Report of the NJDEP Science Advisory Board

Prepared by the Science Advisory Board
Water Quality and Water Quantity Working Group

The Long Term Effects of Eutrophication

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Final Report

Long Term Effects of Eutrophication

June 1, 2018

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Introduction

The Water Quantity and Quality standing committee (WQQC) of the New Jersey Science Advisory Board (SAB) has been charged by the NJDEP to study and report on the following questions:

> *Are there existing methods that would be applicable to any or all types of New Jersey's waters that can predict the rate and magnitude of change in sediment sources of nutrients following a reduction in source loading from the contributing watershed?*
>
> *If not, what research is recommended to elucidate methods that would accomplish this objective and would be suitable for use in Total Maximum Daily Load (TMDL) and/or Water Quality-Based Effluent Limit (WQBEL) development?*

The WQQC formed a working group to address these questions. The working group determined that the nutrient that is of primary concern in this regard is phosphorus. As described below, it also determined that this issue could be best addressed, at least initially, only in freshwater lakes and impoundments.

The release of phosphorus stored in sediment back into the water column is called "internal load" (IL). This contrasts with external load (EL) from tributaries, runoff, etc. The following excerpt from Chapra (2015) below describes well the motivation behind this question.

> Efforts to remediate the eutrophication of lakes through management of phosphorus loading and associated primary production have met with considerable success, especially in North America (e.g., Lake Washington, USA, Edmondson and Lehman 1981; Onondaga Lake, USA, Effler and O'Donnell 2010) and Europe (e.g., Lake Arresø, Denmark, Jeppesen et al. 2007; Lake Constance, Austria/Germany/Switzerland, Müller 2002). In some cases, however, feedback of phosphorus resident in lake sediments (i.e., legacy deposits) has retarded the restoration response (e.g., Shagawa Lake, USA, Larsen et al. 1979, 1981; Rostherne Mere, UK, Carvalho et al. 1995; Großer Müggelsee, Germany, Kleeberg and Kozerski 1997). In reviewing the importance of sediment phosphorus release to lake restoration, Marsden (1989) concluded that internal loads play a dominant role in determining trophic state. Cooke et al. (2005, p. 90) recognized the transient, albeit extended, nature of the phenomenon in suggesting that, "the question is not whether or not a lake will respond to reductions in loading, but when and to what extent."
>
> At issue here are features of the sediment environment that stand in contrast to those of the water column. First, as the repository for a large fraction of the materials loaded to and produced within aquatic systems, sediments represent a reservoir of biogeochemically-active materials potentially impacting water quality. A layer of sediment, only a few centimeters in thickness, may contain more organic carbon and nutrients than the entire water column (Avnimelech et al. 1984). Second, the purging of contaminants from sediments through reaction and burial (the "slow eigenvalue", Chapra 1997) proceeds at a much slower rate than in the water column where constituents are acted upon by sedimentation, reaction, and flushing (the fast eigenvalue, Chapra 1997).

The NJDEP has found that internal loading could be a big component of the overall loading (Pang, 2018). In one case, 20% of load is from tributaries, 40% from runoff, and 40% from IL. In a review, Boynton et al (2017) estimated that estuarine and coastal sediments at depths less than ten meters accounted for an average of 15% to 32 % of N and 17% to 100% of P demand, and sometimes exceeded external load of nutrients. Tidal energy subsidy and stratification were cited as complicating factors for these environments.

NJDEP expressed the need for a way to estimate how IL changes with EL, and especially how internal loading would be reduced eventually when the external loading is reduced. In addition, the magnitude of the internal loading needs to be considered when evaluating the close-to-natural condition (the best that can be achieved for a waterbody) as part of the site-specific criteria development Regulatory authorities need the ability to explain when and why certain water quality goals are not achievable.

Currently in some studies, internal load is treated in water quality modeling for regulatory purposes as a unchanged boundary value. But as regulatory actions reduce external load, the internal load will be expected to decline slowly with a time scale likely to be of the order of years or decades. This would be particularly the case in depositional environments such as lakes and impoundments. The potential problems include:

1. Models may underestimate longer-term benefits of eliminating external nutrient loading, thereby leading to unnecessarily strict interventions, or
2. After implementation of interventions, the predicted benefits may not materialize (at least not immediately), again possibly leading to distorted actions

Findings

1. *Applicable mechanistic models exist for predicting sediment sources of nutrients. However, these are likely to be too complex and difficult to calibrate for regulatory purposes.*

2. *Empirical models have been proposed that have the potential to strike a proper balance between complexity of calibration and ability to produce useful results.*

3. *An effort should be made to collect data at a number of lakes over an extended period to formulate empirical model(s) which could be used by decision makers to assess the rate of decrement of sediment nutrient(s) pool and sediment nutrient contributions to the water column.*

4. *The empirical modeling effort would be most fruitfully applied to depositional freshwater environments such as lakes and impoundments. Riverine, estuarine and coastal environments involve additional complexities that would be difficult to account for.*

Current Modeling Capability

The two main water quality models in current use are QUAL2K and WASP. There is currently no one-size-fits-all approach for all types of NJ waters to predict significant changes in sediment sources of nutrients following a reduction in source loading from the contributing watershed. This is due, in part, to the large variability in types of water bodies and in related sediment conditions due to multiple factors. For example, New Jersey's water environments alone include a variety of fresh water lakes and impoundments; high and low energy creeks, streams and rivers; and estuarine, saline coastal tidal waters; all with various water depths, and surrounding land use effects or impacts, which contribute to various sediment conditions that in turn affect sediments as nutrient sources.

Relevant differences in sediments (e.g., thickness, composition, grain size, organic carbon) and variation in sediment deposition dynamics (e.g., seasonal fluctuation, episodic storm events and flooding, irregular scour and accretion) are additional examples of some types of variation that can occur within one body of water (e.g., river, lake, estuary). Non-point source pollutant loading (e.g., septic system discharges via ground water, synthetic chemical contaminants from industry, legacy contamination from historical sediment deposition or on-going ground water discharges) may also impact nutrient cycling and efflux from sediments in some waters. The impacts of these and other factors affect the sediment redox conditions and related biogeochemical cycling that drive nutrient cycling and interaction with the water column.

QUAL2K

QUAL2K could be applicable, as it solves all the necessary parameters and it accounts for all the major feedback components. However, it is a one-dimensional (1D) model in that the water column is vertically integrated. This would probably eliminate the possibility of any real anoxia events because the most likely anoxia event that would affect the long term storage of phosphorus would be a stratification event that could isolate the lower part of the water column from the surface. QUAL2K is actually designed for rivers and streams. Hence the 1D set up, it may not be applicable for lakes and ponds, especially dimictic lakes. That being said, all the components are there to account for a dynamic nutrient boundary condition. Research on model calibration is needed before QUAL2K could satisfy the need.

WASP

The USEPA's Water Quality Analysis Simulation Program (WASP), has been used to develop total maximum daily loads (TMDLs) for specific water bodies in other states (e.g., Florida, Georgia, Virginia) where eutrophication is an important issue in some surface waters. According to Wang et al (2013) "WASP models are suitable for water quality simulation in rivers, lakes, estuaries, coastal wetlands, and reservoirs, including one-, two-, or three-dimensional models." The WASP documentation on sediment diagenesis (Martin and Wool, 2012) provides details:

> "WASP is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. WASP allows the user to investigate 1, 2, and 3 dimensional systems, and a variety of pollutant types. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model."

> "One of the processes long been known to impact the water quality of surface waters is the oxygen demand by, and nutrient release from, sediments. Sediment oxygen demand (SOD) and nutrient releases, due to the mineralization (diagenesis) of organic materials in bottom sediments, can contribute to eutrophication, harmful algal oxygen blooms and hypoxia."

SOD and sediment nutrient releases are generally incorporated into water quality models (such as WASP) as temperature-corrected zeroth order rates, which are estimated by model calibration or through direct measurement. The non-tidal watershed TMDL studies in the Passaic and Raritan River basins estimated SOD and sediment nutrient releases through calibration, and benchmarked the SOD magnitude with field measurements. While SOD is important in certain segments, sediment nutrient fluxes are rarely needed to account for observed concentrations in riverine systems. More common in these environments is the loss of nutrients via organic complexation and settling. It is often not realistic to establish SOD rates based on field measurements alone, due to the costs involved and difficulty in obtaining direct measurements, as well as the heterogeneity and consequent difficulty in interpolation between limited samples over a waterbody.

> "The use of a zeroth order rate, or constant source term, in water quality model applications does not provide for a mechanistic link between sediment organic matter and its conversion into oxygen demand and nutrient release. In the absence of this missing link, one of two alternative approaches have commonly been employed. The first and most commonly used approach has been to assume the rates of SOD and nutrient release are unchanged following waste load reductions, or implementation of other water quality management alternatives. […] An alternative approach has been to assume linearity and lower SOD in direct proportion to a load reduction (Chapra 1997). However, there are rarely sufficient data available to estimate the magnitude and rate for the reduction."

> "The latest release of WASP contains the inclusion of a sediment diagenesis model linked to the Advanced Eutrophication sub model, which predicts sediment oxygen demand and nutrient fluxes from the underlying

> sediments. […] In a landmark paper, Di Toro et al. (1990) developed a model of the SOD that mechanistically arrives at the observed non-linear relationships (Chapra 1997). Di Toro's approach, as described in his book on Sediment Flux Modeling (Di Toro 2001), calculates sediment oxygen demand and phosphorus and nitrogen release as functions of the downward flux of carbon, nitrogen, and phosphorus from the water column. This approach, well founded in diagenetic theory and supported by field and laboratory measurements, was an important advancement in the field of sediment-water interactions."
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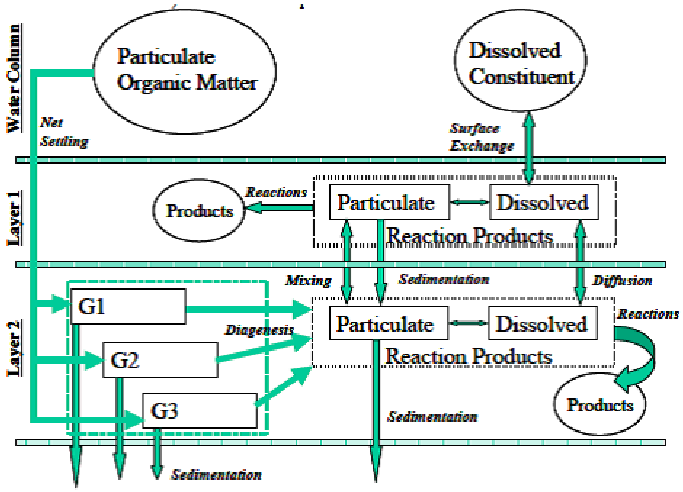
> "The basic framework of the sediment diagenesis model consists of two well-mixed sediment layers, underlying each surface water column segment: a thin upper sediment layer (the aerobic layer, on the order of 0.1 cm thick, Di Toro 2001) and a thicker active layer (anaerobic, on the order of 10 cm thick; Di Toro 2001, Figure 1). Three major processes included in the sediment model are the:
>
> 1. Fluxes of particulate organic matter from the water column to the sediments (note that since the upper sediment layer is assumed to have a negligible thickness, the fluxes are deposited directly into the second, or anaerobic layer),
> 2. Mineralization (or diagenesis) of the particulate organic matter, and
> 3. Reactions and transfers (between sediment layers, to the water column and deep inactive sediments) of the reaction products."



(Figure from Martin and Wool, 2012)

WASP appears to be designed primarily for situations such as lakes and reservoirs where vertical water column segments would be defined. Initial conditions must be defined for sediment and pore water concentrations for all fractions in both sediment layers. Model coefficients and constants are assigned default values in the model based on studies in Chesapeake Bay, Long Island Sound, Massachusetts Bay, and Jamaica Bay. There appears to be little if any application to freshwater riverine environments. This is not surprising, since sediment nutrient fluxes are more important in estuarine and lacustrine environments. However, this suggests the research need to develop coefficients that are validated for freshwater environments.

Consider the following scenario, one that is most relevant to NJDEP's questions: an impounded river segment that exhibits considerable SOD and acts as a settling sink for nutrients under current EL conditions. NJDEP wants to know what would happen in the future if the current nutrient EL was substantially reduced. Would SOD rates remain the same, or would rates slow down as less nutrient-rich sediments are deposited? Would the current nutrient sink become a source as water column concentrations decrease? How long would it take for the nutrients in the sediment sink to become either utilized or buried?

Given all these considerations, the current state of the art for situations like this is to assume zero order SOD rates. This remains the best available assumption, especially for riverine systems, until the state of the art improves or a water body-specific rate is empirically developed. Impounded rivers often drain large watersheds, and accretion of sediments and nutrients, particularly in higher-order streams, will always be important even under a future scenario that assumes substantial reduction of anthropogenic nutrient sources. To the extent that sediment sinks could evolve into sources, and SOD rates decrease as sediment organic material is depleted, such changes, if they occur at all in impounded riverine environments that drain large watersheds, would occur over very long time periods. Understanding, much less simulating, such changes over nearly geologic time frames presents a difficult challenge that cannot be overcome with the current state of scientific understanding and modeling.

Proposed Mechanistic Models

Most of the previous attempts to assess SOD and nutrient dynamics in interstitial waters have been conducted in laboratory settings; whereby, test and core samples have been subjected to various analyses, and supernatant waters have been measured for various constituents such as oxygen, nitrogen, and phosphorus. These estimates were then transferred to models to measure the contribution of sediments to the water column quality. Chapra, et al. (2015) reviewed existing efforts to develop mechanistic models. Their review summarizes prior research efforts:

> "… research models are comprehensive in their treatment of the biogeochemistry of diagenesis and rigorous in their solution, but are complex in their conceptual and mathematical structure and demanding in their requirements for information supporting application. This may be the reason that management application of such models is rare, and evaluation of their utility, strengths, and weaknesses is limited (cf. Boudreau et al. 1998)"
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> "One exception is found in the SPIEL model (Schauser et al. 2004), a one-dimensional, distributed-system framework for phosphorus in sediments that retain levels of spatial segmentation and biogeochemical detail similar to those of complex research models, but offers a management focus. Although the SPIEL model was designed to accommodate analysis of engineered, in-lake remediation measures (e.g., dredge and cap, chemical augmentation, etc.), this tool has apparently not been widely adopted."
>
> "Chapra and Canale (1991) developed a single-layer, lumped system model for sediments and successfully applied it to phosphorus dynamics in Shagawa Lake, Minnesota"..."However, lumped-system models suffer from two primary issues of transparency, potentially compromising their credibility/reliability in management applications. The first issue relates to testing model performance."
>
> "The two-layer model described by Di Toro (2001) represents a marked departure from the traditional mass balance approach used in other models. Appreciated for its insight, elegance and sophistication, the Di Toro (2001) framework is not conceptually accessible to users at a level comparable to that of broadly-accepted and widely-applied lake and river models."

In response, Chapra, et al. (2015) made another attempt to develop a mechanistic sediment model. The result is called **Sed2K**. The model tracks the fate of particulate organic matter (POM) (C, N and P) in sediment, plus transport of electron acceptors and donors. Soluble components are transported in the sediment by burial and diffusion; particulates by burial. Model segmentation ranges from 0.5 (near interface) to 10 millimeters (at depth).

> "Sed2K. The model framework seeks to balance levels of complexity (scientific rigor), transparency (capacity for confirmation) and applicability (demands for input) in a manner which will facilitate its adoption in support of management decisions."

These modeling approaches are limited by availability of data. The section below on monitoring describes the data requirements. Only after such arduous efforts will it be possible to arrive at a modeling tool based on mechanistic principles which may be used to generate meaningful TMDLs in inland waterbodies of concern. Despite these limitations, mechanistic modeling may become a feasible approach in the future. But under the current state of the art, other approaches described below have better potential to yield practical results.

Proposed Empirical Models

The ability to predict the response to a reduction in the phosphorus load from a watershed to a pond requires knowledge of the inventory of phosphorus stored within the pond sediments and the outflow. While a great deal of research has gone into mechanistic modeling of the sediment water column interaction for the transport of nutrients across the sediment-water interface via the sediment diagenesis model proposed by Di Toro (2001), applications of this model have been limited. The sediment diagenesis model is a complex model that requires many inputs that may or may not be available for a particular stream, and many of these parameters must be predicted themselves thus increasing the uncertainty of the model. An alternative approach could be to develop simplistic site specific empirical models based upon measurements collected in situ that can then be used to extrapolate an outcome. The method is similar to one that has been used by Larsen (2015) and Chapra (1997) that involved calculation of a first order decay coefficient for the phosphorus content in the sediment.

The proposed methodology would involve periodic sampling of the sediment in a pond to try to accurately determine the inventory of sediment phosphorus after the “new” or “reduced” watershed phosphorus loading to the pond. The decrease in the phosphorus inventory over time would be used to calculate a decay coefficient via regression techniques. Chapra (1997) proposed a first order decay response model of the form:

$$t_R = \frac{1}{k_d} \cdot ln\frac{100}{100 - R}$$

where k_d is a first-order decay coefficient, and R is percent of recovery

This approach is a simplistic alternative to in depth modeling to try to understand all the processes occurring in this pond. It is site specific and would not be representative of the sediment response in other locations or with dynamic phosphorus loading conditions. The loading must be approximately constant for the decay pattern to be realized, thus it should be used to model recovery of a pond in a watershed after some large-scale nutrient mitigation project is completed.

There is a potential for this model to provide insight into the response of ponds to nutrient mitigation if the approach is completed at many locations with a variety of conditions so that statistical techniques can be employed to determine the underlying pond and watershed characteristics that determine the ability of a pond to recover after nutrient load mitigation occurs.

Where appropriate, application of any empirical modeling effort will include data collection for model input and should incorporate calibration and follow-up monitoring, which may be costly and time consuming. While an empirical model will be specific to a water body, there may be opportunities to develop profiles of “typical” scenarios that facilitate standardizing modeling approaches for water body characterization to facilitate modeling of similar water regimes.

Monitoring Approaches

Monitoring is needed for two reasons: (1) to track changes in IL and to develop a database for empirical modeling and to develop improved calibration methods for mechanistic models; and (2) because TMDLs may need revisiting as IL changes.

The following steps need to be done to improve the current understanding and estimation of IL in lacustrine environments:

1. Experiments need to be devised to assess the rate of accretion and decretion of sediments in an impounded body of water.
2. Simple yet long-term monitoring of nutrient concentrations in influents and effluents from such waterbodies will provide an idea about the fluxes of such nutrients and help determine the atmospheric losses and estimated rate of deposition of nutrients in the sediment.
3. Direct measurement of SOD and phosphorus flux to and from sediment should be conducted over time and for a variety of water bodies.
4. Conducting such experiments in a number of lacustrine environments will provide the necessary data to formulate empirical tools to assess the nutrient depletion, and thus IL, which is supported by a reliable data base.
5. If the data are to be used for mechanistic modeling, it is essential to characterize the sediments in detail. For example, the amount of nutrients that exist in the surficial layers of the sediments and that may be available to the water column under various biogeochemical conditions and processes should be assessed, and a profile of the redox and other biogeochemical conditions should be developed.

IL could be measured indirectly from mass balance measurements, which should be carried out over a year at a time, and repeated at multi-year intervals (e.g., every five to ten years). If conducted at a range of water bodies of varying characteristics, enough data could potentially be collected to relate IL to site conditions.

In addition, it might be possible to utilize methods for direct in situ measurement of nutrient flux, like methods used to directly measure SOD. Such methods have been implemented by the USGS in studies in the Salem River and Barnegat Bay [Pang, 2018].

In addition to monitoring IL, potential independent variables should be monitored at the same time. These are physical, chemical and biological factors that may affect long-term accretion or depletion of SOD and IL. Physical factors include mixing and stratification. Chemical factors will cover a wide range of water quality parameters, including dissolved oxygen (DO) and diurnal variation in DO. Biological factors may include measures of eutrophication, such as chlorophyll-*a* levels. Complicating things is the fact that these parameters vary strongly with season, and these seasonal variations will be important to understanding the behavior.

IL and SOD relate to impacts of sediment properties on the water column. Of equal importance for the long-term prediction of IL and SOD are the fluxes of substances from the water column into the sediment. Current models such as WASP do adequately account for this, but monitoring seasonal deposition would improve future model development and calibration.

Overall, if monitoring is to support future empirical or mechanistic model development, data will need to be collected for a number of “typical” scenarios. For example, a number of lakes could be monitored for IL covering a range of size, retention times, and external loading rates. Also, data should be collected on water bodies that have had marked changes in external loading, whether increases or decreases, to develop information on the time constant for changes in sediment properties.

Monitoring is the only reliable currently available approach for tracking and understanding IL. However, it is inherently backward-looking. It does not, in itself, predict the future. For that, one needs models.

Other Considerations

The committee felt that the findings of this report could be reliably applied only to freshwater lakes and impoundments. Sophisticated coastal and estuarine multi-layer sediment models have been in existence for some time; nevertheless, their use has been hampered due to a lack of data and the complexities of such models to attain the desired objective.

Rivers and streams also introduce additional complexities due to sediment movement dynamics. "Run of the river" lakes represent an intermediate case between rivers and impoundments. The potential for development of models that would include this type of water body seemed more uncertain.

Wetlands introduce even more complications. Some have been found to be sinks for nutrients, while others are sources. Reliable predictions of their behavior has been elusive.

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