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The need for sustained, long-term phosphorus modeling in the Great Lakes

The 1978 Great Lakes Water Quality Agreement contained annual phosphorus load targets for each of the Great Lakes and larger bays. These targets were developed to combat eutrophication symptoms that resulted in the impairment of what we now refer to as ecosystem services. The targets were derived from several models of differing complexity and spatiotemporal resolution. As an ensemble those models reflected the knowledge and technology of the time. In the 1970s, this approach was new and somewhat of an experiment. Ecosystem management at this scale was unprecedented and the result was uncertain. However, it put the Great Lakes region at the forefront of innovative environmental management, and the approach has been widely copied in what we now refer to as Total Maximum Daily Loads. In the 1980s, there were signs that the experiment was working as eutrophication symptoms began to diminish. Unfortunately, these improvements were interpreted to indicate that the job was done. We declared success and moved on to other concerns such as toxic chemicals. The models were largely shelved, and the monitoring efforts supporting them were substantially reduced. At the time, such actions probably seemed sensible. Our view was that the lakes were fixed, and we could move on to other important concerns. This outlook was not confined to the Great Lakes community, but reflected the broader prevailing wisdom of the time.

Flash forward to 2015 and the Great Lakes community is actively engaged in a reevaluation of the 1978 target loads and the development of substance objectives (concentration targets) for phosphorus to combat eutrophication. These efforts are underway pursuant to the 2012 updated Great Lakes Water Quality Agreement which was renegotiated with the recognition that eutrophication management was still necessary. Eutrophication symptoms are reoccurring, though the nature of the problem differs somewhat from that of the 1970s. *Microcystis* blooms now occur in some areas; in 2011 the largest bloom ever was recorded in Lake Erie and in 2014 the Toledo drinking water supply was temporarily interrupted due to unacceptably high microcystin levels. These problems are ongoing despite substantial phosphorus input reductions since the 1978 load targets were implemented. There are several hypotheses to explain what may be fostering these problems: dreissenid mussels, climate change, modified land-use practices, and periodic nitrogen limitation, but the bottom-line is that eutrophication symptoms persist and changes in cause–effect relationships since the 1970s contribute to uncertainty in pending management decisions. This uncertainty is less about *what* to do, phosphorus reduction is still our primary management tool, and more about: *how much* must phosphorus be reduced?

Addressing this question is the domain of modeling. Models are tools that allow us to assemble our best understanding of the relevant system processes and evaluate the logical outcome as these processes are manipulated. Like the lakes themselves, models should not be static, but should reflect changes in the lakes and incorporate evolving insights of lake behavior. Had the modeling efforts that generated the 1978 target loads been actively supported since that time, reflecting the changes that have occurred over that period, the Great Lakes community would currently be in a better position to promulgate updated load targets pursuant to the commitments of the updated 2012 Agreement. Instead, we are in a reactive rather than proactive mode with respect to modeling efforts to support these decisions.

The Great Lakes will continue to experience changes that cannot be anticipated, and will respond to renewed phosphorus mitigation efforts in ways that we cannot fully predict. Phosphorus management is likely to be with us in perpetuity. Our understanding of the processes that influence phosphorus biogeochemistry and algal responses will continue to develop, as will computational capacity, data acquisition capabilities, and modeling techniques. Thus, it would be prudent for the Great Lakes community to invest in a sustained, coordinated modeling effort to carry us into the future.

Ideally this endeavor would include:

- A suite of models of differing complexity and resolution, based on alternative assumptions.
- An ongoing skill assessment of model capabilities.
- Models with the capacity for rigorous uncertainty analysis.
- A home on the internet with documented code and supporting data available to make the process as transparent as possible and allow the community to use and vet the models.
- Regular updating.
- A standing committee to guide development and implementation.
- Support by well-designed monitoring program.

The final bullet is important; models must be grounded by appropriate monitoring for effective decision-support. Models facilitate an extension of the information provided by data, based on imposed process and statistical structure (aka assumptions). Without data, models are primarily hypothetical. Data generation to support past phosphorus modeling has been inconsistent, and largely ad hoc. Resources supporting the synthesis of these data to generate annual phosphorus load estimates have also been inconsistent, and the work was mainly done by one person. Dave Dolan's unfortunate passing in 2013 constitutes a considerable loss for the Great Lakes community; he developed the methods to synthesize the available data that have allowed us to assess compliance with annual phosphorus load targets. Moving forward, load estimation at finer spatial and temporal scales will probably be necessary, both to evaluate compliance with updated targets, and to

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drive models. With Dave's passing it would be appropriate to reassess our needs, evaluate contemporary data synthesis and load estimation approaches, and devise a plan to proceed.

A sustained, coordinated phosphorus modeling and monitoring program would benefit the Great Lakes community in many ways, in addition to decision-support for ongoing eutrophication management. Models provide a framework for organizing information and identifying important uncertainties that could be reduced with directed investigations. They would be a resource for researchers to conduct numerical experiments that could be compared with field and laboratory investigations. A sustained modeling program would be a basis to investigate the fundamental limits to accurate ecological forecasting.

Additionally, these models would provide the framework for an active Adaptive Management program. Adaptive Management was a developing concept in 1978, but it is firmly embraced in the 2012 GLWQA. It is strongly premised on the recognition that ecosystems are not stationary, and our knowledge of their behavior is approximate, thus environmental management decision-making will always occur under a degree of uncertainty. Updating models to incorporate new understanding, as an integral component of Adaptive Management, will help ensure that we get ahead of the eutrophication problem, as the lakes continue to respond to unforeseen influences into the future. It may be hard to believe that eutrophication will be an ongoing management problem — we have understood the basic principles for a long time. But in the 1970s who would have imagined that the issue would be “front and center” 40 years hence?

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