Conowingo Reservoir Infill and Its Influence on Chesapeake Bay Water Quality

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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 www.chesapeake.org/stac.

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Executive Summary

Workshop participants expressed a general consensus with previous findings of the Lower Susquehanna River Watershed Assessment (LSRWA) that the Conowingo Reservoir is very near to (and essentially at) a condition of "dynamic equilibrium" with regard to discharge of fine sediments and particle-associated nutrient loads (USACE 2016). As defined in this report, this condition refers to a situation where fine sediments that accumulate within the reservoir under "normal" (lower flow) conditions are eventually scoured and removed during periods of higher flows and especially during major flood events. After such events, normal flow net deposition of sediment and particulate nutrients continues for a period of time until another high flow scouring episode occurs once again to remove the sediment and particulate nutrients, repeating the cycle. As a result of Conowingo Reservoir reaching dynamic equilibrium, the average annual sediment and particulate nutrient load reaching the Bay from the Susquehanna will be elevated relative to the period prior to reaching equilibrium.

In addition to increased storm scour, slower on-going processes of changing bed bathymetry and composition also affect Conowingo Reservoir retention performance at most discharge levels. Evidence presented at the workshop demonstrated that the rates of net sediment and particulate nutrient deposition behind the dam are decreasing over a wide range of flows – including flows well below levels typically viewed as scour events, with commensurate increased loading of sediment and particulate nutrients to the Bay relative to earlier periods prior to reservoir infill. Infill is the process of geomorphic evolution that all reservoirs undergo as they fill with suspended sediment and particulate nutrients, with changes to their bathymetry due to increased settling within their impounded waters (Morris, current workshop).

Overall, and in the absence of dredging or other major implementations within the reservoir system, the amount and nature of sediments and particulate nutrient species reaching the Chesapeake Bay will, over time, obtain long-term average values that closely resemble those at the influent of the Lower Susquehanna River Reservoir System (LSRRS). The enhanced sediment load due to infill is a considerably different situation from the first eighty or ninety years of reservoir operation, with important implications regarding the impacts of the Susquehanna watershed loads on Bay water quality. Additionally, the slow ongoing changes in the LSRRS bathymetry and bed composition will continue to alter the timing and quantity of sediment and nutrient loads for some time to come, offering additional challenges to accurate modeling and management of the system.

To quantify the influence that Conowingo infill has on Chesapeake water quality, the following processes must be considered in the Conowingo Reservoir: 1) increased sediment and nutrient loads from scour during relatively rare extreme events; 2) decreases in the scour threshold during moderately high flow events; 3) loss of trapping capacity during low and moderate flow; and 4) a variety of biogeochemical processes that influence the mobility, fate and bioavailability of the nutrients present in the reservoir bed. The relative importance of these four processes, quantified in terms of loads to the Bay, will continue to vary over time along with loss of reservoir performance at “normal” conditions.

Major loads from extreme events have occurred throughout the history of the dam and are only one component of the influence Conowingo infill has on Chesapeake water quality. Under conditions of dynamic equilibrium, it is likely that scour events deliver greater loads than they did in the recent past and therefore have the potential for greater acute impacts. However, our understanding in regard to the additional loads that the Bay has been receiving due to changing dam performance includes increased transport of sediment and particulate nutrients through the reservoir over the full range of flow conditions. Low flows have little impact due to their inherently low particulate loads, but they are by far more common. Additionally, moderate flows are an important focus for continuing scientific research, as well as for future management decisions. Moderate flows, with increased particle loading, decreased reservoir trapping, and increased potential for scour under dynamic equilibrium, are more common than extreme flows and therefore have the potential to introduce more total additional material to the Bay. Indeed, statistical models indicate that loading of particulate nutrients from Conowingo Reservoir to Chesapeake Bay has been increasing in recent years despite reductions in loads to the reservoir system from the watershed, and that these increases are occurring despite the absence of extreme events.

The workshop presentations and discussions focused on how the reservoir system is likely to modulate the inputs of suspended sediment (SS), total phosphorus (TP), total nitrogen (TN), and particulate organic carbon (POC) from the watershed to produce a set of outputs. Specific engineering solutions, including but not limited to modifications of the dams, dredging of the reservoirs, or creating sediment bypassing systems were not addressed at the workshop, as these topics were extensively considered by the LSRWA report (USACE 2016). The effects of Conowingo infill on receiving water quality was the primary focus of this STAC workshop because of the potential for changes throughout the estuary, which is dependent on a variety of factors. Bay water quality is influenced not only by total loads of nutrients and sediments but also by the physical transport of sediments and associated particulate nutrients through the tidal waters of the upper Bay, the locations of near term deposition and long-term burial of these particles, biogeochemical processes that control the fate of nutrients bound to the particles, and the bioreactivity of the nutrients. The biogeochemical environment of near-bottom waters and sedimentary pore waters into which Conowingo particles are deposited strongly influence the timing and extent of nutrient transformation and release, and hence the impact on Bay water quality. Particulate nutrients that are delivered into the head of the deep trough of the mid-Bay have greater impacts on water quality during summertime hypoxic (low oxygen) conditions than particles that are deposited and buried in relatively fresh, normoxic upper Bay waters. The extent to which the Susquehanna Flats and the Estuarine Turbidity Maximum (ETM) trap or seasonally modulate the delivery of Conowingo particles is critical to a full evaluation of the transport effect. Redistribution of newly deposited particles through resuspension and transport by waves and tides must also be accounted for and considered within the context of other particle sources, such as channel dredging and subsequent placement of newly dredged sediment.

Due to the evidence that substantial sediment and particulate nutrient loads are delivered under a wide variety of flow conditions, workshop participants recommended that any future assessment of the impacts of Conowingo infill on Chesapeake water quality standards, and ultimately on TMDL (Total Maximum Daily Load) achievement, consider the full range of hydrologic conditions (from low flow to extreme events). To provide a thorough understanding of water quality effects, an estimation of sediment and nutrient delivery to the Bay would need to consider amounts delivered from the watershed to the reservoir, storage in and release from the reservoir, and the timing of and form in which they are delivered to the Bay. Furthermore, the ultimate transport and fate of particulate nutrients from the lower Susquehanna after delivery to the Bay would need to be accounted for to understand water quality effects. The analysis would need to include seasonally variable changes in 1) the transport behavior of delivered particles, 2) particle trapping by upper Bay physical and biological features, and 3) biogeochemical transformations of newly deposited particles in different receiving waters, in addition to consideration of all of these factors following rare large events.

Workshop participants acknowledged that the most conservative management assumption from the standpoint of water quality protection is that all of the delivered organic material scoured from Conowingo is fully degradable to inorganic nitrogen and phosphorus. Current Chesapeake Bay Program (CBP) model assumptions for the 2010 Water Quality and Sediment Transport Model (WQSTM) are that all the particulate organic material scoured from the Conowingo is slowly degradable. The state of the science is currently limited on the details of these issues, but workshop participants nonetheless supported the current approach and urged continuing refinement of the splits of particulate organic material into labile, refractory, and inert reactive categories as new knowledge becomes available.

The science required to predict these processes in the future is challenging. However, there is enough known on the basis of monitoring records over the past several decades and from first principles of sediment transport and biogeochemistry that appropriate models of the future behavior can be constructed in the near term. Past monitoring and research data can help to constrain such models. Fortunately, various funding parties and scientists have mounted significant efforts in the last five years aimed at improved data collection and interpretation, and new process research. This work is already enhancing the understanding of this changing system. Workshop participants attest that over a period of a few years, this work will lead to more accurate models of future system behavior. These models will continue to help managers make adjustments to actions in all parts of the Chesapeake Bay watershed that will help the Chesapeake Bay partners efficiently achieve the TMDL.

Introduction

The Susquehanna River is the largest tributary to both the Chesapeake Bay and to the Atlantic Slope. It drains more than 71,000 square kilometers (27,500 square miles) across New York, central and eastern Pennsylvania, and northeastern Maryland (Figure 1). Annually, the Susquehanna River contributes about 41 percent of the total nitrogen (TN), 25 percent of the total phosphorus (TP), and 27 percent of the suspended sediment (SS) to the tidal Bay (Linker et al. 2016). Thus, changes in these inputs from the Susquehanna are significant to the overall status of the Bay.

Between 1910 and 1931, a series of three hydropower plants were constructed along the lower 62 km (39 miles) to harness the river power generated by a steepened gradient and the high volume of water which moves through a deeply incised bedrock channel before crossing the Piedmont Fall Line (Reusser et al. 2006). Since construction, the three tiered reservoir system has neared full sediment storage capacity (Table 1); only Conowingo Pond has limited potential to trap additional sediments and associated nutrients, estimated at less than about 5 percent of original storage volume. In aggregate, this system of reservoirs has come very close to its full capacity in terms of sediment storage over the past 90 years. At present Conowingo Reservoir is estimated to be about 94 percent full; the others approximately 100 percent full (Reed and Hoffman 1997, USACE 2016 Langland 2015).

Table 1. Reservoir features along the Lower Susquehanna River System (source: Reed and Hoffman 1997, USACE 2016)

Reservoir (Dam) Area in ha/mi^2	Susquehanna River Mile Upstream of Havre D'Grace	Year Completed	Watershed Area at Dam miles^2	Initial Water Storage Capacity (thousands of acre-ft)	Estimated Existing Sediment Storage Capacity
Lake Clarke (Safe Harbor Dam) 2,970 / 11.5	32	1931		150	0%
Lake Aldred (Holtwood Dam) 971 / 3.75	25	1910	26,740	60	0%
Conowingo Pond (Conowingo Dam) 3,600 / 14	10	1928	27,100	310	~5 %

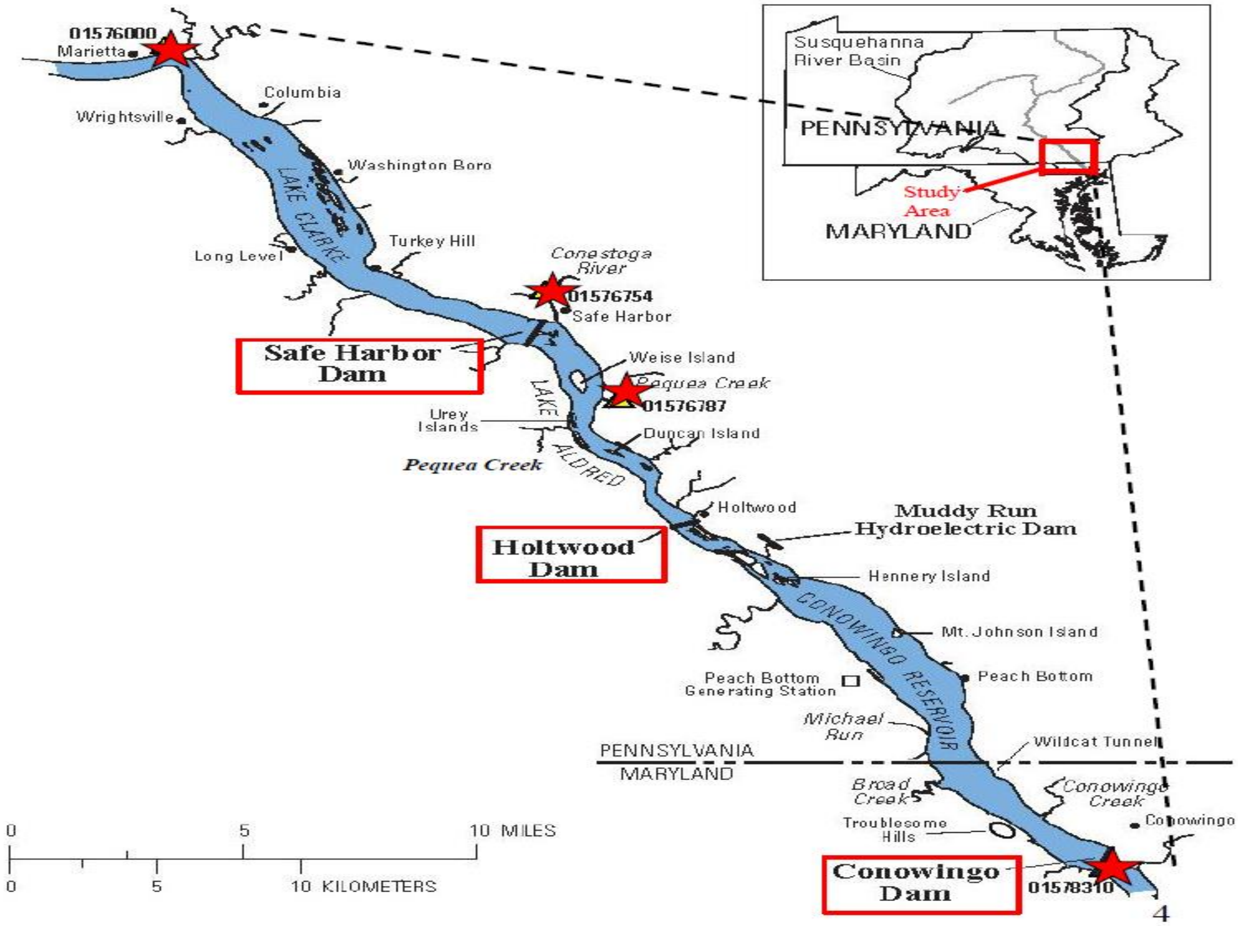

Figure 1. The three reservoirs of the lower Susquehanna (source: Langland, current workshop. *Sediment Transport and Bathymetric History in Three Reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland 1900-2015*)

The Chesapeake Bay Program (CBP) is a state-federal partnership engaged in restoring the United States' largest estuary. Chesapeake Bay restoration work has been underway for three decades and since 2010 has been supported by the nation's most extensive total maximum daily load (TMDL) program (USEPA 2010, Linker et al. 2013). The Chesapeake TMDL requires the states of the Chesapeake watershed to establish appropriate uses for their waters, to adopt water quality standards that are protective of those uses, and to identify and list waterways that are impaired by pollutants, causing them to fail to meet the adopted water quality standards. The 2010 Chesapeake TMDL was developed with the assumption that the Conowingo Reservoir was still effectively trapping nutrients and sediment. However, increasing evidence suggests that the system may have reached its trapping capacity, and thus may no longer provide the water quality benefits provided since dam construction. As the 2017 Midpoint Assessment and TMDL model update approaches, assumptions regarding the reservoir's trapping efficiency require careful reconsideration. Loss of trapping capacity could require offsets and additional watershed management to meet the TMDL objectives.

To address scientific and technical aspects of the influence Conowingo infill has on tidal Chesapeake water quality, the CBP Scientific and Technical Advisory Committee (STAC) held a workshop titled "Conowingo Infill Influence on Chesapeake Water Quality" on January 13-14, 2016 in Annapolis, Maryland. The workshop was a scientific discussion among a group of over 70 participants invited by the workshop steering committee. This report summarizes the ideas (from completed scientific research or reports of work in progress) presented at the workshop and the major consensus conclusions.

The workshop was supported by the STAC based on a recognition that on-going changes in the net trapping efficiency of the reservoirs in the lower Susquehanna River Basin (primarily changes in Conowingo Pond) could have substantial impact on nutrient delivery to the Chesapeake Bay, and those impacts could limit progress in achieving the water quality and ecosystem goals of the Bay Agreement and TMDL.

In recent decades, sediment input to the three reservoirs of the Lower Susquehanna has diminished by about 60 percent from levels that prevailed in the early part of the 20^{th} century, however, in the last two decades the rate of net deposition (note that "net deposition" is the algebraic sum of deposition minus losses from the reservoir) of this sediment has been declining (Langland 2015). This is important to Bay water quality, particularly because the sediments entering the Bay from the Lower Susquehanna carry a substantial fraction of the TP input of the Susquehanna. Suspended solid loads also contain particulate organic carbon, nitrogen, and phosphorus.

It has long been recognized that at some point the reservoir system would reach its capacity for sediment storage and would no longer serve the role of trapping of TP, TN, and SS before reaching the Bay (Langland and Hainly 1997). More recent evaluations by others (Hirsch 2012, Zhang et al. 2013, Zhang et al. 2016**a**) have served to better quantify the nature of changes in sediment trapping. These more recent estimates (e.g., Hirsch, current workshop, Zhang et al. 2016**a**), indicate that TP trapping behind the reservoir has changed from about 50 percent two decades ago to a situation where little or no phosphorus is being trapped and, in some periods of time, the reservoirs may even be releasing more than they receive. For TN, which occurs predominantly in the dissolved phase, the prior removal was much less – in the range of 5 to 15 percent – two decades ago, but today the Lower Susquehanna River Reservoir System (LSRRS) traps little to no TN and on many days is releasing more than it receives (e.g., Hirsch, current workshop, Zhang et al. 2016**a**). Moreover, Zhang et al. (2016**a**) have recently published estimates of output-to-input (O/I) ratios of flux for all three constituents for each of five different ranges of discharge, covering the breadth of Susquehanna River flow. The results show increases in O/I in recent times for all ranges of discharge, including particularly strong increases in TP load at flows well below the median river discharge (See Figures S20, S21, and S22 in Supporting Information to Zhang et al. 2016**a**). Overall, the data confirm that increased loadings in recent time reflect not only the effects of scour but also a major influence of reduced deposition at all ranges of flow, particularly so for P-laden particulates.

Specifically, recent estimates by Hirsch (2012) examined trends in flow-normalized fluxes of sediment and nutrients at Conowingo using a statistical model known as Weighted Regressions on Time, Discharge, and Season (WRTDS). The findings indicated a 55 percent increase in TP and a 97 percent increase in SS in the flow-normalized flux from 1996 to 2011 at Conowingo. The phosphorus and sediment changes estimated by Hirsch (2012) represented the changes in the loads from the entire Susquehanna watershed as well as changes in reservoir scour and deposition. Nevertheless, the increases in phosphorus and sediment flux from the Conowingo Reservoir occurred despite observed reductions in the fluxes of sediment and phosphorus from the upriver Marietta, PA gauge as well as other upstream gauges and were therefore attributed to Conowingo infill (Zhang et al. 2013, Zhang et al. 2016**b**). Recent trend work by the U.S. Geological Survey (USGS) points to similar findings (http://cbrim.er.usgs.gov/maps.html).

Based on multiple lines of evidence, the reservoir system is approaching its sediment storage capacity. The term that is now used for this condition is "dynamic equilibrium" which simply means that although there continue to be periods of deposition (when storage grows) and briefer periods of loss of stored sediments (mostly due to bed scour) the net effect is that there is now minimal change in storage for most finer fractions of sediments (all but the coarsest gravels and rocks) when averaged over many years. In effect, the reservoir system is reverting to the condition of a river reach that over time delivers loads equivalent to what is received (Fan and Morris 1998). That which had been viewed, prior to 2011, as an important "future problem" has now become recognized as a present day problem. In terms of watershed inputs of TN, TP, and SS, the reduced trapping efficiency indicates that, relative to the first nine decades since dam creation, increasingly greater fractions of the total upstream load (e.g., as observed at Marietta) are now reaching the Chesapeake Bay.

Dynamic equilibrium thus does not imply equality of sediment inflow and outflow on a daily, monthly, or even annual basis. The "dynamic" balance occurs over a longer period of time (currently many years) determined by the frequency and magnitude of scour events, the overall rate at which sediment enters the reservoir, and the state of the underlying (scour-resistant) reservoir bathymetry. In the latter regard, and despite the so-called "dynamic equilibrium," more gradual changes are continuing to occur in the bathymetry of the bed (both before and after major scour events) and in the size distributions of stored bed sediments at different locations in the reservoir system. In the absence of dredging and other intervention, the durations of net deposition for many of the smaller size fractions are likely to decrease, such that loads released during major scour events may eventually be less than at present, reflecting lower mass accumulations of readily mobilized sediment between events and the eventual evolution of the bed toward coarser particle sizes.

Against this background, there is a considerable amount of attention being paid to the Conowingo Dam relicensing by a variety of public and private entities. For example, the U.S. Army Corps of Engineers (USACE) and a group of 7 partner organizations conducted a congressionally-mandated study titled the Lower Susquehanna River Watershed Assessment (LSRWA). The draft report was released for public comment November 13, 2014 and finalized on March 10, 2016 (http://dnr.maryland.gov/bay/lsrwa/report.htm). STAC provided formal comments to an earlier draft of the LSRWA report in August 2014, accessible here. In addition, considerable research, data collection and interpretation has been conducted by the U.S. Geological Survey (USGS) and by investigators at Johns Hopkins University dealing directly with the historical trends of nutrient and sediment loads in the Susquehanna watershed and the accumulation of sediments in the basin. Additionally, within the past year major new research and data collection activities have been undertaken as part of a collaborative project involving several organizations: Exelon Generation Company, LLC (Exelon, owners of the dam who have provided a large share of the total funding), several of Exelon's private contractors including Gomez and Sullivan Engineers, AECOM, HDR, and WEST Consultants, USGS, and the University of Maryland Center for Environmental Science (UMCES). As a result, the topic has become one of intense political interest and active research and the subject of a rapidly growing body of both scientific publication and news reporting in recent years. Furthermore, the CBP is working to incorporate new information on Conowingo infill into its 2017 Midpoint Assessment of TMDL progress. The attention to the issue can be seen in the agendas of the Bay Program's Modeling Workgroup and Water Quality Goal Implementation Team.

The workshop goals laid out by the steering committee were:

- Given the current state of knowledge based on recorded observations and our current understanding of first principles which can be used to build simulation models, together with the 2017 Midpoint Assessment timeframe, what is the best approach to evaluate impacts from the reservoir system to the Chesapeake Bay ecosystem? It is expected that current research will advance future modeling efforts, but there is an immediate and critical need to evaluate current and future impacts from reservoir infill and outputs based on the best information currently available.

- Formulate a plan of study and experimentation, including field data collection related to mass balance and biogeochemical transformations, which will improve understanding of the processes at play in these reservoirs and our ability to model the system's response to candidate management strategies.

- Explore approaches to improving understanding and simulation of the transport and ultimate fate of particulate nutrients from Conowingo Reservoir: including the transport, settling, resuspension, chemical and biological processes taking place under all states of flow and wind conditions, in order to better understand the impact of particulate nutrients on Bay water quality, especially with regard to the location and timing of nutrient remineralization, bioavailability, and burial.

Overall, the steering committee sought to find consensus among participants regarding fundamental ideas, the relative degree of certainty concerning these ideas, and the relative importance of various questions.

In addition to these explicit goals, there were implicit goals of achieving a higher level of communication addressing this rapidly developing topic across a diverse range of scientists and technical program managers in the public and private sectors. The steering committee believes that the workshop served this purpose well, and the findings of the workshop will benefit future research and decision-making on this topic.

The workshop presentations and discussions focused on how the reservoir system is likely to perform in the future in terms of how it modulates the inputs of SS, TP, and TN from the watershed to produce a set of outputs. Unaddressed were specific types of engineering solutions having to do with modifications of the dams, dredging of the reservoirs, or creating sediment bypassing systems, as these were extensively considered by the LSRWA report (USACE 2016) and found to provide minimum, short-lived benefits at prohibitively high costs. In this regard however, keynote speaker Dr. Gregory Morris highlighted three types of questions that could be raised: (1) whether the system can be manipulated to restore its prior "removal" functions, e.g., renewing its sediment and nutrient storage capacity through dredging; (2) whether the dynamic equilibrium processes can be manipulated to manage the timing of net depositional and net scouring processes, e.g., to somehow release more sediments during "favorable" times; and (3) whether better understanding of mechanistic processes and performance of the LSRRS can be used to inform a more appropriate TMDL allocation process that remains protective of the Bay and local ecosystems. In this context, the cost-effectiveness of dredging was viewed as beyond the workshop scope and in regard to operational change, some workshop participants noted several important current constraints (relating to power generation, nuclear power plant cooling, and Baltimore water supply intake levels) that effectively prevent extensive manipulation of reservoir water levels or deliberate by-passing of sediments. Only the third question fell within the scope of the workshop's original objectives, with the majority of subsequent presentations and discussions focused on seeking better understanding of the water quality impacts and informing the TMDL allocation process.

It is the expectation of the steering committee, and the STAC, that this report will help to document the new knowledge and understanding of this issue that has developed in the last few years, as well as provide an overview of new research currently underway. It is the intention that the report will point to the most important published research as well as lay out the key consensus views of the scientific community.

The body of the report is divided into two sections. The first section, titled **Lower Susquehanna Reservoir Research, Monitoring, and Modeling**, describes the state of the science in understanding the Conowingo infill processes and the condition of the other two reservoirs in the Lower Susquehanna. The second section titled **Chesapeake Bay Research, Monitoring, and Modeling** documents the current understanding of the impacts of particulate nutrients and suspended sediments on Chesapeake Bay water quality from the Susquehanna and associated Conowingo infill processes. These processes include physical transport of sediments and associated particulate nutrients through the tidal waters of the upper Bay, the locations of initial deposition, and the long-term transport, fate, and burial of the particles including the biogeochemical processes that control the fate of bound nutrients, as well as the bioreactivity of the nutrients.

Links to all of the workshop's presentations can be found in **Appendix C**.

Lower Susquehanna Reservoir Research, Monitoring, and Modeling

As context for subsequent discussions on this topic, several presentations reminded workshop participants of some well-accepted basic concepts regarding the nature and role of nutrient and sediment loading to the Chesapeake Bay. These included the following:

1) The major source of the sediments phosphorus (P) and nitrogen (N) exiting the Conowingo Dam is the upstream watershed of the Susquehanna River basin. In regard to sediment and sediment-bound fractions of nutrients, a substantial fraction of the load has been historically retained ("stored") behind the dam. This is not the case for N, however.
2) Although phosphorus tends to be predominantly associated with sediments, LSRRS nitrogen occurs primarily in dissolved form (predominantly nitrate), such that the N has historically been only marginally reprocessed or removed, with the majority passing through the LSRRS primarily in the form of nitrate and at concentrations in the effluent not dissimilar from those in the influent.
3) Although N and P are both limiting nutrients in the Chesapeake in different regions and times of the year, N has generally been the limiting nutrient for algal growth (and resulting hypoxia) in the summer and early fall months in the middle to lower Bay (Kemp et al. 2005). In terms of the mass of N that is "retained" in the Bay proper (e.g., as algal mass), the majority was derived from dissolved forms that are not affected in major ways by the reservoir system.

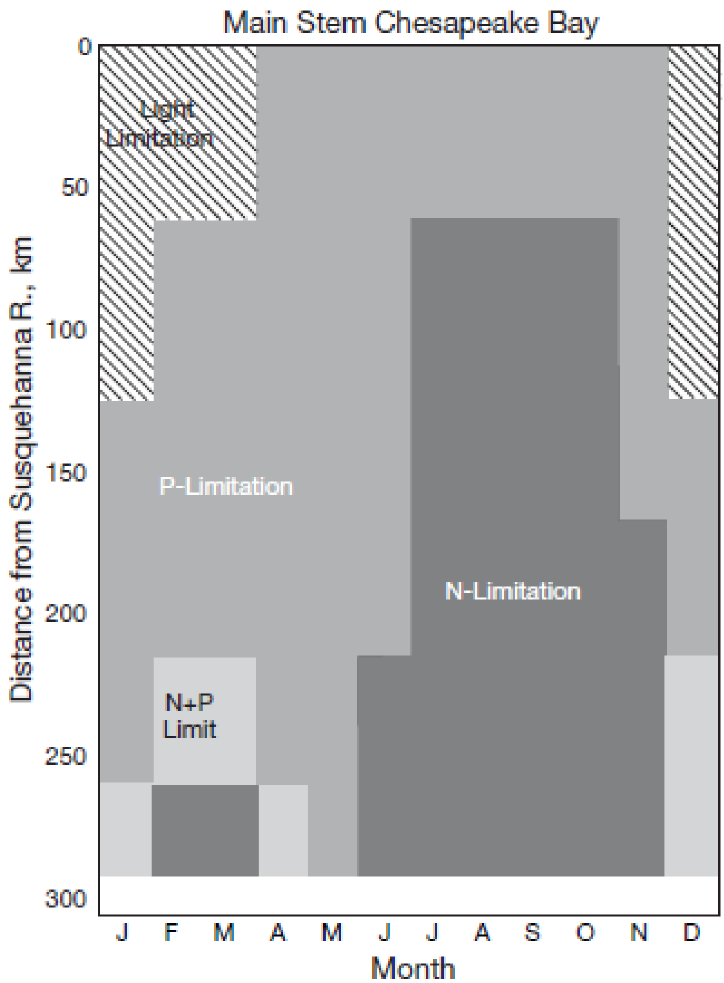

Figure 2. Seasonal and regional variations in nitrogen, phosphorus, or light limitation for phytoplankton growth synthesized from bioassay experiments in mainstem Chesapeake Bay between 1992 and 2002 (source: Kemp et al. 2005)

Within the above context, the LSRRS has been serving for nearly 90 years to modulate the delivery of sediment and nutrients from the Susquehanna basin to the Chesapeake Bay. Long-term monitoring data, however, suggest changes in reservoir storage capacity have reduced trapping efficiencies over the past thirty years, and a key question for the management of water quality in the Bay is: How will the reservoir act in the future in terms of how it stores and releases materials that enter it? Undoubtedly, large scour events with flow greater than 11,300 m^3/s (400,000 cfs) will continue to occur in the future, and the timing and the magnitude of these events will remain unpredictable. Less certain, however, is the magnitude of deposition and scour associated with more frequent and typical high flow events, i.e., flows between 2,830 m^3/s (100,000 cfs) and 9,900 m^3/s (350,000 cfs). These events produce loadings of nutrients and organic matter, derived both from the watershed upstream as well as scoured from the reservoir bottom, which will be delivered to the Bay. Following each scour event, the resulting additional storage capacity will accommodate deposition, which will amount to diminished effluent loads from the reservoir for an indeterminate period. Concurrently, the longer-term processes of changes in the patterns of infill are reducing particle capture between the major scour events at even low and moderate flow conditions.

Workshop participants expressed a general consensus with previous findings of the LSRWA report (USACE 2016) that the Conowingo Reservoir is very near to (and essentially at) a condition of "dynamic equilibrium" with regard to discharge of fine sediments and particle-associated nutrient loads. In this state, sediments and particulate nutrients accumulate in the reservoir until an episodic high flow scouring event occurs. The scour event then increases storage capacity, allowing for more deposition until the reservoir gradually fills and another scour event occurs. Dynamic equilibrium does not imply equality of sediment inflow and outflow on a daily, monthly, or even annual basis. The balance occurs over a period of time, currently many years, that is determined by (1) the frequency and magnitude of scour events, (2) the overall rate at which sediment enters the reservoir, (3) the state of the underlying reservoir bathymetry, and (4) longer-term processes of change with regard to the spatial distribution of coarse and fine sediments in the reservoir bed. The bed-coarsening and bathymetric effects continue to occur at a much slower rate and in this regard the system is still far from true equilibrium.

In regard to impacts of long-term changes in the composition of the bed and its bathymetry, evidence was presented at the workshop (from Zhang et al. 2016**a**) illustrating that rates of net sediment and particulate nutrient deposition have been decreasing over a wide range of flows, including values well below that typically associated with scour. Overall, and in the absence of intervention, the quantity and nature of sediments and nutrients reaching the Chesapeake Bay are likely to obtain long-term average values that more closely resemble those at the LSRRS influent than in the first sixty years of reservoir operation, with important implications regarding the impacts of the Susquehanna watershed loads on Bay water quality. Despite the "dynamic equilibrium" condition, the slow on-going changes in the bed are likely to continue to alter the timing and amounts of sediment and nutrient loads for some time to come, offering additional challenges to modeling and management.

To quantify the influence Conowingo infill has on Chesapeake water quality, the following processes must be considered in the Conowingo Reservoir: 1) scour during relatively rare extreme events, e.g., 10 year storm events with flow greater than 11,300 m^3/s (400,000 cfs); 2) scour during moderately high flow events; 3) trapping during low and moderate flows; and 4) biogeochemical nutrient cycling that influence bioavailability in the reservoir sediments, especially under low flow conditions.

Given that particulate erosion rates increase with flow velocity, and that dissolved constituent loadings derive substantially from groundwater sources in the watershed, it is not surprising that high flow events will increase particulate loads more than dissolved nutrient loads and that we can expect the differences to be especially pronounced under reservoir scour conditions. In this regard, for example, the authors of the LSWRA report (USACE 2016) noted that, *"[a]t the highest observed flows, the dissolved nitrogen fraction declines [from 86 percent under normal-flow conditions] to 60 percent or less. For example, during Tropical Storm Lee, 40 percent or more of the nitrogen was in particulate form [and] 90 percent of the phosphorus was in particulate form."* Previous studies primarily evaluated the risks and magnitude of scour during major storm events with greater than 11,300 m^3/s (400,000 cfs) flow; however, loss of trapping efficiency may impose more continuous sediment and nutrient transfer from Conowingo Reservoir to the upper Bay ecosystem (USACE 2016). Reduced reservoir deposition during more frequent moderate to high flows, i.e., 2,830 m^3/s to 11,300 m^3/s (100,000 to 400,000 cfs), could impose a more continuous supply of excess sediment and particulate nutrient loads to the Bay ecosystem. If accumulated sediments remain susceptible to mobilization, a major event such as Tropical Storm Agnes in 1972 could restore considerable trapping capacity (Langland 2009). However, under low to moderate flows and depositional infill, reservoir depths will decrease resulting in a diminished cross sectional area of the reservoir which is expected to increase flow velocities and reduce deposition (Scott, current workshop), thus leading to elevated sediment and nutrient discharge during more frequent high flow event (< 8,500 m^3/s or <300,000 cfs) conditions. Indeed, a comparison of inflow measured at the Marietta monitoring station and outflow measured below Conowingo Dam indicated that storm flows between the 75th and 99.5th percentile, i.e., between 1,467 m^3/sec (51,800 cfs) and 7,646 m^3/sec (270,000 cfs), contributed the most TN, TP, and SS through the system, despite the sub-scour status (Zhang, current workshop, Zhang et al. 2016**a**). Further, stationary-model analysis to evaluate discharge conditions under varying reservoir infill conditions also indicated diminished trapping capacity since 1990 (Zhang, current workshop, Zhang et al. 2016**a**). As previously noted, recent publications (Hirsch 2012, Zhang et al. 2013, 2016**a**) have provided more specific and detailed statistical analyses that serve to better quantify the nature of changes in sediment trapping.

Patterns of Deposition and Scour in Conowingo Reservoir - Observations and Modeling

Changes in reservoir bathymetry over time indicate changes in a reservoir's storage capacity and can both influence and be affected by processes of scouring and deposition (Morris and Fan 1998). In the LSRRS, a combination of increased scour potential during more frequent high flow events and reduced deposition under low flow conditions will lead to average O/I ratios that approach 1.0, and could increase annual nutrient and sediment loads to the Bay relative to those observed in the past (Langland 2015). Recently published USGS summaries of decadal (2005-2014) trends indicate decreases in loads at the Marietta gage (-12 percent for TP, -13 percent for TN, and -23 percent for SS) and yet over this same period of time loads at the Conowingo gage have increased (+44 percent for TP, +1 percent for TN, and +7 percent for SS) (http://cbrim.er.usgs.gov/maps.html retrieved May 27, 2016). These results, decreasing inputs and increasing outputs from the reservoir reach, fail to inform how much of the increase is due to the remobilization of reservoir sediments and how much is due to a decrease in deposition. What is clear is that the dynamics of the system have changed over the past several decades, coinciding with the timeframe used to develop the TMDL. Understanding the mechanics and relative importance of the full range of depositional and remobilization processes is critical to estimating future impacts on loadings to the Bay under all flow conditions, including major storms, and to evaluating the benefits of alternative management actions aimed at mitigating impacts.

Improved and more frequent mapping and spatially explicit models of active scour and deposition zones within each of the three Lower Susquehanna reservoirs could indicate how reservoir sediment processes influence nutrient and sediment discharges to the upper Chesapeake Bay. To date, bathymetric surveys together with measured inflows and outflows observed during the past 30 years indicate that the reservoir system had a long term sediment trapping capacity of about 60 percent (Langland, current workshop). Preliminary model applications to evaluate reservoir sediment dynamics indicate discrete areas of sediment deposition and scour within each reservoir. The spatial extent of these processes are related to the structure of the reservoir's dam, the reservoir's morphometry, as well as the influence of tributaries discharging to a reservoir (Sullivan, current workshop). In Conowingo Reservoir, turbine operations reduce deposition within 2 km (1.25 miles) upstream of the dam (Langland and Hainly 1997). Furthermore, 85 percent of scour reported by Langland and Hainly (1997) for the January 1996 storm occurred in Conowingo Reservoir, with more than 40 percent of scour occurring within the zone of turbulence generated by the dam. The flood gates, which are approximately 7 meters (23 feet) below mean lake level also reduce deposition albeit at a lesser extent than the turbines, which are 30 meters (98 feet) below mean lake level (Langland 2009). Model results also indicated that the scour areas expand during high flow events, mainly along the shoreline length of Conowingo Reservoir, and that shallow, off-channel areas could continue to trap sediment and may eventually become vegetated (Morris, current workshop).

Multiple lines of evidence suggest that scour is limited within the Lake Clarke and Lake Aldred reservoirs and that scour potential has not changed significantly over the past 60 to 70 years. A series of six bathymetric surveys across Lake Clarke and Lake Aldred between 1950 and 1964 indicated little change in water or sediment storage capacity (Langland 2009).

To investigate patterns of scour and deposition within Conowingo Pond, ten (10) sediment cores were collected by AECOM in August 2015 at locations representing a range of geomorphic and geologic conditions, including in-channel verses out-of-channel, deep versus shallow waters, and near inflows and outflows. Results revealed classic reservoir infill patterns (Sullivan et al., current workshop; Morris and Fan 1998). In the upper and middle sections of Conowingo Reservoir, distinct laminations of sand, silt, and coal suggested limited disturbance and mixing of the layers. In the lower section of the reservoir, the cores consisted primarily of homogenous clayey silt, with little distinct layering (Sullivan et al., current workshop, Palinkas, current workshop). Results indicated a mixture of storm deposits and suspended load deposition remobilized from upstream sources. Overall, the reservoir core samples also had relatively high organic matter content, ranging from 2 to 45 percent of the total content with the lower reservoir samples having an organic matter content from 7 to 45 percent (Sullivan et al, current workshop). Pockets of soft-sediment deposition indicated downslope slumping or sliding under influence of gravity or overloading by rapid sediment deposition, perhaps suggesting the influence of density currents (Sullivan et al., current workshop).

Temporal and spatial patterns of sediment deposition and scour in the reservoir influence the same biogeochemical processes that control nutrient availability in all fresh water saturated and flooded environments. In particular, the supply of organic matter (Cornwell, current workshop) to the reservoir sediment and the development of a reduced environment – which can develop under low flow conditions – could significantly increase concentrations of orthophosphate (and other redox-sensitive pollutants of concern). Recent USGS trend results estimate an increase in dissolved orthophosphate at Conowingo of 44 percent from 2005 to 2014 and yet, over the same period trends at Marietta noted a decrease of 34 percent (http://cbrim.er.usgs.gov/maps/, retrieved May 27, 2016). Methane voids prominent in the clayey-silt sediments of the Lower Conowingo Pond confirmed sediment anoxic reducing conditions (Sullivan et al., current workshop). Storm events with flow exceeding 11,040 m^3/s (390,000 cfs) could scour the anoxic sediments just below the sediment-water interface (Langland 2009).

Overall, minor changes in the bathymetry data suggest the reservoir system has nearly reached its full trapping capacity (Figure 3). Insufficient understanding of how reservoir bathymetry changes in response to storm flow below 11,300 m^3/s (400,000 cfs) limits the ability to characterize how dynamic scour and deposition patterns currently influence sediment and nutrient discharge on an average annual basis. Additional modeling and monitoring studies to characterize the vertical and horizontal extent of scour in relation to flow discharge are needed.

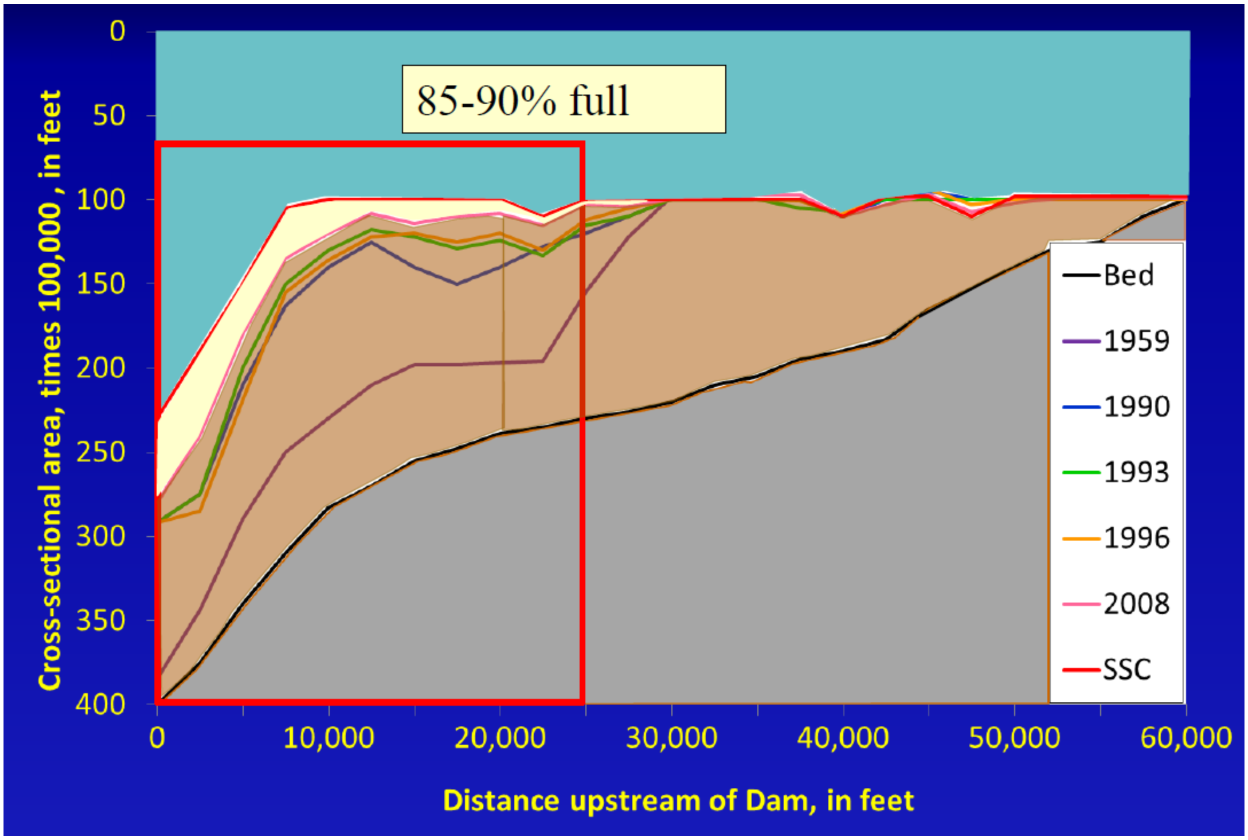

Figure 3. Bathymetry surveys of the Conowingo Reservoir showing also the original Susquehanna River bed and the full reservoir Sediment storage Capacity (SSC). The red box depicts the lower reservoir section within 5 miles of the Conowingo Dam (source: Langland, current workshop. *Sediment Transport and Bathymetric History in Three Reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland 1900-2015*)

Chesapeake Bay Research, Monitoring, and Modeling

The impacts of particulate nutrients and suspended sediments on Chesapeake Bay water quality are determined by more than the sheer amounts that are delivered over Conowingo Dam. Other factors influencing Bay water quality include the physical transport of sediments and associated particulate nutrients through the tidal waters of the upper Bay, the locations of initial deposition, and the long-term transport, fate, and burial of the particles – including the biogeochemical processes that control the fate of nutrients bound to the particles and their bioreactivity. The biogeochemical environment of the tidal near-bottom waters and sedimentary pore waters into which Conowingo particles are deposited strongly influences the timing and extent of nutrient transformation and release, and hence the impact on Bay water quality. Particulate nutrients that are delivered into the head of the deep trough of the mid-Bay have much greater impacts on water quality than particles that are deposited and buried in relatively fresh, normoxic upper Bay waters. Determining the extent to which the Susquehanna Flats and Chesapeake Bay Estuarine

Turbidity Maximum (ETM) trap or seasonally modulate the delivery of Conowingo particles is critical to a full evaluation of this transport effect. Redistribution of newly deposited particles through resuspension and transport by waves and tides must also be accounted for. Finally, the influences of channel dredging and sediment placement also need to be evaluated.

An assessment of the impacts of Conowingo infill on Chesapeake water quality standards and ultimately on TMDL achievement needs to consider the full range of hydrologic conditions observed in the past, including low, moderate, and extreme flow conditions. In addition, estimation of the delivery of sediment and nutrients to the Bay must consider the timing and form in which constituents of concern are delivered to the reservoir system and the Bay. These factors significantly influence chemical and physical processes that control the sediment storage and release and must be considered across the full range of stream flows and across all seasons.

Careful consideration should be given to the ultimate transport and fate of particulate nutrients from the lower Susquehanna after delivery to the Bay. This includes seasonally variable changes in the transport behavior of delivered particles, particle trapping by physical and biological features in the upper Bay, and biogeochemical transformations of newly deposited particles in different receiving waters, in addition to consideration of all of these factors following rare large events. The most conservative management assumption is that all of the delivered organic material scoured from Conowingo is fully degradable to inorganic nitrogen and phosphorus. Current CBP model assumptions for the 2010 Water Quality and Sediment Transport Model (WQSTM) are that particulate organic material scoured from the Conowingo is slowly degradable with a reaction rate of 0.005/day. The state of the science is currently limited on the details of these issues, but workshop participants nonetheless supported the current approach and urged continuing refinement of the splits of particulate organic material into labile, refractory, and inert reactive categories as new knowledge becomes available.

Sediment Trapping in Upper Chesapeake Bay and Impacts of Large flows

The Susquehanna River is the largest source of fresh water, suspended sediment, and nutrients to upper Chesapeake Bay (Schubel and Pritchard 1986, Cronin et al. 2003). From Havre de Grace, Maryland the river opens up to the tidal fresh Susquehanna Flats (the 'Flats') and connects with the Chesapeake Bay. Above Havre de Grace the river channel depths range from 6 to 20 m (20 to 66 ft), and above Port Deposit shoal to less than 3m (10 ft) (NOAA- Office of Coast Survey; Chart 12274, Head of Chesapeake Bay). The Flats constitute the head of the Susquehanna River estuary, which extends almost to the mouth of the Potomac River, 161 km (100 miles) seaward (Schubel and Pritchard 1986). The Flats describe a broad, shallow delta where predominantly sand sized particulates are deposited where the Susquehanna River emerges from a narrow rock walled valley as it crosses the Piedmont Physiographic Province and opens into the Chesapeake Bay. The Flats formed during the latter stages of Susquehanna River migration up its ancestral valley over the past 3,000 to 7,000 years in response to sea level change. Water depths on the

Flats are generally are less than one meter, except for the former thalweg, which hugs the western side of the Flats, and is partially dredged to maintain navigation between Port Deposit and the main stem of the Chesapeake Bay below Turkey Point. In the upper Chesapeake Bay a deeper shipping channel provides a connection between the Chesapeake and Delaware Canal and the port of Baltimore. The channel is maintained at a width of 137 m (500 ft) and depth of 11 m (35 ft) deep (Dovel and Edmunds IV 1971). Net water movement along the shipping channel is from the Chesapeake to the Delaware Bay and has been linked to shifts in the ecological structure of the Upper Bay (Dovel and Edmunds IV 1971, Jackson and Jesien 1996).

The daily to weekly volume of Susquehanna freshwater discharge controls the location of the ETM in the upper Chesapeake Bay (Schubel and Pritchard 1986, North et al. 2004, Park et al. 2007). The ETM refers to the zone of elevated suspended sediment concentrations observed near the estuarine salt limit and induced by tidal and wind-induced scour, differences in salinity and water density, and other physical factors (Sanford et al. 2001). The salt front is defined as the 1 percent bottom isohaline (Jassby et al. 2012). In the Chesapeake Bay, the ETM extends approximately 20 km (12 miles) in length from north to south, between Turkey Point and Tolchester (latitudes 39°10'N and 39°28'N) (Sanford et al. 2001, North et al. 2004). As flow increases, the salt front is pushed seaward and the salt 'wedge' is compressed, thereby intensifying the vertical salinity gradient (Figure 4). As river flow decreases, the salt water wedge extends northward; the bottom, saltier water advances more rapidly than surface waters, thereby extending the longitudinal salinity gradient along the main stem of the Bay. The response time of the ETM to changes in freshwater inflow is a matter of days to weeks, as exemplified by the response of the 1‰ bottom isohaline following Hurricane Agnes, from June through September, 1972 (Schubel and Pritchard 1986). Immediately following the June 21 record discharge of 32,000 m^3/s (1,130,000 cfs) and stream gauge height of 11.23 m (36.85 ft), the salt front moved 70 to 80 km (43 to 50 miles) seaward, to a location south of the William Preston Lane Memorial Bridge. By late July, average daily flow dropped to less than 85 m^3/s (3,000 cfs), and by late August, the salt front rebounded northward, extending well into the Susquehanna Flats. Since implementing the Susquehanna River low flow guidelines in 1987 (http://www.srbc.net/policies/lowflowpolicy.htm, retrieved July 11, 2016) the ETM generally occurs beyond Turkey Point and migrates along the shipping channel between Baltimore and the Chesapeake and Delaware (C&D) canal (North et al. 2004, Park et al. 2007).

The sediments deposit and accumulate in tidal Chesapeake waters in reverse order of their particle size, beginning with sands in the Susquehanna Flats at the river mouth and grading to clayey silts by the Annapolis Bay Bridge (Colman et al. 1979; Kerhin et al. 1988). Under normal river flow conditions, the vast majority of sediments delivered by the Susquehanna River are trapped and accumulate in the upper Bay above the bridge (Schubel and Pritchard 1986, Donoghue et al. 1989), but under high flow conditions some fraction of the sediment load can be delivered well into the mid-Bay (Stumpf 1988, Sanford et al. 2001). Furthermore, sediment loads initially deposited on the broad shoals of the upper Bay seem to be effectively focused into the shipping channels by subsequent wave-induced resuspension (Sanford 1994). Maintenance dredging of these shipping channels may remove the majority of the trapped sediment load, though exact calculations are difficult (Sanford et al. 2001). Locations and methods of dredged sediment disposal will in turn influence the potential for additional environmental impacts. Since 2010, all sediments dredged from the major shipping channels are removed from the Chesapeake Bay and placed in confined facilities such as the Poplar Island Restoration Project or the soon to be reactivated Pearce Creek Confined Disposal Facility.

The fate of particulate organic carbon (POC) and particulate nutrients from the river is not as clear, though it is likely that much of this material is trapped or escapes in a similar manner to that of fine inorganics. For example, Keller et al. (2014) found a significant transition between riverine and estuarine phytoplankton across the location of the ETM, with indications of significant degradation and trapping of degraded riverine phytoplankton in the ETM. Malpezzi et al. (2013) also found that a large fraction of the POC in the ETM region was associated with Transparent Exopolymer Polysaccharides (TEP) that likely resulted from phytoplankton degradation and tended to be associated with large, rapidly settling aggregates (Figure 4). The upper Bay is a region of limited new phytoplankton production due to persistent high turbidity (Fisher et al. 1988, Smith and Kemp 2001), which makes it a net heterotrophic environment.

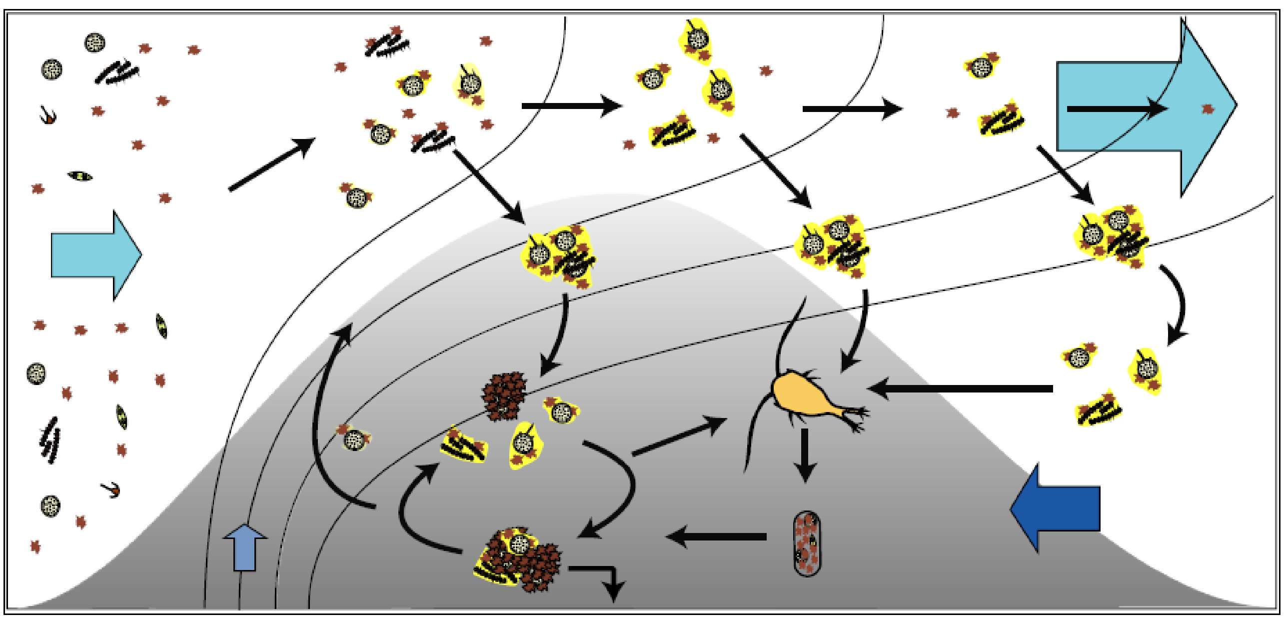

Figure 4. A Conceptual Model of Particle Dynamics in Chesapeake Bay ETM. ETMs are established and maintained through a combination of near bottom transport convergence, particle settling, and tidal resuspension. The efficiency of particle trapping is enhanced by flocculation/aggregation, which is enhanced by biological activity (source: Sanford, current workshop. *How Does the Bay Respond to Large Freshwater Events?*)

There are four main processes that contribute to sediment and particulate nutrient trapping in the upper Bay above the Chesapeake Bay Bridge at Kent Island. First, the rapid expansion in cross-sectional area where the Susquehanna River empties into Chesapeake Bay south of Havre de Grace rapidly reduces river flow, resulting in a settling of coarse particles and continuous formation of the broad, sandy delta known as Susquehanna Flats. Recent research also indicates an increased tendency for fine particle trapping during summer months due to the presence of the extensive submerged aquatic vegetation (SAV) bed over the Flats (C. Gurbisz and C. Palinkas, personal communication). Second, fine wash-load particles from the Susquehanna River tend to flocculate and/or agglomerate when they reach estuarine waters (Schubel and Kana 1972, Sanford et al. 2005, Malpezzi et al. 2013), increasing their settling speeds and likelihood of being trapped in the upper Bay. Third, the persistent ETM that forms in upper Chesapeake Bay near the limit of near-bottom salt intrusion (between latitudes 39°10’N and 39°28’N) greatly increases the residence time and burial rate of particles settling at intermediate speeds (Geyer 1993, Sanford et al. 2001, North et al. 2004). Finally, deposition and burial of these particles seem to be preferentially focused in the shipping channels of the upper Bay, most likely by wind-wave resuspension and transport following initial deposition (Halka et al. 1991, Sanford 1994). Sediments that are deposited in the channel downstream of the ETM can be subsequently transported back upstream by the combined estuarine and tidal circulations.

High riverine discharge may transport fine particles beyond the turbidity maximum (Sanford et al. 2001) resulting in sediment plumes extending from the Susquehanna to as far as the mouth of the Potomac, visible from space (Stumpf 1988). Sediment concentrations in these plumes are high relative to normal surface concentrations in Chesapeake Bay, but low compared to source concentrations at the mouth of the Susquehanna River (Figure 5). High concentrations tend to be present only in the surface layer (Cheng et al. 2013) and dissipate through settling and mixing within a few days. There are very few *in situ* observations of storm plumes, but it is likely that significant delivery of particulate nutrients from the Susquehanna to the mid-Bay is dominated by these plume events. The fraction of the total particulate nutrient load delivered in this manner is not yet known.

The timing of a storm event affects the magnitude of the water quality impacts on the Bay (Wang and Linker 2005, Cerco and Noel 2016, Linker et al. 2016). A spring or summer storm event, during critical life stages for many species of concern, poses greater risks to the Bay ecosystem than a fall event. The worst example of this on record was Tropical Storm Agnes in 1972, which had enormous, long-lasting impacts on Bay water quality and ecosystem dynamics (CRC 1977), largely due to its June timing. Interestingly, many of the adverse impacts of Agnes on living resources were attributed to the enormous freshwater inputs as well as, or instead of, the enormous sediment inputs (CRC 1977).

Scientists continue to investigate linkages between the health of the upper Bay ecosystem and Susquehanna discharge. Examples of sudden, rapid degradation or reestablishment of SAV in the upper Chesapeake Bay suggest threshold effects have a strong role in regulating ecosystem health (Gurbisz and Kemp 2014; Gurbisz et al. 2016). For example, abundance of SAV precipitously declined after Tropical Storm Agnes in June 1972. For nearly 30 years, abundance remained extremely low. In the mid-2000s, however, SAV bed health resurged to pre-Agnes conditions on the tidal Susquehanna Flats (Gurbisz and Kemp 2014; 2016, Gurbisz, current workshop). Although bed area declined after the 2011 Tropical Storm Lee, surveys in 2013 and 2014 showed increasing abundance and no major changes to the remaining SAV bed health (Gurbisz et al. 2016).

Figure 5. The large sediment plume from Tropical Storm (TS) Lee (2011) was confined to the relatively fresh upper layer (~ 5-7 m thick). In order to remain suspended, the particles must be very fine and settle very slowly, but the finer particles are, the better they reflect light (think of fog vs. rain). Therefore, the plumes visible from space are relatively thin and contain high, but not huge concentrations of fine particles. For example, a suspended sediment concentration of 50 mg/l in a 5 m thick layer amounts to 0.25 kg/m^2 of material, or about 1 mm of deposition on the bottom. Most of the precipitation from TS Lee was in central Pennsylvania within the Susquehanna watershed (source: Sanford, current workshop. *How Does the Bay Respond to Large Freshwater Events?*)

Spatial Variation and Environmental Controls on Sediment-Water Nutrient Fluxes in Chesapeake Bay

The fate of both organic and inorganic material (carbon, nitrogen, and phosphorus) delivered to Chesapeake Bay from external sources (including the Conowingo reservoir) is tightly connected to controls on sediment-water nutrient and oxygen exchanges along the Bay's salinity gradient. This is because the majority of particulate materials discharged into the Bay sink to the bed relatively quickly, where they are subjected to biological and chemical processing that influences the fraction of the imported material that is released back to the water-column to support phytoplankton growth and other processes. The nature and extent of biogeochemical processing of these materials varies as a function of burial rate, salinity, and oxygen variability (Cowan and Boynton 1996), all of which change dramatically as one moves from the mouth of the Susquehanna to the lower Bay regions south of the Potomac River.

Fortunately, there are more measurements of sediment-water nutrient and oxygen exchanges in the Chesapeake Bay than any other estuary worldwide. This abundance of high-quality data allows for a rich data synthesis, which in combination with numerical model simulations, allows for a relatively complete understanding of controls on sediment processes and the fate of externally-derived carbon and nutrients (Figure 6). The first result of this synthesis revealed that although observed sediment carbon and phosphorus content are highest in the upper Bay and decrease down-estuary, observed sediment-water NH_4^+ and PO_4^{3-} fluxes are highest in downstream reaches of the middle Chesapeake Bay, i.e., between the Bay Bridge and Potomac mouth (Cowan and Boynton 1996). The peaks in sediment-water fluxes occur in the mid-Bay for several reasons, including: 1) deposition of labile organic matter derived from internal phytoplankton production is highest here (Cowan and Boynton 1996, Brady et al. 2013); 2) oxygen concentrations are highly depleted (hypoxia and/or anoxia) in the water-column during warm months (Hagy et al. 2004, Testa 2014); and (3) relatively low iron (Fe) availability allows for limited retention of phosphorus within sediments (Cornwell and Sampou 1995, Testa et al. 2013). Numerical model simulations support the finding that Bay-wide peaks in sediment-water NH_4^+ and PO_4^{3-} fluxes occur in the most oxygen-depleted regions (down-estuary of the Bay Bridge), highlighting the role of hypoxia/anoxia in allowing for enhanced sediment nutrient recycling via reduced coupled- nitrification-denitrification and enhanced Fe-oxide dissolution (Testa et al. 2014). These results emphasize the fact that externally derived organic material, such as that originating from Conowingo Reservoir, must be deposited to seaward regions of the Chesapeake Bay in order for the associated nutrients to be significantly recycled back to the water-column to support additional phytoplankton growth.

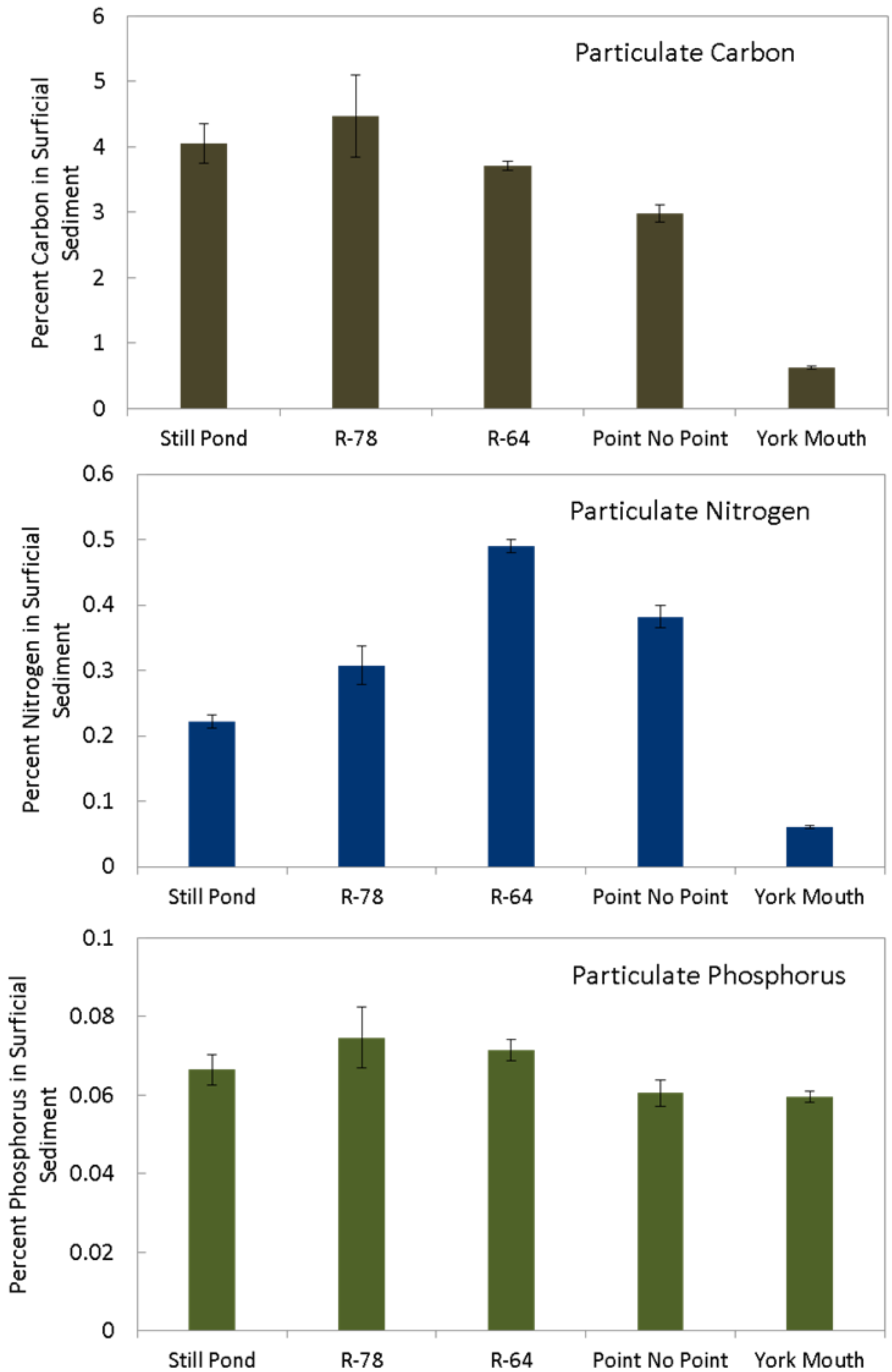

Figure 6. Particulate organic carbon (POC), particulate organic nitrogen (PON) and particulate phosphorus (particulate inorganic phosphorus, PIP and particulate organic phosphorus, POP) from surficial sediment cores. Still Pond is in the upper Bay off the Sassafras River, R-78 is in the upper mid-Bay at the north end of Kent Island, R-64 is mid-Bay off the Choptank River, Point No Point is lower mid-Bay off the Potomac, and the York. Mouth is in the lower Chesapeake off the York River (source: Testa, current workshop. *Sediment Nutrient Fluxes in the Tidal Chesapeake Bay*)

Impact of Reservoir Sediment Scour on Chesapeake Bay Water Quality

Cerco and Noel (2014, 2016) examined the impact of a Conowingo Reservoir scour event on Chesapeake Bay water quality, specifically dissolved oxygen (DO) concentration, chlorophyll concentration, and light attenuation. Their investigation employed coupled multi-dimensional hydrodynamic (Kim 2013) and eutrophication models (Cerco et al. 2010) of the Bay called the Water Quality and Sediment Transport Model (WQSTM). Two distinguishing features of the model were representations of sediment transport for multiple grain sizes (Cerco et al. 2013) and of diagenetic processes in bottom sediments (DiToro 2001). Both features proved essential in diagnosing the effect of reservoir scour on downstream water quality.

The most significant finding by Cerco and Noel (2016) was that suspended solids loads produced by a Conowingo scour event are relatively non-detrimental to Bay water clarity and SAV survival. For the fall and winter seasons, solids scoured from the reservoir settle out before the season during which light attenuation is critical, and even in the spring and summer seasons of SAV growth the suspended sediment settles quickly with minimal impacts to SAV or water clarity. The organic matter and nutrients associated with the solids are, however, detrimental. As illustrated in their model, this material settles to the estuary bottom and is mineralized in bed sediments. Carbon diagenesis spurs oxygen consumption in bottom sediments and release of reduced materials to the water column. Nutrients are recycled to the water column and stimulate algal production. As a result of a winter scour event, computed bottom-water DO in the subsequent summer declines up to 0.2 g m^{-3} although the decline is 0.1 g m^{-3} or less when averaged over the summer season.

Cerco and Noel (2016) also emphasize the significance of nitrogen loading generated by a scour event. The hypoxic volume of Chesapeake Bay is closely linked to the nitrogen load from the Susquehanna River (Hagy 2004, Murphy et al. 2011). Based on analysis of bottom sediment composition in the reservoir, the quantity of particulate nitrogen eroded during a scour event is three times the quantity of phosphorus. Preceding studies (Langland and Hainly 1997, Hirsch 2012) emphasize additional phosphorus rather than nitrogen, however, because the preponderance of the nitrogen load is in the dissolved form.

Impact of Reservoir Infill on Water Quality Standards

The projected impact of reservoir scour on downstream water quality is low when compared to normal intra- and inter-annual variations. The most detrimental projected effect is a DO decline of 0.1 g m^{-3} or less over a summer season (Cerco and Noel 2016). This amount is significant, however, when the minimum bottom-water DO concentration, after implementation of the TMDL, is projected to be 1 g m^{-3} in some regions of the Bay. Moreover, regulatory requirements prohibit any increase in nutrient loads that cause diminishment of water quality standard achievement. The impact of a scour event, with an emphasis on regulatory requirements, was examined by Linker et al. (2016).

For assessment purposes, the Bay system is divided into 92 segments, determined by multiple criteria including geometry, salinity, and living resources. Linker et al. (2016) examined, for each segment and water quality standard, the percent of time and volume that a given water quality criterion (i.e., DO, chlorophyll, water clarity) was outside an allowed exceedance. Attaining DO standards in the volume-time integral represented by deep-channel water from June to September is critical to the TMDL. A reservoir scour event places an additional 1 percent of the volume-time integral outside of DO standards.

Workshop Findings

- Research findings indicate a need to better understand how the LSRRS influences nutrient and sediment loads delivered to the Chesapeake Bay.
- Evaluation of water quality trends upstream and downstream of the reservoir system indicate decreased Conowingo trapping capacity since as early as 1995. Indications suggest that substantially more sediment and P – but only slightly more N – will regularly come from a "full" reservoir (one in a state of dynamic equilibrium) than would come from the reservoir in its original state.
- Future progress in Bay restoration depends in part on accurately predicting how upstream inputs to the LSRRS will be modulated by reservoir processes. Analysis of historical monitoring data can help constrain new models of how these processes will evolve in the future.
- Initial research on inflow and outflow measures, bathymetry surveys, and spatially explicit sediment quality evaluations to better understand N and P transport to, and fate in, tidal waters under varying flow conditions are underway and should continue.
- Infilling of the Conowingo Reservoir primarily influences particulate nutrient delivery, with negligible influence on fresh water discharge or dissolved nutrient delivery to the Chesapeake Bay system. This is important in the context of nitrogen, which occurs predominantly in the dissolved form. For dissolved N, extreme events are of relatively less concern than the moderate and moderately-high flows that provide the majority of mass over the course of the year. Moreover, and depending heavily on its time of arrival, the N loads from extreme events may have comparatively short residence times in the Bay and may thus contribute in only a minor way to the Bay's N stores and hypoxia.
- During extreme events (i.e., exceptionally large discharges) there is uncertainty as to what fraction of the total load exiting the dam during such events is from the reservoir, relative to what comes in from upstream, and as to how these ratios have changed over time. With or without reservoir infill, loads to the Bay during such events are exceptionally high, and timing is very important. Each event is a case in itself and there

is uncertainty regarding how the state of reservoir bathymetry affects sediment discharge during these extreme events.

- Under low to moderately high flow conditions, it is likely most of the sediment loading from the Susquehanna is trapped (and buried) by processes at or before the ETM. Therefore, the impacts of added fluxes of sediment during these "normal" flow conditions are likely to be primarily important for the upper Bay. Thus, any effects of dredging or other changes to reservoir bathymetry will most likely be localized to the upper regions of the Bay.
- There is significant bypassing of the ETM under very high flow conditions, but when and how much remains to be determined.
- Wind resuspension and sediment focusing into dredged channels and other deep waters redistributes settled particles in the upper Bay.
- Characterizing and parameterizing particle settling speed distributions, and possible changes in these distributions with flow and location, is important.
- The Susquehanna Flats may not be a significant long-term trap for particulate nutrients, though seasonal modulation of nutrient loading may be more important.

Recommendations

Support sustained studies of Conowingo infill that are a combination of monitoring, data analysis, process research, and modeling:
Changes in the functioning of the Conowingo Reservoir system are well documented. There was consensus among workshop participants that forecasting the future performance of the system is a complex challenge that will require multi-disciplinary research and will need to be updated in the future as conditions evolve. There is a need to better understand how the Lower Susquehanna reservoirs influence the delivery of nutrient species and sediments of various size and composition to the Chesapeake Bay. Obtaining such understanding will require sustained efforts that are a combination of monitoring, data analysis, process research, and modeling.

Estimating the impact of Conowingo infill on Chesapeake water quality:
Efforts to model the effects of Susquehanna flow and Conowingo bathymetry on net accumulation in or release of nutrients and sediment from the reservoir should be evaluated based on its ability to "hindcast" the documented declines in net trapping by the reservoir over the past two decades, as inferred from water quality observations and statistical evaluations of past data. To quantify the influence Conowingo infill has on Chesapeake water quality, the following processes must be considered in the Conowingo Reservoir: 1) scour during relatively rare extreme events, e.g., 10 year storm events or greater with flow greater than 11,300 m^3/s (400,000 cfs); 2) scour during moderately high flow events; 3) trapping during low and moderate flows; and 4) biogeochemical nutrient cycling that influence bioavailability in the reservoir sediments, especially under low flow conditions.

High priority science needs on Conowingo infill effects on Bay water quality:
High priority science needs include: 1) continued and enhanced measurements of inflow and outflow of N, P, and sediment (including consideration of the roles of various sediment size fractions); 2) regular bathymetric surveys; and 3) spatially explicit evaluations of the physical, chemical and biological processes occurring in sediment deposits in the reservoirs and the upper Bay to better understand the impact of particulate nutrients from behind the Conowingo Dam on Bay water quality – especially with regard to the location and timing of nutrient remineralization, bioavailability, and burial.

Short-term research and modeling objectives for the next six months:
In the short term (next six months) recommended research and modeling objectives include: 1) provision of better estimates of how sediments scoured from the Conowingo Reservoir partition into reactivity classes that will inform the WQSTM TMDL simulations; 2) provision of better estimates of the C, N, and P content of the sediments scoured from the Conowingo Reservoir that will inform the WQSTM TMDL simulations; 3) provision of improved representation/parameterization of the effects of salinity on sediment phosphorus retention capacity, which will improve the WQSTM ability to represent phosphorus dynamics under scour and non-scour conditions; and 4) development of improved representations of the reservoir reach within the Chesapeake Bay Watershed Model (CBWM) that reflect current and projected relationships of sediment, phosphorus and nitrogen outputs from the reach as a function of inputs (including water inputs) and reservoir bed configurations.

Develop scenario methodology that incorporates both extreme flow events and longer-term trends in Conowingo solids and nutrient loads to Chesapeake Bay:
Investigations of Conowingo infill effects on Chesapeake Bay water quality have focused on a dichotomy of approaches. One approach is represented by scour events such as the January 1996 ice melt or the 2011 Tropical Storm Lee (e.g., Cerco and Noel 2016, Linker et al. 2016). The other approach considers changes in long-term net deposition (e.g., Hirsch 2012, Zhang et al. 2013). In fact, deposition and scour processes often occur simultaneously and both should be considered by management. Design of management scenarios should be reconsidered with an eye towards inclusion of long-term loading trends and extreme flow events. Going forward beyond 2017, a more spatially-resolved model of the reservoir system that simulates a larger suite of physical, chemical, and biological processes is recommended.

Improve representation of reactivity of particulate organic material in Conowingo outflow:
Previous and current management models for the Bay (e.g., Cerco et al. 2010, Cerco and Noel 2016) have allocated particulate organic material from the Conowingo into a refractory, slowly reactive classification (G_2). Particulate phosphorus was additionally split between a refractory organic and a non-reactive mineral form. For deposition to bottom sediments in tidal waters, all

particulate organic material in the water column must be routed into sediment diagenesis model variables. Water column algae are split into a fast reacting labile fraction (G_1), a slowly reactive refractory portion (G_2), and an inert fraction (G_3) according to the classification of Westrich and Berner (1984)[1]. Refractory particulate organic material is routed into G_2 and G_3 classes only. Both the initial allocation of the watershed particulate organic loads and the G-series splits upon deposition to sediments were determined empirically during long-term model calibration and validation (e.g., Cerco and Noel 2004). That is, the allocations and splits provided satisfactory model representation of observed conditions in the water column and observed sediment-water fluxes of DO and nutrients. The allocations and splits might be unrepresentative, however, of extreme events such as mass scour of Conowingo bottom sediments.

Moreover, the management model has recently been revised to include particulate organic matter classes in the water column which correspond directly to the G_1, G_2, and G_3 classes in the bottom sediments. Guidance will be provided by experiments underway to investigate reaction rates of particulate organic material in Conowingo bottom sediments and at the Conowingo outfall (Cornwell, current workshop). Model investigations are also proposed to develop guidance for particulate organic matter classification into classes employed by the Bay model (Fitzpatrick et al., current workshop).

Investigate modeled deposition of particulate organic matter:
Particles, both inorganic and organic, flowing over the Conowingo outfall are largely trapped in the upper Bay's ETM. During extreme flow events, however, particles will break through the barrier imposed by the ETM and penetrate into the mid-Bay before settling into bottom sediments. The location of particulate organic matter deposition influences Bay water quality when the material is respired and mineralized. Respiration consumes DO and mineralized nutrients feed algal production. The location of organic matter deposition in the Bay management model remains to be investigated. This investigation should be conducted and, if possible, model parameters may be adjusted to represent current understanding. Deposition must be examined under typical flow conditions and also under conditions of an extreme flow event.

Investigate allocation of suspended solids into size classes:
The Bay management model (WQSTM) includes a predictive sediment transport model (Cerco et al. 2013). The model considers four particle size classes: fine clay, clay, silt, and sand, and assigns distinct settling velocities to each. The allocation of suspended solids loads at the Conowingo outfall into size classes is derived from the CBWM. Until recently, no significant data were available to validate the splits from the CBWM. Data are becoming available,

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[1] G_1, G_2, and G_3 are assumed mineralization rates of particulate organic material, usually assigned on the basis of laboratory measurements. G_1 material is very labile, or reactive, and is oxidized in a matter of days to weeks; G_2 is refractory but oxidized in weeks to months and G_3 is recalcitrant and relatively inert taking many years to mineralize.

however (Sanford, current workshop). The particle splits employed in the current model should be compared to the available data. Revisions, if necessary, should be conducted to the extent that time allows before the 2017 Midpoint Assessment. Complete recalibration of the WQSTM could be infeasible within the time available, however (Linker, personal communication), in which case this task might be considered as a long-term model improvement.

Support Long-term improvements to the WQSTM:
Going forward, an effort to dynamically link the sediment transport component of WQSTM with the biologically-generated organic carbon, nitrogen, and phosphorus pools from the water-column biogeochemical model in WQSTM would be a significant movement toward first – principal modeling of the transport and fate of organic nutrients in the tidal Bay. In addition, there is need for a more representative model of iron dynamics in the WQSTM, particularly in the upper Bay, that can simulate spatial and temporal variations in iron that relate to sulfur and phosphorus dynamics, and impact the reactivity of reservoir-derived phosphorus in the tidal Chesapeake.

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Appendix A: Workshop Agenda

Scientific and Technical Advisory Committee Workshop

Conowingo Infill Influence on Chesapeake Water Quality

January 13-14, 2016
Crowne Plaza Annapolis Hotel, 173 Jennifer Road, Annapolis, MD 21401
http://www.chesapeake.org/stac/workshop.php?activity_id=249

Workshop Goals

- Given the current state of knowledge based on 1) the past record of observations, 2) first principles which can be used to build simulation models, and 3) the 2017 Midpoint Assessment timeframe, what would be the best approach to modeling the processes by which inputs to the reservoirs are transformed into outputs in past, current, and in future conditions? It is expected that as the science improves the modeling approach will evolve and improve as well, but it is critical that current and future estimates of reservoir infill and outputs be based on the best representation of the processes that can be made at the present time.

- Formulate a plan of study, including field data collection related to mass balance and biogeochemical transformations, as well as experimentation that will improve understanding of the processes at play in these reservoirs. The plan of study also needs to consider the conceptual framework in which the field data are examined to quantify the rates at which the major processes are taking place in the reservoir system.

Day 1: Wednesday, January 13

8:30 Registration, light breakfast (provided)

9:00 Welcome – Ben Grumbles, Secretary of the Environment

9:15 Introduction and Purpose of Workshop – Lee Currey, MDE

Plenary Speaker
9:30 Sedimentation Dynamics of Reservoirs – Gregory Morris, GLM Engineering COOP
A discussion on the world-wide situation of reservoirs that are at or near their sediment storage capacity. What do we know about how they work? What is the state of the science in terms of prediction of changes in their trapping efficiency as they near dynamic equilibrium?

Session I: Introduction and Background

10:00 Findings of the Lower Susquehanna River Watershed Assessment (LSRWA) – Anna Compton, CoE Baltimore District
Key findings of the LSRWA report will be described.

10:20 Net Trapping Efficiency of the Lower Susquehanna Reservoirs – Qian Zhang and Bill Ball, JHU
The use of statistical inference to describe the changing behavior of the system with the fundamental conclusions that net trapping efficiency has declined over the last 15 to 20 years. Long-term changes in nutrient and sediment fluxes from the Lower Susquehanna reservoirs, what this means in terms of trends in total inputs of N and P to the Bay, and thoughts about the potential future trajectory of these inputs. How these questions motivate the need for improved data, process research, and modeling.

10:40 Recent history of the Conowingo Reservoir Infill in the Broader Context of Trends of Nitrogen and Phosphorus Fluxes to the Chesapeake Bay – Robert Hirsch, USGS
Hirsch will present an evaluation of trends in annual average river inputs of total nitrogen and total phosphorus from Conowingo along with inputs to Conowingo and the relationship of these changes to inputs of N and P to the Bay from most of the other major sources. These results will also be viewed from the perspective of changes in the N:P ratio which may have important ecological implications.

11:00 Bathymetric history of the Lower Susquehanna River Reservoir System and History of Scour Events from 1930 to 2015 – Mike Langland, USGS

11:20 How Does the Bay Respond to Large Freshwater Events? – Larry Sanford, UMCES and Carl Friedrichs, VIMS

11:40 Sediment Transport and Deposition in the Upper Chesapeake – Jeff Halka, MD Geological Survey (*retired*)

12:00 DISCUSSION (Moderator: Lee Currey, MDE)
What are fruitful opportunities for future work, particularly as applied to downstream Chesapeake Bay water quality?

12:30 LUNCH (provided)

Session II: Ongoing Lower Susquehanna Reservoir Research, Monitoring, and Modeling

1:30 State of Current Conowingo Monitoring – Bruce Michael, DNR
All aspects of monitoring including inputs of water, nutrients and sediment; nitrogen, phosphorus and suspended sediment in the water column in the reservoirs; sediment storage with associated nutrient storage in the reservoirs, and the outputs of water, nutrients and sediment from the reservoir system to Chesapeake Bay will be described. The presentation includes activities that are part of long-term monitoring programs, such as the Chesapeake Bay Program Non-tidal monitoring network, as well as monitoring efforts initiated over the last couple of years through funding by Exelon.

1:40 Conowingo Monitoring Study – Tim Sullivan/Gary Lemay (Gomez and Sullivan) and Marjie Zeff (AECOM)
Initial results relative to the physical parameters associated with the Conowingo Monitoring Program (e.g., 2013 – 2015 bathymetry results for Conowingo Impoundment, Lake Clarke and Lake Aldred/bulk density results for Conowingo) will be reported. Characterization of the storm events monitored and sampling strategy will also be provided.

2:00 Sediment Composition and Diagenesis – Jeff Cornwell and Jeremy Testa, UMCES
The composition of Conowingo sediments in long and short cores, the estimated reactivity of their organic material, and their estimated biogeochemical fate in tidal water deposition will be described. Measured sediment nutrient flux rates of Conowingo Sediment will be discussed.

2:20 Sedimentation Rates and Patterns – Cindy Palinkas (UMCES)
Conowingo long cores and particle dynamics

2:40 BREAK

2:50 Simulation of the Conowingo and Lower Susquehanna Reservoirs in the Watershed Model – Gopal Bhatt, PSU and Gary Shenk, USGS/CBPO
How does the Phase 6 Watershed Model estimate the outputs of Conowingo water, nutrients, and sediment as a function of their inputs to the reservoir system? What plans are being considered or are being tested to modify this aspect of the watershed model in light of new understanding of the evolving state of the reservoir system?

3:10 ADH Modeling of Conowingo Reservoir – Steve Scott, USACE/ERDC (via webinar)
Quantification of shear stress for scour decreasing with infill

3:30 Lower Susquehanna River Impoundment Modeling Studies Jim Fitzpatrick/Mark Velleux (HDR) and Marty Teal (WEST Consultants)
Presentation on a sediment and nutrient mass balance model of Conowingo Pond as well as enhanced sediment transport models of Lake Clarke and Lake Aldred. The plans and

schedule for completing these models, their current state and potential for integrating with the Phase 6 Watershed model will be discussed.

4:00 DISCUSSION (Moderator: Robert Hirsch, USGS)

How can the data and understanding identified in the previous two sections be best used to characterize how the decline in reservoir storage capacity will change the outputs of nutrients and sediment to the Chesapeake Bay? What monitoring and field studies need to continue to improve this understanding and document the continuing evolution of this system? What improvements should be considered for these monitoring systems and to the analytical frameworks for evaluating that monitoring data? What additional research is needed to enhance the state of the science on the behavior of the reservoir system and how it modulates outputs of nutrients and sediment to the Bay?

5:00 Recess

Day 2: Thursday, January 14

8:00 Light breakfast (provided)

8:30 Welcome, Summary of Day 1, and Comments from Workshop Participants

Session III: Chesapeake Bay Research, Monitoring, and Modeling

8:50 Unexpected Resurgence of a Large Submersed Plant Bed in Chesapeake Bay – Cassie Gurbisz, UMCES
An ecosystem perspective.

9:10 Sediment Nutrient Fluxes in the Tidal Chesapeake Bay – Jeremy Testa and Jeff Cornwell, UMCES
A presentation on environmental controls on sediment-water fluxes in the Chesapeake Bay.

9:30 BREAK

9:45 Circulation, wave and sediment transport in the Chesapeake Bay – Xiaohui Xie, UMCES
New observations in Chesapeake Bay have suggested that wind can drive strong lateral circulation and generate large amplitude internal waves near the seabed. The circulation and wave motions may play a significant role in the lateral transport of nutrients and sediments. A coupled modeling system (COAWST) of Chesapeake Bay is developed to investigate how estuarine circulation and waves affect sediment transport and deposition during storms.

10:10 Representation of Conowingo Infill in the WQSTM – Carl Cerco, USACE/ERDC
What does the existing Water Quality and Sediment Transport Model (WQSTM) of the Bay tell us about the response of the Bay ecosystem to the types of Susquehanna input changes of nutrients, and sediment that we might expect as the trapping efficiency of the reservoir system decreases?

10:40 DISCUSSION (Moderator: Lew Linker, EPA/CBPO)
A discussion focused on how the WQSTM could be improved to better predict the key outcomes associated with changing inputs of nutrients and sediment from Conowingo. What additional research and monitoring should be undertaken to improve the understanding of the linkages and lead to improved modeling? Does current understanding and its representation in the model properly consider the different roles played by inputs of particulate and dissolved organic and inorganic nutrients in their various forms, including sorption to different particle sizes of sediment?

11:30 LUNCH (provided)

12:30 WRAP UP DISCUSSION (Moderator: William Ball, JHU/CRC)

There are many physical, chemical, and biological processes that take place in the reservoirs, in the Bay, and in the sediments that reside in their beds. In order to better evaluate future behavior of the entire system (the reservoirs and the Bay) under a variety of management scenarios that are focused on the Susquehanna River basin and/or its reservoirs, what are the most important questions that need to be answered? The steps needed to answer them may include improvements in the monitoring of the Lower Susquehanna Reservoir system and the Upper Bay in terms of the inputs, changes in storage, and outputs of nutrients and sediment. This includes considerations of what, when, where and how to sample the water column (including particulates and dissolved nutrients and biota) and the bed material (volumes, particle size distribution, chemical composition, and redox state), and how to synthesize the data to improve understanding of the system. Also, what laboratory and theoretical studies should be undertaken to better understand the physical, chemical, and biological processes that control the transport, storage, and transformation of sediment and nutrients through this reservoir/estuary system? In addition to these longer-term science priorities, we need to consider what steps are needed to make the best use of the current state of our understanding to evaluate management decisions that must be made in the next year as a part of the 2017 Midpoint Assessment. In particular, what are the most important improvements that should be made to the suite of models (watershed and Bay) in order to better predict how the reservoir system will modulate inputs of nutrients and sediment into outputs and how these outputs will affect the achievement of the TMDL goals in the Bay?

2:00 Adjourn

Appendix B: Workshop Participants

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Appendix C: Presentation Summaries and Links to Presentations

Plenary Session

Sedimentation Dynamics of Reservoirs – Gregory Morris, GLM Engineering COOP.
Morris described and gave international examples of the 1) variability of sediment transport over time, 2) the geomorphic evolution of reservoirs, 3) the changes in depositional patterns and resulting changes in reservoir geometry, and 4) management options for sediment in reservoirs.
http://www.chesapeake.org/stac/presentations/249_Morris%20Conowingo.pdf

Session I: Introduction and Background

Key Findings of the Lower Susquehanna River Watershed Assessment (LSRWA) – Anna Compton, **USACE Baltimore District**.
The LSRWA goals were to 1) determine Bay health effects due to the loss of Conowingo trapping capacity, 2) describe the sediment and associated nutrient transport effects during high flow storm events, and 3) evaluate sediment and associated nutrient load reduction strategies
http://www.chesapeake.org/stac/presentations/249_Compton_LSRWASTAC13Jan2016.pdf

Net Trapping Efficiency of the Lower Susquehanna Reservoirs – Qian Zhang and Bill Ball, **Johns Hopkins University**.
The Susquehanna River, the bay's largest tributary, has drawn attention because SS loads from behind Conowingo Dam (near the river's mouth) have been rising dramatically. To better understand these changes, we evaluated histories of concentration and loading (1986–2013) using data from sites above and below Conowingo Reservoir. First, observed concentration-discharge relationships show that SS and TP concentrations at the reservoir inlet have declined under most discharges in recent decades, but without corresponding declines at the outlet, implying recently diminished reservoir trapping. Second, best estimates of mass balance suggest decreasing net deposition of SS and TP in recent decades over a wide range of discharges, with cumulative mass generally dominated by the 75~99.5th percentile of daily Conowingo discharges. Finally, stationary models that better accommodate effects of river flow variability also support the conclusion of diminished trapping of SS and TP under a range of discharges that includes those well below the literature-reported scour threshold. Overall, these findings suggest that decreased net deposition of SS and TP has occurred at sub-scour levels of discharge, which has significant implications for the Chesapeake Bay ecosystem.
http://www.chesapeake.org/stac/presentations/249_ZhangBall_v2.pdf
Link to paper: <http://pubs.acs.org/doi/abs/10.1021/acs.est.5b04073>

Recent history of the Conowingo Reservoir Infill in the Broader Context of Trends of Nitrogen and Phosphorus Fluxes to the Chesapeake Bay – Robert Hirsch, USGS
Hirsch presented an evaluation of trends in annual average river inputs of total nitrogen and total phosphorus from Conowingo along with inputs to Conowingo and the relationship of these changes to inputs of N and P to the Bay from most of the other major sources.
http://www.chesapeake.org/stac/presentations/249_Hirsch_Conowingo%20Workshop_rev.pdf

Bathymetric history of the Lower Susquehanna River Reservoir System and History of Scour Events from 1930 to 2015 – Mike Langland, USGS

A comprehensive history of Conowingo infill was described. The historical context to transported sediment loads into and out of the reservoirs of the lower Susquehanna was provided And major influences on sediment load transport were discussed. The loss of the Conowingo Reservoir sediment storage capacity (SSC) over time was quantified.
http://www.chesapeake.org/stac/presentations/249_Langland%20STAC_Res_mtng_1-2016_new.pdf

How Does the Bay Respond to Large Freshwater Events? – Larry Sanford, UMCES and Carl Friedrichs, VIMS

http://www.chesapeake.org/stac/presentations/249_SanfordSTACConowingoPresentation011316.pdf

Sediment Transport and Deposition in the Upper Chesapeake – Jeff Halka, MD Geological Survey (retired)

http://www.chesapeake.org/stac/presentations/249_Halka%20STAC%201-13-16.pdf

Session II: Ongoing Lower Susquehanna Reservoir Research, Monitoring, and Modeling

State of Current Conowingo Monitoring – Bruce Michael, MD Department of Natural Resources.

All aspects of monitoring including inputs of water, nutrients and sediment; nitrogen, phosphorus and suspended sediment in the water column in the reservoirs; sediment storage with associated nutrient storage in the reservoirs, and the outputs of water, nutrients and sediment from the reservoir system to Chesapeake Bay will be described. The presentation includes activities that are part of long-term monitoring programs, such as the Chesapeake Bay Program Non-tidal monitoring network, as well as monitoring efforts initiated over the last couple of years through funding by Exelon.
http://www.chesapeake.org/stac/presentations/249_Michael_STAC%20Conowingo%20Infill%20Workshop%201%2013%2016_Final.pdf

Conowingo Monitoring Study – Tim Sullivan/Gary Lemay, Gomez and Sullivan and Marjorie Zeff, AECOM.

Initial results relative to the physical parameters associated with the Conowingo monitoring program, e.g., 2013 – 2015 bathymetry results for Conowingo Reservoir, Lake Clarke and Lake Aldred and bulk density results for Conowingo, were described. Characterization of the storm events monitored and the sampling strategy was also discussed.
http://www.chesapeake.org/stac/presentations/249_Conowingo%20Monitoring%20Study%20-%2001.13.2016%20[FINAL].pdf

Sediment Composition and Diagenesis – Jeff Cornwell and Jeremy Testa, UMCES.
The composition of Conowingo sediments in long and short cores, the estimated reactivity of their organic material, and their estimated biogeochemical fate in tidal water deposition was described and measured sediment nutrient flux rates of Conowingo Sediment was discussed.
http://www.chesapeake.org/stac/presentations/249_Cornwell%20STAC%20Meeting%20FINAL.pdf

Sedimentation Rates and Patterns – Cindy Palinkas, UMCES.
http://www.chesapeake.org/stac/presentations/249_STAC16_palinkas.pdf

Simulation of the Conowingo and Lower Susquehanna Reservoirs in the Watershed Model – Gopal Bhatt, PSU and Gary Shenk, USGS/CBPO.
Initial Phase 6 Watershed Model estimates of the outputs of Conowingo water, nutrients, and sediment as a function of their inputs to the reservoir system were presented as well as the plans to modify the Phase 6 Conowingo infill simulation in light of new understanding of the evolving state of the reservoir system.
http://www.chesapeake.org/stac/presentations/249_20160113%20-%20BHATT%20-%20Simulation%20of%20the%20Conowingo%20and%20Lower%20Susquehanna%20Reservoirs%20in%20Phase%206.pdf

ADH Modeling of Conowingo Reservoir – Steve Scott, USACE/ERDC (via webinar).
The key points of Scott's ADH model presentation were his findings that:

- Reservoir capability to store sediments was at a maximum after construction in the 1920's.
- Over time sedimentation changed the hydrodynamics of the Conowingo Reservoir.
- As the reservoir becomes shallower velocities increase.
- Increased velocity results in higher bed shear stress and scour potential.
- Turbulence increases at lower discharges increasing sediment transport.

http://www.chesapeake.org/stac/presentations/249_Scott_Conowingo.pdf

Lower Susquehanna River Impoundment Modeling Studies – Jim Fitzpatrick, Mark Velleux, HDR and Marty Teal, WEST Consultants.
A sediment and nutrient mass balance model of Conowingo Pond as well as enhanced sediment transport models of Lake Clarke and Lake Aldred were described. The plans and schedule for completing these models, their current state and their potential for integrating with the Phase 6 Watershed Model were discussed.
http://www.chesapeake.org/stac/presentations/249_LSR%20Impoundment%20Modeling%20Studies%20-%2001.13.2016%20[FINAL].pdf

Session III: Chesapeake Bay Research, Monitoring, and Modeling

Unexpected Resurgence of a Large Submersed Plant Bed in Chesapeake Bay – Cassie Gurbisz, UMCES.
http://www.chesapeake.org/stac/presentations/249_Gurbisz_conowingo_meeting.pdf

Sediment Nutrient Fluxes in the Tidal Chesapeake Bay – Jeremy Testa and Jeff Cornwell, UMCES.
A presentation on environmental controls on sediment-water fluxes in the Chesapeake Bay.
http://www.chesapeake.org/stac/presentations/249_Testa_Bay_Sediment%20Fluxes_Final.pdf

Circulation, wave and sediment transport in the Chesapeake Bay – Xiaohui Xie, UMCES.
New observations in Chesapeake Bay have suggested that wind can drive strong lateral circulation and generate large amplitude internal waves near the seabed. The circulation and wave motions may play a significant role in the lateral transport of nutrients and sediments. A coupled modeling system (COAWST) of Chesapeake Bay is developed to investigate how estuarine circulation and waves affect sediment transport and deposition during storms.
http://www.chesapeake.org/stac/presentations/249_Xie_Circulation%20wave%20and%20sediment%20transport%20_xxh.pdf

Representation of Conowingo Infill in the WQSTM – Carl Cerco, USACE/ERDC.
The Conowingo Reservoir is situated at the lower terminus of the Susquehanna River watershed, immediately above Chesapeake Bay. Since construction, the reservoir has been filling with sediment to the point where storage capacity is nearly exhausted. The potential for release of accumulated sediments, organic matter and nutrients, especially through the action of storm scour, causes concern for water quality in Chesapeake Bay. We used hydrodynamic and eutrophication models to examine the effects of watershed loads and scour loads on bay water quality under total maximum daily load conditions. Results indicate that increased suspended solids loads are not a threat to Bay water quality. For most conditions, solids scoured from the reservoir settle out before the season during which light attenuation is critical. The organic matter and nutrients associated with the solids are, however, detrimental. This material settles to the estuary bottom and is mineralized in bed sediments. Carbon diagenesis spurs oxygen consumption in bottom sediments and in the water column via release of chemical oxygen demand. The nutrients are recycled to the water column and stimulate algal production. As a result of a scour event, bottom-water dissolved oxygen declines up to 0.2 g m^{-3} although the decline is 0.1 g m^{-3} or less when averaged over the summer season. Surface chlorophyll increases 0.1 to 0.3 mg m^{-3} during the summer growing season.
http://www.chesapeake.org/stac/presentations/249_Cerco_011416.pdf

Appendix D: Additional Resources

- ERDC report: "Sediment Transport Characteristics of Conowingo Reservoir" http://dnr.maryland.gov/bay/lsrwa/docs/report/appb.pdf

- Langland, M., E. Koerkle. 2014. Calibration of a One-Dimensional Hydraulic Model (HEC-RAS) for Simulating Sediment Transport through Three Reservoirs, Lower Susquehanna River Basin, 2008-2011. U.S. Army Corps of Engineers.

- Palinkas, C.M., J.P. Halka, M. Li, L.P. Sanford, P. Cheng. 2014. Sediment deposition from tropical storms in the upper Chesapeake Bay: Field observations and model simulations. Continental Shelf Research 86: 6-16.

- STAC Review of the Lower Susquehanna River Watershed Assessment (LSRWA) Report http://www.chesapeake.org/stac/stac_rw_details.php?activity_id=247