Journal of Great Lakes Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

A multi-model approach to evaluating target phosphorus loads for Lake Erie

Donald Scavia [a,*], Joseph V. DePinto [b], Isabella Bertani [a]

[a] Graham Sustainability Institute, University of Michigan, 625 East Liberty Road, Ann Arbor, MI 48193, USA
[b] LimnoTech, 501 Avis Drive, Ann Arbor, MI 48108, USA

ARTICLE INFO

Article history:
Received 6 March 2016
Accepted 10 September 2016
Available online xxxx

Communicated by Robert E. Hecky

Index words::
Loading targets
Great Lakes Water Quality Agreement
Lake Erie
Eutrophication models

ABSTRACT

In response to water quality changes in the Great Lakes since implementing the 1978 Amendment to the Great Lakes Water Quality Agreement, the US and Canada renegotiated the agreement in 2012, requiring the governments to review and revise phosphorus (P) load targets, starting with Lake Erie. In response, the governments supported a multi-model team to evaluate the existing objectives and P load targets for Lake Erie and provide the information needed to update those targets. Herein, we describe the process and resulting advice provided to the binational process. The collective modeling effort concluded that avoiding severe Western Basin (WB) cyanobacteria blooms requires: 1) focusing on reducing total P loading from the Maumee River, with an emphasis on high-flow events during March–July, 2) focusing on dissolved reactive P load alone will not be sufficient because there is significant bioavailable P in the particulate phosphorus portion of the load, and 3) loading from the Detroit River is not a driver of cyanobacteria blooms. Reducing Central Basin (CB) hypoxia requires a CB + WB load reduction greater than what is needed to reach the WB cyanobacteria biomass goal. Achieving *Cladophora* thresholds will be challenging without site-specific load reductions, and more research is needed.

Introduction

In response to significant water quality changes in the Great Lakes since implementing the 1978 Amendment to the Great Lakes Water Quality Agreement (GLWQA) (e.g., Evans et al., 2011; IJC, 2014; Scavia et al., 2014), the US and Canada renegotiated the GLWQA (GLWQA, 2012). Annex 4 of the 2012 GLWQA Protocol set interim phosphorus (P) loading targets identical to those established in the 1978 Amendment, and required the US and Canadian governments to review those targets and recommend adjustments if needed, starting with Lake Erie.

As part of the GLWQA review, a committee of modelers examined data and models used to support the P target loads in the 1978 Amendment relative to the current status of the Lakes and models (DePinto et al., 2006). At that time, a set of Great Lakes eutrophication models were used to help establish target P loads designed to eliminate excess algae growth and to reduce areas of low dissolved oxygen (DO) concentration — key eutrophication symptoms at that time. Those models ranged from simple empirical relationships to kinetically complex, process-oriented models (Bierman, 1980; Vallentyne and Thomas, 1978), and post-audit of several of those models confirmed they had established sound relationships between P loading and system-wide averaged P and chlorophyll-*a* concentrations (e.g., Di Toro et al., 1987; Lesht et al., 1991).

However, DePinto et al. (2006) concluded that those models were not resolved enough spatially to capture the characteristics of nearshore eutrophication, nor the impacts of more recent ecosystem changes, such as impacts from dreissenid mussels and other invasive species. Nor were they designed to address harmful algal blooms (HABs). Their recommendation was to establish a new effort to quantify relative contributions of the factors controlling Great Lakes re-eutrophication (Scavia et al., 2014), and to revise quantitative relationships among those stressors and eutrophication indicators such as HABs, hypoxia, and nuisance benthic algae.

In response, several new Great Lakes modeling efforts were initiated, and given the availability of these new models, the parties to the GLWQA, Environment Canada and the US EPA, supported a new team to evaluate the interim P objectives and load targets for Lake Erie and to provide the information needed to update those targets. Herein, we describe that process and the resulting advice provided to the GLWQA process because the Lake Erie plan is intended to also serve as a template for the other Great Lakes.

Approach

Ecosystem Response Indicators

Before initiating the modeling work, Ecosystem Response Indicators (ERIs) and their associated metrics were established with the GLWQA Annex 4 Nutrient Objectives and Targets Task Team (GLWQA, 2015). Four ERIs of Lake Erie eutrophication appropriate for the Annex 4 Objectives were selected:

- *Western Basin (WB) cyanobacteria biomass* represented by the maximum 30-day average cyanobacteria biomass

---

* Corresponding author.
E-mail address: scavia@umich.edu (D. Scavia).

http://dx.doi.org/10.1016/j.jglr.2016.09.007

Please cite this article as: Scavia, D., et al., A multi-model approach to evaluating target phosphorus loads for Lake Erie, J. Great Lakes Res. (2016), http://dx.doi.org/10.1016/j.jglr.2016.09.007

- *Central Basin (CB) hypoxia* represented by number of hypoxic days; average extent of hypoxic area during summer; and average hypolimnion DO concentration during August and September
- *Basin-specific overall phytoplankton biomass* represented by summer average chlorophyll-*a* concentration
- *Eastern Basin (EB) Cladophora* represented by dry weight biomass and stored P content.

Multi-model strategy

A multi-model approach was used to explore relationships between the ERIs and P loads because a suite of models with a broad range of complexities and approaches affords an informative comparison of results. Bierman and Scavia (2013) and Weller et al. (2013) identified a number of benefits of applying multiple models of differing complexity:

- Problems and data are viewed from different conceptual and operational perspectives
- The level of risk in environmental management decisions is reduced
- Model diversity adds more value to the decision process than model multiplicity
- Findings are stronger when multiple lines of evidence are available
- Using multiple models increases knowledge and understanding of underlying processes
- Average predictions from a set of models are typically better than from a single model
- Information from multiple models can help quantify uncertainty
- Multiple models can expand opportunities for additional stakeholders to participate
- Reconciling differences among models provides insights on key sources and processes

There is also precedent for using multi-model approaches to support management decisions. As noted above, this approach was used in the late 1970′s to establish the original target P loads for the Great Lakes (Bierman, 1980). In that case, the six models ranged in complexity from an empirical steady state model (Vollenweider, 1976) to more complex, mechanistic models of Lake Erie (Di Toro and Connolly, 1980) and Saginaw Bay (Bierman and Dolan, 1981). Additional examples include addressing polychlorinated biphenyls (PCBs) in Lake Ontario (IJC, 1988), and nutrient loads for the Neuse River Estuary (Stow et al., 2003), the Gulf of Mexico (Scavia et al., 2004), and the Chesapeake Bay (Weller et al., 2013).

After establishing the ERIs, model equations, coefficients, driving variables, assumptions, and time step of predictions were described; calibrations, confirmations, and uncertainties/sensitivities were compared; and the ability of each model to develop ERI metric load–response curves was reviewed. With this information and results from previous publications, the model capabilities were reviewed with respect to the following evaluation criteria:

- *Applicability to ERI metrics*: The models' ability to address the spatial, temporal, and kinetic characteristics of the ERI metrics. While models that address other objectives can be informative, highest priority was given to those that can address the ERIs directly.
- *Extent/quality of calibration and confirmation*: Calibration — The models' ability to reproduce ERI metric state-variables and internal processes. Post-calibration testing — The models' ability to replicate conditions not represented in the calibration data set.
- *Extent of model documentation*: The extent of documentation, including descriptions of model kinetics calculations, inputs, calibration, confirmation, and applications.
- *Level of uncertainty analysis*: The extent to which the models evaluated uncertainty and sensitivity, including for example, those associated with measurement error, model structure, parameterization, aggregation, and uncertainty in characterizing natural variability.

The models

The models that satisfied these criteria are summarized in Table 1 and described briefly below. Model formulation, calibration, confirmation, and sensitivity/uncertainty, as well as the construction of load–response curves are provided in more detail in Scavia et al. (2016) and in this issue (Bertani et al., in this issue; Bocaniov et al., in this issue; Chapra et al., in this issue; Rucinski et al., in this issue; Stumpf et al., in this issue; Valipour et al., in this issue; Verhamme et al., in this issue; Zhang et al., in this issue), and in Auer et al. (2010), Canale and Auer (1982), Tomlinson et al. (2010) and Lam et al. (2008, 1987, 1983).

Total Phosphorus Mass Balance Model (Chapra et al., in this issue)

The original version of this parsimonious total phosphorus (TP) mass balance model was used (along with other models) to establish P loading targets for the 1978 Great Lakes Water Quality Agreement. The model has been subsequently revised and updated, including the expansion of the calibration dataset through 2010 and an increase in the post-1990 apparent TP settling velocity to improve model performance, suggesting that mussel invasion may have enhanced the lakes' ability to retain P (Chapra and Dolan, 2012). The model predicts annual average TP concentrations in the offshore waters of the Great Lakes as a function of external load. For Lake Erie, the model computes basin-wide annual average TP concentrations as a function of loads to each basin. In this application, an empirical relationship between summer chlorophyll and TP concentrations derived for each basin was used to predict basin-specific average chlorophyll levels under different TP load scenarios.

U-M/GLERL Western Lake Erie HAB model (Bertani et al., in this issue)

A probabilistic empirical model developed by Obenour et al. (2014) relates peak summer cyanobacteria biomass in the WB to spring P loading from the Maumee River. The model is calibrated to multiple sets of in situ and remotely sensed bloom observations through a Bayesian hierarchical approach that allows for rigorous uncertainty quantification. The model includes a temporal trend component that suggests an apparent increased susceptibility to cyanobacteria blooms over time. For this application, the original model (Obenour et al., 2014) was modified to include an empirical estimate of the bioavailable portion of the TP load as bloom predictor.

NOAA Western Lake Erie HAB model (Stumpf et al., in this issue)

This model is based on an empirical regression between spring P load or flow from the Maumee River and peak summer cyanobacteria biomass in the WB as determined through satellite imagery (Stumpf et al., 2012). For this application, the model has been modified to account for the potential difference in cyanobacteria response to load intensity in warm vs. relatively cold early summers. An estimate of bioavailable P load was also tested as bloom predictor.

Nine-box model (Lam et al., 2008, 1987, 1983)

This coarse grid (9-box) P mass balance model was developed to quantify the main physical and biochemical processes that influence Lake Erie eutrophication and related hypoxia (Lam et al., 1983). The model was previously calibrated and validated with water quality observations from 1967 to 1982 (Lam et al., 1987). For this application, the original calibration was modified to account for changes in settling and re-suspension processes due to dreissenid mussel invasion as described in Scavia et al. (2016).

Please cite this article as: Scavia, D., et al., A multi-model approach to evaluating target phosphorus loads for Lake Erie, J. Great Lakes Res. (2016), http://dx.doi.org/10.1016/j.jglr.2016.09.007