic Carbon
ppb	Parts Per Billion
SOD	Sediment Oxygen Demand
SRP	Soluble Reactive Phosphorus
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USDA	U.S. Department of Agriculture
WLEEM	Western Lake Erie Ecosystem Model
WHO	World Health Organization

1. EXECUTIVE SUMMARY

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). Under Annex 4 the U.S. and Canada committed to address eutrophication issues in Lake Erie by first establishing phosphorus objectives, loading targets and allocations for nearshore and offshore waters and subsequently developing phosphorus-reduction strategies and domestic action plans. In December 2014, the EPA received early advice from the SAB on a modeling approach to develop phosphorus-reduction targets. A workgroup of Lake Erie Scientists (The Annex 4 Objectives and Targets Task Team Modeling Subgroup) then used a suite of models to generate a series of load-response curves to simulate the impact of phosphorus loads on cyanobacteria biomass, hypoxia and *Cladophora* growth. These load-response curves were used by the Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team (Task Team) to identify phosphorus reductions needed to produce desired ecological conditions for Lake Erie.

The EPA requested that the SAB review the modeling used to develop the phosphorus-reduction targets for Lake Erie. The SAB was also asked to provide advice on how to periodically evaluate the nutrient reduction targets. The EPA submitted two documents to the SAB for review: (1) a report titled *Annex 4 Ensemble Modeling Report (May 2016 Peer Review Draft)* and (2) a report titled *Recommended Phosphorus Loading Targets for Lake Erie, Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee (May 11, 2015)*. The SAB was asked to respond to six charge questions that focused on: (1) the adequacy of the evaluation of the models used to develop load-response curves; (2) whether the recommended phosphorus load reduction targets are based on the best available information on drivers of cyanobacteria growth and seasonal hypoxia in Lake Erie; (3) whether scientifically-sound phosphorus load reductions can be developed to address the problem of *Cladophora* growth in Lake Erie; (4) whether nitrogen control, in addition to phosphorus, is warranted in Lake Erie to prevent harmful algae blooms and manage hypoxia; (5) how to account for inter-annual variability in hydrology when assessing progress in reducing loadings of phosphorus to Lake Erie; and (6) recommendations for an adaptive management approach to implement nutrient reduction goals for Lake Erie. This executive summary highlights the findings and recommendations of the SAB in response to the charge questions provided in Appendix A.

Evaluation of the Models to Inform Interpretation of Results

The SAB was asked to comment on: (1) whether the evaluation of the models was adequate to inform how model results should be interpreted, and (2) any additional analyses that may be needed to improve future development and interpretation of the load-response curves for the eutrophication response indicators. The SAB notes that the models were applied and evaluated independently, not as part of an ensemble approach, and some models were accepted for use despite deficiencies relative to the criteria used to evaluate models. The SAB recognizes that the models are limited by the data for calibration and validation and this affects our ability to rigorously evaluate model quality. A better understanding of the limitations of the data and the data requirements needed to produce higher certainty in estimates should be sought. The model evaluations did not attempt to characterize the relative strengths of each model nor the consistency of descriptions of underlying key processes. Furthermore, all of the load-response curves were treated as equally likely, despite differences in estimated load and uncertainty. The SAB finds that the models are not of equal reliability, and the assessment of load-responses would have benefited by more heavily weighting response curves generated by the models that appear most reliable. Although the model evaluation included efforts to characterize uncertainty, the approaches used to quantify uncertainty differed among the models. Therefore, assessed uncertainties cannot be compared across models and uncertainties were not used to evaluate the likelihood that loading targets would achieve desired threshold values of the selected ecosystem response.

The suite of models considered should be reduced. Priority should be given to the process-based models that have the capability to account for the response to load reductions, climate changes and internal storage and recycling of nutrients. Given practical limits of funding and the limitations of some of the models evaluated, the SAB suggests selecting a single process-based model to predict eutrophication in response to nutrient load reduction. The SAB recommends that the Western Lake Erie Ecosystem Model be further developed for this purpose. The SAB also recommends that synoptic sampling of key variables be conducted on an ongoing basis to support continuing model evaluation and refinement for Lake Erie. It is important to monitor flow, nutrient concentration and total suspended solids in all of the significant tributaries of Lake Erie at sufficient frequencies to make accurate estimates of loading. Estimates of loading could be further improved by linking land-use models with loading models. If multiple models are used to derive load-response information, consideration should be given to combining model estimates using either likelihood based methods or Bayesian model averaging to produce a weighted quantitative characterization of the loading curve and associated uncertainty.

Phosphorus Loading Targets

In order to meet ecosystem objectives[1], the Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team (Task Team) recommends a 40% reduction in the total phosphorus load to the Central and Western Basins of Lake Erie. The SAB was asked to comment on whether the recommended loading target reflects the best available information on the drivers of cyanobacteria growth and seasonal hypoxia. Based upon coupling a suite of models to the relatively long term observational record, the SAB finds a 40% reduction in total phosphorus load will improve water quality and reduce harmful algal blooms in keeping with the stated goals in the Task Team report. However, even with this reduction, blooms will still occur relatively frequently, perhaps even routinely, in the western arm of the western basin in Maumee Bay. Ultimately, further load reductions may be necessary to achieve the desired thresholds of the eutrophication response indicators. Attenuation of hypoxia has a higher degree of uncertainty.

Continued lake and tributary monitoring will be needed to support further development of the modeling and adaptive management programs. Additional information will be needed in order to include missing components in the models. These components include: temporal variability in hydrodynamics; the role of nitrogen limitation; controls of algal toxin production; internal phosphorus loading (i.e., resuspension fluxes and sediment-water interactions); the role of dreissenid mussels; seasonality in the timing of nutrient loads; winter-spring diatom blooms under ice; and the effects of climate change. Development

[1] The desired thresholds identified for eutrophication response indicators in Lake Erie were: (1) Western Basin cyanobacteria bloom biomass no less than that observed in 2004 or 2012, nine years out of ten, and/or reduced risk of nearshore localized blooms; and (2) Central Basin hypoxia August – September average hypolimnetic dissolved oxygen concentration of 2.0 mg/L or more (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015).

and implementation of management action plans will also require a better understanding of the effectiveness of best management practices.

Development of Recommendations to Address Nuisance Levels of *Cladophora* Growth

The SAB was asked to comment on whether scientifically sound phosphorus-load reduction recommendations could be developed to reduce *Cladophora* growth in the Eastern Basin of Lake Erie. *Cladophora* is a green algae that grows attached to hard benthic substrates. The nuisance attribute of *Cladophora* is largely the formation of “beach muck” and problems that arise from it. The SAB finds that recommendations to reduce the phosphorus loadings to reduce *Cladophora* growth cannot be developed at this time. There is insufficient information to understand and weigh the relative importance of environmental factors (including phosphorus inputs) that might cause *Cladophora* growth and senescence. Moreover, there are limited observations of the spatial extent of the *Cladophora* problem along the shore of the Eastern Basin of Lake Erie.

The Great Lakes *Cladophora* Model (GLCM) appears to provide first-order evaluation of *Cladophora* occurrence and initial predictions regarding the reduction of *Cladophora* biomass. However, knowledge gaps must be filled before phosphorus-load reduction recommendations to reduce *Cladophora* growth can be developed with an adequate level of certainty and scientific confidence. These knowledge gaps include: the need to calibrate the GLCM for use in the Eastern Basin of Lake Erie, the need to understand the importance of phosphorus loads from key tributaries and the effect of local hydrodynamics on *Cladophora* growth, the need to understand processes that lead to sloughing of *Cladophora* and its decay to “beach muck.,” and the need to include the GLCM in a broader whole lake model to forecast the likelihood of *Cladophora* growth. The GLCM would be more useful if it could be further developed to understand the growth of other nuisance benthic algae (e,g., *Chara, Lyngbya, and Spirogyra*) that cause problems similar to those associated with *Cladophora*.

Determination of Whether Nitrogen Control is Warranted

The SAB was asked to provide recommendations to help determine whether consideration of nitrogen control, in addition to phosphorus, is warranted to reduce eutrophication in Lake Erie. In particular, the SAB was asked to identify questions, relationships, or research priorities related to nitrogen loading and cycling that must be addressed. The SAB notes that there is mounting evidence that nitrogen control, as well as phosphorus control, is needed to reduce eutrophication in Lake Erie. The toxic cyanobacterium, *Microcystis*, the major concern in western Lake Erie, does not fix nitrogen. Therefore it requires a fixed nitrogen source. Moreover, *Microcystis* can become nitrogen-limited in late summer in western Lake Erie and it becomes more toxic under nitrogen replete conditions.

In order to evaluate the importance of nitrogen control in Lake Erie, future research should answer key questions and clarify important relationships. Key research questions include: What are the total nitrogen loadings entering Lake Erie over time and space (including all of the major species of nitrogen)? What is the nitrogen budget for Lake Erie? How much external nitrogen loading can be removed by internal processes like denitrification, dissimilatory nitrate reduction to ammonium, ammonia volatilization and burial? What are the consequences of legacy nitrogen and phosphorus in the sediments and the differences in internal nitrogen cycling? What are the downstream consequences of not following a dual nutrient strategy? What is the importance of concentrations and ratios of nitrogen to other nutrients in directing or controlling ecosystem functions? What is the ratio of nitrogen to phosphorus that would be best for ecosystem functioning? How reliable are current models for assessing the role of nitrogen in Lake Erie eutrophication and how can the models be improved to model the effects of nitrogen? In addition, the SAB recommends that Best Management Practices be developed or applied to achieve nitrogen reduction in Lake Erie, and "lessons-learned" case studies of nutrient reduction strategies for the Baltic Sea or other areas be applied to Lake Erie.

Assessing Progress in Reducing Tributary Loadings of Phosphorus

The SAB was asked to comment on the use of flow-weighted mean concentrations (FWMC) and other approaches that should be considered to account for inter-annual variability in hydrology when assessing progress in reducing tributary loadings of phosphorus to Lake Erie. The Task Team has recommended using flow-weighted mean concentrations of phosphorus in Lake Erie tributaries as a benchmark to track progress in load reduction. A flow-weighted mean concentration normalizes loadings with respect to flow so that year-to-year progress in nutrient control is not confounded by inter-annual hydrology. This is a useful approach, however, the SAB recommends that all available tributary monitoring data (discharge, flow, concentrations and loads) and multiple assessment approaches (including FWMC and flow adjusted concentrations) be reviewed and used to evaluate controls on nutrient loadings. FWMC analysis alone may mask elevated concentrations of nutrients that can result in algal blooms. Nutrient concentration, not loading, controls organism responses, and the effect of temporal variability in nutrient concentration is an important consideration in the management of harmful algae blooms, particularly for organisms that have rapid life cycles and a rapid response to shifts in nutrient concentrations. The SAB notes that flow adjusted concentrations (relating nutrient concentration to discharge flow) have been used to remove seasonality from tributary monitoring data and more clearly identify annual trends.

The SAB recommends that the uncertainty in values derived using flow-weighted or flow-adjusted assessment approaches be explicitly quantified and presented, and that detailed information on the implementation of phosphorus reduction strategies be collected to help explain patterns observed in the future. Without this information, it will not be possible to identify the primary reasons for observed changes in phosphorus loads delivered to the Lake. If control of nutrients other than phosphorus (e,g., nitrogen, silica, or other micronutrients) is considered, the SAB recommends that the same assessment approaches be applied to tributary monitoring for those nutrients in order to evaluate efforts to control sources of loadings.

Adaptive Management Program

The SAB was asked to comment on the key elements that should be included in an adaptive management program to implement and evaluate nutrient reduction goals for Lake Erie. In addition, the SAB was asked to comment on the value of using existing eutrophication models to periodically evaluate phosphorus loading targets and response indicators. The SAB strongly endorses development of an adaptive management program to implement and evaluate nutrient reduction goals for Lake Erie and recommends that the EPA formally appoint a standing committee to develop and coordinate adaptive management. The program should test alternative hypotheses and associated conceptual models that can be used to adjust management operations and guide future monitoring and modeling. It is beyond the scope of this SAB report to develop a comprehensive list of alternative hypotheses for Lake Erie eutrophication. However, the SAB suggests a number of potential hypotheses and accompanying research, monitoring and modeling tasks that focus on nutrient-load reduction, control of cyanobacteria and *Cladophora* blooms and increasing hypolimnetic dissolved oxygen.

The adaptive management program should include long-term monitoring to assess whether loading and eutrophication response targets are being met. Long-term monitoring should involve: assessing loading information and developing standardized protocols for loading estimates; maintaining and expanding current tributary monitoring; considering the potential for monitoring additional eutrophication response indicators; and ensuring that appropriate data are collected to calibrate and validate models and test alternative hypotheses.

The SAB recommends that eutrophication models be used as part of the adaptive management process. It may not be necessary to run all of the models that were originally included in the ensemble modeling suite, but models can make annual predictions of eutrophication response indicators and test alternative hypotheses. The SAB recommends that: the models be refined based on changing loadings and other new data; estimates of uncertainty be improved in the models; lake models be linked to upstream source functions through watershed modeling; and that cases where models do not perform well be used to develop alternative hypotheses.

2. INTRODUCTION

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). Under Annex 4 the U.S. and Canada committed to address eutrophication issues in Lake Erie by first establishing phosphorus objectives, loading targets and allocations for nearshore and offshore waters and subsequently developing phosphorus reduction strategies and domestic action plans. In December 2014, the EPA received early advice from the SAB on a modeling approach to develop phosphorus reduction targets (U.S. EPA Science Advisory Board 2015). A workgroup of Lake Erie Scientists (The Annex 4 Objectives and Targets Task Team Modeling Subgroup) then used a suite of models to generate a series of load response curves to simulate the impact of phosphorus loads on cyanobacteria biomass, hypoxia and *Cladophora* growth. These load response curves were used by the Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team (Task Team) to identify phosphorus reductions needed to meet indicator thresholds that reflected desired ecological conditions for Lake Erie.

The EPA requested that the SAB review the modeling results and process used to develop the phosphorus reduction targets for Lake Erie. In addition, the EPA requested advice on an approach to periodically evaluate the nutrient reduction targets. The agency submitted two documents to the SAB for review: (1) a report titled *Annex 4 Ensemble Modeling Report (May 2016 Peer Review Draft)*, and (2) a report titled *Recommended Phosphorus Loading Targets for Lake Erie, 20154 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee (May 11, 2015).*

The SAB was asked to respond to six charge questions that focused on: (1) the adequacy of the evaluation of the models used to develop load-response curves; (2) whether the recommended phosphorus load reduction targets are based on the best available information on drivers of cyanobacteria growth and seasonal hypoxia in Lake Erie; (3) whether scientifically-sound phosphorus load reductions can be developed to address the problem of *Cladophora* growth in Lake Erie; (4) whether nitrogen control, in addition to phosphorus, is warranted in Lake Erie to prevent harmful algae blooms and manage hypoxia; (5) approaches to account for inter-annual variability in hydrology when assessing progress in reducing loadings of phosphorus to Lake Erie; and (6) an adaptive management approach to implement nutrient reduction goals for Lake Erie. In response to the EPA's request the SAB convened its Lake Erie Phosphorus Objectives Review Panel to conduct the review. The Panel held a public meeting on June 21-22 and teleconference meetings on <<*insert date*>> to deliberate on responses to the charge questions and develop a consensus report of its findings and recommendations. The Panel's draft report was reviewed and discussed by the chartered SAB at a teleconference on <<*insert date*>>. This SAB report provides the findings and recommendations of the SAB in response to the EPA charge questions (Appendix A).

3. RESPONSES TO EPA'S CHARGE QUESTIONS

3.1. Approach for Developing Lake Erie Phosphorus Load Reduction Targets

The Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup (Modeling Subgroup) evaluated nine models to predict the response of selected eutrophication response indicators (ERIs) to different phosphorus load scenarios. Four response indicators were evaluated: (1) overall phytoplankton biomass, as represented by chlorophyll a; (2) cyanobacteria blooms in the Western Basin; (3) hypoxia in the hypolimnion; and (4) *Cladophora* in the nearshore areas of the Eastern Basin.

The document, *Ensemble Modeling Report (May 2016 Peer Review Draft)* (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup 2016) describes evaluation of the models and development of load-response curves for the selected ERIs for Lake Erie. These load response curves were used to develop phosphorus reduction targets to meet thresholds of desired ecological conditions for Lake Erie (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). The SAB was asked to comment on: whether the evaluation of the models by the Modeling Subgroup was adequate to inform interpretation of model results; whether additional analyses were needed to improve development and interpretation of load-response curves; whether the recommended targets reflect the best information on the drivers of cyanobacteria growth and seasonal hypoxia; and whether the recommended targets are appropriate to meet the nutrient Objectives defined in the Great Lakes Water Quality Agreement.

3.1.1. Evaluation of the Models to Inform Interpretation of Results

> *Charge Question 1. Please comment on whether the evaluation of the models was adequate to inform how model results should be interpreted, given differences in model complexity and scale. Please identify any additional analyses that may be needed to improve future development and interpretation of the load-response curves for the eutrophication response indicators.*

The SAB broke the response to this charge question into two sub-questions:

1. Was the evaluation of the models adequate to inform how the model results should be interpreted?

2. What additional analyses may be needed to improve future development and interpretation of the load-response curves?

Model Evaluations

The original approach for developing Lake Erie Phosphorus load reduction targets, as described by the EPA in a 2014 consultation with the SAB (U.S. EPA Science Advisory Board 2015), was to estimate load-response curves from multiple models and combine these into a single model or ensemble estimate. However, the models were applied and evaluated independently and were not used to develop an ensemble estimate. The independent model evaluations were intended to ensure that the results of each model met standards that would provide confidence that the model-generated load-response curves could be regarded as reasonably accurate and reliable. While adequate in concept, the criteria used for the model evaluations were only loosely applied and models were accepted despite deficiencies relative to the criteria. For example, the Estuary, Lake and Coastal Ocean Model (ELCOM) was accepted and used to develop a load-response curve for Lake Erie Central Basin hypoxia despite having not been calibrated to Central Basin dissolved oxygen. A sensitivity analysis was not performed for the ELCOM. The use of a common set of metrics to evaluate model fit is admirable; however, these metrics were not uniformly applied across the ensemble models. In addition, if prediction is a goal of management, the evaluation should have included a predictive measure of fit. The standard measures of goodness of model fit are not predictive, and assessments of the quality of the fit may be optimistic for purposes of nutrient management.

The model evaluations had other limitations: these evaluations did not characterize the relative strengths of each model nor the consistency of descriptions of underlying key processes; and the suite of load-response curves were treated as equally likely, despite significant differences in estimated load and uncertainty. The SAB finds that the assessed models are not of equal reliability and that the assessment of load-responses would have benefited by more heavily weighting response curves generated by the models deemed most reliable.

The overall model evaluation included efforts to characterize model uncertainty. The approaches used to quantify model uncertainty differed among the models and, as a result, the assessed uncertainties cannot be readily compared across models. Perhaps most important, the model uncertainties were not used to evaluate the likelihood that the chosen loading targets would achieve the desired thresholds of ecosystem response.

While it is clear that meeting the loading targets would lead to improved values of the selected ecosystem response indicators, other important outcomes are less clear. These include the likelihood that the desired threshold levels would be achieved; how long it would take for improvements to occur after the loading is reduced; and the effect of variations in hydrometeorological forcing and timing of loading on responses to load reduction.

Improving Future Development of the Load-Response Curves

Given the practical limits of funding and the limitations of a number of the included models, the SAB recommends reducing the suite of models considered. Priority should be given to the process-based models that can account for the response of key processes to changes driven by load reductions, climate changes and internal storage and recycling of nutrients. This recommendation comes with the recognition that such models should have process descriptions consistent with current technical ability to measure and model those processes. That is, the models should not have process resolution that cannot be parameterized based on measurements. It might prove more efficient to choose a single model and to further develop that model using the insights and demonstrated capabilities provided by the other models and the results of ongoing process research and monitoring. Consideration should be given to making Western Lake Erie Ecosystem Model (WLEEM) the consensus model for this purpose, with a goal of extending this model to all of Lake Erie.

Analyses of the ability of the chosen model(s) to predict responses to changing conditions should be conducted on an ongoing basis. Research and model development work should be funded to improve model accuracy and reliability within the overall nutrient-loadings management and decision-making framework. This continued model evaluation and refinement would facilitate making the model or models useful operational tools as part of an ongoing adaptive management process.

The models are limited by the data available for calibration and validation, which affect the ability to rigorously evaluate model quality. A better understanding of the limitations of the data and the data requirements needed to produce higher certainty in estimates should be sought. Additional in-lake synoptic sampling of key variables such as vertically averaged cyanobacteria abundance, water column and surface sediment nutrients, e.g., nitrogen (N) and phosphorus (P), total suspended solids (TSS) and dreissenid mussel biomass should be conducted on an ongoing basis to support model evaluations and refinements.

Measurements of flow, TSS and nutrient concentrations in all the significant tributaries to Lake Erie should be made at sufficient frequency each year to make accurate estimates of loading, particularly during the March to July period. While there is adequate information available on historical loading from major tributaries, there is inadequate information available on small tributaries. It would be useful to develop a model of nutrient and TSS loading that includes inputs from smaller tributaries. This would most likely be a hierarchical or Bayesian hierarchical model that accounts for multiple factors and might require additional monitoring for adequate estimation of model parameters and subsequent estimates of nutrient loadings from the smaller tributaries.

It seems worthwhile to improve the estimates of loading by linking land use models with loading models. Correspondingly, there might be an opportunity to collaborate with farmers in the Lake Erie watershed who are practicing precision agriculture to better estimate optimal fertilizer application rates as a way to reduce nutrient loading. Perhaps there is an opportunity to collaborate with the U.S. Department of Agriculture (USDA) to increase the participation by local farmers in agricultural technologies aimed at more efficient use of fertilizers and reducing nutrient loadings to Lake Erie.

To the extent that multiple models are retained for use in determining phosphorus load reduction targets, consideration should be given to combining model estimates using either likelihood based methods or Bayesian model averaging to produce a combined model-weighted quantitative characterization of the loading curve and associated uncertainty.

Key Recommendations

- The SAB finds that the models used in the analysis are not of equal reliability. The assessment of load-responses could be improved by more heavily weighting response curves generated by the models deemed most reliable.

- Given the practical limits of funding and the limitations of a number of the models used in the analysis, the suite of models considered should be reduced. Priority should be given to the process-based models that have the capability to account for the response of key processes to changes driven by load reductions, climate changes and internal storage and recycling of nutrients.

- It might prove efficient to choose a single model and to further develop that model using the insights and demonstrated capabilities provided by the other models and the results of ongoing process research and monitoring. Consideration should be given to making the Western Lake Erie Ecosystem Model (WLEEM) the consensus model for this purpose, with a goal of extending this model to all of Lake Erie.

- Analyses of the ability of the chosen model(s) to predict responses to changing conditions should be conducted on an ongoing basis. Research and model development work should be funded to improve model accuracy and reliability within the overall nutrient loadings management and decision-making framework.

- Additional in-Lake synoptic sampling of key variables such as vertically averaged cyanobacteria abundance, water column and surface sediment nutrients (e.g., N, P), TSS and dreissenid mussel biomass should be conducted on an ongoing basis to support model evaluations and refinements.

- Measurements of flow, TSS and nutrient concentrations in all the significant tributaries to Lake Erie should be made at sufficient frequency each year to determine accurate estimates of loading, particularly during the March to July period.

- It would be useful to develop a model of nutrient and TSS loading that includes inputs from smaller tributaries. This would most likely be a hierarchical or Bayesian hierarchical model that accounts for multiple factors and it might require additional monitoring for adequate estimation of model parameters and subsequent estimates of nutrient loadings from the smaller tributaries.

- It seems worthwhile to improve the estimates of loading by linking land use models with loading models. Correspondingly, there might be an opportunity to collaborate with farmers in the Lake Erie watershed who are practicing precision agriculture to better estimate optimal fertilizer application rates as a way to reduce nutrient loading.

- To the extent that multiple models are retained for use in the analysis, consideration should be given to combine model estimates using either likelihood based methods or Bayesian model averaging to produce a combined-model weighted quantitative characterization of the loading curve and associated uncertainty.

3.1.2. Phosphorus Loading Targets

Charge Question 2. Please comment on whether the recommended targets reflect the best available information on the drivers of cyanobacteria growth and seasonal hypoxia in Lake Erie and are appropriate to meet the nutrient Lake Ecosystem Objectives defined in the GLWQA (as reflected in Table 1 on page 7 of the document titled Recommended Phosphorus Loading Targets for Lake Erie).

The Annex 4 Objectives and Targets Task Team (Task Team) recommended a target of 40% reduction in the total phosphorus (TP) load to the Central and Western Basins of Lake Erie (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). This is based upon the results from the suite of models that compute load-response relationships between metrics of eutrophication response indicators, namely harmful algae blooms (HABs) and hypoxia, and loads leading to values for those metrics. The principal issues considered by the SAB are: (1) whether this target of a 40%

reduction (from a 2008 baseline which is essentially equivalent to the current target load of 11,000 MT) is based on and results from a rigorous analysis and modeling framework, and (2) whether such a reduction will meet the Lake Erie Ecosystem objectives[2].

In general, the SAB finds that, while the models that were used in the analysis vary in complexity, and not all incorporate the same level of process dynamics, their congruence provides sufficient confidence in the stated recommended target P load. A 40% reduction represents a major and substantial decrease in phosphorus inputs, but is in keeping with reductions deemed necessary in other aquatic environments suffering similar ecosystem impairments (e.g., Chesapeake Bay, Tampa Bay); therefore, by comparison this does not seem out of line in terms of the recommended magnitude of the reduction.

Drivers of Cyanobacteria Growth and Seasonal Hypoxia

The principal driver for these models and their results is that phosphorus loading stimulating primary production leading to excessive algal growth, harmful algal blooms and the production of cyanobacterial toxins, principally microcystin – for which the World Health Organization (WHO) drinking water limit is 2 ppb. Concentrations of microcystin have reached in excess of 1,200 ppb in the Western Basin of Lake Erie. While the target load reductions appear adequate to reduce cyanobacterial blooms, they do not ensure that toxin levels will be reduced to levels that no longer pose health threats. The controls on toxin production are not well understood and represent an important research need.

A secondary effect of excessive algal growth is the rapid deposition of algal-derived, labile detrital organic matter that drives elevated oxygen consumption leading to the formation of extensive zones of hypoxic hypolimnetic waters in the central basin of the lake during thermally stratified summertime conditions.

The relationships developed between P loads and ecosystem response indicators (ERIs) are inherently approximate, variable and relatively uncertain. This is, in part, due to the relative simplicity of the models in attempting to reproduce a very complex ecosystem having a very large degree of natural biological and hydrodynamic variability. Clearly not all processes are modeled, and the process modeling is not always conducted at a level of temporal and spatial resolution that would resolve all the active dynamics. Some processes and dynamics are missing. However, the basic relationship between phosphorus loading and algal production, though highly variable and likely influenced by other biogeochemical processes, is deemed central and definitive for Lake Erie. Most telling in this regard is the simple observation of a direct relationship between extent of cyanobacterial blooms and the spring phosphorus loading to the Western Basin (see Stumpf et al. 2012, and subsequent data). A notable example is the dramatic difference between 2011 and 2012 blooms. The 2011 bloom was the largest on record until 2015. In 2012, the spring P load was approximately one sixth of the 2011 P load and the corresponding 2012 bloom was only about 10% of the 2011 observation. The Lake Erie system clearly appears to respond to changes in P loading with a strong correlation generally captured by the models. It must be recognized that other biogeochemical processes, including nitrogen and silica cycling, are

[2] The desired thresholds identified for eutrophication response indicators in Lake Erie were: (1) Western Basin cyanobacteria bloom biomass no less than that observed in 2004 or 2012, nine years out of ten, and/or reduced risk of nearshore localized blooms; and (2) Central Basin hypoxia August – September average hypolimnetic dissolved oxygen concentration of 2.0 mg/L or more (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015).

important. However, the SAB finds that setting phosphorus loading as the initial driver in the Lake Erie system is appropriate and is consistent with the evidence. The SAB notes that some of the process models do include other nutrients (nitrogen and silica) and other algal speciation and as such do not totally rely on P loading to drive the system. In fact, nitrate concentrations in the Maumee River have actually been dropping and the relationship between P and N is not one of simple stoichiometry. Taking a dual nutrient management approach in Lake Erie clearly warrants investigation, and is currently limited by a lack of data, primarily on N cycling. The algal community in Lake Erie should be characterized to better understand the relative contribution of N-fixers versus non-fixers. The role of both N-fixation and denitrification in nitrogen cycling and nitrogen budgets in the system should also be assessed. This will inform both the question of N limitation and the potential impact of nitrogen reduction strategies (i.e., if N is low, it might stimulate N-fixing species).

The forms of P coming off the landscape are also critical to changes within the Lake Erie system. While TP load has not changed significantly (i.e., there has been no long term trend up or down, even though year to year variation has been high), the fraction of this TP that is "bioavailable" has increased significantly in the last 20 years. This appears to be one of the drivers of cyanobacterial growth, although it should be noted that "turning off" SRP (soluble reactive phosphorus) in the models does not result in the elimination of cyanobacteria (i.e., particulate phosphorus also plays a role in cyanobacterial growth).

The timing of nutrient inputs is also important to cyanobacterial blooms. It would be useful to evaluate whether there has been an increase in sensitivity of blooms to nutrient inputs over time and to recognize how the critical spring period may change or shift in the future.

Uncertainties in predictions of hypoxia are considerably larger. This is due to the fact that the extent and dynamics of hypoxia are confounded by many factors including physical processes, as well as biological processes such as the extent of the winter bloom. Furthermore, whereas the connection between P loads and algal production is relatively direct, the connection between P loading and central basin hypoxia is not. Hypoxia is propagated through several functions from P loading to algal production to rapid deposition of algal detritus to benthic metabolism and respiration to oxygen depletion and hypoxia and the potential flux of SRP (and dissolved inorganic nitrogen) from the sediment bed during hypoxic events. These functions, in turn, are heavily modified by thermal stratification driven by both short term physical mixing and long term regional climate change. Hence, the lack of a tight relationship between P loading and hypoxia is to be expected, since (in the words of Professor Clifford Mortimer of the Center for Great Lakes Studies at the University of Wisconsin-Milwaukee) "many other spoons stir the pot." These processes may influence whether hypoxia targets are achievable, and certainly impact the ability of the models to capture the dynamics of hypoxia and predict a robust relationship between phosphorus loading and oxygen depletion in the central basin. Better parameterization of benthic metabolism and sediment oxygen demand is necessary as well, through inclusion of explicit sub-models of sediment diagenesis.

One current weakness of the hypoxia simulation models derives from the fact that the process models, while run for multiple years, have only been run as one year simulations using the same initial boundary or starting conditions in each case. This means that the development or accumulation of a forwarded residual or "legacy" phosphorus or organic matter over time is not currently simulated. This accumulating residual would affect the response time of the system to a reduction in loading. This response time is probably related to the residence time of metabolizable material and the build-up of reduced chemical species in the sediments that may prolong hypoxia. In some systems this has resulted in a lag in response to loading reductions on the order of years (Jeppesen et al. 2005; Matzinger et al. 2010).

The rationale for an August-September hypolimnetic oxygen tolerance of 2 mg/L, as opposed to a more stringent 4 mg/L which would require a greater P load reduction, is described in the document *Recommended Phosphorus Loading Targets for Lake Erie* (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). Given the uncertainties in the hypoxia simulations the SAB finds that 2 mg/L is a reasonable initial target. It should be noted, however, that the water quality standard of 5 mg/L will, almost certainly, not be met in Central Basin bottom waters even with a 40% reduction of P loading, and the predicted hypoxic area ranges from approximately 2,000 to nearly 6,000 km^2 for periods in excess of a month. The SAB recommends that the WLEEM be deployed for the whole lake in order to better understand how to address the issue of hypoxia.

Missing Components of the Models

The Modeling Subgroup acknowledged that some of the simulation models had missing components (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup 2016). Undoubtedly missing components reflect a variety of processes that are absent or minimally incorporated into the models – although some models are capable of including these in future renditions. Such components include:

- Temporal variability in the underlying hydrodynamics (e.g., strength and propagation of the Detroit River plume in controlling the water residence time and flushing of the western basin);
- Variations and the vagaries of weather for which the models have no simple means of inclusion;
- The role of nitrogen limitation, denitrification and nitrogen fixation;
- The controls of algal toxin production (not all *Microcystis* produces toxin, and there is some indication that N may play a role);
- The internal phosphorus loading and resuspension and sediment-water interactions in general – although the WLEEM model does include a diagenetic submodel based on a 10-cm thick sediment mixed layer (The SAB finds that a 10-cm thick sediment mixed layer may be too deep approximately 5 cm would seem to be more appropriate and in agreement with radionuclide chronologies); (e.g., Robbins et al. 1977) **<<DFO Note: can additional references be included?>>**
- Role of dreissenid mussels, the populations of which are likely not in steady state;
- Changes in seasonality (e.g., the timing in load delivery and how that is tied to activities in the watershed such as fertilizer application and tillage;
- Changes in the response of cyanobacteria and other algal species to TP over time (there is clear evidence that the system has and is shifting and that recent blooms are fundamentally different from those experienced in the 1970s); and
- Incorporation of winter-spring diatom blooms under the ice.

All of these issues were discussed to varying degrees by the experts who attended the SAB Lake Erie Phosphorus Objectives Review Panel meeting on June 21-22, 2016. Model predictions could be improved by undertaking work to incorporate these missing components. In particular, the SAB notes the importance of extending mechanistic models to include sediment diagenesis and nutrient flux (and refine the depths of the active layer) and incorporating the influence of winter blooms into the models. Consideration should also be given to embedding a *Cladophora* model within the whole lake WLEEM model (the SAB's findings and recommendations concerning *Cladophora* growth are discussed in the response to Charge Question 3).

Importance of Climate Change

It has also been well recognized that, because of climate change, management practices put in place today may not result in the same ecosystem outcomes in the future (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015; Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup 2016). The Task Team has indicated that achieving flow weighted mean concentrations (FWMC) objectives for TP and SRP is expected to result in phosphorus loads below targets 90% of the time (i.e., 9 out of 10 years) "if precipitation patterns do not change" (Great lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). The Lake Erie region is projected to be both warmer and wetter in the future. As outlined by Bosch et al. (2014), projections of climate change scenarios include:

- Increased precipitation (~10-20%);
- Increases in the frequency of intense precipitation events (important in a system that is event driven and where perhaps 70% or more of the loading from the watershed occurs in 10-15 days);
- Expanded summertime conditions, longer growing season;
- Prolonged thermal stratification and hypolimnetic sequestration;
- Changes in regional climatology and wind fields;
- Changing lake levels, which in Lake Erie have the potential to significantly change the thickness of the hypolimnion and its oxygen carrying capacity;
- Changes in ice cover – including extent, duration and timing; and
- Watershed changes (e.g., increases in crop production due to increased precipitation and atmospheric CO_2; increases in evapotranspiration rates, which in some systems actually is projected to decrease runoff; and changes in soil microbial activity).

The SAB notes that some of the models used by the Task Team to predict the response of selected eutrophication response indicators to phosphorus loading (e.g., WLEEM) are capable of incorporating elements of climate change scenarios.

Effects of Nutrient Load Reductions on Fish Production

Experts who attended the SAB Lake Erie Phosphorus Objectives Review Panel meeting on June 21-22, 2016 noted the concern of some resource managers that P load reductions could have a detrimental effect on fish production. To the contrary, reductions in P loading could shift algal speciation in favor of more palatable species and may in fact enhance the food web by restoring a trophic pathway to secondary and tertiary production. At present, much of the primary production (cyanobacteria) in Lake Erie probably represents an ecological dead end (i.e., it does not enter the food chain, but simply goes to sink). Alterations in fish habitat also have an effect on fish abundance, but this effect is not well understood.

Appropriateness of the Phosphorus Load Targets

In general, the SAB finds that, based upon the coupling of a state-of-the-art suite of models to a relatively long term observational record, a conservative estimate of a 40% reduction in TP load ***<<DFO NOTE: should this indicate that the load reduction is to the Western and Central Basin?>>***, *at a minimum*, projects a response which improves water quality and reduces HABs in keeping with the stated goals in the Task Team report (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). However even with this reduction, blooms will still occur relatively frequently, perhaps even routinely, in the western arm of the western basin in Maumee Bay. Ultimately, greater load reductions may be necessary to achieve the desired thresholds for the ERI's. Attenuation of hypoxia is more problematic, with a higher degree of uncertainty. The recommendation that the 40% reduction be applied "across the board" also makes sense in both practical and equitable terms.

Lake and tributary monitoring is critical for continued development of the models and for adaptive management. Lags in indicator response and inter-annual trends can only be elucidated accurately with an adequate monitoring program in place. In particular, monitoring of the 11 priority tributaries identified by the Annex 4 Objectives and Targets Task Team is essential and should include measurement of: flow, nitrogen species (good *in situ* NO_3 sensors are available for high temporal resolution sampling), phosphorus (all forms) and organic carbon (dissolved organic carbon, DOC, and particulate forms). Event based sampling (to capture the effects of the rising and falling limb) within these systems is also critical for calculating loads.

The SAB also finds that linking the in-lake models to models of nutrient loading in the watershed is essential, and is underway in some regions. The inclusion of these landscape models is an inescapable necessity since it is actions and practices on the land that will enable a 40% load reduction ***<<DFO NOTE: Should this indicate that the load reduction is to the Western and Central Basin?>>***. In this regard, is also important to characterize the effectiveness of best management practices (BMPs) with respect to spatial distribution, type of BMP and life cycle effectiveness.

Key Recommendations

- A conservative estimate of a 40% reduction in TP load ***<<DFO NOTE: Should this indicate that the load reduction is to the Western and Central Basin?>>***, *at a minimum*, projects a response which improves water quality and reduces HABs. However, continued research and monitoring is needed to reduce uncertainty.

- Lake and tributary monitoring is critical for continued development of the models and for adaptive management. Lags in indicator response and inter-annual trends can only be elucidated accurately with an adequate monitoring program in place. In particular, monitoring of the 11 priority tributaries identified by the Annex 4 Objectives and Targets Task Team is essential and should include measurement of: flow, nitrogen species (good *in situ* NO_3 sensors are available for high temporal resolution sampling), phosphorus (all forms) and organic carbon (dissolved organic carbon, DOC, and particulate forms). Event based sampling (to capture the effects of the rising and falling limb) within these systems is also critical for calculating loads.

- Mechanistic models should be extended to include sediment diagenesis and nutrient flux. The depths of the active layer should be refined (e.g., 10 cm is too large - the depth may be 5 cm or less).

- The WLEEM should be deployed for the whole lake in order to better understand how to address the issue of hypoxia.

- Consideration should be given to embedding a *Cladophora* model within the whole lake WLEEM model.

- Simulations should be run continuously over a period of years as an extended sequence rather than resetting initial conditions every year.

- A better understanding of the influence of winter blooms (under ice phenomena) should be developed and incorporated into the models, particularly for hypoxia in the Central Basin.

- The algal community should be characterized to better understand the relative contribution of N-fixers versus non-fixers. The role of both N-fixation and denitrification in nitrogen cycling and nitrogen budgets in the system should be assessed. This will inform both the question of N limitation and the potential impact of nitrogen reduction strategies (i.e., if N is low, it might stimulate N-fixing species).

- The effectiveness of BMPs should be characterized with respect to spatial distribution, type of BMP and life cycle effectiveness. This is a large effort, but it is needed if action plans and adaptive management are to be effectively implemented.

3.2. Cladophora Growth

In its charge to the SAB, the EPA has indicated that additional phosphorus load reductions may be necessary to reduce nuisance levels of *Cladophora* in the nearshore waters of the Eastern Basin of Lake Erie. The SAB was asked to comment on whether scientifically sound phosphorus load reduction recommendations could be developed to address *Cladophora* growth at this time. In responding to this charge question, the SAB considered available information about *Cladopohora* ecology, its occurrence in Lake Erie, the ecosystem consequences of *Cladophora* blooms and capabilities of the Great Lakes *Clodophora* Model.

3.2.1. Development of Recommendations to Address Nuisance Levels of *Cladophora* Growth

Charge Question 3. Can scientifically-sound phosphorus load reduction recommendations be developed at this time that will reduce Cladophora growth in the Eastern Basin of Lake Erie?

The SAB finds that scientifically sound phosphorus load reduction recommendations to reduce *Cladophora* growth in the Eastern Basin of Lake Erie cannot be developed at this time. There is insufficient information to understand and weigh the relative importance of environmental factors (including P inputs) that might have causal links to *Cladophora* growth and senescence. Moreover, there are limited observations of the spatial extent of a perceived *Cladophora* problem that seems to have been identified at sites along the shores of the Eastern Basin of Lake Erie. That said, the issue of nuisance *Cladophora* growth in nearshore regions has been identified as a universal issue in the Great Lakes because it affects selected sites in each of the Great Lakes (Auer et al. 2010).

Basic Ecology of Cladophora

Cladophora glomerata is a macroscopic, filamentous, branched green alga (Chlorophyceae) that usually grows attached to hard benthic substrates in a variety of lakes, streams and rivers worldwide (Wehr et al. 2015). This alga can grow in such profusion that it forms extensive, dense mats achieving several meters in length. The occurrence of this alga is usually associated with ample nutrients (Dodds and Gudder 1982; Higgins et al. 2008). There is experimental evidence that *Cladophora* grows best under high concentrations of both N and P (e.g., Rosmarin 1982). Experimental enrichment of both N and P performed *in situ* in Lake Michigan has led to extensive growth of *Chaetophora*, a close relative to *Cladophora* (Carrick and Lowe 1988; 2007).

Occurrence of Cladophora in Lake Erie

Occurrences of *Cladophora* were reported in the Great Lakes as early as 1930 (Neil and Owen 1964). The distribution of *Cladophora* appeared to expand through the Great Lakes from 1960 - 1975, and this was attributed to large nutrient inputs in the nearshore regions of Lakes Huron, Michigan and Erie with biomass ranging from 100 - 800 g dry weight/m^2 (Auer et al. 1982). While the biomass declined during the 1970s and into the early 1980s coinciding with the P abatement programs in the Great Lakes, its abundance underwent a surprising upturn again in the mid-1980s and early 1990s (Higgins et al. 2008). More recently, standing crops up to 700 g dry weight *Cladophora glomerata* /m^2 have been observed in shallow nearshore waters (0.5 – 2 m depth) along the northern shore of the Eastern Basin; its occurrence in this location may be linked to the presence of suitable hard substrate as well as other factors. Interestingly, hard substrate also supported colonization of dense populations of dreissenid mussels (*Dreissena polymorpha* and *Dreissena bugensis*), which may exacerbate the growth of *Cladophora* by increasing water clarity and enriching local regions with excreted nutrients, especially readily available P as SRP (Heath et al. 1995). Increased water clarity allowed *Cladophora* populations to develop to depths up to 20 m. Recent studies indicate that tissue content of P (i.e., P-quota) is an important metric of growth potential of this alga: tissue of <0.07 µg P/mg dry weight is unproductive; tissue of >0.20 µg P/mg dry weight is considered to be highly productive, capable of producing significant biomass, likely leading to significant sloughing and formation of large amounts of "beach muck" upon decomposition. The levels of P storage in algal tissues appear to be useful indicators of aquatic ecosystem eutrophication and thus subsequent remediation (Price and Carrick 2016).

Ecosystem Consequences of Cladophora Blooms

Cladophora often plays a key role as an "ecosystem engineer" with both important positive influences as well as potentially negative consequences. This alga can serve as a substrate for adnate[3] algal and bacterial assemblages, which may also contain invertebrates (Lowe et al. 1982; Chilton et al. 1986). While it may not be fed upon directly by invertebrates and fish, as substrate it provides food for upper trophic levels indirectly. It is generally found in shallow, nearshore environments where turbulent wave action is common. Because of its turbulent environment, filaments frequently break or slough off,

[3] Botanical term meaning growing closely attached.

forming mats that can wash ashore and decay to a smelly mass (”beach muck”). The processes that lead to sloughing and decay of the standing crop are not well understood, and a recent workshop (Lake Erie Millennium Network 2016) identified *Cladophora* senescence and decay as a necessary research topic. As this “muck” decays, it gives off noxious odors, and provide a habitat for biting flies and a substrate for *E. coli* and the bacterium responsible for avian botulism. Because of its ability to scavenge and store excess phosphorus, it has often occurred as a nuisance alga, capable of growing to large standing stocks, leading to beach fouling as large stands of “muck.” Although there is no stated limit of acceptable standing crop, it is generally considered that 30 g dry weight /m^2 is indicative of “good” conditions.

The Great Lakes Cladophora Model (GLCM)

The Great Lakes *Cladophora* Model (GLCM) is a mechanistic, mass balance model with two state variables, net algal biomass (growth minus respiration and sloughing) and stored P. The forcing conditions are available SRP, incident light intensity and temperature (see Appendix B-9 of Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup 2016). The model was calibrated by direct observation in the field (Lake Huron) and laboratory studies; it was confirmed by comparing observations in Lake Michigan with fit-to-model predictions. Sensitivity analysis showed that the model was most sensitive to the minimum cell P-quota, the maximum growth rate and the maximum respiration rate; it was marginally sensitive to parameters related to phosphate uptake. Model curves for SRP vs. maximum standing crop and SRP vs. stored P content show that SRP of 0.9 µg P/L would yield a maximum standing crop of 30 g dry weight/m^2 and a stored P content of 0.075 percent P. That is, 0.9 µg P as SRP/L would yield an acceptably low standing crop and low growth potential for *Cladophora*. This level of SRP was related to TP concentrations and total P load to Lake Erie via load-response curves derived empirically (Figures B9-2 and B9-3 in Appendix B-9 of Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup 2016) to imply that the *Cladophora* growth and P-quota could be met with a TP load reduction to 7,000 MT/year, or a load reduction of 25 percent. Because the goal of 40 percent reduction in TP load to Lake Erie appears to be necessary to attain other desired ERIs, the implication of the GLCM is that by meeting those goals, the goal of reduced *Cladophora* growth would also be met.

The GLCM appears to provide first order evaluation of *Cladophora* occurrence and initial predictions regarding attainment of the ERI of reduction of *Cladophora* standing crops to acceptable levels with little growth potential, as indicated by P-quota. However, research must be completed to fill knowledge gaps (listed in the key recommendations below) before recommendations for phosphorus load reductions to reduce *Cladophora* growth can be developed with an adequate level of certainty and scientific confidence.

Key Recommendations

- The GLCM was calibrated and confirmed on Lake Huron-Michigan. It should be calibrated and confirmed in the Eastern Basin of Lake Erie using existing data because there are significant differences between Lake Erie and the lakes on which this model was developed.

- *Cladophora* growth may be linked to SRP content in the overlying water column. The presence of SRP is linked to the swift turnover of TP levels in the open lake (as modeled in the GLCM) but also to local inputs from nearby tributaries, as well as the presence of dreissenid mussels (Higgins 2004).

A scientifically-sound model must incorporate site-specific factors, including local hydrodynamics. Current and future studies should include investigation of P load inputs from key tributaries (e.g., the Grand River, Ontario) and the relative significance of local inputs and open Lake P on stimulating and supporting *Cladophora* growth**.**

- The GLCM specifically focuses on *Cladophora* as the only issue of concern. However, the model would be more useful if it could be applied to the diversity of benthic algae that are important in the Great Lakes, thereby extending the usefulness of the model to other nuisance benthic algae (e.g., *Chara, Lyngbya, Spirogyra,* etc.) that can cause similar problems. The similarities and differences among these various species need to be considered in order to provide an adequate representation of the problems of nuisance benthic algae in general.

- The nuisance attribute of *Cladophora* is largely the formation of "beach muck" and the attendant problems that arise from it. The formation of "beach muck" is initiated by sloughing of standing crops of the benthic alga. The GLCM provides only a crude estimate of this process, modeling sloughing as a constant coefficient of the calculated standing crop. The process or processes that lead to sloughing (local hydrodynamics, algal senescence, etc.) and eventual decay to "beach muck" need further investigation and likely need to be appended to the GLCM. A spatial model was linked to remote sensing information to better understand cyanobacterial HABs. Perhaps a similar approach could be taken with regard to *Cladophora* to capture information on spatial coverage.

- The GLCM should be included in a broader whole-lake model to forecast the likelihood of *Cladophora* growth along the shores. Consideration should be given to the possibility that as hazardous algal blooms abate, the likelihood of *Cladophora* growth along the shores may be increased due to improvements in water clarity and colonizable habitat.

3.3. Nitrogen Control

The current nutrient strategy for Lake Erie focuses on limiting phosphorus loading to the Lake. However, the Task Team has also recommended tracking tributary nitrogen loads to the lake. The EPA has asked the SAB to provide recommendations to help determine whether consideration of nitrogen control is warranted.

3.3.1. Determining Whether Nitrogen Control is Warranted

Charge Question 4: What recommendations can the SAB provide for development of an approach to help determine whether consideration of nitrogen control, in addition to phosphorus, is warranted in Lake Erie to prevent harmful algae blooms and manage hypoxia? In particular, what questions, relationships, or research priorities related to nitrogen loading (different forms and sources) and in-lake cycling must be addressed?

While the focus in Lake Erie has been phosphorus reduction because it is considered the limiting nutrient, there are good reasons to include nitrogen as part of a dual (N + P) nutrient strategy. Phytoplankton species composition and seasonal succession can vary with both N and P concentrations and ratios, and some may experience co-limitation of N and P. The western Lake Erie phytoplankton species composition has changed over time, likely reflecting changes in N and P inputs and cycles due to changes in agriculture, the invasion of dreissenid mussels, climate change and other causes (Smith et al. 2015). N and P cycles are both coupled and uncoupled. Both nutrients are required in algal biomass in roughly Redfield ratios (106:16:1 C:N:P), but are cycled differently through the environment. N can be internally removed by a number of biotic and abiotic processes including: denitrification, anaerobic ammonium oxidation (anammox), dissimilatory nitrate reduction (DNRA) and ammonia volatilization. Nitrogen cycling is likely influenced by the presence of dreissenid mussels (Svenningsen et al. 2012) and this may in turn affect N:P stoichiometry and availability for phytoplankton and macroalgae. Nitrogen can also be biologically fixed. In contrast, P is only advected in or out of the system or buried. Therefore, rates of internal N and P cycling are important, as well as the loading rates. The treatment of N cycling in current Lake Erie models is limited to three models and none address internal N and P pools, fluxes and ratios. Agricultural Best Management Practices (BMPs) for P control may help control N but may not be sufficient. The Mississippi River Basin may be a useful model for additional BMPs to control N.

Need for a Multiple Nutrient Strategy

There is increasing support for adopting a multiple nutrient strategy to reduce eutrophication, in both fresh and salt waters (Conley et al. 2009; U.S. EPA 2015). For Lake Erie, this means that N and P control should be considered, as is done in the Baltic Sea (Conley et al. 2011), after initial consideration of P only. Many documents urge additional control of external P loading in the Lake Erie watershed (e.g., Stumpf et al. 2012; Michalak et al. 2013; IJC 2014; Scavia et al. 2014; Dove and Chapra 2015; Powers et al. 2015); however, there is mounting evidence that N control is also needed (Chaffin et al. 2013; Davis et al. 2015). The toxic cyanobacterium *Microcystis*, the major concern in western Lake Erie, does not fix nitrogen and so requires a fixed nitrogen source. *Microcystis* can become nitrogen limited in late summer in western Lake Erie (Chaffin et al. 2013). In addition, it becomes more toxic under nitrogen replete conditions (Harke et al. 2016). Furthermore, *Microcystis* is very good at scavenging low levels of phosphate. It can use alkaline phosphatase to hydrolyze phosphate esters and other readily-utilizable P compounds and thrives offshore in lower phosphate environments (Harke et al. 2016). While nitrate is the predominant form of nitrogen in Lake Erie and is highly mobile, there are also lower levels of ammonium and other reduced nitrogen compounds (Chaffin et al. 2013) in the Lake. Since these can be readily used by most cyanobacteria, they could be significant contributors to blooms, even at low concentrations.

The Maumee River drains a mostly agricultural watershed and discharges into the Western Basin of Lake Erie, where annual cyanobacterial blooms have occurred since the mid-1990s. Stow et al. (2015) document a decrease in total nitrogen (TN) load from the Maumee River since 2000, despite concurrent increases in discharge. They also provide evidence for decreased inputs in summer months (May-July) in recent years, and seasonal shifts in the TN:TP ratio (decrease in March-April; increase in September-November). Recent cyanobacterial blooms in the Western Basin are fundamentally different from those occurring in Lake Erie prior to P load reductions implemented in the 1970s. While most blooms prior to the 1990s were comprised of filamentous, heterocystous cyanobacteria (e.g., *Aphanizomenon*, a potential nitrogen N-fixer), the modern blooms are comprised mostly of the non-N-fixing genera *Microcystis* (Steffen et al. 2014). The inability of these cyanobacteria to fix atmospheric N suggests an important role for external N loads from the watershed as well as an essential role of internal N recycling mechanisms in modulating the total biomass and especially the composition of the cyanobacteria community in the Western Basin. In addition, the toxin produced by *Microcystis* (and other cyanobacteria), microcystin, contains a large proportion of N (10 N atoms per molecule), and production of microcystin is strongly correlated with available N (Davis et al. 2015). This apparent N problem in Lake Erie is not confined to the *Microcystis* blooms in the western basin. Indeed, algal blooms in other parts of the Lake, including annual *Planktothrix* blooms in Sandusky Bay (Davis et al. 2015) and ongoing blooms of *Cladophora* (Davies and Hecky 2005), also involve non-N-fixing algae.

Limitation of N can cause a switch from *Microcystis* to *Anabaena*. Thus, if N concentrations increase, the persistence of *Microcystis* blooms could increase even if P concentrations are lowered. In addition, both inorganic and organic nitrogen species can be important. Davis et al. (2010) found that growth of the toxic *Microcystis* strains were enhanced by inorganic nitrogen whereas the non-toxic strains were stimulated by organic nitrogen. Moreover, Zhang et al. (2015) found that microcystin production appeared to be regulated by total N and NO_3 but not by NO_2 or NH_4. Many phytoplankton physiologically respond more to N:P than to either N or P separately. Numerous studies have shown that the combination of N and P often results in higher cyanobacterial biomass than either nutrient added singularly (e.g., Elser et al. 2007; Lewis and Wurtsbaugh 2008; Scott and McCarthy 2010, 2011). With increasing frequency since 2002 there have been reports of the algal blooms being N and P co-limited or N limited, especially during mid- to late summer. Also, increased availability of P from both external and internal sources can enhance N limitation, especially under conditions where biological N_2 fixation is not possible.

Model Capability

The model descriptions in the draft Annex 4 ensemble modeling report suggest that among the eight models used to predict ERIs (not including the Cladophora model), only the Ecological Model of Lake Erie (EcoLE), Western Lake Erie Ecosystem Model (WLEEM) and Estuary and Lake Computer Model – Computational Aquatic Ecosystem Dynamics Model (ELCOM-CAEDYM) include state variables for nitrogen. None of the models appear to address internal accumulations of N and P by phytoplankton and corresponding N:P ratios, which could be used to explore possible N-loading scenarios.

Best Management Practices

The Maumee Basin is characterized by extensive row crop agriculture with tile drainage as well as concentrated animal feeding operations. Best Management Practices (BMPs) for P control often target sediments because much P is in particles. N, especially nitrate, is mostly dissolved and much more mobile, so additional BMPs may be required to increase N removal. The agricultural activity of the Mississippi River Basin leads to the hypoxia in the Gulf of Mexico. Studies of the Mississippi should provide useful BMPs for the Maumee Basin. Mississippi River N loading is predominantly from fertilizer and P loading is predominantly from animal waste (Alexander et al. 2008). There is some evidence that P loads from agricultural lands in Iowa have declined as a result of the implementation of best management practices (Wang et al. 2016).

In order to evaluate the importance of nitrogen control in Lake Erie, research is needed to answer key questions and understand important relationships. These are listed in the key recommendations provided below.

Key Recommendations

- Research should be conducted to determine the total N loadings entering Lake Erie over time and space, including all the major species of nitrogen, oxidized, reduced, organic and particulate, including flow-weighted mean concentrations (FWMC). An N budget should be developed for Lake Erie, especially the Western Basin, similar to that for Lake Michigan (Han and Allan 2012). Dissolved organic or non-reactive P (DNP) in Lake Erie and tributaries should also be further investigated.

- Research should be conducted to determine: 1) how much of the external N loading can be removed by internal removal process like denitrification, dissimilatory nitrate reduction to ammonium (DNRA), anammox, ammonia volatilization and burial; 2) the consequences of legacy N and P in the sediments and the differences in internal cycling; and 3) the downstream consequences of not following a dual nutrient strategy.

- Research should be conducted to further understand: 1) the importance of concentrations and ratios of nitrogen to other nutrients (P, but also Si) in directing or controlling ecosystem functions, such as nutrient cycling, primary production, species composition and toxin production; and 2) the balance in the ratio of N to P that would be best for ecosystem functioning. Much is already understood about these topics.

- Research should be conducted to show the reliability of current models for assessing the role of nitrogen in Lake Erie eutrophication and whether the models can be improved (or new models developed) to more completely incorporate N including internal N and P pools and ratios.

- Research should be conducted to understand the expected response of the four eutrophication response indicators to N reduction in the improved models.

- BMPs should be developed or applied to achieve additional N reduction in Lake Erie if needed. Given the difficulty and expense of controlling and reducing N loadings, it is important to optimize ecologically and economically the N sources to be reduced.

- Lessons learned from case studies of nutrient reduction in the Baltic Sea and other areas should be applied to Lake Erie. This could include scientific, technical, policy and governance strategies. An obvious lesson would be to standardize monitoring protocols among the different groups involved.

3.4. Evaluation of Nutrient Reduction Targets

The EPA has learned that the inter-annual loading targets for the Maumee River are greatly influenced by annual variability in flows. The Task Team identified a maximum flow below which the target load should be met and recommended the use of flow-weighted mean concentrations (FWMC) as a benchmark for any given tributary load. The SAB was asked to comment on the use of FWMC and any other approaches that should be considered to account for inter-annual variability in hydrology in assessing progress in reducing tributary loadings of phosphorus.

The Task Team also recommended development of a comprehensive adaptive management program that would include annual routine monitoring of appropriate load, FWMS and in-Lake nutrient eutrophication response indicators in conjunction with an intensive monitoring, research and operational model application program every five years. The SAB was asked to comment on the adaptive management approach.

3.4.1. Assessing Progress in Reducing Tributary Loadings of Phosphorus

Charge Question 5. Please comment on the use of FWMC and any other approaches that should be considered to account for inter-annual variability in hydrology in assessing progress in reducing tributary loadings of phosphorus to the Lake.

Flow Weighted Mean Concentrations (FWMC) are recognized as a useful means to address inter-annual variability by normalizing the tributary phosphorus loading/delivery with respect to flow so that year-to-year performance (referring to nonpoint source nutrient controls) is not confounded by inter-annual hydrology (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). The Task Team recommends using tributary FWMC as a benchmark to track progress in load reduction. The SAB recommends reviewing all available tributary monitoring outputs (e.g., discharge, flow, concentrations, loads) and multiple assessment approaches (including FWMC and flow-adjusted concentrations) to evaluate efforts to control nutrient loadings. In addition, uncertainty in the values derived using the flow-weighted or flow-adjusted approaches should be explicitly quantified and presented, and detailed information on the implementation of phosphorus reduction strategies should be collected to help explain patterns observed in the future.

The use of FWMC analyses alone may “mask” elevated concentrations that could result in algal blooms. Any analysis of the effect of nutrient concentrations needs to consider the response of the organisms intended to be controlled. Nutrient concentrations (not loadings) control organism responses and the effect of temporal variability is an important consideration, especially for organisms that have rapid life cycles and may respond quickly to shifts in nutrients.

With the stratified sampling program typically used in loading studies (e.g., Heidelberg University’s monitoring of Ohio tributaries), each sample does not have equal weight in determining the average. Some samples may represent time intervals of one or more days, while others represent intervals of only a few hours. Some form of sample weighting must be used to properly average tributary data collected at such varying frequencies. In river systems, two types of mean concentrations can be considered: a time-weighted mean concentration and a flow-weighted mean concentration (FWMC). The FWMC is the preferred average for calculating concentrations in tributaries with variable flows. For example, FWMC can be used to represent the average TP concentration in water discharged from the Sandusky River to Sandusky Bay. To determine FWMC, the concentration in each sample is weighted by both the accompanying time interval and the flow. FWMC represents the total load for the time period (e.g., annually or March-July) divided by the total discharge for the same time period.

The Heidelberg Tributary Loading Program (Heidelberg University 2016) collects and analyzes approximately 450-500 water samples for pollutants at its monitoring stations each year. From that information it calculates annual pollutant loads from each station and the loads of nutrients, sediments and pesticides delivered to Lake Erie or the Ohio River. The Program makes the tributary data for most the monitoring stations publicly available, and also distributes a spreadsheet for data analysis that calculates FWMC along with loadings for the nutrient parameters (TP, SRP, NO_2+NO_3, Total Kjeldahl Nitrogen or TKN) measured, so FWMC is a readily available statistic. For pollutants that tend to increase in concentration as flow increases (like TP in the Maumee River), the FWMC will be greater than the time-weighted mean concentration.

FWMC is considered by the Task Team to be a key tool for nonpoint nutrient control efforts (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). FWMC has intuitive appeal because it is a concentration, which may be easier to understand and communicate than "mass loading." FWMC is also useful for developing tributary inputs appropriate for the advanced process-based models (WLEEM and ELCOM- CAEDYM) that require specification of both flow and nutrient concentration in each tributary, instead of the tributary or basin-aggregate mass loadings used by the simpler phosphorus mass balance models. An example showing how the FWMC approach can be implemented is presented by Sether et al. (2004). The authors used this method to compare annual load estimates of multiple water quality constituents across several subbasins, accounting for differences in average annual stream flow. Sether et al. (2004) also demonstrated an approach for calculating confidence limits for FWMC estimates, explicitly acknowledging the uncertainty of these estimates and recognizing that this uncertainty can influence how the results are interpreted in a management context. FWMC estimates for Lake Erie also should be accompanied by an appropriate quantitative estimate of their uncertainty.

Annual discharge from the Maumee River is highly variable due to variations in the intensity, amount and timing of precipitation. This variability is also an important factor leading to yearly differences in phosphorus loads. Similarly, discharge from spring to early summer (March-July) varies annually, and inter-annual variability during this period has been associated with variations in the size of the summer cyanobacteria bloom (Stumpf et al. 2012; Obenour et al. 2014); therefore, tributary loadings during this "critical period" merit particular attention. The Task Team has attempted to account for this confounding behavior by identifying a maximum flow below which the target load should be met and by recommending the use of FWMCs to track progress for any given tributary target load. Examination of Figures 9 (Maumee River discharge), 10 (TP FWMC and load) and 11 (DRP FWMC and load) in the *Recommended Phosphorus Loading Targets* (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015) suggests that similar trends are evident in FWMC and loading, especially for 5-year running averages. It appears that appropriate filtering (e.g., 5-year running average) is also a necessary component of assessing trends in Maumee River discharges, concentrations and loads. Although the Task Team's use of FWMC has focused on the Maumee River, the calculation should be considered for other Lake Erie tributaries that are monitored using stratified sampling programs.

The SAB notes that FWMCs are distinct from flow-adjusted concentrations (FACs), another tool that should be considered in assessing progress in reducing tributary loadings of phosphorus. FACs are the residuals from a statistical model relating concentration to discharge flow. FACs are used to remove the seasonality from tributary monitoring data, and for detecting annual trends in the data once seasonality is removed. For example, flow-adjusted concentrations were demonstrated by Stow and Borsuk (2003) to aid in assessment of nutrient TMDL implementation on the Neuse River. Helsel and Hirsch (2002) also provide information on the flow-adjusted concentration method.

Stow et al. (2015) note that Maumee River discharge increased from 1984-2013, a pattern that has been shown to be consistent with long-term precipitation increases. In order for FWMC to offer an honest assessment of progress in reducing tributary loadings of phosphorus to Lake Erie, the assessment must also consider the long-term trends in precipitation and discharge, and the FWMC benchmarks must be adjusted as necessary to compensate for such trends affecting nutrient loadings. Discussion by Stow et al. (2015) is particularly relevant regarding the use of FWMC or other approaches that should be considered to account for inter-annual variability in hydrology:

> "While it is generally acknowledged that targets may be exceeded during years of unusually high precipitation and tributary discharge, the use of load targets remains a common management tool. However, Milly et al. (2008) highlighted the growing recognition that, for variables such as tributary discharge, the assumption of stationarity, in an era of uncertain climate change, poses management challenges. Our results, indicating progressive precipitation and discharge increases in the Maumee River basin and concurrent phosphorus input increases to Lake Erie, suggest that imposing fixed load targets may require phosphorus concentrations to be persistently lowered to compensate for increasing discharge, if the targets are to be achieved. As phosphorus load targets are re-evaluated pursuant to the updated 2012 GLWQA, it may be appropriate to address the possibility that continued discharge increases into the future may affect target attainment even if phosphorus reduction strategies are successful. "

This statement highlights the need for future collection of detailed information on the implementation of phosphorus reduction strategies in each major watershed. Without this information, it will not be possible to adequately identify the primary reasons for the observed changes (or lack thereof) in phosphorus loads delivered to Lake Erie. This will limit the ability to adequately assess the effect of phosphorus reduction strategies in light of other confounding factors such as those related to climate change.

The SAB also notes that, as previously discussed, phosphorus may not be the only factor affecting algal growth in Lake Erie, as nitrogen, silica or other micronutrients may also affect algal growth. If the focus of the Task Team expands to consider the control of other nutrients, the same assessment approaches should be applied to tributary monitoring data for those nutrients to evaluate efforts to control sources of nutrient loadings.

Key Recommendations

- The SAB recommends reviewing all available tributary monitoring data (e.g., discharge, flow, concentrations, loads) and multiple assessment approaches (including FWMC and flow-adjusted concentrations) to evaluate efforts to control sources of nutrient loadings.

- Uncertainty in the values derived using the flow-weighted or flow-adjusted assessment approaches should be explicitly quantified and presented, and detailed information on the implementation of phosphorus reduction strategies should be collected to help explain patterns observed in the future.

- Detailed information on the implementation of phosphorus reduction strategies in each major watershed should be collected into the future. Without this information, it will not be possible to adequately identify the primary reasons for the observed changes (or lack thereof) in phosphorus loads delivered to Lake Erie.

- If the focus of the Annex 4 Objectives and Targets Task Team expands to consider the control of nutrients other than phosphorus, the same assessment approaches should be applied to tributary monitoring data for those nutrients to evaluate efforts to control sources of nutrient loadings.

3.4.2. Adaptive Management Program

Charge Question 6. Please comment on the value of applying the existing eutrophication models on an ongoing basis to periodically evaluate phosphorus loading targets and eutrophication response indicators. What key elements should be included in the adaptive management approach to successfully implement and evaluate our nutrient reduction goals for Lake Erie?

The SAB strongly endorses the development of an adaptive management program to implement and evaluate nutrient reduction goals for Lake Erie. This is particularly important given uncertainties in the present phosphorus-reduction targets with respect to the response indicators as well as the potential for changing conditions in the future. A key feature of adaptive management is the development of explicit alternative hypotheses and their associated conceptual models, which are then used to adjust management operations and to guide future monitoring and modeling efforts. The SAB provides the following recommendations for adaptive management.

1. A standing adaptive management committee should be appointed. The SAB recommends that the EPA formally appoint a standing adaptive management committee that is supported over the long-term. The committee should include technical experts (both academic and agency scientists) and be charged with coordinating ongoing modeling and monitoring to evaluate progress towards meeting loading targets and ERI's and developing a research program that investigates alternative hypotheses and long-term forecasts in order to inform future management decisions.

2. A coordinated long-term monitoring program should be developed. It is critical to provide support for long-term monitoring in order to assess whether loading and ERI targets are being met. In developing the monitoring program consideration should be given to:

   - Assessing available loading information and developing standardized protocols for loading estimates;
   - Maintaining current tributary monitoring capabilities and adding additional tributaries;
   - Developing standardized protocols for tracking ERIs (cyanobacteria; hypoxia; *Cladophora*);
   - Considering the potential for additional ERIs (i.e.. chlorophyll a, biological endpoints such as benthic organisms in hypoxic area and general fish productivity; measuring the health and diversity of fish communities (particularly Whitefish, *Coregonus clupeiformis*);
   - Ensuring that measurements are being made of those variables that are necessary for calibrating and validating the various models as well as for evaluating alternative hypotheses (see below).

3. Recommended models should be used as part of the adaptive management process. As previously indicated, it may not be necessary to run all of the models that were included in the ensemble

modeling effort. However, the SAB finds that models can be used as part of the adaptive management process to both identify and evaluate alternative hypotheses. They can also be used to identify data gaps and to run future scenarios. In particular the SAB recommends that:

- Models be used to make annual predictions of ERIs (cyanobacteria, hypoxia and *Cladophora*), and then conduct post-audits to evaluate these projections;
- Models be refined based on changing loadings and other new data;
- Estimates of uncertainty be improved in the models;
- Lake models be linked to upstream source functions via watershed models;
- Cases where models do not perform well be used to develop alternative hypotheses;
- Models be built into each of the hypotheses identified below, as appropriate.

4. Alternative hypotheses should be developed and tested. The null hypotheses being tested by the proposed phosphorus-load reduction target is that external P loading is not related to HABs, hypoxia, or *Cladophera* proliferation. A task for the adaptive management committee is to propose alternative causes for these ERIs and to assess what monitoring/modeling/experiments could be conducted to most effectively distinguish among them. This can be done using a more passive approach wherein hypotheses are modified and tested iteratively by adjusting design operations (sometimes called "monitor and modify") or by taking a more active approach such as setting up field manipulations to test competing hypotheses. The adaptive management options in Lake Erie will generally fall into the former category, although it may be instructive to use differences between tributaries or among the five Great Lakes when evaluating potential hypotheses. Ideally, the alternatives should be framed such that one can learn from either outcome.

   It is beyond the scope of this SAB report to develop a comprehensive list of alternative hypotheses for Lake Erie eutrophication. However, the SAB suggests the following potential hypotheses and provides an initial list of the accompanying research, monitoring and modeling tasks to address for each topic. We offer these as a starting point for further consideration and prioritization by the adaptive management committee. As part of this process, it would be instructive for the adaptive management committee to consider what the potential management response might be if a given alternative is found to be important.

Loading

Hypothesis: BMPs targeting P reduction do not affect N.
Research, monitoring and modeling:

- Compare N runoff in areas using different BMPs targeted at P control.
- Conduct small-scale experiments that quantify the efficiency of BMPs over space and time.

Hypothesis: Spatial and temporal application of BMPs affects P loading.
Research, monitoring and modeling:

- Link watershed models to in-Lake models and run a suite of scenarios to evaluate this hypothesis.

Cyanobacteria

Hypothesis: N is co-limiting cyanobacterial blooms.
Research, monitoring and modeling:
- Calculate N loading to compare with P (including N:P ratios).
- Monitor key N constituents in the tributaries.
- Run N scenarios in models; potentially develop new models.
- Evaluate the seasonal timing of N loading.
- Consider conducting *in situ* experiments (limno-corrals) to evaluate nitrogen limitations in the field.

Hypothesis: Cyanobacterial biomass is linked to toxin production.
Research, monitoring and modeling:
- Measure toxins in standardized, coordinated way.
- Evaluate correlations between POC, cyanobacteria and microcystin concentration.
- Develop model to explore relationships between P, N, phytoplankton community composition and implications for toxins.

Hypoxia

Hypothesis: The winter/spring diatom bloom is driving hypoxia (via oxygen demand).
Research, monitoring and modeling:
- Quantify diatom bloom.
- Evaluate relationship between diatoms and seasonal N, P and Si loading.
- Use models and empirical analyses to evaluate relationship between diatoms and hypoxia.

Hypothesis: Stratification (timing and magnitude) affects hypolimnion thickness, and is an important driver of DO response in the Lake.
Research, monitoring and modeling:
- Monitor temperature, discharge, wind and currents.
- Run model scenarios with varying stratification for a given P load.

Hypothesis: Accumulated SOD (legacy C) is an important contributor to hypoxia.
Research, monitoring and modeling:
- Develop an SOD model.

Cladophora

Hypothesis: Internal P release (reintroduction) from sediments, exacerbated by hypoxia, is an important source of P for *Cladophora*.
Research, monitoring and modeling:
- Monitor near-surface sediment concentrations, upper active mixed layer of sediments in the Western Basin.

Hypothesis: Dreissenid mussels promote *Cladophora* proliferation by providing substrate, increased light and nutrients
Research, monitoring and modeling:

- Monitor *Dreissenid* populations in the Central and Eastern Basins
- Compare light levels, N and P release in dreissenid beds (with and without *Cladophora* removed) and control areas.

Hypothesis: Near-shore sources of P are important drivers of *Cladophora* growth.
Research, monitoring and modeling:

- Improve on current *Cladophora* modeling to include nearshore processes.

5. Future scenarios should be evaluated. Part of the reason that the loading targets for phosphorus are being re-evaluated is because of the changing response of the Lake over the past few decades. As part of the adaptive management process, it will be important to understand the effects of climate variability and other factors that may change in the future (Smith et al. 2015). The SAB recommends that the adaptive management committee: (a) evaluate recent trends in the relationships between loading and ERIs for evidence of increasing sensitivity or changes in seasonality (e.g., March-July) or spatial patterns, and (b) develop a suite of future scenarios that can be explored using models.

   Potential scenarios that could be evaluated include:

   - Climate change: increased precipitation and discharge; increased temperature.
   - Anticipated changes in land use and population density.
   - Regional economic development.
   - Zero P input: with no additional load, how long will it take for internal stores of P to run out? This is not so much an anticipated future scenario as a way to establish an end member.
   - Combinations of the above that use integrated modeling approaches (e.g., combining watershed landscape and hydrology models with Lake models).

6. The work proposed here should be structured to provide answers to the following questions on an ongoing basis:

   - Are load reduction targets being met?
   - Are ERI's responding?
   - Are ERI's being predicted accurately? If not, what alternative hypotheses need to be considered?
   - Are there additional management measures that need to be considered based on additional understanding gained from evaluating alternative hypotheses?
   - Are the environmental and land use conditions changing or likely to change in the future? If so, what implications does that have for management?

In order to be in a position to address these questions the SAB recommends that the adaptive management committee meet regularly and establish concrete targets for identifying key variables to be monitored; deciding which alternative hypotheses are most important and what models/data are needed to accomplish this; and agreeing on forecasting scenarios. This requires a long-term institutional commitment to the process at the local and regional levels.

Key Recommendations

- A standing adaptive management committee should be appointed to develop a program that investigates alternative hypotheses and long-term forecasts in order to inform future management decisions.

- A coordinated long-term monitoring program should be developed.

- Recommended models should be used as part of the adaptive management process. Models can be used as part of the adaptive management process to identify and evaluate alternative hypotheses. They can also be used to identify data gaps and to run future scenarios

- Alternative hypotheses for Lake Erie eutrophication should be developed and tested.

- Future scenarios should be evaluated to understand the effects of climate variability and other factors that may change in the future.

- The proposed work should be structured to provide answers to key questions (e.g., are load reduction targets being met, are ERIs responding, are ERIs being predicted accurately) on an ongoing basis.

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APPENDIX A: THE EPA'S CHARGE QUESTIONS

Background

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)(i) of the GLWQA. Under Annex 4, the U.S. and Canada committed to address eutrophication issues in Lake Erie by first establishing phosphorus objectives, loading targets and allocations for the nearshore and offshore waters by February 2016, and subsequently develop phosphorus reduction strategies and domestic action plans by 2018. A binational workgroup of Lake Erie scientists used a suite of models to generate a series of load response curves in order to simulate the impact of phosphorus loads to cyanobacteria biomass, hypoxia and *Cladophora* growth, and identify the phosphorus reductions needed to meet the desired ecological condition for the Lake. EPA sought early SAB advice on the modeling approach in December 2014. The SAB's feedback was considered in the subsequent deliberations by the binational workgroup, and resulted in improved documentation of the uncertainties and sensitivities of the models. The U.S. and Canada released the recommended binational phosphorus reduction targets in June 2015 and sought public input during July and August. The phosphorus load reduction targets were accepted by the U.S. and Canada on February 22, 2016, as follows:

> *To minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie: a 40 percent reduction from 2008 loads in total phosphorus entering the western basin and central basin of Lake Erie – from the United States and from Canada – to achieve a 6,000 metric ton central basin load. This amounts to a reduction from the United States and Canada of 3,316 metric tons and 212 metric tons, respectively.*

> *To maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie: a 40% percent reduction in spring total and soluble reactive phosphorus loads from the following watersheds where localized algae is a problem: in Canada, the Thames River and Leamington tributaries; and in the U.S., the Maumee River, the River Raisin, the Portage River, Toussaint Creek, the Sandusky River, and the Huron River, OH.*

> *To maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the waters of the western basin of Lake Erie: a 40 percent reduction in spring total and soluble reactive phosphorus loads from the Maumee River in the U.S.*

Further reductions in phosphorus may be necessary to address benthic nuisance algal growth and shoreline impacts in Lake Erie's eastern basin. The Annex 4 Objectives and Targets Task Team will meet later this year to reconsider the viability of developing a target for the eastern basin, given the current state of the science on *Cladophora* and recent updates to the *Cladophora* growth model.

EPA is currently working with other federal, state and Canadian partners to develop a long-term plan that will identify the monitoring, data and analyses needed to support implementation and evaluation of these nutrient reduction goals as part of an ongoing, adaptive management approach. We are also working to develop a binational phosphorus reduction strategy and domestic action plans which will outline actions to be taken to achieve the targets.

Furthermore, a binational task team was formed under Annex 4 to initiate steps required to develop Lake Ontario nutrient targets. That team is currently assessing the status of nutrients and eutrophication impacts in Lake Ontario, identifying gaps in monitoring and modeling needed to support targets development. The Lake Ontario Nutrients Task Team will benefit from lessons learned and consideration of modeling approaches in Lake Erie.

Charge to SAB:

The EPA requests Science Advisory Board (SAB) review of the current modeling results and other information used to inform development of the binational phosphorus reduction targets. We are seeking a critical review so that we can ensure the Agency's ongoing efforts to develop, implement and evaluate nutrient reduction goals for Lake Erie are based on sound scientific data, analyses, and interpretations. In a spirit of adaptive management, we are most interested in SAB advice on enhancements to the modeling approach, or new approaches to consider, that will help us proactively manage eutrophication issues in Lake Erie in the long term.

Review Documents: The panel will review the following documents, which taken together explain the process followed to develop the binational phosphorus loading targets for Lake Erie:

- The Annex 4 Ensemble Modeling Report and Appendix B
- Recommended Phosphorus Loading Targets for Lake Erie: Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee. May 11, 2015

Additional Documents: The following documents (and associated references), provide important context and information related to our current efforts:

- A Multi-Model approach to evaluating target phosphorus loads for Lake Erie. Scavia, DePinto and Bertani. Journal of Great Lakes Research, in press.
- State of Knowledge of *Cladophora* in the Great Lakes. Executive Summary of Workshop held at NOAA-Great Lakes Environmental Research Laboratory January 26-28, 2016

Charge Questions:

Approach for Developing Lake Erie Phosphorus Load Reduction Targets

Nine different Lake Erie models were used to predict the response of selected eutrophication response indicators to different phosphorus load scenarios (see Table 1 in the Annex 4 Ensemble Modeling Report). The eutrophication response indicators evaluated were (1) overall phytoplankton biomass represented by chlorophyll a, (2) cyanobacteria blooms in the Western Basin, (3) hypoxia in the hypolimnion of the Central Basin, and (4) *Cladophora* in the nearshore areas of the Eastern Basin. Technical evaluation criteria were used to assess the capabilities of each model (see Section 2.3 and Appendix B of the Annex 4 Ensemble Modeling Report) and load-response curves were generated for each eutrophication response indicator (see Section 3 and Appendix B of the Annex 4 Ensemble Modeling Report).

1. Please comment on whether the evaluation of the models was adequate to inform how model results should be interpreted, given differences in model complexity and scale. Please identify any additional analyses that may be needed to improve future development and interpretation of the load-response curves for the eutrophication response indicators.

The document, R*ecommended Phosphorus Loading Targets for Lake Erie* describes the process followed by the Annex 4 Objectives and Targets Task Team to develop phosphorus loading targets for Lake Erie. The document indicates that, to achieve a Western Basin cyanobacteria bloom biomass threshold no greater than that observed in 2004 or 2012, 90% of the time, a spring Maumee River load of 860 metric tons of total phosphorus and 186 metric tons of dissolved reactive phosphorus is recommended. In addition, a 40% reduction in the spring load of total phosphorus and dissolved reactive phosphorus from other Western Basin tributaries and the Thames River is recommended. To meet a threshold of 2.0 mg/L or higher of hypolimnetic dissolved oxygen, an annual total phosphorus load of 6,000 metric tons to the Western and Central Basins is recommended. The Task Team did not recommend new phosphorus concentration objectives for the open waters or the nearshore be identified at this time.

2. Please comment on whether the recommended targets reflect the best available information on the drivers of cyanobacteria growth and seasonal hypoxia in Lake Erie and are appropriate to meet the nutrient Lake Ecosystem Objectives defined in the GLWQA (as reflected in Table 1 on page 7 of the document titled *Recommended Phosphorus Loading Targets for Lake Erie*).

Cladophora Growth

Additional phosphorus load reductions may be necessary to reduce nuisance levels of *Cladophora* in the nearshore waters of the Eastern Basin of Lake Erie. The Annex 4 Objectives and Targets Task team did not recommend a specific phosphorus objective or loading target to address *Cladophor*a growth. EPA and Environment and Climate Change Canada convened a workshop in January 2016 to assess the current state of knowledge of *Cladophora* growth in the Great Lakes and identify potential options for nutrient target development to be considered by the Annex 4 subcommittee. (Please see the background document titled "State of the Knowledge of *Cladophora* in the Great Lakes. Executive summary of Workshop held at NOAA-Great Lakes Environmental Research laboratory, January 26-28, 2016.")

3. Please comment on whether scientifically-sound phosphorus load reduction recommendations to address *Cladophora* growth in the Eastern Basin of Lake Erie could be developed at this time.

Nitrogen Control

While the current strategy focuses on limiting phosphorus loading to the Lake (total and dissolved forms) as the key mechanism for controlling excessive algal growth, it is implied or assumed that nitrogen loading likely will also be reduced through implementation of agricultural best management practices, and the Task Team recommended that tributary nitrogen loads to the Lake be tracked in addition to phosphorus.

4. What recommendations can the SAB provide for development of an approach to help determine whether consideration of nitrogen control, in addition to phosphorus, is warranted in Lake Erie to prevent harmful algae blooms and manage hypoxia? In particular, what questions, relationships, or research priorities related to nitrogen loading (different forms and sources) and in-lake cycling must be addressed?

Evaluation of Nutrient Reduction Targets

The inter-annual loading trends for the Maumee River are greatly influenced by annual variability in flows. The Objectives and Targets Task Team identified a maximum flow below which the target load should be met and recommended the use of flow-weighted mean concentrations (FWMC) as a benchmark for any given tributary target load.

5. Please comment on the use of FWMC and any other approaches that should be considered to account for inter-annual variability in hydrology in assessing progress in reducing tributary loadings of phosphorus to the Lake.

The Task Team recommended development of a comprehensive adaptive management program that would include annual routine monitoring of appropriate load, FWMC, and in-lake nutrient-eutrophication response indicators in conjunction with an intensive monitoring, research, and operational model application program every five years.

6. Please comment on the value of applying the existing eutrophication models on an ongoing basis to periodically evaluate phosphorus loading targets and eutrophication response indicators. What key elements should be included in the adaptive management approach to successfully implement and evaluate our nutrient reduction goals for Lake Erie?