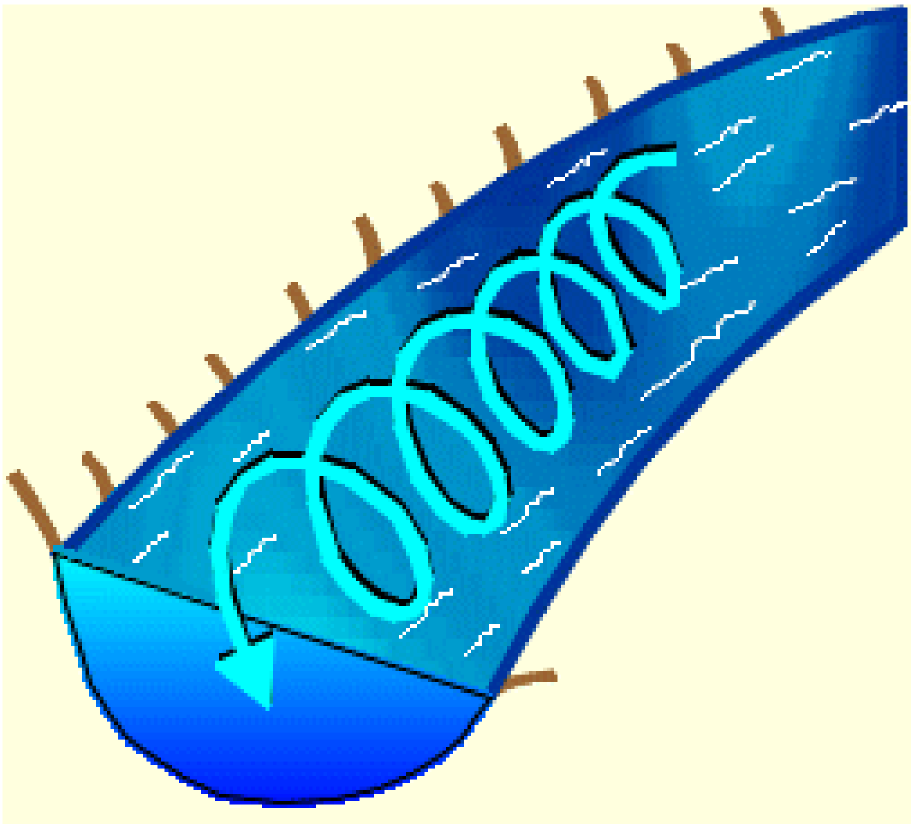
Assessing the Environment in Outcome Units (AEIOU): Using Eutrophying Units for Management



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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at http://www.chesapeake.org/stac.

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Executive Summary

The Chesapeake Bay Total Maximum Daily Load (TMDL) sets goals for total nitrogen (TN), total phosphorus (TP), and total sediment reduction by political jurisdiction and by river basin in order to restore aquatic habitat. However, using total nitrogen and phosphorus rather than specific species of these nutrients, can mask processes that ultimately determine restoration success in terms of supporting fish communities and human safety, among other outcomes. For example, in some areas of the Chesapeake Bay Watershed, the proportion of phosphorus entering in a bio-available dissolved form (ortho P) is increasing, despite or even as a side effect of management efforts. A growing body of scientific evidence indicates that the speciation of nutrients influences algal biomass and the extent of hypoxia, which are reflected in water quality standards. Yet nutrient species effects are not factored into targeting TMDL effort nor the crediting system that tracks progress of jurisdictions towards their goals.

The consideration of nutrient species within the Chesapeake Bay TMDL and the broader management strategies of the Chesapeake Bay Program (CBP) would likely increase the efficiency of management by targeting effort to the nutrient species most responsible for hypoxia. For example, practices that reduce nitrate delivered to the Bay are likely more effective in reducing hypoxia than practices that reduce organic nitrogen, the latter likely being more effective in reducing harmful algal blooms. Additionally, achieving water quality goals within freshwater rivers, lakes, and reservoirs may require different reductions of nutrient species and timing of delivery. Management plans might better address multiple endpoints at a reduced cost, if these relationships were understood and made part of the management evaluation structure.

Calculations similar to those proposed have already been estimated and reflect geographic differences of nutrient loads in terms of hypoxia effects. Loads of N and P generated from different locations were converted into the common currency of "eutrophying units" to support the exchange of N and P reductions requested by some jurisdictions. A similar system to incorporate how nutrient species affect ecological outcomes could use the same concept of eutrophying units but has substantial information needs. Synthesis of existing science and new research or expert judgement to fill data gaps are required to build an understanding of the relative magnitude of speciation effects on hypoxia. Such effects must be considered under heterogeneity of nutrient inputs, land use, watershed physical characteristics, stream processes, and water body biogeochemistry. In addition, the ability of management practices to reduce specific nutrient species is understood for some, but not all, practices.

Movement toward a system that incorporates nutrient species is critical to successfully achieving the TMDL goals. In many areas of the Chesapeake Bay watershed, total nutrients are declining while bioavailable forms that contribute the most to hypoxia are increasing. These trends suggest that some waterways may not respond as expected to achieving the total nutrient cap. Synthesizing what is known about bioavailable forms of nutrients has the potential to improve the CBP's ability to quantify effects of management efforts under a variety of conditions to ensure efforts are ultimately effective at restoring water bodies.

Overall recommendations to the Chesapeake Bay Program:

1. The CBP should move to set program goals and assess progress through "eutrophying units" that characterize algal and hypoxia effects, as soon as feasibly possible. Because this transition may take some time, it is critical that the CBP begin working towards this goal in 2020, and not wait until 2025. For example, speciation is well understood in wastewater treatment effluent, providing a good starting point for differential credit.
2. An appropriate analytical framework for implementing eutrophying units is needed to ensure desired water quality outcomes will be achieved.

   a. The effects of land use, Best Management Practice (BMP) type, and transport effects in the watershed will need to be incorporated.
   b. The effects of load location relative to environmental endpoints will need to be tracked.
   c. Both the dissolved organic nitrogen (DON) reactivity formulations and the N and P species limitations in the CBP estuarine water quality model need to be re-examined and updated with results from current research.
   d. The hydrodynamic model must be improved in the shallow waters where considerable nutrient transformations occur.
   e. Conceptual models that synthesize existing science can suggest important endpoints and processes to track.
3. To attain management goals, the CBP needs to promote gap-filling research on the following factors affecting nutrient speciation and the effects of nutrient speciation on multiple environmental endpoints:
   a. The effects of BMPs and treatment trains on the speciation of nutrients reaching streams
   b. Nutrient transformations and transport in soil
   c. Nutrient transformations in streams and rivers, with particular emphasis on the typical distance traveled prior to transformation
   d. The reactivity of the various types of organic matter entering the estuary via the watershed needs to be better understood
   e. Speciation and N:P ratio effects on algal communities

Introduction

The Chesapeake Bay TMDL (US EPA 2010) established nitrogen, phosphorus, and sediment caps using a suite of modeling tools to evaluate the levels of organic and inorganic nutrient levels necessary to achieve quantitative ecological goals for dissolved oxygen, water clarity, and chlorophyll. Those ecological endpoints were set at levels designed to restore conditions that promote fish habitat and safe human and animal water use. The Chesapeake Bay Program measures progress towards meeting the TMDL using total average annual nutrient loads to tidal waters. This accounting approach simplifies progress tracking but could lead to inefficiencies in designing management strategies. Specifically, the process lumps organic and inorganic species, but inorganic nutrients may have a greater impact on eutrophication compared to organic forms. Inefficiencies may arise because management options may have varying, even conflicting, effects on the fate of different forms of nutrients. Different forms of inorganic nitrogen also have different ecological effects; therefore, more direct accounting of nutrient species or fractions could lead to more cost-effective management by making explicit the effects of practices or their location on water quality outcomes.

The nutrient caps of the TMDL embed some scientific understanding of the differential effects of nutrient species on the quantitative ecological targets for dissolved oxygen, water clarity, and chlorophyll, which describe the goals to restore fish habitat and promote human safety and enjoyment of the Bay. However, information about how management choices affect outcomes is not available to those designing the watershed implementation plans (WIPs), which are the strategies detailing how states will meet the TMDL. This gap is relevant because the effect of management on nutrient species delivery and timing to water bodies can depend on a variety of conditions on site and in the runoff pathway, including soil and aquifer properties and conditions of the receiving water bodies including salinity, temperature and sediment load.

An alternative approach that characterizes how management practices influence the bioavailability or timing of specific species of nitrogen and phosphorus could help to more cost-effectively target management. However, using lumped TN and TP to describe management action effectiveness hinders those who are designing nutrient reduction strategies from optimizing their approach to cost-effectively restore fish habitat and prevent harmful algal blooms. A potential impediment to moving in this direction is our current inability to quantify how nutrient species and timing of delivery depends on a variety of conditions in the runoff pathway, including soil and aquifer properties and conditions of the receiving water bodies including salinity, temperature, and sediment load.

The objective of this workshop was to explore whether the science is ripe and appropriate for calculating *eutrophying units* as a common currency that can be used to compare alternative restoration strategies. Eutrophying units could be calculated from the combined species concentrations of nitrogen (N) and phosphorus (P) using transfer functions that depend on their effect on environmental outcomes. The workshop facilitated synthesis of the state of knowledge and organizing approaches for developing eutrophying units, reflecting spatial, and temporal conditions of the Bay and its watershed.

Background

Conditions within the watershed and the Chesapeake Bay partnership support the need for this workshop and an outcome-based approach to management priorities. Analysis of River Input Monitoring data shows statistically significant differences in flow-normalized trend direction for total P and ortho-P (an inorganic and highly bioavailable form of P) for four of nine river input stations (Zhang, et al, 2015). In some areas of the Chesapeake Bay Watershed, ortho-P is increasing, despite or even as a side effect of management efforts, and this issue is common to large watersheds throughout the world (for example, Choquette *et al, 2019)*. Understanding these loading trends is hindered by the fact that, currently, the Chesapeake Bay

Program Watershed Model does not fully capture processes including flow dynamics, land use practices, and ‘nutrient spiraling’ in which stream communities assimilate and chemically transform nutrients.

Synthesizing what is known about bioavailable forms of nutrients has the potential to improve the CBP’s ability to quantify effects of management efforts under a variety of conditions that control nutrient transformations to ensure efforts are ultimately effective at restoring water bodies. Nutrient speciation matters to water quality outcomes because it affects total phytoplankton biomass and can cause preferential growth of some phytoplankton groups and taxa in tidal waters. Some literature (for example, Glibert *et al*, 2016) suggests that the ratio of N to P (N/P) or dissolved fractions (DIN/DIP, NH4/NO3) can determine phytoplankton species composition. In some systems, a low N/P ratio selects for nitrogen-fixing cyanobacteria and several known toxin producers. Hence, nutrient species, concentrations, and ratios, along with mixing, can govern species composition and water quality outcomes in many water bodies.

Chesapeake Bay managers are already somewhat comfortable with the concept of different N and P fractions and are receptive to expanding this concept because of the potential to use such knowledge to select the nutrient reduction strategies most protective of water quality and human health. The Chesapeake Bay Modeling Suite already explicitly simulates the effect of nutrient species on TMDL outcomes of dissolved oxygen, clarity, and chlorophyll in the Bay. However, such information is not easily accessible for planning. Managers are also interested in the potential to expand the concept of exchanging N and P reductions, as has been used by jurisdictions since 2010, to include species of N and P.

Conceptual models of nutrient speciation and effects

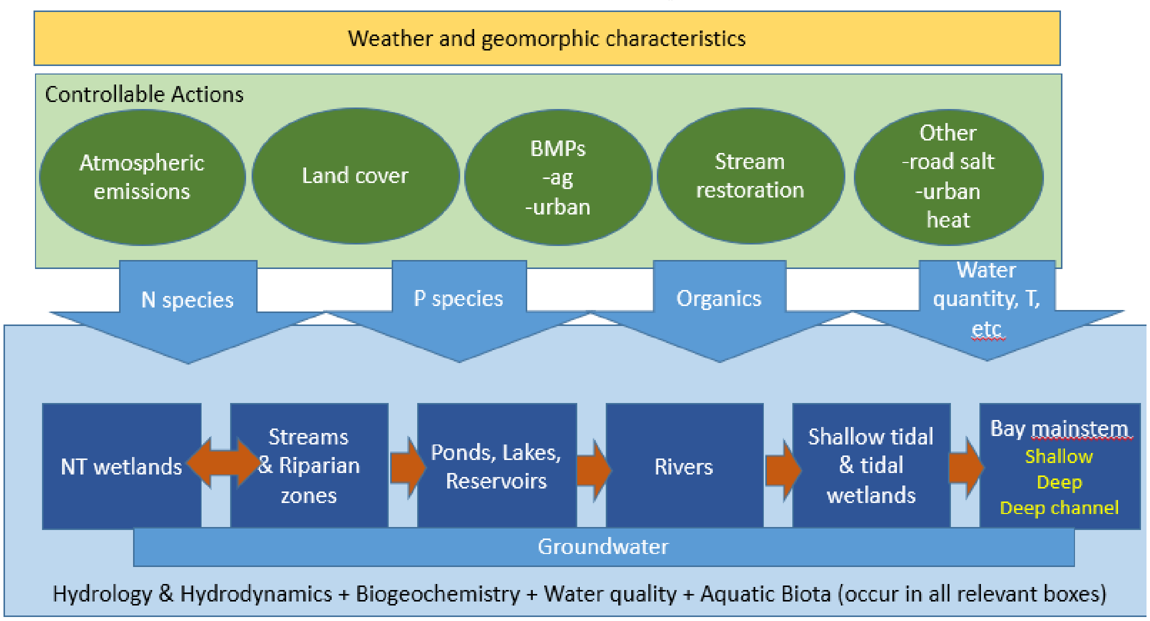

Figure 1: High-level representation of factors influencing speciation and physical systems where speciation has an effect within the Chesapeake system

Figure 1 shows a conceptual model of the Chesapeake Bay and Watershed, indicating the processes and system components that control speciation of nutrients. Controllable actions are broken out (green box) to suggest some available methods to manage nutrient species entering water bodies. However, each subsystem of nontidal wetlands, streams, lakes, rivers, tidal wetlands and the Bay mainstem includes biotic and abiotic components that can remove and transform nutrients. Thus, using eutrophying units to set restoration goals is potentially complex unless the system can be simplified by considering which processes have the largest effect on aquatic habitat. BMPs are used to manage total nutrients but they differ in their ability to reduce nutrient species and might need to be combined to control the most bioavailable forms of nutrients. Other approaches to controlling species include watershed-scale management of soil condition, temperature of water runoff, lake & reservoir management, and hydrologic flow paths.

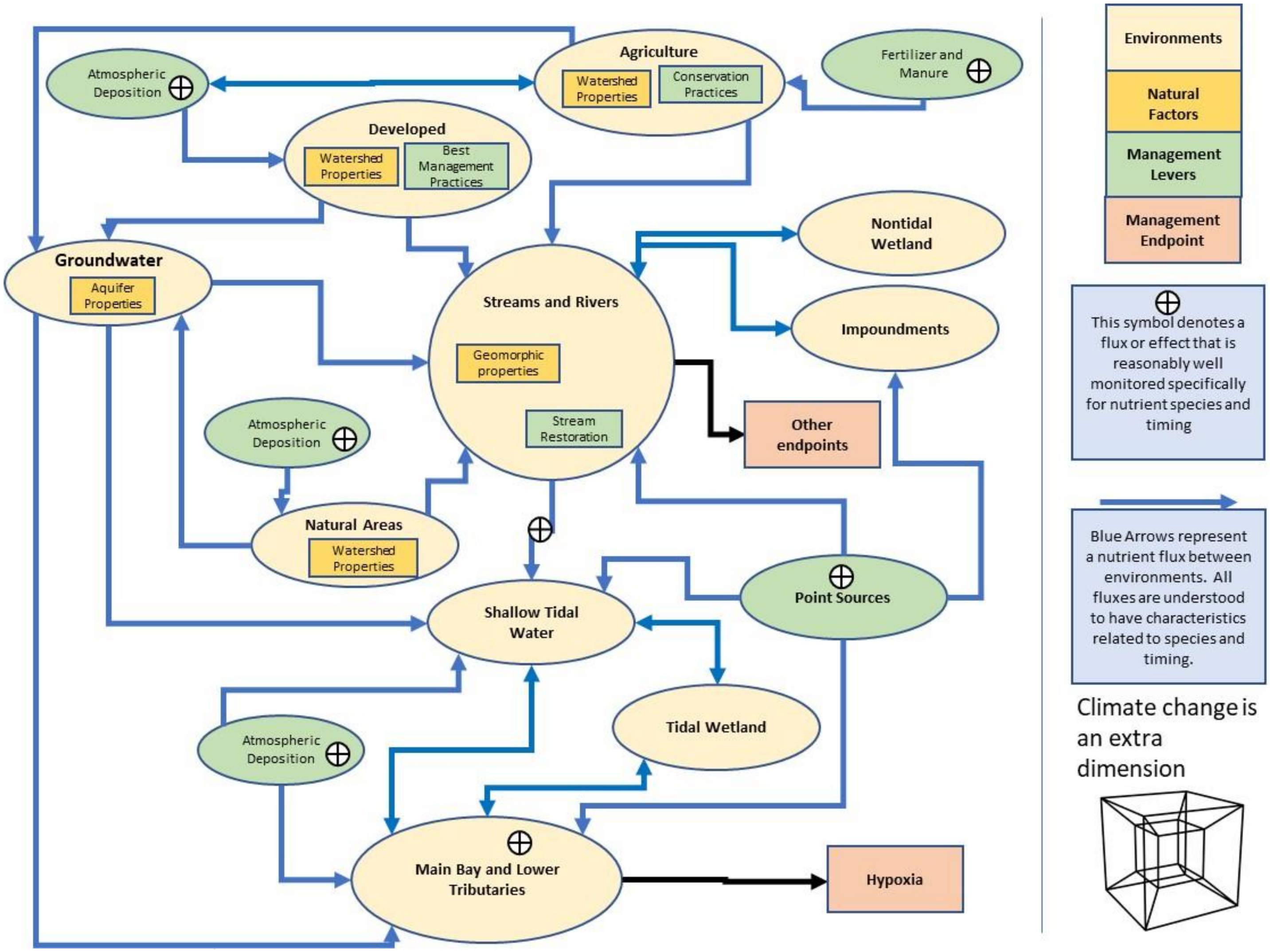

Figure 2: Conceptual model of the Chesapeake Bay Watershed and Estuary indicating landscape settings and management actions that would have an effect on nutrient speciation

Figure 2 is a representation of the interaction of components of the Chesapeake Bay and Watershed relevant to nutrient speciation and the effects on environmental endpoints. Components of the natural system are shown as beige ovals and generally correspond to modeling components of current Chesapeake Bay Program Models. Golden rectangles indicate physical properties of the natural system that may influence nutrient speciation. Green indicates management levers that can affect nutrient speciation, either as inputs shown in ovals or as management actions shown in rectangles. Management endpoints are represented in salmon rectangles.

Fluxes (effects shown by a cross in Figure 2) are reasonably well understood with respect to speciation. Data on atmospheric deposition, fertilizer, manure, and point source generally include nutrient species, as do the CBP nontidal and tidal monitoring networks. However, there are other areas associated with considerable uncertainty. The speciation of nutrient inputs to the landscape is well understood, but the processes that transform nutrients prior to delivery to the fluvial system are not. The effect of land use, physical properties, and management likely all have effects that are not fully described. Land processes may well be unimportant to hypoxia endpoints, however, if nutrient spiraling in streams and rivers is the dominant process determining speciation of nutrients delivered to tidal waters. Streams and rivers have their own management endpoints, which are dependent on river processes and may or may not be dependent on land-based processes. Hypoxia is separated from stream-influenced speciation by shallow water, tidal wetland, and main Bay and lower tributary processes. The relative influence of land-based, fluvial, and estuarine processes on speciation effects is unknown.

Management relevance and urgency

Adoption of eutrophying units by the CBP has significant management relevance since the outcomes have the potential to greatly reduce costs and increase effectiveness of the states' watershed implementation plans. Although workshop results will not be available for use in the implementation plans submitted in 2019, they will be available to inform allocation of effort as plans evolve through the 2-year milestone process. The results are expected to be useful for guiding operation of wastewater treatment plants, BMP selection and siting, and design of BMP systems to preferentially control nutrient species with higher eutrophying potential.

Presentations

Optimal Phosphorus Abatement (Antti Iho, Natural Resources Institute Finland)

Antti Iho discussed reasons for setting policy goals in units reflecting the environmental outcomes as closely as possible, and why the currently used metrics in water protection could be improved. Due to advancements in point-source abatement, the relative share of non-point nutrient loading from total loading has increased. This reinforces the importance of having efficient policies in place, particularly for agricultural non-point loading. Any agricultural conservation activity affects an array of pollutants. Often the effects are opposite. P loading, for instance includes many chemical species and functional groups. The most important class is soil-bound or particulate P (PP) that is largely controlled by erosion and mass movement of sediment. A major concern identified in this presentation was that widely used conservation measures designed to reduce PP, such as no-till, increase the loading of soluble reactive P (SRP) (Jarvie et al 2017, Uusitalo et al 2018). Unfortunately, a unit of SRP is more potent in promoting algal growth in receiving waters than a unit of PP.

Characterizing the environmental equivalency of the various nutrient species using a single currency would support cost-effective targeting of our management efforts. Having a metric of environmental impact creates a performance metric, rather than an output metric to use in setting restoration priorities. An example of how such a system would work is the approach used to represent equivalent atmospheric effects of diverse types of greenhouse gases. The system uses the relative effect on global warming to measure all greenhouse gases in the common unit of CO2 equivalents. A nutrient metric would similarly transform the environmental effects of different nutrient species into a common metric of eutrophication potential or related ecological impact.

To define such a unified performance metric, we need several types of information. We require information on the effects of management practices on production of different species, the fate of these during their transport from sources to receptors point, and their bioavailability at the receptor point. The importance of having a metric tied to environmental outcomes is it allows decision-makers to more appropriately evaluate the effect of a management action on the ultimate goal. Metrics that measure outcomes not directly aligned with the environmental goals may negatively affect the way we incentivize and advise farmers to curtail their loading and in the way states allocate their abatement efforts between point and non-point sources. Therefore, we should include continuous evaluation of the correct metric into our research programs – again in the same way as the coefficients in CO2-equivalent are being modified as our scientific understanding improves.

The Chesapeake TMDL Calculation (Gary Shenk, USGS)

Gary Shenk introduced the Chesapeake Bay Program and the Chesapeake Bay TMDL (USEPA 2010). The TMDL is articulated as limits to total nitrogen and total phosphorus calculated by state and major basin, but the bay partnership has experience with calculating and performing exchanges between nutrients and between basins using ratios of effectiveness. The idea of giving differential credit spatially and between nutrient types is well-established. The exchanges are possible because the limits in total nitrogen and total phosphorus are based on achieving acceptable levels of dissolved oxygen in the tidal Bay. The use of dissolved oxygen as the common currency allows exchanges between reductions in nitrogen and reductions in phosphorus within a basin. Exchanges rates are also calculated between regions. Nutrient reductions in northern areas tend to be more effective in increasing dissolved oxygen than reductions in southern areas and so states can choose to raise their overall nutrient limits by shifting reductions to more effective basins.

The CBP partnership considered two issues during the CBP's 2017 midpoint assessment of the TMDL where, for the first time, timing and speciation of nutrients were explicitly considered in calculations of effectiveness. The infill of the Conowingo reservoir between the 1990s and 2010s is expected to increase total nitrogen by 13 million pounds and total phosphorus by 1.8 million pounds. However, since the additional nutrients tend to be less available forms and are delivered during periods less likely to cause oxygen problems, an equivalent reduction can be calculated as 6 million pounds of total nitrogen and 0.26 million pounds of total phosphorus (CBP 2017). Initial estimates of climate change effects were calculated in a similar manner (CBP 2017).

The current models used by the CBP account for some aspects of speciation and timing of nutrient delivery. The current watershed model has a deterministic simulation of rivers with an average flow greater than 100 cubic feet per second. Generally, ammonia is converted to nitrate and inorganic forms of nitrogen and phosphorus are converted to more particulate organic forms as the rivers flow toward tidal waters. Speciation in landscapes are coefficient based and are not modified in small streams. The estuarine Water Quality and Sediment Transport Model (WQSTM) handles speciation explicitly. A test of speciation effectiveness in reducing hypoxia was performed for the workshop. Generally, dissolved inorganic nutrients and highly labile organic nutrients (G1 classification) input to the Chesapeake had similar effects on hypoxia, with phosphorus having a higher effect. Refractory (G3) organics and particulate inorganic phosphorus had an effect about an order of magnitude less with G2 organics having an effect roughly half of the dissolved inorganics.

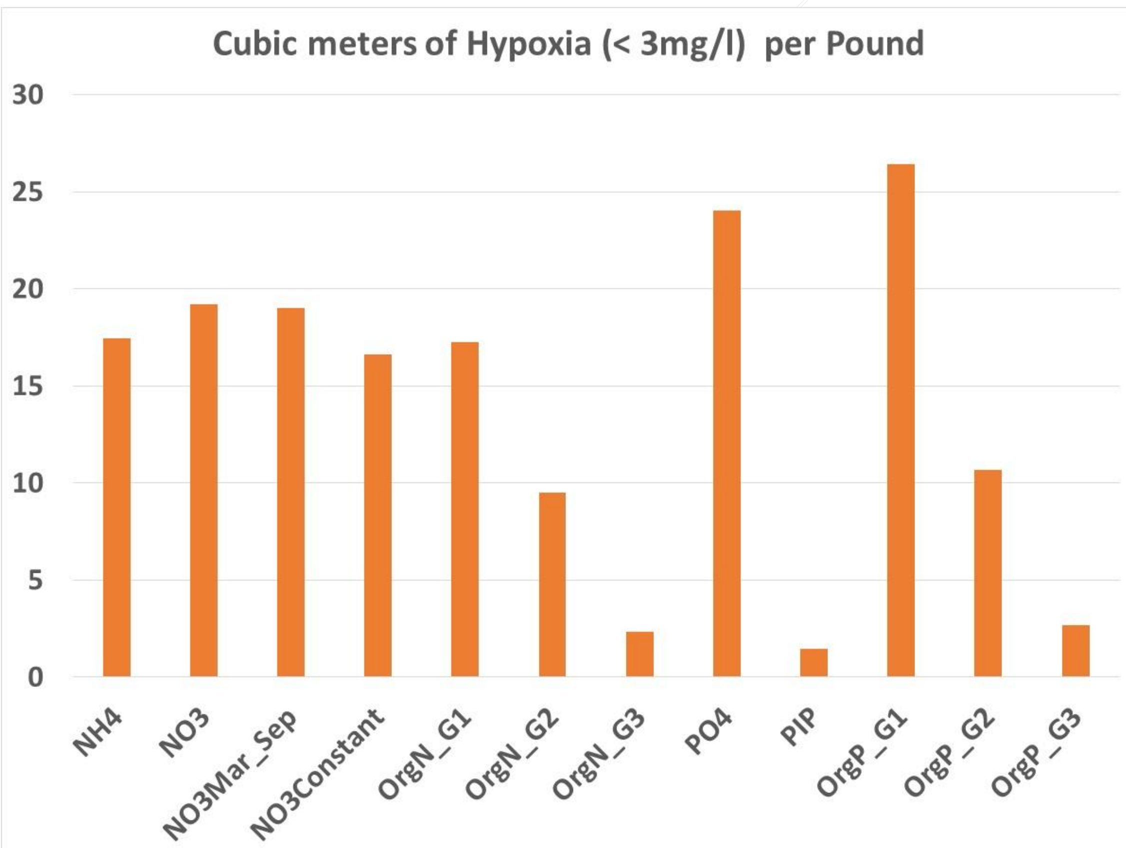

Figure 3: Relative effects on hypoxia of increases in different nutrient species. Estimates were made using the Chesapeake Bay Program's Water Quality and Sediment Transport Model starting from a condition where the TMDL was implemented

Landscape and BMP Nitrogen Processes (Jason Kaye, PSU)

Jason Kaye reviewed how plant-soil processes in forests and agricultural fields affect N species that move through soils toward streams. The N species reviewed were dissolved organic nitrogen (DON), ammonium (NH_4^+), and nitrate (NO_3^-). In general, across both forests and agricultural fields, small amounts of DON and very small amounts of NH_4^+ move through soils to streams and transport of these species doesn't vary much across landscapes or BMPs. Thus, most variation in soil-to-stream transport is from variation in nitrate transport arising from variation in: 1) denitrification, 2) atmospheric N deposition, 3) long-term vegetation suppression, including pest outbreaks, 4) land use history, 5) seasonality, and 6) storms (e.g. Nitrate flushing when surface soils are hydrologically connected to streams). There are some exceptions to the general pattern that DON and NH_4^+ smaller and less variable species in soil-to-stream transport than NO_3^-. In forests, important exceptions are that: 1) sandy soils lose NH_4^+ and DON, 2) wetlands and peatlands have DON > NO_3^-, 3) Conifer forests often have DON > NO_3^-, 4) pulses in DON occur after litterfall lasting weeks to a month, 5) DON often has a flushing response after storms. In agricultural systems, important additional exceptions include: 1) site with high macroporosity (no-till may increase DON loss), 2) sites with a long history of manure inputs, 3) sites where fertilizers or manures were recently surface applied or stored hydrologic source areas.

Based on this review of the literature, Jason concluded that the key landscape properties that affect N speciation in soil-to-stream transport are soil texture, hydrologic source areas, and ecosystem types. The key BMPs that affect N speciation in soil-to-stream transport are no-till, cover cropping, manure incorporation, and manure input history. Some key questions that remain unanswered in considering landscape and BMP effects on N speciation are: 1) what is the impact of nitrate and urease inhibitors?, 2) what forms of N are in DON?, 3) are the deep soil N species concentrations that I reviewed reflective of inputs to streams?, and 4) do surface soils become saturated with DON or NH_4^+?, and 5) how important is particulate N as minerals, crop residue, or leaves?

Management Practice Effects on Phosphorus (Peter Kleinman, USDA)

Distinguishing between dissolved and particulate P is important to agricultural management strategies intended to improve water quality. The management of non-point source phosphorus losses from agriculture has evolved from a principal focus on soil conservation, hence particular phosphorus mitigation, to one in which dissolved P mitigation is also a priority. Unfortunately, there are trade-offs associated with many management practices and, until recently, relatively few options existed to curtail dissolved P losses. Indeed, there is ample evidence that soil conservation strategies that prioritize the adoption of no-till and cover crops, while effective in curtailing particulate P losses, can exacerbate dissolved P losses. Where erosion is a concern, increases in dissolved P may not significantly reverse trends in total P reductions, but long-term trends in Chesapeake tributaries, recorded by USGS, point to increases in dissolved P over the past decade. Key processes of vertical nutrient stratification, preferential enrichment of P in eroded sediments from soils with lesser rates of erosion, and wash-off of broadcast fertilizer and manure all contribute to the potential for greater dissolved P losses from agricultural landscapes. Further, P sorption saturation in critical source areas of watersheds (especially riparian zones) and in the sediments of headwater streams results in the release of dissolved P in both storm and base flow, respectively. When these processes are not considered in management programs, they may undermine the efficacy of practices in mitigating watershed P concerns: a recent survey of Conservation Reserve Enhancement Program (CREP) forested riparian buffers found the average concentration of P in buffer soils was twice what is required for crop production, a problem that could be addressed by modifying site establishment guidelines. While dissolved P is clearly an important concern at local (field, headwater catchment) scales, its reaction with riverine sediments and biota undoubtedly modifies its downstream effects over the short- and long-term. Understanding these effects remains a research priority.

Riverine Processes (Doug Burns, USGS)

This presentation was designed to provide a general background on nutrient transport and transformation processes that occur within or near river channels. The focus of the presentation was nitrogen and phosphorus transport in rivers. Physical hydrologic processes such as groundwater inflows and outflows move nutrients to and from the river channel. The hyporheic zone where groundwater and surface water mix and interact is of particular interest as a hot spot of nutrient transformation processes. The balance of autotrophic and heterotrophic processes in the river produce and consume available dissolved oxygen and govern trophic status. Other topics discussed included nutrient stoichiometry, the concept of a limiting nutrient, and nutrient spiraling in rivers.

Nutrients can be viewed from a mass balance perspective that focuses on net sources and sinks of N and P during downstream transport. River channels are generally sinks for N and P delivered from the terrestrial environment, but there is distinct seasonality to nutrient mass balance. Additionally, high flows move large nutrient loads downstream, turning the river channel to a net source of loads, especially those in particulate form. In summary, models of watershed nutrient transport and transformation should consider the important role that riverine processes play in delivering N and P to the Chesapeake Bay.

Bay Loading Signatures (Qian Zhang, UMCES)

This presentation provided an overview of the characteristics and temporal trends of nutrient and sediment loads to Chesapeake Bay from its nontidal rivers. The presentation was focused on the nine major tributaries that have been monitored by the U.S. Geological Survey River Input Monitoring (RIM) Program.

True-condition loads estimated from the Weighted Regressions on Time, Discharge, and Season (WRTDS) method (Hirsch et al., 2010) revealed loading signatures by (1) tributaries, (2) seasons, and (3) flow quantiles in the period of 1985-2015 (Moyer et al., 2017). In terms of tributaries, the Bay's three largest tributaries, namely, Susquehanna, Potomac, and James, represent over 90% of total flow and total load from the RIM network. NOx represents a major fraction of TN in Maryland rivers but a minor fraction in Virginia rivers, whereas PO4 is a minor fraction of TP in all nine rivers. For TN:TP and NOx:PO4 molar ratios, Susquehanna is the only river that exceeds the RIM average, whereas James is the only river that is below the Redfield ratio (i.e., 16:1) (Figure 1). In terms of seasons, contributions of the RIM total load by the four seasons are generally similar to their contributions of flow. NOx is a major fraction of TN in all four seasons, whereas PO4 is always a minor fraction of TP. TN:TP and NOx:PO4 molar ratios are both above the Redfield ratio in all four seasons, implying P-limitation. In terms of flow quantiles, Q4 alone represents ~58% of total flow, a similar contribution of load for TN, NOx, and PO4, but a much higher contribution of load for SS (91%) and TP (77%), suggesting non-linear export of particulate constituents. NOx is a major fraction of TN in all four flow quantiles, whereas PO4 is always a minor fraction of TP. TN:TP and NOx:PO4 molar ratios are both above the Redfield ratio in all four flow quantiles.

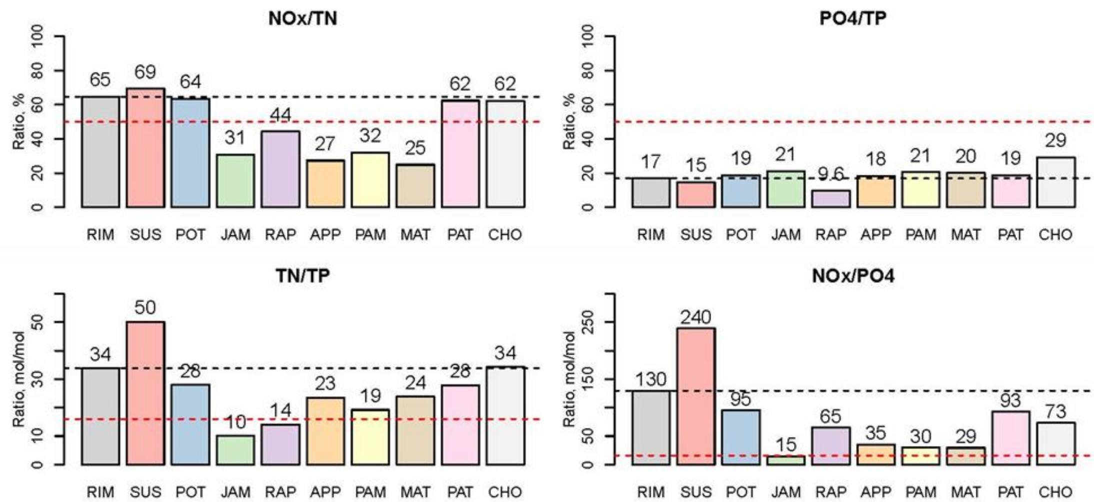

Figure 4. Ratios of NOx/TN (in percent), PO4/TP (in percent), TN/TP (in mol N/mol P), and NOx/PO4 (in mol N/mol P) in the nine major tributaries of the River Input Monitoring (RIM) network. Black dashed line indicates the RIM average. Red dashed line indicates the Redfield ratio (16:1). SUS: Susquehanna, POT: Potomac, JAM: James, RAP: Rappahannock, APP: Appomattox, PAM: Pamunkey, MAT: Mattaponi, PAT: Patuxent, and CHO: Choptank.

Flow-normalized loads from WRTDS revealed long-term trends in the nutrient and sediment loads after accommodating for the interannual variability in river discharge. Sediment, TP, and particulate nutrients from the RIM network have increased dramatically since around 1995, which were largely driven by Susquehanna trends that were in turn related to the declined trapping efficiency of Conowingo Reservoir (Hirsch, 2012; Zhang et al., 2013; Zhang et al., 2016). By contrast, TN and dissolved nutrients from the RIM network have declined, likely indicating the effects of management controls that included at least point source treatment technology upgrade and reduction in air deposition due to the Clean Air Act. Although TN:TP and NOx:PO4 molar ratios have been above the Redfield ratio in all years, TN:TP ratios have declined in recent years due to the opposing trends of TN and TP, which may lead to some potential changes in nutrient limitation in the downstream estuaries (Zhang et al., 2015).

Estuarine Nutrient Cycling (Jeremy Testa, UMCES)

The ultimate fate of a watershed-derived nutrient that enters the tidal waters of Chesapeake Bay and its tributaries is determined by how and where the nutrient is distributed and processed within the estuary of interest. In general, particulate nutrients delivered to tidal waters from the watershed are poorly reactive (J. Cornwell et al., unpublished), efficiently trapped in low salinity waters due to sinking or trapping in the estuarine turbidity maximum (ETM; e.g., Sanford et al. 2001), and a small portion of the overall Chesapeake Bay carbon budget (~6%; Kemp et al. 1997). For nitrogen, particulate nutrients are also a small fraction of total nitrogen inputs, where nitrate contributes 70-80% of Susquehanna TN inputs and is the dominant N form that drives hypoxia by virtue of its efficient advection to seaward tidal waters to relieve N-limitation of phytoplankton growth (e.g., Testa et al. 2014). The input and fate of phosphorus is more complicated. Particulate phosphorus (PP) is a large fraction of watershed-derived P inputs and increases in relative proportion as river flow increases, in part because PP is associated with sediments scoured from streams and reservoirs. Recent measurements in Conowingo Reservoir, however, indicate that only 25-33% of scoured sediments could ultimately be released in a bioavailable form, and that this P can only be made bioavailable if it is transported far down estuary to anoxic and sulfidic waters. As stated above, prior work has clearly demonstrated that watershed-derived sediments are effectively trapped in the ETM (an oxygenated, sulfide-free environment) and that even during large storms, the majority of sediment deposits in the upper Chesapeake (Palinkas et al. 2014). Dissolved inorganic phosphorus, in contrast, is a small fraction of watershed inputs (15-20% of TP input in Susquehanna), but is bioavailable for phytoplankton and can stimulate hypoxia (Testa et al. 2014). In conclusion; (1) phytoplankton drive the production of organic matter that contributes to hypoxia and dissolved forms of N and P are the most direct form of input to fuel phytoplankton growth; (2) these dissolved forms of N and P are different in their relative contribution to total N and P inputs, but they may be effectively transported seaward to productive waters while their particulate cousins are trapped upstream; (3) although particulate phosphorus is a large contributor to total P inputs, it is poorly reactive and must be transported to salty anoxic waters to be substantially mobilized.

Estuarine Biological Responses to Nutrients (Patricia M. Glibert, UMCES)

Eutrophication is a complex process and often associated with not only a change in overall algal biomass but also with a change in algal biodiversity, including promoting species associated with harmful algal blooms (HABs). Common metrics of eutrophication (e.g., chlorophyll a), total nitrogen and phosphorus are not adequate for understanding biodiversity changes. While total nutrient load may set the biomass that a system can support, it is the form and proportion of nutrients that set the biodiversity trajectory. Harmful algae can increase disproportionately with eutrophication, depending on which nutrients change and in what proportion. Many harmful algae are associated with chemically-reduced forms of N (e.g., NH_4^+, DON), while diatoms are considered specialists in use of oxidized forms of N, namely NO_3^-. High levels of NH_4^+ may even be repressive or inhibitory for production. These differences are a function of the differences in physiology between the assimilation of N forms by these different phytoplankton groups.

In addition to the physiological differences between and among taxa with respect to use of different N forms (and recognizing that differences also apply to other N forms, such as urea or DON), there is other evidence that production of some algal toxins may be different under growth on different forms of N. Evidence is mounting that toxin content of some HABs can be higher on chemically reduced relative to oxidized forms of N.

Substantial evidence is also accumulating that algal biodiversity changes under altered stoichiometric (e.g., N:P) conditions, both in freshwater and marine systems. Many cyanobacterial and dinoflagellate harmful algal taxa have been shown to be more abundant under conditions of increasing N:P in estuarine or marine waters. Many dinoflagellates are mixotrophs, thus being able to acquire nutrients from particulates and not just dissolved forms.

Another classic paradigm currently being challenged is the view that if nutrients loads are high in a eutrophic system and are not limiting for growth, they play no regulatory role in algal community composition. Numerous examples are emerging from direct experiments showing qualitative changes in nutrients have effects on community composition even when the ambient nutrients are seemingly in the saturating portion of the response curve.

What needs to be better understood is the fact that a number of classic perceptions regarding nutrients – conceived in world when nutrients were typically at vanishingly low levels or at least at limiting concentrations– may not provide adequate constructs for addressing today's problems where nutrients are copiously available.

- Nutrient proportion and forms have consequences for ecosystem structure and function at all levels of the food web whether nutrients are limiting or not and they play key roles in promotion of HABs and their toxicity;
- While algal biomass may be controlled through reduction in the limiting- nutrient, such an approach may not be equally successful for HABs; P control without concomitant N control has unintended consequences such as increased potential for some HABs and for their toxicity;

- Physiological regulation of nutrients operates dynamically from limitation to excess and at all levels of the food web.

Conventional vs Conservation Tillage Experiments on Dissolved Reactive Phosphorus (Risto Uusitalo, Natural Resources Institute Finland)

Risto shared the results from conventional and conservation tillage experiments done in Kotkanoja field from 1991 to 2017, on a clay soil representative to Southern and Southwestern Finland coastal areas. The mean slope of the experiment field is 2% which is typical for agricultural soils in Finland. Both surface runoff and drain flow of each plot are sampled flow-proportionally by tipping bucket arrangement. The 4 plots of the field are hydrologically isolated by plastic curtains and mounted soil.

Four cultivation experiments were performed, including autumn-plowed vs. stubble over winter, autumn-plowed vs. shallow autumn cultivation, autumn-plowed vs. no-till, and uniform management. Risto showed the water flow, dissolved reactive phosphorous (DRP), and particulate phosphorous (PP) losses for surface runoff and subsurface drain flow for all the experiments.

The result shows that for all the experiments, DRP losses were higher when a conservation tillage option was applied. Only under no-till was PP runoff clearly lower than from plowed soil. Risto added nutrient losses at Kotkanoja were very much associated with snowmelt in spring and practices that would delay surface runoff generation in spring may decreases P loss. He recommended not to destabilize the soil surface, if temporary water storage is not created at the same time. It is observed that modified Morgan type extractant (STP) shows stratification to occur as tillage depth decreases or tillage is omitted, and topmost soil surface layer seem to affect DRP concentration of both flow pathways. The author commented that the increase in subsurface DRP loss due to increasing concentration during the 9 year no-till period was remarkable. No-till farming is a good mitigation option for sloping soils but not necessarily for less erodible ones.

Results of the Three Breakout Group Discussions

Workshop participants separated into three sub-groups (Estuarine, Land Management and Riverine) to discuss issues involving the science of nutrient speciation. The Estuarine group discussed how nutrient species delivered to the tidal waters would affect dissolved oxygen and other endpoints. The Land Management group discussed nutrient transformation processes in the soil and the effects of land use practices and BMPs on nutrient species delivered to the streams. The Riverine group discussed processes occurring in freshwater systems that may alter or control the speciation of nutrients delivered to the tidal waters and the potential effects of nutrient speciation on environmental endpoints in freshwater systems.

1. Estuarine Breakout Group

The estuarine breakout group discussed how riverine waters with different nutrient speciation characteristics may impact environmental endpoints including hypoxia and living resources.

Overall Recommendation

Group members agreed that ***the CBP should switch to response, i.e. "eutrophying", units as soon as feasibly possible***. Although this may be a difficult transition, it is well known that certain types of nutrients have a much greater impact on environmental endpoints than others, and this must be taken into account when deciding upon appropriate nutrient reduction management strategies. Because this transition may take some time, it is critical the CBP begins working towards this goal in 2020, and not wait until 2025. In an effort to attain this goal, the CBP needs to promote further research on nutrient speciation and the reactivity of the various types of organic matter entering the estuary from the upland watershed. An appropriate analytical framework for implementing eutrophying units must be developed as soon as possible.

Short-term Recommendations

1. In the near-term, the Estuarine group felt that ***the CBP should conduct additional model experiments, as follows***: first, the numerical experiments presented at the workshop should be redone using current baseline (realistic) nutrient conditions based on potential future management strategies, secondly, additional environmental endpoints should be investigated. For example, the impact on chlorophyll and water clarity should also be quantitatively characterized.
2. Another short-term recommendation provided by the estuarine group was that ***the CBP should re-examine the available data on the reactivity of estuarine dissolved organic nitrogen (DON) and the corresponding DON reactivity formulations in the estuarine model.*** In order to accurately represent the impact of nutrient speciation on estuarine environmental endpoints, the water quality model may need more than one class of DON, which is now standard for most Chesapeake Bay water quality models (Feng et al. 2015; Clark 2019; Testa et al. 2014).
3. Finally, the Estuarine group agreed that ***a better understanding of (reactive) nitrogen to phosphorus (N:P) ratios is needed***. The N:P ratios of the inputs to the estuary derived from the Phase 6 watershed model should be re-examined, and how these ratios characterizing the water entering the estuary impact the ratios in the estuary requires further study. The impact of the N:P ratios in the estuary on environmental endpoints such as oxygen concentrations, chlorophyll and water clarity is not yet well understood. In addition, ***the N and P species limitation formulations in the model need to be updated with results from new research***.
4. ***The concept of eutrophying units should first be applied to waste water treatment plants (WWTPs***). Future permits should consider speciation. Although implementing the concept of eutrophying units across all management decisions may be difficult, it would be relatively straightforward and feasible to apply this concept first to WWTPs. This would involve giving WWTPs more credit for reducing more reactive nitrogen species that have more detrimental

impacts on environmental endpoints, rather than giving WWTPs the same credit for reducing all species of nitrogen regardless of reactivity, as is current standard practice.

Long-term Recommendations

In the longer term, the Estuarine breakout group felt there were multiple issues related to eutrophying units that require further investigation. Four of the group's primary recommendations are included below.

1. Instead of considering nitrogen and phosphorus species concentrations separately, the CBP ***should instead experiment with using N:P ratios***. This is because the impact of changing phosphorus will depend on nitrogen concentration, and the impact of changing nitrate inputs will depend on ammonium concentrations. This is well established in the literature and must be considered by the CBP in the future (Glibert et al. 2016; Flynn 2010; Glibert et al. 2013).
2. As discussed above, it is critical that multiple environmental endpoints be considered when setting the TMDLs in the future. In the past, the TMDLs have been based on oxygen, chlorophyll and water clarity; however in setting the TMDLS in the future, the CBP ***must consider other environmental endpoints*** such as habitat (submerged aquatic vegetation), living resources and the potential for HAB outbreaks as they respond to both nutrient concentrations and ratios.
3. In order to accurately simulate the impact of varying nutrient species entering the estuary from the watershed, ***the skill of the estuarine model must be improved in the tributaries***. As found in the shallow water model intercomparison project (https://www.chesapeake.org/stac/wp-content/uploads/2020/01/Friedrichs_Apr20_SWmodel_comparisons.pdf) the low spatial (horizontal and vertical) resolution of the current version of the estuarine model makes it of little use in shallow waters and the tidal tributaries. A "next generation" estuarine model, as discussed in the Model Visioning Workshop (Shenk and Hood, 2019) must either contain high-resolution nests or an unstructured grid, thus allowing the shallow water regions to be accurately simulated. Implementing multiple models would also allow for more robust decision-making, as it could provide the basis for an uncertainty analysis as in Irby and Friedrichs (2019).
4. It is not yet well understood how climate change, including changes in temperature, precipitation, sea level rise, and more frequent and severe coastline inundation will impact the preference of phytoplankton for specific nutrient species or alter the ratio of nutrients within the load. Thus, the CBP needs to ***consider climate change in all their efforts to switch to the implementation of eutrophying units***.

2. Land Management Breakout Group

The land management breakout group discussed the land management and landscape properties and processes (classifications) that determine the timing and speciation of nutrients delivered to the tidal waters of the Chesapeake Bay.

Description / Background

It is commonly assumed that the original speciation of N and phosphorus P, as delivered to a stream/river network, influences the transformation processes and impact of nutrients on the Chesapeake Bay ecosystem (i.e. there is memory of the original speciation of the nutrients by the time they reach the Bay). However, due to the potential bioremediative capacity of upland and headwater catchments, large scale environmental problems such as hypoxia in the Chesapeake Bay and the Gulf of Mexico necessitate focused efforts to improve quantitative understanding of land use and chemical (e.g. nutrient) transformation relationships and processes. These process interactions are often confounding, since nutrient loading and speciation is so greatly dependent on land use type, climate and physical hydrologic processes. Conceivably, with advanced information, there may be inland mitigation practices that could (should) be implemented to further reduce nutrient loading to the Chesapeake Bay. This is important for the Chesapeake Bay, because (for example) data from the USGS's River Input Monitoring Program

(Moyer and Blomquist, 2019) shows increases in orthophosphate (the bioavailable form of phosphorus) loads from a variety of rivers, with a variety of land use practices and processes, in every major catchment of the Chesapeake Bay Watershed (USGS, 2017). Thus, a compelling question may be, "Do land use practices, and vegetation at and in the terrestrial-aquatic interface affect transformation, amelioration, and attenuation of P (nutrient) processing, and if so what are those dynamics?

Points of Discussion and General Recommendations

The land management breakout group discussed a number of land use related issues and in particular focused initial points of conversation on a) what is known, b) what information is needed, and why is this issue important to managers. Breakout group members agreed that more information is needed to elucidate the relationship between conservation practices and the apparent increase in soluble reactive phosphorous (SRP). For example, does reduced soil disruption result in increased microbial populations and subsequently increased SRP? If so, how soon after conservation practices are initiated? When? Where? It was also discussed that there is a need for a renewed focus on edge of field studies to identify mechanistic relationships in terms of which BMPs work and which do not seem to work. There was an in-tandem need identified for investigations in small streams, headwaters, mixed land use, and various watershed scales. This is particularly important for headwater systems that have relatively higher surface area to volume (mixing) ratios, which is important for chemical/nutrient transformation processes. It was similarly identified that there is a need for in-tandem stream monitoring / shallow groundwater riparian zone studies, and a need for streambed/bank boundary layer exchange processes.

It was further discussed that there is a great need to better understand "hot spots" for specific nutrient speciation processes and species end points. In particular, there may be locations on the landscape (land use types) that are well suited for favorable nutrient transformation endpoints that could be utilized and/or replicated for specific BMP outcomes? Coupled to this, there is a general and ongoing need to better understand how BMPs affect speciation. There are landscape characteristics (e.g. variable source area, soil types and likely others) that are important influence on nutrient speciation to edge of stream nutrient delivery, and vertical stratification of N and P. It was also identified that there is a need to reassess the 4Rs (right source, right rate, right time, right place) for fertilizer application practices.

A key issue was the extent to which speciation affects propagate downstream. Might N or P be transformed so many times (or sorbed-desorbed to particles) from the time it gets in the stream to receiving water that it might not matter what form comes off land? This question drove a need to identify and better understand mechanisms of nutrient fractionation and what the drivers of biogeochemical processes are in stream systems and better understand/quantify the relative importance of different flow paths in transporting nutrient species to streams. Coupled to this observation was identification of specific variable source areas that may be important for runoff, transport and speciation processes. Other landscape heterogeneities within the land use practice continuum that may affect appropriate practices were also noted as a concern. Similarly, animal operations were identified as areas of needed further investigation for speciation processes. It was also discussed that the transitional area between point and non-point source(s) should be reexamined. It was identified that there is a need for economic incentives and to do better to understand disconnects between metrics and local needs that may be more or less stringent, for example how do urban areas affect speciation? A particularly pointed question was with regard to the magnitude of change necessary to affect environmental outcomes, and is the necessary magnitude feasible?

Cross-breakout group issues that were raised include the idea of moving towards a floating "eutrophication" currency based on valuation of ecological outcomes to better determine cost-effectiveness of BMP implementations. For example, if we knew we needed to reduce a nutrient species by 25%, could we work backwards from that and figure out if implementation was feasible? Since the relative importance of nutrient speciation depends on the endpoint, can we determine the most appropriate endpoint that we should use to evaluate outcomes? As with the current TMDL, it may not be possible to set nutrient species goals that optimize water quality everywhere. This issue raises the question, are we primarily considering the stream habitat or Bay mainstem conditions in establishing accounting principles? Similarly, a question was, should we use different currencies? And, to promote cost-effectiveness, the group asked, should we consider a pay for performance system rather than paying for implementing a specific BMP system.

Breakout Session Outcomes

The land management breakout group was able to come to agreement in terms of a) short-term recommendations, b) long-term recommendations and c) cross cutting breakout boundaries, as follows:

Short-term recommendations:

- Reevaluate how BMPs function in terms of speciation and improve understanding of how the location and timing and appropriateness of BMP implementations, including lifetime efficacy, affect desired outcomes. A result of such work should include methods to promote transformations that diminish negative impact, including grouping or combining BMPs for maximum benefit.
- Improve understanding of the ratio of surface – vadose – saturated zone transport and speciation processes to loading, and a need to conduct sensitivity analysis (model and data) to manage speciation, hot spots, and most effective management locations in the watershed.

Long-term recommendations:

- Create a framework to better understand mechanisms of nutrient speciation and transport processes related to receiving water concentrations and work to better inform expectations for current BMPs based on the fraction that may come from groundwater.
- Reassess soil fertility recommendations for the Chesapeake Bay to better identify when P deficiencies may affect crop yield.
- Identify optimal goals (tradeoffs, targets, endpoints), and then enlist area experts to assess feasibility.

3. Riverine Breakout Group

Overview of Discussion

The riverine breakout group focused on the changes in N and P speciation within the riverine network including retention, transformation, and transport processes. We defined the major pathways influencing mass load and speciation as stormflow, groundwater movement, and point sources. We identified biological and chemical processes, that lead to retention and transformation within the river network. We discussed if, and under what circumstances, there could be "memory" of speciation from the point of delivery to the stream network to an endpoint, such as the Bay. In contrast, species that arrive at the edge of stream may not stay in that form as they move down the river network. The discussion led to the identification of upstream and living resource inputs, that should be considered by the CBP in addition to TMDL endpoints as they assess the overall importance of speciation.

We discussed places in the stream network that are important in resetting the N/P speciation (e.g., reservoirs, wetlands, stream restoration projects). Of particular interest was the effect of stream spiraling on nitrogen concentrations and delivered load. Spiraling length is the distance traveled by one atom as it completes a cycle from inorganic to organic and back to inorganic forms (Newbold *et al.* 1981). Spiraling time is the time that this process takes. When the riverine transit time was much greater than the spiraling time (length), the system's "memory" of the original N species would be lost. Phosphorus, on the other hand, was largely considered in terms of sediment association, deposition, and resuspension, with interconnected changes in speciation. The movement of phosphorus through the river network, particularly sediment-bound phosphorus, is generally episodic. Phosphorus can be stored for long periods of time in bottom sediments and stream channels, where species can change. There are fundamentally different biogeochemical processes governing the speciation, behavior, and transport of the two elements. This makes the relations between their speciation and the river network residence times fundamentally different, and challenging to quantify across time, space, and hydrologic flow path.

For nitrogen, perhaps the slowest changes in speciation involve the formation of organic nitrogen in biological growth and the transformation and mineralization of organic nitrogen back to inorganic species. From a water quality perspective, the rates of the mineralization processes are extremely important, but largely unquantified. These rates are generally estimated by lumping the spectrum of labile forms of organic nitrogen into a few fractions (G1, G2, G3) for modeling purposes. But little is known about the relative abundance of organic nitrogen molecules across this spectrum of lability.

Recommendations:

1. Analyze the potential magnitude of effect of speciation on environmental outcomes with conceptual models and existing science
   The group discussed that current Bay modeling is insufficient to represent in-stream processes or landscape processes that affect what is delivered to the stream from "speciation hot spots" such as variably saturated areas, wetlands, reservoirs, lakes and ponds. It is understood that there are many processes affecting speciation, but magnitudes of effects on eutrophication tend to be small. However, the magnitudes of effects throughout the water system are uncertain and the cumulative effects even more so. Therefore, a first step to considering the priority of a research effect would be to conduct a reconnaissance study (or build a "toy model") that established a conceptual model of the processes involved, reviewed existing science, and elicited expert judgment to evaluate the maximum potential magnitude of effect of speciation on eutrophic conditions or aquatic habitat outcomes.

   If the magnitude of speciation effects on ecological outcomes is sufficient, then the second step would be to work towards partitioning the source of species among sources and understand which management options are effective at altering speciation effects. A suggestion was to start with an empirical (statistical) model that could test different variables for their ability to describe variation in observed species in parts of the water system. Such modeling would only be enabled by monitoring for the species of interest. The Estuarine team has examples of how this has been conducted with the RIMS station monitoring data.

Some research has been done on new management approaches to control speciation, such as the use of gypsum byproducts for reducing movement of soluble nutrients. Other work has looked at pairing complementary BMPs. For example, no-till has a tendency to mobilize soluble reactive phosphorus but adding organic material to farm drainage networks may be able to trap some of that phosphorus.

More detailed research steps would be to improve understanding and ability to model the microbial community that is responsible for mediating speciation, particularly soluble reactive phosphorus, which may be one of the most critical needs. Other important processes could be mechanistic such as transfer across the hyporheic zone. How processes scale across sizes of streams and rivers, is another research gap.

2. Consider trade-offs associated with controlling organic and inorganic species and jointly meeting the Bay TMDL and upstream water quality and habitat goals.

   Some BMPs create tradeoffs in meeting nutrient controls because they may reduce some nutrient species while increasing other species. The influence of these tradeoffs may have different impacts on upstream areas compared to the Bay, and therefore restoration priorities may influence which BMPs are considered desirable or acceptable. For example, work presented by Testa suggested that particulate inorganic phosphorus (PIP) had almost no effect on bay hypoxia. But is PIP benign in fresh water systems? What other impacts is PIP having? Although problems may be common across locations throughout the riverine/Bay system, the drivers and dynamics may differ.

   To understand these tradeoffs, the group suggested exploring the potential for and implications of promoting BMPs or landscape management strategies that delivered the least bioavailable nutrients. Such a policy may have implications for BMP costs, effectiveness of non-target BMPs and co-benefits. Some examples were that some BMPs work best if they receive soluble nutrients (e.g., algal scrubbers) and some BMPs would need to be adjusted to change speciation effects and those adjustments may be costly enough to prevent implementation.

   A long-term recommendation is to distinguish the locations and endpoints within the riverine and estuarine system that vary in N/P speciation effects. In the riverine network, many specific locations could be identified, whose management could benefit from consideration of N/P speciation, such as problematic reaches of streams with “nuisance” or harmful algae, reaches downstream from point source discharges, areas of sediment deposition that would store phosphorus, and reservoirs, particularly those reservoirs that provide drinking water.

   In addition to evaluating multiple spatial locations, the management of other chemical contaminants could benefit from consideration of their speciation. Some examples would be iron, mercury, PCBs, and sorptive emerging contaminants. The same type of quantitative approaches linking chemical speciation to impact on the aquatic system that will be used for N/P could also be used to provide insights for these other chemicals.

3. Identify and quantify the spiraling and retention properties associated with N/P speciation that are important relative to each endpoint.

a. Synthesize research, including identifying gaps.
There are a number of important gaps in the current understanding of N/P speciation relative to transport through the riverine system to each endpoint. The CBP should consider convening a group, or multiple groups, to synthesize existing research and guide new research and monitoring efforts to better understand and quantify processing and transport of N/P the within the stream network. Filling many of the gaps will be a relatively large effort, but the result will be an organizing framework of addressing issues of N/P for the future.

One of the data gaps is better understanding the travel time (or lengths) relative to changes in N/P speciation. Other gaps include changes due to BMP implementation, land use, and hydrologic modification both in terms of land conversion and stream networks. The group should evaluate whether there are models that can accurately explain species exports at particular scales. The CBP should consider convening a group to create a conceptual model of in-stream processes that would guide new research and monitoring efforts within the stream network. One of the outcomes could be a map of spiraling times or lengths for nitrogen and retention times for phosphorus across the stream network that quantifies this understanding of the relative scales.

In general, there is also a need to better understand the spatially-variable sources and flow paths of N/P species to the stream, and the travel times from various sources to the stream. These travel times could be on very short (minutes to hours for storm runoff) to very long time scales (years to decades for groundwater). One of the outcomes of this effort could be a process-based quantification, visualized as maps, of the localized speciation of N/P delivered to the stream as a function of land use, flow path, duration of flow path, streamflow condition, and season. The modeling of localized N/P speciation delivered to the streams could be incorporated into future versions of the CBP watershed model.

b. Convene a group to list stream characteristics that would be useful in understanding and mapping in-stream capacity for N/P transformation/speciation.
A short-term recommendation would be to identify and map multiple stream characteristics that are important in the spiraling and retention processes associated with N/P speciation. Many of the physical, chemical, and biology process that control the movement and speciation of N/P are strongly influenced by characteristics of the stream and the stream channel. A few examples of these characteristics include locations of wetlands in the stream network, channel width, depth, extent of incision, floodplain topography, locations of the man-made surface ditch network, and degree of canopy cover. Quantitively linking these various physical characteristics of the stream network to their effects on chemical and biological parameters (PAR, DO, primary productivity, biomass) would advance the ability to model N/P speciation and magnitude in the stream network. In order to be able to have a high-resolution, space-variable quantitative analysis of changes in N/P speciation, it is necessary to have mapped details of the stream and channels. A convened group could prioritize these characteristics and formulate a plan to convert LIDAR and other types of remotely-sensed data into mappable stream and channel characteristics.

c. Convene a group which would identify the data collection necessary to characterize in-stream processes.
A short-term recommendation would focus on advancing a common language for N/P species, identifying common analytical methods for N/P speciation, new field data collection, and identification and quantification of reaction kinetics of organic N/P.

Currently, the state-of-the-art is limited to theoretical and operational definitions of organic N/P.

For some very practical reasons, various different methods are used to quantify N/P species by various fields of environmental sciences. In the complex challenge of eutrophication of the Bay, the participation of scientists from many different fields representing the watershed, riverine network, and estuary are required. Therefore, a common language of N/P species should be developed across disciplines. Many specific N/P species are difficult to analyze and tend to be reported by operational definitions. With a new focus on the importance of N/P speciation, new (or modified) analytical methods should be developed and implemented across the range of scientific fields within the Bay community to allow a direct comparison of N/P speciation data throughout the system from source to Bay.

A method to increase the data needed to advance understanding of speciation is to use automated sensors that take high-frequency measures over long periods of time. In recent years, high-frequency sensors have been widely adopted for nitrate, carbon, turbidity, and other water quality parameters in studies of point sources, field runoff, rivers, and estuaries. Although sensors for phosphorus are not as advanced, some early models do exist. The data resulting from the high-frequency sensors would benefit investigations in the dynamics of N/P speciation. The contribution of non-traditional types of sampling strategies, like Lagrangian sampling, could also be considered. Finally, there are many researchers already doing work in the area of stream processing of N/P in the Bay watershed that are not closely tied to these conversations. It would be useful to identify these researchers and incorporate their work into the conversation on N/P speciation.

Identification of the current approaches of quantifying organic nitrogen mineralization and future avenues of research that will add to our understanding could be a valuable contribution of this convened group.

This common language and common methods for quantification of N/P speciation, together with new sources of data, could be used to strengthen and advance the current and future water quality models used by the Bay community.

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Appendix A: Workshop Agenda

Scientific and Technical Advisory Committee Workshop

Assessing the Environment In Outcome Units (AEIOU): Using Eutrophying Units for Management

March 20-21, 2019
The Westin Annapolis
100 Westgate Circle
Annapolis, MD 21401

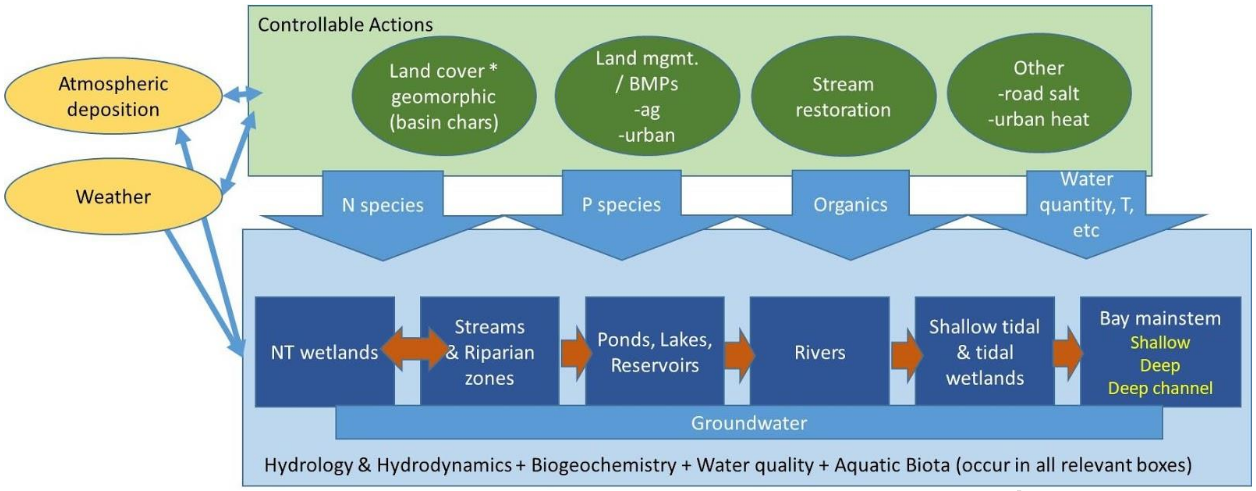
Workshop Motivation

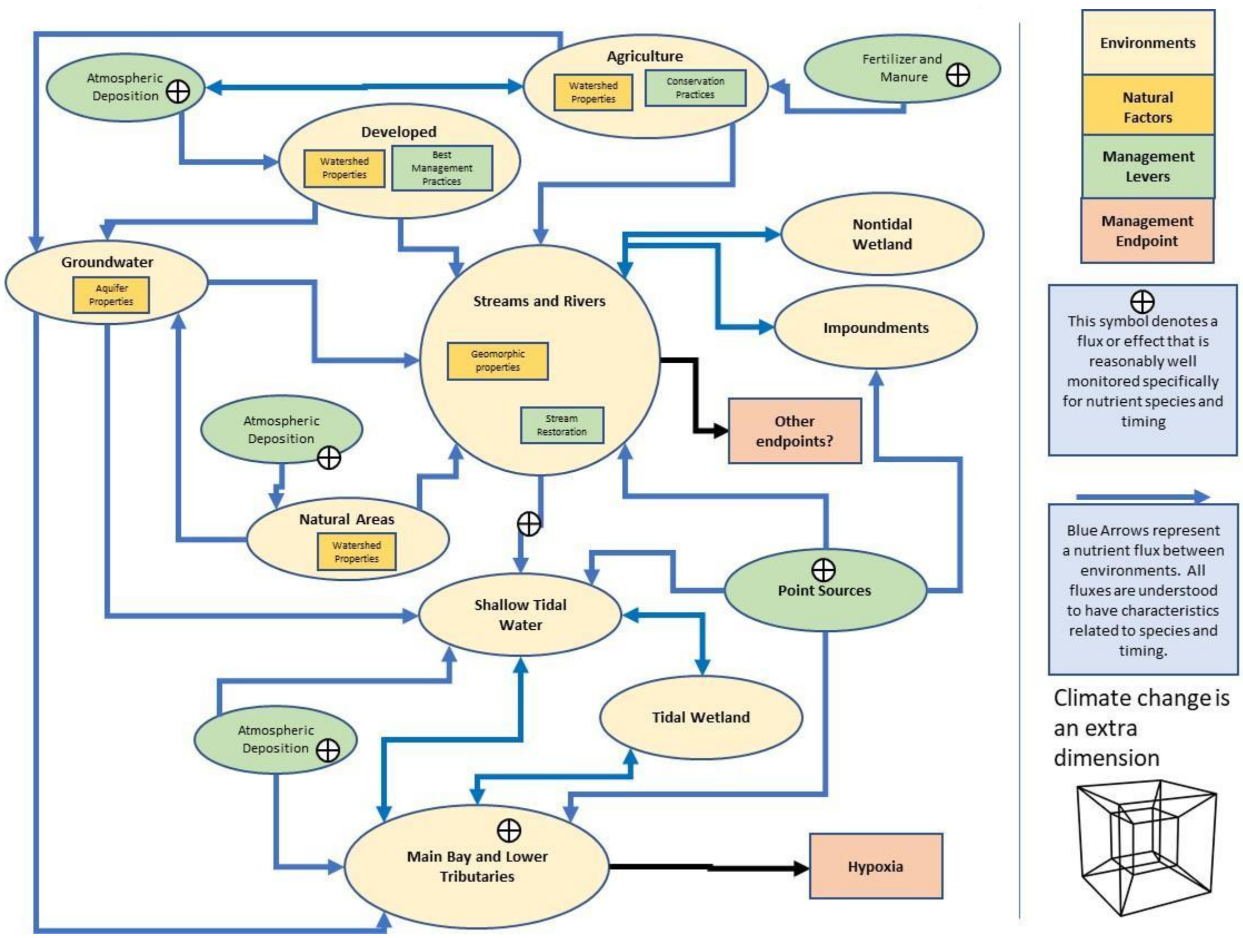
The Chesapeake Bay TMDL sets a cap on total average annual nutrients without regard to the bioavailability or timing of different nutrient species deliveries to the Bay. While this approach creates a metric for the TMDL that is relatively simple for accounting and communication, lumping nutrient species into a total annual average creates inefficiencies and inconsistencies when allocating scarce resources to improve water quality. Specifically, inorganic nutrients may have a greater impact on eutrophication compared to organic forms. In addition, management options may have varying, even conflicting, effects on the fate of different forms of nutrients. Therefore, more direct accounting of nutrient species or fractions could lead to more cost-effective management by making explicit the effects of practices or their location on water quality outcomes.

The TMDL has specific endpoints of dissolved oxygen, water clarity, and chlorophyll, which are related to other important endpoints such as harmful algal species and fish habitat quality. The relationships of nutrient species and timing to water quality and biotic responses can depend on a variety of covariates including salinity, temperature, sediment load, and soil and aquifer properties in the runoff pathway. The objective of this workshop will be to explore whether the science is ripe and appropriate for calculating *eutrophying units* as a common currency that can be used to compare alternative restoration strategies. Eutrophying units could be calculated from the combined species concentrations of nitrogen (N) and phosphorus (P) using transfer functions that depend on their effect on environmental outcomes. The workshop will facilitate synthesizing the state of knowledge and organizing approaches for developing eutrophying units, reflecting spatial and temporal conditions of the Bay and its watershed.

Workshop Questions

- Does nutrient speciation and timing of delivery to the bay depend strongly on BMPs, land use, watershed characteristics, and the presence or reservoirs?
- To what extent do in-stream transformations and spiraling dominate the speciation and timing of nutrient delivery to the Bay?
- How do nutrient pathways (groundwater, shallow underground flow, surface flow) affect speciation and timing of nutrient delivery to the Bay?
- How do endpoints and outcomes associated with the CBP TMDL or other environmental goals respond to changes in nutrient species and timing and what practical strategies could be used to incorporate such science into BMP performance?
- How do all of the above vary with salinity, stratification, energy regime, or climate?


Controllable Actions
Atmospheric deposition
Weather
Land cover * geomorphic (basin chars)
Land mgmt. / BMPs -ag -urban
Stream restoration
Other -road salt -urban heat
N species
P species
Organics
Water quantity, T, etc
NT wetlands
Streams & Riparian zones
Ponds, Lakes, Reservoirs
Rivers
Shallow tidal & tidal wetlands
Bay mainstem
Shallow
Deep
Deep channel
Groundwater
Hydrology & Hydrodynamics + Biogeochemistry + Water quality + Aquatic Biota (occur in all relevant boxes)


Atmospheric Deposition
Agriculture
Watershed Properties
Conservation Practices
Fertilizer and Manure
Developed
Watershed Properties
Best Management Practices
Groundwater
Aquifer Properties
Streams and Rivers
Geomorphic properties
Stream Restoration
Nontidal Wetland
Impoundments
Other endpoints?
Atmospheric Deposition
Natural Areas
Watershed Properties
Shallow Tidal Water
Point Sources
Tidal Wetland
Atmospheric Deposition
Main Bay and Lower Tributaries
Hypoxia
Environments
Natural Factors
Management Levers
Management Endpoint
This symbol denotes a flux or effect that is reasonably well monitored specifically for nutrient species and timing
Blue Arrows represent a nutrient flux between environments. All fluxes are understood to have characteristics related to species and timing.
Climate change is an extra dimension

Day 1: March 20th

8:30 Sign-In for Attendees, light breakfast (provided)

9:00 Welcome, Introductions, and Goals – Lisa Wainger

9:20 Optimal Phosphorus Abatement – Antti Iho
An example using more information about nutrient species leading to cost effective solutions.

9:50 The Chesapeake TMDL Calculation – Gary Shenk
A conceptual description of speciation in the Chesapeake system. The calculation of hypoxic response to watershed management actions designed to reduce total nitrogen and total phosphorus and the extent to which the spatial differences in load effectiveness are taken into account.

10:15 Break

10:45 Bay Loading Signatures – Qian Zhang
An overview of the characteristics and temporal trends of nutrient and sediment loads to Chesapeake Bay from its nontidal rivers.

11:10 Riverine Processes - Doug Burns
Discussion of riverine nutrient transformations

11:35 Estuarine Biological Responses to Nutrients – Pat Glibert
Estuarine biological processes including phytoplankton response to different forms and loads of nutrients.

12:00 Lunch

1:00 Estuarine Nutrient Cycling – Jeremy Testa
Estuarine processes describing how input loads and internal cycling of nutrient species affect hypoxia in the Chesapeake

1:25 Management Practice Effects on Phosphorus – Peter Kleinman
Effects of management practices on the speciation of nutrients delivered to downstream points

1:50 Landscape and BMP Nitrogen Processes – Jason Kaye
BMPs and Landscape properties and their effects on nitrogen speciation in loads delivered to streams.

2:15 Break

2:30 Instructions for Breakout Groups – Lisa and Gary
Estuarine, Riverine, and Land Management

Each breakout will have a leader/facilitator, and a recorder.
The goal of the breakouts is to produce 3 items:

1. *A list of questions for other breakout groups*
2. *A powerpoint slide with high level recommendations*
3. *Longer description of thoughts from discussion to be captured in the workshop writeup*

- *What do we know*
- *What do we need to know*
- *Why should managers care*

3:00 Breakout Group

Internal Round-Robins
Informal; each member should come prepared to share their thoughts and ideas on the previous large group discussion in regard to their breakout topic and in consideration of the Breakout Questions below - discuss resource and data needs, advantages and disadvantages for each.

Focused Breakout Discussion
by the end of discussion you should have created
an extended list of recommendations
a list of questions crossing breakout boundaries

5:00 Recess

<u>Day 2: March 21st</u>

8:00 Light breakfast (provided)

8:45 Cross-Breakout Requests (Breakout Leaders)
Quick articulation of priority questions crossing breakout boundaries.

9:00 Focused Discussion of breakout priorities
Breakout groups reach consensus on draft recommendations from the previous day that can be communicated to the plenary group on a single presentation slide taking into account questions from other breakout groups. Also work on longer descriptions of the draft recommendations.

10:30 Break

11:00 Plenary Presentation of Breakout Proposals (20 mins per breakout)
All participants will reconvene, and each breakout group leader will briefly present the single slide of recommendations

12:00 LUNCH (provided)

1:00 Compiling Recommendations & Management Response – ***Attending managers***
Facilitated discussion of final recommendations presented before lunch focused on compatibility between proposed components with a view toward the most effective recommendations for the CBP management. Managers will present their perspectives on the consensus recommendations and their major takeaways.

2:00 Adjourn

2:15 Convene Steering Committee for Workshop Documentation
Focussed messages for managers relevant to hypoxia and other environmental endpoints

Overarching Breakout Questions

A. What do we know?

In the expert opinion of the people in the breakout group, what can be said about the factors that cause differences in speciation? What can be said about effects on hypoxia, living resources, or other environmental endpoints of different speciation or timing of delivery?

Are there important locations or times of the year for nutrient speciation or effects, such as hyporheic zones, freshets, or summer bottom water?

What is the relative influence of the different factors?

The breakouts may create a prioritized list of existing knowledge.

B. What more do we need to know?

In the expert opinion of the people in the breakout group, what are the most important research questions regarding speciation, timing, and their environmental effects on hypoxia, living resources, or other environmental endpoints?

The breakouts may create a prioritized list of research topics.

C. Why is this important to managers?
The management community are used to dealing with goals of TN and TP. Why should they move to a different metric?

How could they incorporate the knowledge from this workshop?

Why should they support research on these topics?

Appendix B: Workshop Participants

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