EPA-SAB-17-xxx

The Honorable E. Scott Pruitt
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 Pruitt:

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 approach and results used to develop 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 (Modeling Subgroup) 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 alga, *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 simulate and 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 Modeling Subgroup applied and evaluated the suite of models independently, rather than as part of an ensemble approach; some models were accepted for use despite deficiencies relative to model evaluation criteria. The SAB's major comments and recommendations are as follows:

- The models evaluated and used by the Modeling Subgroup are not of equal reliability. Assessment of the response to phosphorus loads could be improved by giving greater weight to the load-response curves generated by the models deemed most reliable. Given the limitations of some of the models evaluated, and the practical limits of funding, the number of models considered should be reduced. It might prove most 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 the consensus model for this purpose, with a goal of extending this model to all of Lake Erie.

- The SAB finds 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 may still occur with some frequency, perhaps even routinely, in Maumee Bay in the Western Basin of Lake Erie. Ultimately, greater load reductions may be necessary to achieve the desired thresholds in the eutrophication-response indicators. Uncertainties in predictions of hypoxia are considerably larger than uncertainties associated with predictions of algal blooms. Continued lake and tributary monitoring and research will be needed to support adaptive management 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.

- While phosphorus has always been considered the limiting nutrient for Lake Erie and most other lakes, there is increasing evidence of the possible need for nitrogen control as well. 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 issues are identified and discussed in the enclosed 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 monitoring data (discharge, flow, concentrations and loads) from significant tributaries 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 identify the reasons for observed changes in phosphorus loads delivered to Lake Erie.

- 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 adaptive management program should include long-term monitoring and application of process-based eutrophication models to make annual predictions of eutrophication response indicators. The program should assess empirical data against model results and test alternative hypotheses and conceptual models to help explain discrepancies and use new knowledge to adjust management operations. The results of these assessments and hypothesis and model testing will also guide future monitoring and modeling efforts. In the enclosed report the SAB suggests a number of important research, monitoring, and modeling tasks to provide information needed for nutrient-load reduction and management of harmful algal blooms and hypoxia.

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

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Acronyms and Abbreviations

NH_4^+	Ammonium
ANAMMOX	Anaerobic Ammonium Oxidation
BMP	Best Management Practice
CAEDYM	Computational Aquatic Ecosystem Dynamics Model
cm	Centimeter
DIN	Dissolved Inorganic Nitrogen
DOC	Dissolved Organic Carbon
DOP	Dissolved Organic Phosphorus
DNRA	Dissimilatory Nitrate Reduction to Ammonium
EcoLE	Ecological Model of Lake Erie
ELCOM	Estuary, Lake and Coastal Ocean Model
ELCM	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 Algal 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
P-Quota	Cellular Phosphorus Concentration
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 (P) objectives, loading targets and allocations for nearshore and offshore waters and subsequently developing P-reduction strategies and domestic action plans. In December 2014, the EPA received early advice from the SAB on a modeling approach to develop P-reduction targets. A binational workgroup of 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 P loads on cyanobacteria biomass, hypoxia and nuisance *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 P load reductions needed to produce desired ecological conditions for Lake Erie.

The EPA requested that the SAB review the modeling approach and results used to develop the P load 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 P 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 P load reductions can be developed to address the problem of *Cladophora* growth in Lake Erie; (4) whether nitrogen (N) control, in addition to P, is warranted in Lake Erie to prevent harmful algal blooms and manage hypoxia; (5) how to account for inter-annual variability in hydrology when assessing progress in reducing loadings of P 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 Modeling Subgroup applied and evaluated the suite of models independently, rather than as part of an ensemble approach; some models were accepted for use despite deficiencies relative to model evaluation criteria. The SAB recognizes that the models are limited by the data available for calibration and validation and this affects 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. The model evaluations did not attempt to characterize the relative strengths of each model or 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 model uncertainty. The SAB finds that the models are not of equal reliability, and the assessment of load-responses would have benefited by giving greater weight to response curves generated by the models that appear to be most reliable on the basis of the model evaluation. 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 number of models considered for use 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 relevant ecological processes such as the internal storage and recycling of nutrients. Given practical limits of funding and the limitations of some of the models evaluated, consideration should be given to further developing one process-based model using the insights and demonstrated capabilities provided by the other models; the Western Lake Erie Ecosystem Model (WLEEM) could be the consensus model for this purpose.

The SAB also recommends that synoptic sampling of key variables be conducted on an ongoing basis to support continued model evaluation and refinement for Lake Erie. It is important to monitor flow, nutrient concentration and total suspended solids in the significant tributaries to 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) recommended a 40% reduction in the total P 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 key drivers of cyanobacteria growth in the Western Basin, and the potential link with seasonal hypoxia in the Central Basin. Based upon coupling of the suite of models to the relatively long term observational record, the SAB finds a 40% reduction in total P load will improve water quality and reduce the magnitude and extent of harmful algal blooms in keeping with the stated goals in the Task Team report. In addition, the SAB recognizes that the focus of abatement programs should be on reducing those nutrient components that readily support growth of phytoplankton communities. This implies that a focus should be placed on reduction of soluble reactive P (SRP), which is generally regarded as completely bioavailable, as well as those fractions of total P (TP) that may be partially available to phytoplankton (e.g., certain particulate P and dissolved organic P (DOP) fractions. However, even with this reduction, blooms may still occur with some frequency, perhaps even routinely, in Maumee Bay in the Western Basin of Lake Erie. Ultimately, further load reductions may be necessary to achieve the desired thresholds of the eutrophication response indicators. Uncertainties in predictions of hypoxia are considerably larger than uncertainties associated with predictions of algal blooms; the link between algal blooms and hypoxia in the Western Basin is not well understood. A current weakness of the hypoxia evaluation is that multiple year runs of the process

[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).

models have not been conducted. Therefore, the development of a forwarded residual of P or organic matter over time has not been simulated.

As previously indicated, continued lake and tributary monitoring will be needed to support further development of the modeling and adaptive management programs. Additional information (e.g., resuspension fluxes and sediment-water interactions, changes in the response of algal species to P over time, N limitation information) will be needed in order to incorporate currently missing components in the models. These components include: temporal variability in hydrodynamics; factors affecting P uptake by algae; the role of N in mediating algal growth; controls of algal toxin production; internal P loading; 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 of Recommendations to Address Nuisance Levels of *Cladophora* Growth

The SAB was asked to comment on whether scientifically sound P-load reduction recommendations could be developed to reduce nuisance *Cladophora* growth in the Eastern Basin of Lake Erie. *Cladophora* is a green alga that grows attached to hard benthic substrates. The nuisance attribute of *Cladophora* is that expansive growths of this alga can cover large nearshore regions leading to the formation of "beach muck" and problems that arise from it. The SAB finds that recommendations to reduce the P loadings to control *Cladophora* growth cannot be developed at this time. There is insufficient information available to understand and weigh the relative importance of environmental factors (including P inputs) that might cause *Cladophora* growth and senescence. There are limited observations of the spatial extent of the *Cladophora* problem along the shore of the Eastern Basin of Lake Erie. However, available information does point to a developing basin-wide problem of significant magnitude that warrants immediate action.

The Great Lakes *Cladophora* Model (GLCM) provides a first-order evaluation of *Cladophora* occurrence and initial predictions regarding the reduction of *Cladophora* biomass. However, knowledge gaps must be filled before P-load reduction recommendations to control *Cladophora* growth can be developed with an adequate level of certainty and scientific confidence. These knowledge gaps include the needs to: calibrate the GLCM for use in the Eastern Basin of Lake Erie, understand the importance of P loads from different tributaries and the effect of local hydrodynamics on *Cladophora* growth, understand processes that lead to sloughing of *Cladophora* and its decay to "beach muck," and 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*. It is particularly important to link the data needs of the GLCM with the data collection process. The EPA should evaluate what data are needed to reduce uncertainty in the model and better predict algal growth and presence.

Determination of Whether Nitrogen Control is Warranted

The SAB was asked to provide recommendations to help determine whether consideration of N control, in addition to P, is warranted to reduce eutrophication in Lake Erie. In particular, the SAB was asked to identify questions, relationships, and research priorities related to N loading and cycling that must be addressed. As further discussed in this report, there is increasing evidence that N control, as well as P control, may be needed to reduce eutrophication in Lake Erie. The toxic cyanobacterium, *Microcystis*, the major concern in western Lake Erie, does not fix N and therefore requires a fixed N source. *Microcystis* becomes more toxic when nitrate is abundant in lake water, but it can become N-limited in western Lake Erie in late summer. Furthermore, the growth of nuisance benthic algae in the Lake is fueled by loading of both N and P.

In order to evaluate the importance of N control in Lake Erie, future research should answer some key questions and clarify important relationships. Key research questions include: (1) What are the total N loadings entering Lake Erie over time and space (including all of the major species of N)? (2) What is the N budget for Lake Erie? (3) How much external N loading can be removed by internal processes like denitrification, ammonia volatilization and burial, and transformed by dissimilatory nitrate reduction to ammonium (DNRA)?[2] (4) What are the consequences of legacy N and P in the sediments and the differences in internal P and N cycling? (5) What are the downstream consequences of not following a dual nutrient strategy? (6) What is the importance of concentrations and ratios of N to other nutrients in directing or controlling ecosystem functions? (7) What is the ratio of N to P that would be best for ecosystem functioning? (8) How reliable are current models for assessing the role of N in Lake Erie eutrophication and how can the models be improved to model the effects of N? In addition, the SAB recommends that best management practices (BMPs) be developed or applied to achieve N reduction in Lake Erie, and "lessons-learned" case studies of nutrient reduction strategies for the Baltic Sea, Gulf of Mexico, and other areas be applied to Lake Erie. Agricultural BMPs for P may help to control N but may not be sufficient to attain the degree of N control that could be necessary.

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 P to Lake Erie. The FWMC is the preferred approach for calculating average concentrations in tributaries with variable flows. To determine FWMC, the concentration in each sample is weighted by both the accompanying time interval and the flow. The Task Team has recommended using FWMCs of P 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 variability in inter-annual hydrology. This is a useful approach but the SAB recommends that all available monitoring data (discharge, flow, concentrations and loads) from significant tributaries 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 (affected by nutrient loading) controls organism responses, and the effect of temporal variability in nutrient concentration is an important consideration in the management of harmful algal 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 P reduction strategies be collected. Without this information, it will not be possible to

[2] DNRA is dissimilatory nitrate reduction to ammonium, NO3- to NH4+. It is a transformation (not a removal) process

identify the primary reasons for observed changes in P loads delivered to the Lake. If control of nutrients other than P (e.g., N, 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. The SAB was also asked to comment on the value of using existing eutrophication models to periodically evaluate P loading targets and key 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 report to develop a comprehensive list of alternative hypotheses for Lake Erie eutrophication. However, the SAB suggests a number of research, monitoring and modeling tasks that focus on nutrient-load reduction, control of cyanobacteria and *Cladophora* blooms and evaluating processes that influence 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 P and N 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 collecting appropriate data to calibrate and validate models. The adaptive management committee should be tasked with evaluating alternative management strategies for Lake Erie eutrophication and evaluating future scenarios.

The SAB recommends that process-based eutrophication models be used as part of the adaptive management process (as previously indicated, consideration should be given to developing one process-based model). These models can be used to make annual predictions of eutrophication response indicators and to test alternative hypotheses. The SAB recommends that: the models be refined based on changing loadings and other new data; future scenarios be evaluated to understand the effects of climate variability, 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 (P) objectives, loading targets and allocations for nearshore and offshore waters and subsequently developing P reduction strategies and domestic action plans. In December 2014, the EPA received early advice from the SAB on a modeling approach to develop P reduction targets (U.S. EPA Science Advisory Board 2015). A binational workgroup of 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 P loads on cyanobacteria biomass, hypoxia and *Cladophora* growth. An ensemble modeling approach was considered for this analysis but the load-response curves were generated by running the models individually. These load-response curves were used by the Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team (Task Team) to identify P reductions needed to meet indicator thresholds that reflected desired ecological conditions for Lake Erie.

The SAB provided early advice to the EPA on the proposed ensemble modeling approach for developing P targets for Lake Erie (U.S. EPA Science Advisory Board 2015). The EPA then requested that the SAB review the modeling results and process used to develop P load reduction targets for the Lake. In addition, the EPA requested advice on an adaptive management 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, 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 P 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 P load reductions can be developed to address the problem of *Cladophora* growth in Lake Erie; (4) whether nitrogen (N) control, in addition to P, is warranted in Lake Erie to prevent harmful algal blooms and manage hypoxia; (5) approaches to account for inter-annual variability in hydrology when assessing progress in reducing loadings of P 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, 2016 and teleconference meetings on October 12 and 13, 2016 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). Key recommendations are highlighted at the end of each section of the report. The key recommendations are grouped to provide a relative indication of whether it may be most appropriate to implement them in the short, intermediate, or long term. This listing is intended to offer suggestions that may be helpful to the EPA in deciding how and when to allocate resources to support this work.

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 P load scenarios. Four response indicators were considered and evaluated: (1) overall phytoplankton biomass, as represented by chlorophyll a; (2) cyanobacteria blooms in the Western Basin; (3) hypoxia in the hypolimnion in the Central Basin; 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 ecosystem response indicators (ERIs) for Lake Erie. These load-response curves were used to develop P 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 P 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[1] 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 Modeling Subgroup's use of a common set of metrics to evaluate model fit is admirable; however, these metrics were not uniformly applied across the suite of 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,[2] and Modeling Subgroup 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 or 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 giving greater weight to 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 importantly, 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 hydro-meteorological forcing and timing of loading on responses to load reduction.

Improving Future Development of the Load-Response Curves

Given the limitations of a number of the models used in the analysis and the practical limits of funding, the SAB recommends reducing the number of models considered. Priority should be given to the process-based models that can account for the response of key environmental 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 most 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

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[1] The Task Team Modeling Subgroup applied the following criteria to evaluate the models: 1) ability to develop load response curves or provide other output for quantitative understanding of relevant questions; 2) applicability to objectives and metrics of interest; 3) extent and quality of calibration and confirmation; 4) extent of model documentation; and 5) level of uncertainty analysis available.

[2] Goodness of fit is a measure of how well the model fits the data already used to estimate its parameters; predictive fit is a measure of the model's accuracy in predicting future data.

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. The EPA should seek a better understanding of the limitations of the data and the data requirements needed to produce higher certainty in estimates. Additional in-lake synoptic sampling of key variables such as vertically averaged cyanobacteria abundance, water column and surface sediment nutrients (e.g., N and 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 (e.g., the Detroit River and the Maumee River), there is inadequate information available on small[3] tributaries. It would be useful to develop a model of nutrient and TSS loading that includes inputs from small tributaries. This would most likely be a hierarchical or Bayesian hierarchical model that accounts for multiple factors. Additional monitoring might be required for adequate estimation of model parameters and subsequent estimates of nutrient loadings from the small tributaries.

It seems worthwhile to improve the estimates of loading by linking land use models with loading models to achieve a realistic picture of the landscape-level interactions that are likely to produce in-lake changes (e.g., algal blooms, hypoxia, and *Cladophora* growth). Correspondingly, there might be an opportunity to collaborate with farmers who are practicing precision agriculture in the Lake Erie watershed to better estimate optimal fertilizer application rates as a way to reduce nutrient loading. The EPA should seek opportunities to collaborate with the U.S. Department of Agriculture (USDA) to increase local farmers' use of agricultural technologies aimed at more efficient use of fertilizers and reducing nutrient loadings to Lake Erie.

If multiple models are retained for use in the analysis, model estimates should be combined 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] For the time period 2011-2013, flows from the Detroit River contributed 94% of the flow into the Western Basin of Lake Erie and flows from the Maumee River contributed 4% of the flow into the Western Basin (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). Small tributaries do not contribute significantly to the total discharge but they may have high concentrations of phosphorus. Maccoux et al. (2016) have estimated phosphorus loading for Lake Erie tributaries.

Key Recommendations

Short Term:

- Because the models used in the analysis are not of equal reliability, the SAB recommends that the assessment of load-responses be improved by giving greater weight to response curves generated by the models deemed most reliable.

- Given the limitations of some models used in the analysis and the practical limits of funding, the number of models considered should be reduced and priority should be given to the process-based models that have the capability to account for the response of key processes. It might prove most 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.

- Research and model development work should be funded to improve model accuracy and reliability within the overall nutrient loadings management and decision-making framework.

- The EPA should investigate when and where data collection is needed to best inform the models and reduce model and estimation uncertainty. 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.

- Estimates of loading should be improved by linking land use models with loading models.

Intermediate Term:

- Analyses of the ability of the chosen model(s) to predict responses to changing conditions should be conducted on an ongoing basis.

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

Long Term:

- A model of nutrient and TSS loading that includes inputs from small tributaries should be developed.

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 P (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 algal blooms (HABs) and hypoxia, and loads leading to values for those metrics. The principal issues considered by the SAB were: (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 (reflecting the drivers of cyanobacterial growth and seasonal hypoxia), and (2) whether such a reduction will meet the Lake Erie Ecosystem objectives[4].

In general, the SAB finds that, while the models used in the analysis vary in complexity and assessment of uncertainty, 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 P inputs, but is in keeping with reductions deemed necessary in other aquatic environments suffering similar ecosystem impairments (e.g., Chesapeake Bay, Tampa Bay, and the Gulf of Mexico); therefore, by comparison, the recommended magnitude of the load reduction target does not seem unreasonable. However, it should also be recognized that the P load-response curves were generated from models that have been developed over the past 40 years. There are compelling reasons to believe that the lake ecosystem has changed since 1995 and these models may no longer provide reliable responses to P load reductions. In general, the models disregard the potential role of "legacy P" in sediments and the role of other elements (e.g., N and Si) in controlling blooms of phytoplankton populations, which may compromise the rate and extent of ERI responses to external P load reductions.

Drivers of Cyanobacteria Growth and Seasonal Hypoxia

The principal driver for the models used in the analysis and their results is stimulation of primary production by P loading which leads 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 1 part per billion (ppb) free plus cell bound (WHO 2003). Concentrations of microcystin have exceeded 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.

[4] 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).

A secondary effect of excessive algal growth is the rapid deposition of algal-derived, labile detrital organic matter that enhances consumption of dissolved oxygen 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 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. As further discussed below, some processes and dynamics are missing. However, the basic relationship between P 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 P loading to the Western Basin (see Stumpf et al. 2012; Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). A notable example is the dramatic difference between the 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 N and silica cycling, are important. However, the SAB finds that setting P loading as the initial driver in the Lake Erie system is appropriate and is consistent with the evidence.

The SAB recognizes that the focus of abatement programs should be on reducing those components that readily support growth of phytoplankton communities. This implies that a focus should be placed on reduction of soluble reactive P (SRP) that is generally regarded as completely available, as well as those fractions of total P (TP) that may be partially available to phytoplankton (e.g., certain particulate P and dissolved organic P [DOP] fractions). For example, in the Maumee River on average in 2002-2013 only about 45% of the TP load was actually bioavailable, and although SRP makes up only 21% of the average TP load, SRP makes up about 46% of the average bioavailable load.[5] The mineralization of organic phosphorus to orthophosphate is a pathway to bioavailability for part of the nonreactive phosphorus component of total dissolved phosphorus. However, Baker et al. (2014a) found that in the Maumee River at Waterville, Ohio, the conversion of dissolved organic phosphorus to orthophosphate added little to the bioavailable P loads entering the Lake. Gradient driven desorption of orthophosphate from particulate phosphorus provides a pathway to bioavailability for particulate phosphorus. However, the portion of the particulate phosphorus that is chemically or physically bioavailable may not support algal growth if that sediment is deposited or buried prior to orthophosphate release to the water column. A study of storm water movement through the lower Maumee River and Maumee Bay showed substantial deposition of sediment between the Waterville, Ohio sampling station and Maumee Bay (Baker et al, 2014b). These observations of sediment deposition underscore the relative importance of SRP loading as a driver of cyanobacterial blooms. Moreover, a recent study indicates that changes in agricultural practices, including some conservation practices designed to reduce erosion and particulate

[5] Comments to the Science Advisory Board from Dr. David. Baker, October 24. 2016, available at: https://yosemite.epa.gov/sab/sabproduct.nsf/AF08F14F2631437D85258057007053C8/$File/Comments+from+David+Baker,+Heidelberg+University.pdf

P transport, may have had unintended, cumulative, and converging impacts contributing to increased SRP loads to Lake Erie during the past 20 years (Jarvie et al. 2017).

The SAB notes that some of the process models do include other nutrients (N 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 decreasing and the relationship between P and N is not one of simple stoichiometry. As discussed in Section 3.3.1 of this report, 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 N cycling and N budgets in the system should also be assessed. This will provide information about the importance of N limitation and the potential impact of N 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 in the models does not reduce cyanobacteria growth enough to reach the maximum allowable cyanobacterial mass in established objectives (i.e., particulate P 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 frequency and magnitude of blooms in response 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 than uncertainties associated with predictions of algal blooms. 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 N (DIN) 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 direct 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 (see footnote 3 of this report) are achievable, and certainly impact the ability of the models to capture the dynamics of hypoxia and predict a robust relationship between P 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 evaluation of the hypoxia simulation models derives from the fact that these process models, which can be 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 of "legacy" P or organic matter over time is not currently simulated. This accumulating residual, which would affect the response time of the system to a reduction in loading, is present in both the Western and Central Basins of Lake Erie (Carrick et al. 2005). 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 even with a 40% reduction in P loading, the dissolved oxygen water quality standard of 5 mg/L will, almost certainly, not be met in Central Basin bottom waters and the predicted hypoxic area will range from approximately 2,000 to nearly 6,000 km^2 for periods in excess of a month. The WLEEM is a process-based model that can provide information on the relationship between loadings of water, sediments, and nutrients and the responses of algal biomass and turbidity/sedimentation. The SAB recommends that the WLEEM be deployed for the whole lake in order to provide information to better understand how load reductions impact hypoxia development.

Missing Components of the Models

The Modeling Subgroup acknowledged that some of the simulation models used to develop load-response curves 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 processes in future renditions. Such missing 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 N limitation, denitrification and N 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 P loading and resuspension and sediment-water interactions in general – although the WLEEM does include a diagenetic sub-model 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) (Klump et al. unpublished data 2006[6]; Robbins et al. 1977).
- Role of dreissenid mussels, the populations of which are likely not in steady state;
- Changes in seasonality (e.g., the timing and the biogeochemical composition of P in load delivery and how that is tied to activities in the watershed such as fertilizer application and tillage;

[6] Klump, J.V. Great Lakes Water Institute, University of Wisconsin-Milwaukee, Milwaukee, WI.

- Changes in the P-uptake response of cyanobacteria and other algal species to TP and other forms of P (e.g., bioavailable forms) over time (there is clear evidence that the system continues to shift 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 (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 concentration (FWMC) objectives for TP and SRP is expected to result in P 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, where perhaps 70% or more of the loading from the watershed occurs over 10-15 days of the year, and where high precipitation after fertilizer application is likely to be important);
- Expanded summertime conditions and a 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 variables such as 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 P loading (e.g., WLEEM) are capable of incorporating elements of climate change scenarios.

Effects of Phosphorus 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 species that are more palatable to primary consumers and may in fact enhance the food web by restoring a trophic pathway to secondary and tertiary production (Yurk and Ney 1989; Ludsin et al. 2001). Cyanobacteria have long been considered a poor quality food for key zooplankton grazers that link phytoplankton to higher trophic levels (Ali Ger et al. 2016). Therefore, 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 sinks to the bottom). Alterations in fish habitat and the abundance of mussels 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 current models to a relatively long term observational record, a 40% reduction in TP load to the Western and Central Basins projects an estimated 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, cyanobacteria blooms may still occur with some frequency 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. As previously noted, prediction of hypoxia is associated with a higher degree of uncertainty than prediction of cyanobacteria blooms. Therefore, attenuation of hypoxia is more problematic.

As previously mentioned, 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 12 priority watersheds identified by the Annex 4 Objectives and Targets Task Team is essential and should include measurement of: precipitation, flow, N species (good *in situ* NO_3^- sensors are available for high temporal resolution sampling), P (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 in the analysis is an inescapable necessity since actions and practices on the land will enable the 40% P load reduction to the Western and Central Basins.

Key Recommendations

<u>Short Term:</u>

- Lake and tributary monitoring should be conducted to support continued development of the models and adaptive management. In particular, event based sampling to capture the effects of precipitation and tributary flow is critical for calculating loads. Dissolved organic or non-reactive P in Lake Erie and tributaries should also be further investigated.

- 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). This will require calibration of the mechanistic models to field and laboratory data specific to Lake Erie.

- If feasible, given the computational resources that may be required, simulations should be run continuously over a period of years as an extended sequence rather than resetting initial conditions every year.

<u>Intermediate Term:</u>

- If feasible, given the computational resources that may be required, the WLEEM should be deployed for the whole lake to provide information to better understand how load reductions impact hypoxia development.

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

- 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 N cycling and N budgets in the system should be assessed.

3.2. *Cladophora* Growth

In its charge to the SAB, the EPA has indicated that additional P 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 P load reduction recommendations could be developed at this time to address *Cladophora* growth. In responding to this charge question, the SAB considered available information about *Cladophora* ecology, its occurrence in Lake Erie, the ecosystem consequences of *Cladophora* blooms and capabilities of the Great Lakes *Cladophora* 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 further research must be completed before scientifically sound P load reduction recommendations to reduce *Cladophora* growth in the Eastern Basin of Lake Erie can be developed. There is insufficient information available 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 an important issue in the Great Lakes because it affects selected sites in each of the Great Lakes (Auer et al. 2010). This makes it a pressing regional issue in need of scientific and management attention.

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., Rosemarin 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. Hard substrate also supported colonization of dense populations of dreissenid mussels (*Dreissena polymorpha* and *Dreissena bugensis*), which may exacerbate the problem of *Cladophora* growth 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 in *Cladophora* (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 (Higgins et al. 2005, 2008; Lake Erie Millennium Network 2016). 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” (an organism that alters the environment in a way that affects the other organisms present) and this can have both important positive influences as well as potentially negative consequences. This alga can serve as a substrate for epiphytic algal and bacterial assemblages, which may also contain invertebrates (Lowe et al. 1982; Stevenson and Stoermer 1982; Chilton et al. 1986). While it may not be fed upon directly by invertebrates and fish, as substrate it indirectly provides food for upper trophic levels. 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, forming mats that can wash ashore and decay to a foul smelling mass (i.e., 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 provides 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 P, *Cladophora* 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 less than 30 g dry weight /m^2 is indicative of “good” conditions (Lake Erie Millennium Network 2016). Biomass density of greater than 50 g/m^2 has been suggested as the threshold for the onset of problem conditions (Auer et al. 2010).

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 the fit of model predictions to observations in Lake Michigan. *Cladophora* growth may be linked to SRP content in the overlying water column and ultimately with the P-quota. The SRP in the overlying water column is influenced by local inputs from nearby tributaries, as well as the presence and density of dreissenid mussels (Higgins 2004). Therefore, a scientifically-sound model must incorporate site-specific factors, including local hydrodynamics.

Sensitivity analysis has indicated that the model is most sensitive to the minimum cell P-quota, the maximum growth rate and the maximum respiration rate; it is 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 has been related to TP concentrations and total P load to Lake Erie via load-response curves derived empirically and illustrated in Figures B9-2 and B9-3 in Appendix B-9 of the *Annex 4 Ensemble Modeling Report* (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team Modeling Subgroup 2016). This analysis implies that *Cladophora* growth and P-quota could be controlled with a TP load reduction to 7,000 MT/year, or a load reduction of 25 percent. A goal of 40 percent reduction in TP load to Lake Erie was recommended by the Task Team to attain other desired ERI thresholds; the implication of the GLCM analysis is that meeting this goal would also reduce *Cladophora* growth.

The GLCM appears to provide a 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, further research must be completed to fill knowledge gaps (listed in the key recommendations below) before recommendations for P load reductions to reduce *Cladophora* growth can be developed with an adequate level of certainty and scientific confidence. In this regard, it is particularly important to link the data needs of the model with the data collection process. The EPA should evaluate data needs to reduce uncertainty in the model and better predict algal growth and presence.

Key Recommendations

Short Term:

- The GLCM should be calibrated and confirmed in the Eastern Basin of Lake Erie using existing data.

- Site specific factors, including local hydrodynamics, tributary inputs, mussel densities, and other important drivers, should be incorporated into the GLCM.

Intermediate Term:

- 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 process or processes that lead to sloughing (local hydrodynamics, algal senescence, etc.) and eventual decay of *Cladophora* to "beach muck" need further investigation and likely need to be appended to the GLCM.

- The development of a spatial model linked to remote sensing information should be explored to better understand *Cladophora* distribution.

- 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.

Long Term:

- The GLCM would be more useful if it could be applied to the diversity of important benthic algae (e.g., *Chara*, *Lyngbya*, *Spirogyra*, etc.) that can cause similar problems in the Great Lakes. The similarities and differences among these various species should be considered in order to provide an adequate representation of the problems of nuisance benthic algae in general.

3.3. Nitrogen Control

The current nutrient strategy for Lake Erie focuses on limiting P loading to the Lake. However, the Task Team has also recommended tracking tributary N loads to the Lake. The EPA has asked the SAB to provide recommendations to help determine whether consideration of N 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?

The EPA and the European Commission have adopted a dual nutrient reduction strategy, including both N and P, to prevent and reduce eutrophication of both inland and coastal waters (European Commission 2009; U.S EPA 2015) While P has always been considered the limiting nutrient for Lake Erie and most other lakes, there is increasing evidence of the possible need for N control as well. The Baltic Sea can be viewed as a model that exemplifies the strategy to control both N and P. Although the Baltic Sea has some similarities to Lake Erie, most of the Baltic is estuarine but of low salinity. The importance of N control in lakes is currently unsettled and is the subject of vigorous scientific debate (Paerl et al. 2016; Schindler et al. 2016). While N control in Lake Erie may be premature, especially given its difficulty and expense, additional research to determine the importance of N should be a high priority. In Lake Erie, phytoplankton species composition and seasonal succession can vary with both N and P concentrations and ratios, and thus phytoplankton biomass does experience co-limitation of N and P during late summer and early fall (Moon and Carrick 2007). The phytoplankton species composition in western Lake Erie 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) and transformed by 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 nutrient availability to phytoplankton and macroalgae. Rates of internal N and P cycling are important as well as the loading rates. As further discussed below, three of the Lake Erie models currently incorporate N cycling but none address internal N and P pools, fluxes and ratios.

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, after the initial consideration of P control, N and P control should be considered; this would be similar to the approach taken for the Baltic Sea (Conley et al. 2011). 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. 2016); however, there is evidence that N control is also needed (Chaffin et al. 2013; Davis et al. 2015). As previously noted, the toxic cyanobacterium *Microcystis*, the major concern in western Lake Erie, does not fix N and therefore requires a fixed N source. *Microcystis* can become N limited in late summer in western Lake Erie (Chaffin et al. 2013). In addition, it becomes more toxic when nitrate is abundant in lake water (Harke et al. 2016). Furthermore, *Microcystis* is very well adapted to obtaining P when levels of P are low in lake water because it can use enzymes (e.g., alkaline phosphatase) to remove P from organic compounds (hydrolyze phosphate esters) that are more readily abundant in lake water in comparison to simpler dissolved forms of P (Harke et al. 2016). While nitrate is the predominant form of N in Lake Erie and is highly mobile, there are also lower levels of ammonium and other reduced N compounds (Chaffin et al. 2013) in the Lake. Since these other reduced N compounds 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 N (TN) load from the Maumee River since 2000 (despite concurrent increases in discharge). They also provide evidence for decreased nutrient 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 the 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 N-fixer), the modern blooms are comprised mostly of the non-N-fixing genus *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, Ohio (Davis et al. 2015) and ongoing blooms of *Cladophora* (Davies and Hecky 2005), also involve non-N-fixing algae. Furthermore, the proliferation of nuisance benthic algae (e.g., *Cladophora* and closely related species) has been experimentally and empirically linked to available N and P enrichment in the Great Lakes (See Carrick and Lowe 1988, 2007),

Low availability of N in lake water is associated with a switch between species of cyanobacteria (from the occurrence of *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 N species can be important. Davis et al. (2010) found that growth of the toxic *Microcystis* strains were enhanced by inorganic N whereas the non-toxic strains were stimulated by organic N. 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 species exhibit greater physiological response to N:P than to either N or P separately. Numerous studies have shown that the availability of a 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 algal blooms that are N and P co-limited or N limited, especially during mid-to-late summer. In addition, 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, of 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 N. 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. Agricultural Best management practices (BMPs) for P control may help control N but may not be sufficient to attain the level of N control that could be needed. Best management practices for P control often target sediments because much P is particulate. Nitrogen, especially nitrate, is mostly dissolved and much more mobile, so if N removal becomes a goal to be achieved, 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. A recent study indicates that about half of the total N and P in the Mississippi River Basin is contributed by agricultural (about 80% of the agricultural contribution of N comes from fertilizer and 20% comes from manure; and about 55% of the agricultural contribution of P comes from fertilizer and 45% comes from manure) (Alexander et al. 2008; Robertson and Saad 2013). There is some evidence that P loads from agricultural lands in Iowa have declined as a result of the implementation of BMPs (Wang et al. 2016).

In order to evaluate the importance of N 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

<u>Short Term:</u>

- Research should be conducted to determine the total N loadings entering Lake Erie over time and space, including all the major species of N (oxidized, reduced, organic, and particulate). An N budget should be developed for Lake Erie, especially the Western Basin, similar to that for Lake Michigan (Han and Allan 2012).

- Research should be conducted to show the reliability of current models for assessing the role of N 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.

<u>Intermediate Term:</u>

- Research should be conducted to determine: 1) how much of the external N loading can be removed by internal removal processes; 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 N to other nutrients (P, but also Si) in directing or controlling ecosystem functions; and 2) the balance in the ratio of N to P that would be best for ecosystem functioning.

- BMPs should be developed and 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.

- The EPA should determine the reduction in N loading that results from reduction of P loading.

<u>Long Term:</u>

- Lessons learned from case studies of nutrient reduction in the Baltic Sea and other areas should be applied to Lake Erie. This should include scientific, technical, policy and governance strategies.

3.4. Evaluation of Nutrient Reduction Targets

Inter-annual loading trends for the Maumee River are greatly influenced by annual variability in flows (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015). 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 P.

The Task Team also recommended development of a comprehensive adaptive management program that would include annual routine monitoring of appropriate load, FWMCs 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.*

In a 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 approach for calculating average 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.

Flow Weighted Mean Concentrations are recognized as useful measures to address inter-annual variability because they normalize the tributary P 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 recommended using tributary FWMC as a benchmark to track progress in load reduction. The SAB recommends reviewing all available monitoring outputs (e.g., discharge, flow, concentrations, loads) from significant tributaries 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 P reduction strategies should be collected to help identify the reasons for changes in P loads delivered to the Lake.

The use of FWMC analyses alone may "mask" elevated concentrations that could result in algal blooms. Any analysis of the effect of nutrient concentrations should consider the response of the organisms intended to be controlled. Nutrient concentrations (as affected by nutrient 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.

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 of 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 N or TKN) measured. Therefore, 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 P 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 sub-basins, 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. The SAB notes that 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 P 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 (SRP FWMC and load) in *Recommended Phosphorus Loading Targets for Lake Erie* (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 P. 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 accurate assessment of progress in reducing tributary loadings of P 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 P reduction strategies in each major watershed.[7] Without this information, it will not be possible to adequately identify the primary reasons for the observed changes (or lack thereof) in P loads delivered to

[7] The Task Team identified a number of priority watersheds (Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team 2015).

Lake Erie. This will limit the ability to adequately assess the effect of P reduction strategies in light of other confounding factors such as those related to climate change.

The SAB also notes that, as previously discussed, P may not be the only factor affecting algal growth in Lake Erie; N, 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

Short Term:

- 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 P reduction strategies should be collected to help identify the reasons for observed changes in P loads delivered to Lake Erie.

Intermediate Term:

- All available monitoring data from significant tributaries and multiple assessment approaches should be reviewed to evaluate efforts to control sources of nutrient loadings. The evaluation should include relationships between hydrology, climate, agricultural practices, source control and trends in nutrient loads and concentrations.

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 evaluate the responses of eutrophication indicators in relation to nutrient reductions consistent with the goals developed for Lake Erie. The adaptive management program should involve an ongoing evaluation of the efficacy of loading reductions in achieving the desired responses of the eutrophication indicators and the adjustment of management actions, monitoring, and modeling in light of new information. This is particularly important given uncertainties in the present P-reduction targets with respect to the expected response indicator outcomes, as well as the potential for changing future conditions. An important component of adaptive management is the opportunity to identify alternative management actions if reductions in loadings fail to produce the desired or anticipated outcomes. 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 the desired values of the ERIs. The committee should consider alternative

management actions and develop the necessary supporting science if reductions in nutrient loading fail to achieve the desired outcomes as measured by the ERIs. Through this process, adaptive management can usefully inform future management decisions.

2. A coordinated binational long-term monitoring strategy should be developed. It is critical to provide support for stabilizing and enhancing long-term monitoring in order to assess whether loading and ERI targets are being met. Consideration should be given to the following activities:

   – Assessing available loading information and developing standardized protocols for loading estimates, including correlation between P loadings from major tributaries (estimated from hydrologic loads and FWMC of total P and bioavailable P) and ERIs;
   – Maintaining current tributary monitoring capabilities (e.g., Heidelberg University) and adding additional tributaries;
   – Developing standardized protocols for monitoring, evaluating and reporting values of ERIs (cyanobacteria; hypoxia; *Cladophora*) in relation to management objectives;
   – Considering the potential for additional ERIs (i.e., chlorophyll a, biological endpoints such as benthic organisms in hypoxic areas and general fish productivity; measuring the health and diversity of fish communities, particularly Whitefish, *Coregonus clupeiformis*);
   – Ensuring that measurements are made of those variables that are necessary for calibrating and assessing the performance of models and for evaluating alternative management actions as necessary (see recommendations below).
   – Ensuring that measurements are being made of those variables that are necessary for development of new or improved models (i.e., mechanistic models of sediment diagenesis, nutrient flux, and sediment oxygen demand);
   – Incorporating measurements that provide "early warning" for climate change impacts.

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 management actions. 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 post-audits be conducted 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 alternative hypotheses as appropriate.

4. Alternative management actions may be required. The attempt to manage eutrophication in the Western Basin of Lake Erie by reducing external P loading by 40 percent is based on the assumptions that: (1) external P-loading is the sole driver, or at least the overwhelmingly major driver, of HABs, hypoxia, and *Cladophora* proliferation, and (2) reduction in external P loading will result in a reduction of these responses. It should be recognized that nutrient reduction is a management action that can be evaluated within an adaptive management program. Depending on

the success of nutrient reduction in achieving the desired values of the ERIs, additional factors beyond reducing external P loading might need to be identified and incorporated into the management strategy.

An important task for the adaptive management committee is to propose alternative drivers for the ERI's 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. 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 list of issues that might be considered, along with the accompanying research, monitoring and modeling tasks that would be useful for addressing each issue. The SAB offers 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

It is not clear how effective BMPs applied at different times and places in the watershed will be for reducing P, nor is it understood whether BMPs directed at P-retention will be effective for N removal.

Research, monitoring and modeling:

- Characterize BMPs with respect to the geochemical form of nutrient runoff addressed, spatial distribution, type of BMP and life cycle effectiveness.
- Compare N runoff in areas using different BMPs targeted at P control.
- Conduct small-scale experiments that quantify the efficiency of BMPs for reducing both P and N.
- Link watershed models to in-lake models and run a suite of scenarios to evaluate the effectiveness of using different combinations of BMPs over space and time.

Cyanobacteria

The timing and magnitude of cyanobacterial blooms may be affected by the stoichiometric balance of N and P in resource supply because algal growth and nutrient demand can generate conditions where N and P become co-limiting. In addition, it is important to understand the linkage between cyanobacterial biomass and toxin production in order to effectively address the potential effects of blooms.

Research, monitoring and modeling:

- Calculate N loading to compare with P (including N:P ratios) and bioavailable forms of N and P.
- 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 N limitation in the field.

- Measure toxins in a standardized, coordinated way.
- Evaluate correlations between particulate organic carbon (POC), chlorophyll a, cyanobacteria and microcystin concentration.
- Develop models to explore relationships between P, N, phytoplankton community composition and implications for toxins.

Hypoxia

A number of factors contribute to the potential for oxygen depletion and hypoxia in the Lake, including the duration and magnitude of spring diatom blooms, the seasonal progression of stratification, and the extent of sediment oxygen demand. Although many of these factors are incorporated in current models, it would be useful to improve our understanding of the relative importance of these drivers and their relationship to external nutrient loads.

Research, monitoring and modeling:

- Quantify diatom bloom magnitude and duration.
- Evaluate relationship between diatoms and seasonal N, P and silicon (Si) loading.
- Use models and empirical analyses to evaluate relationship between diatoms and hypoxia.
- Run model scenarios with varying stratification for a given P load.
- Expand models to include mechanistic processes to represent sediment nutrient diagenesis and fluxes of inorganic nutrients and sediment oxygen demand.
- Collect site-specific data to support the development and calibration of models of nutrient diagenesis and fluxes of inorganic nutrients and sediment oxygen demand.

Cladophora

Cladophora standing crop and productivity may be linked to internal P release from hypoxic sediments or near-shore sources of P. In addition, the role of dreissenid mussels in promoting *Cladophor*a proliferation is unclear.

Research, monitoring and modeling:

- Monitor near-surface suspended sediment concentrations to characterize the upper active mixed layer in the Western Basin.
- Improve on current *Cladophora* modeling to include nearshore processes.
- 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.

5. Future scenarios should be evaluated. Part of the reason that the loading targets for P 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; shorter duration of ice cover.
- Anticipated changes in land use and population density.
- Regional economic development.
- Zero P input: (i.e., 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 factors need to be considered?
- Are there additional management measures that need to be considered based on additional understanding gained from evaluating alternative hypotheses?
- Which environmental and land use conditions are changing or likely to change in the future? If so, what implications would such changes 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 evaluate them; and agreeing on forecasting scenarios. This requires a long-term institutional commitment to the process at the local and regional levels.

Key Recommendations

Short Term:

- 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 binational long-term monitoring strategy should be developed. A standardized monitoring protocol should be implemented among the different groups involved. The same assessment approaches should be applied to tributary monitoring data for N and P to evaluate efforts to control sources of nutrient loadings.

- Alternative management actions for Lake Erie eutrophication should be identified and evaluated if loading reductions fail to produce the desired management objectives.

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

- 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.

- The effectiveness of BMPs should be characterized with respect to type, spatial location in the watershed, and life cycle effectiveness.

<u>Intermediate Term:</u>

- Detailed information on the implementation of P reduction strategies in each major watershed should be collected into the future (e.g., the areas of the landscape where strategies are being implemented and P monitoring data showing trends in those areas).

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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.*
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> *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 algal 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?