Scientific and Technical Advisory Committee:

Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM) Review

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STAC Review Report

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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in numerous 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

This report presents the findings of the Scientific and Technical Advisory Committee (STAC) review of the 2017 version of the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM). The intent is to determine the model's scientific credibility and utility for use in the 2017 Mid-Point Assessment of the Chesapeake Bay Total Maximum Daily Load (TMDL). The review is based on all material received from the US EPA Chesapeake Bay Program Office (CBPO) between May and September of 2017, including reports, PowerPoint presentations, and previously published literature publications. To guide the panel's review, a set of questions were provided by the CBPO (Appendix A). This report is organized around answering each of those questions and providing recommendations for each topic.

In general, the approaches taken and changes made to the 2010 version of the model (Cerco et. al. 2010) were judged to be sufficiently scientifically defensible and appropriate for preliminary application for the Mid-Point Assessment. The panel's main findings and recommendations are summarized below in this Executive Summary; more detail on each topic is presented in the body of the report.

- **Question #1:** The documentation in the draft of the report the panel received in May 2017, (Cerco and Noel 2017; see Appendix B for link) was not well organized and was incomplete. Although subsequent review material received by the panel filled in many of the gaps, the panel's recommendation is to combine all the material into a single updated and improved documentation report.
- **Question #2:** The representation of organic matter in the water column to more easily couple pelagic and benthic organic matter cycling is appropriate and defensible. The ability of the new model to accommodate more refractory sources of organic matter (shoreline erosion and Conowingo dam scour loads) is commendable; however, we recommend an analysis of the residuals between the 2010 model and current model version to determine if the new formulation significantly shifts organic matter cycling spatially in the Bay (that is, does the new formulation change the spatial distribution of organic matter diagenesis in the Bay?)
- **Question #3:** The WQSTM review panel agrees that the Conowingo Reservoir is rapidly approaching or has effectively reached a state of "dynamic equilibrium," wherein the sediment loads entering the reservoir are now balanced by the sediment loads leaving the reservoir over decadal time scales – i.e., the reservoir is now effectively a "pass-through" for sediment (and associated particulate nutrient loading over these time scales. On the other hand, however, a substantial portion of the decadal-scale loading can occur during a few especially large scour events, the simulation of which can affect model calibration and simulated effects. In this regard, the review panel understands that the Phase 6 Watershed Model (WSM) model has been modified based on the CBP's best current understanding of declining reservoir performance due to reservoir infilling (see **Table B-1** in Appendix B for

link) and that the current modeling of the Conowingo loads is satisfactory for use in the mid-term. However, the panel had difficulty following details of that analysis and believes that modeling improvements are likely to be needed in the future. The panel therefore recommends further review and refinement (if necessary) of this aspect of the model after better documentation has been developed and well before the intended 2025 implementation. In the short term, the panel recommends compiling and publishing more complete documentation on how the simulation of Conowingo Reservoir in the current WSM uses Weighted Regression by Time, Discharge, and Season (WRTDS) interpretations and the recently reviewed Lower Susquehanna River Reservoir System Model Enhancement study (Ball et al. 2017) to simulate infill. The panel also recommends a more complete documentation of the results of sensitivity analyses on the impacts of increased loadings of organic matter – especially nitrogen – that could be associated with intra-decadal scour events. Moreover, the panel also recommends continued long-term attention to this question as more data become available about the amount and nutrient/OM content in both "pass-through" and scoured sediments.

Finally, and as a separate issue, the panel also wishes to go on record as supporting the previous conclusion of the Lower Susquehanna River Watershed Assessment (LSRWA) (USACE 2015) that direct nutrient management and mitigation in the watershed are likely to be much more effective at long-term reductions of nutrient load than would be the management of reservoir sediments.

- **Question #4:** The approach taken for assessing the impact of future sea level rise (SLR) is appropriate for preliminary application. The results showing that SLR reduces hypoxia are in general agreement with those obtained in previous studies (Irby et al. 2017); however, there is an inconsistency in the impact of SLR on upper Bay bottom salinity estimates between the current simulation and previously published literature. The review panel recommends further investigation as to the cause of this inconsistency.
- **Question #5:** The approach taken for estimating the impacts of future temperature changes on summer hypoxic volume in Chesapeake Bay is satisfactory for preliminary application. However, the Panel has some reservations about the climate change modeling protocol for long-term management use. Climate linked processes and metrics should be reexamined (e.g., oxygen solubility, phytoplankton growth rate-temperature relationships, and metrics for the characterization of hypoxic volume). In addition, the review panel notes that the relatively small increase in hypoxic volume due to warming temperatures may result from an underestimate of the increase in bottom water temperature between the 1990s and 2050 – the increase of ~0.5-0.8 °C that was assumed to occur over this time period is considerably lower than previously published estimates and may not properly reflect some sources properly, such as ocean warming at the mouth.
- **Question #6:** The review panel agrees that new additions to the wetland module, while relatively simple, are useful. Although initial results suggest that wetland loss is not a

concern for impacts on water quality standards attainment (i.e., oxygen concentrations), the panel questions whether the SLAMM (**S**ea **L**evel **A**ffecting **M**arshes **M**odel) approach is necessarily an accurate approach for assessing the impacts of wetlands loss in shallow waters. In particular, the CBP should give serious consideration to the issue of whether SLAMM accurately simulates net gains and losses of marsh land. In the future, a more mechanistic and dynamic treatment of wetland accretion and erosion may be helpful, and it would be more useful to consider the difference of various wetland types in regard to ecological consequences.

- **Question #7:** The review panel concurs that the proposed approaches for estimates of shoreline erosion nutrient loads and nutrient attenuation by tidal wetlands are defensible and appropriate for the Mid-Point Assessment. On the other hand, however, the panel is not comfortable answering the question of whether the approaches offer an "improved representation" of shallow-water dynamics because of remaining concerns with some aspects of the model, particularly as related to the assumption of uniform sediment composition, incomplete model-data comparisons, and at least one known concern relating to model fit to data. Model improvement should focus on capturing particulate phosphorus transformations and forms from adjacent land use type. The review panel also notes that in the future a higher resolution model may be needed, since in the upstream reaches of the Chester River, the current model formulation does not accurately reproduce the upstream salinity gradient. Conservative physical variables such as salinity should be accurately modeled before the shallow water quality simulations can be improved in regard to other aspects of biogeochemistry.
- **Question #8:** The limitations of the estimation of oyster biomass and their impact on water quality appear to be mainly due to data limitations. The oyster module appears to use the best and most freely available data for estimating the oyster populations among natural reefs, sanctuaries, and aquaculture leases. The approach for parameterizing factors in the model is certainly defensible, especially given the apparent lack of detailed information on farm sites and culture practices. Conclusions of Cerco and Noel (2007) align well with several other studies that suggest oyster beds (e.g., sanctuaries and wild stocks) can have a meaningful impact on water quality in Chesapeake Bay but that point and non-point sources of nitrogen must be reduced to curb system-wide eutrophication.

Although the panel accepts the model for use in the 2017 Mid-Term Assessment, there are multiple modifications and updates that must be made as soon as possible, to ensure that an improved estuarine model can be successfully recalibrated and its key elements introduced and reviewed in time for its use to re-compute the Chesapeake Bay TMDL in 2025. These model modifications are listed below.

- Given that improved understanding of "transient" loads both into and out of the reservoir can be an important factor in both WSM and WQSTM calibration, the panel recommends that the CBP consider the possibility of future need for improved modeling of the Lower

Susquehanna River Reservoir System (LSRRS) and other major reservoir systems in the watershed. This can be done through synthesis and incorporation of new knowledge being generated by the on-going Exelon-supported studies as well as through other on-going and future efforts of monitoring, data analysis, model development, model sensitivity analysis, and experimental research.

- To better simulate the future impacts of SLR on Chesapeake Bay, the review panel strongly suggests the outer boundary of the model should be moved offshore to the continental shelf. This may solve some critical issues with the current modeling framework, such as the small impacts on bottom salinity in the upper Bay due to SLR. The panel also strongly recommends that the CBP consider other methods (such as use of an unstructured grid or nesting methods) for better handling the outer boundary within the next generation model. Finally, the panel strongly advises the inclusion of methods for simulating coastal wetting/drying processes to allow for consideration of impacts from SLR inundation of the coastline and its wetlands.
- The panel recommends that the impact of climate change on the Chesapeake Bay include specification of the full range of dissolved oxygen (DO) in the Chesapeake Bay Program's assessment of water quality standards – i.e., DO concentrations up through 5 mg O_2 L^{-1}, as well as chlorophyll and water clarity where appropriate (for example, see https://www.chesapeakebay.net/content/publications/cbp_51366.pdf). The panel also suggests examining the impacts of climate change throughout the full year, not just in the summer, and suggests that expert phytoplankton ecologists review the current algal temperature-growth formulations in order to ensure they encompass growth rates of new groups that might arise in the future.
- The review panel recommends that model phosphorus (P) dynamics be refined, with particulate inorganic phosphorus (PIP) no longer being treated as inert particulate matter. It contains bioavailable P from gradient-driven desorption in the water column as well as diagenesis in the sediments when they deposit.
- Finally, the panel strongly recommends that, in the future (and particularly as related to model review for the final 2025 TMDL Assessment), the CBP Modeling Team must finalize sensitivity analyses and calibrations before subjecting models to external review in regard to questions relating to "appropriateness of approaches" for management application. By contrast, however, even earlier review of new model components is encouraged in regard to scientific review of the fundamental principles used, the conceptual bases for approaches taken, technical details of methodology, and model skill assessment. Separate smaller reviews of each element would be a productive approach.
- To assist with these analyses, the panel recommends that the CBP assemble a small advisory group to focus on establishing a plan for the continuing development and improvement of the WQSTM over the next several years. The panel further notes the importance of having the next generation WQSTM recalibrated and revised in the next few years, and subjected to a follow-up technical review well in advance of the 2025 TMDL recalculations.

Scientific and Technical Advisory Committee Panel Report: Chesapeake Bay Water Quality and Sediment Transport Model 2017 Review

Introduction

This report presents the findings of the Scientific and Technical Advisory Committee (STAC) review of the 2017 version of the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM). The intent is to determine the model's scientific credibility and utility for use in the 2017 Mid-Point Assessment of the Chesapeake Bay Total Maximum Daily Load (TMDL). The review is based on all documentation materials received from the Chesapeake Bay Program Office (CBPO) between May and September of 2017, including reports, PowerPoint presentations, and published manuscripts. To guide the panel's review, a set of questions were provided by the CBPO (Appendix A). This report is organized around answering each of those questions and providing recommendations for each topic.

Summary of Documentation and Resources Provided to the Panel

The primary documentation material provided by the CBPO includes:

- An initial summary document by C. Cerco and M. Noel entitled "The 2017 Chesapeake Bay Water Quality and Sediment Transport Model: A Report to the US Environmental Protection Agency Chesapeake Bay Program (May 2017 Draft)" (Cerco and Noel 2017; link provided in Appendix B of this STAC Review Report);
- Appendices to the above report (link provided in Appendix B of this STAC Review Report);
- Several published manuscripts provided by the CBPO as "resource materials." These resources are listed in the "Peer Review Panel Charge and Questions" (Appendix A); and
- Four different sets of PowerPoint presentations that were given at four meetings held between June 6, 2017, and August 9, 2017 – see **Table 1**. Table 1 also lists a fifth presentation on October 17, 2017, that was not considered to be officially within the purview of this review because of its timing – see footnote to Table 1. Links to the presentations at all five meetings can be found in **Table B-1** in Appendix B of this STAC Review report.

Preliminary Remarks from the Panel

The panel found this review especially challenging to conduct because the finalized full 2017 Mid-Point Assessment WQSTM system (including all aspects of land use scenarios and watershed modeling) had not been completed at the time of the review. In fact, final calibration of the model (under the most updated input conditions for key scenarios) had still not been completed by late October, 2017, whereas this report was principally written in early October and finalized in November, 2017. In this regard, only one member of the team (M. Friedrichs) was able to attend a presentation of the "final calibration" results presented by Chesapeake Bay Program Partnership's Modeling Team to the CBP's Modeling Workgroup (MWG) on October 29, 2017, and this panelist also gleaned final information from another related presentation given by Cerco et al. at a meeting of the Coastal and Estuarine Research Federation (CERF) meeting in November, 2017 (Cerco et al. 2017).

In contrast, the last documentation reviewed by most members was associated with the presentations made by the Modeling Team to the MWG on August 9, 2017, which included "interim" calibration of the WQSTM to "key scenarios" using the version of the Phase 6 Watershed Model (WSM) available at that time.

Overall, it is important to appreciate that most of the reviewers on the panel were unable to give full consideration to the final WQSTM calibration results, which included new WSM assumptions about land use changes and Conowingo Pond performance; these were presented to the MWG on October 29, 2017 and were not ready in time for full consideration by the entire panel. This is of importance because such calibration is relevant to the "appropriateness" of model application to management. On the other hand, however, the panel notes that interim calibrations were in fact considered and, based on what it has learned, the panel does not think the final calibration results would affect the conclusions and comments on the conceptual and mechanistic aspects of the model.

Within the above context, the panel emphasizes that the review would have been far more efficient and complete if the full effort (including final calibration) and documentation had been completed in advance of the review, and if more time had been given for the review after the final presentation of modeling results. The panel strongly recommends that, in the future (and particularly as related to model review for the final 2025 TMDL Assessment), the Modeling Team must finalize sensitivity analyses and calibrations before subjecting models to external review in regard to questions relating to "appropriateness of approaches" for management application. By contrast, however, even earlier review of new model components is encouraged in regard to scientific review of the fundamental principles used, the conceptual bases for approaches taken, technical details of methodology, and model skill assessment. Separate smaller reviews of each element would be a productive approach.

Table 1. Information sessions held by the Chesapeake Bay Program (CBP) partnership's Modeling Workgroup that were especially relevant to this review. Links to the presentations at all five meetings can be found in **Table B-1** in Appendix B of this report.

Information Session	New Information Provided
June 5-6. Initial WQSTM Information Session for WQSTM Review Panel (In-person meeting of review panel. One reviewer could only attend on June 6 for special briefing by CBPO)	Primary documentation explained.
July 7. Follow-up Information Session for WQSTM Review Panel (webinar); 7 of 8 reviewers in attendance; all saw materials)	Explanation of model use of G1,G2, G3 organic matter fractions; Comparison of 2010 and 2017 WQSTM results using WSM Phase 5.3 inputs
July 25. Summer CBP Modeling Workgroup Quarterly Review Part 1 (2 of 8 reviewers in attendance; all saw materials)	Phase 6 watershed model application to Conowingo (Bhatt and Shenk); Conowingo Exelon-Sponsored Model Findings (Sullivan and Michael)
August 9. Summer CBP Modeling Workgroup Quarterly Review, Part II (4 of 8 reviewers in attendance; all saw materials)	Interim Calibration of WQSTM to "key scenarios" w/ Phase 6 Watershed Model; Sensitivity scenarios w/ 2050 Sea Level Rise
October 17.* Fall CBP Modeling Workgroup Quarterly Review (7 of 8 did not see these materials prior to write-up.*)	Final WQSTM Calibration Selection based on Finalized Phase 6 Inputs (including modifications relating to Conowingo Dam; Run 223 Time series (1991-2000)

* Due to issues of timing, the information conveyed at the October 17, 2017 Modeling Workgroup Meeting was outside the purview of this review. It was attended, however, by the review coordinators (William Ball and Rachel Dixon of CRC) and by the STAC liaison to this review (Marjorie Friedrichs), all of whom relayed some the contents to the other members of the review panel

Review Panel Responses to Charge Questions

Question 1: "Please comment on the WQSTM documentation. Is it clear, well organized, and complete (taking into account that it is largely based on the fourth Beta release of Phase 6 Watershed Model and 4 months ahead of final release)?"

The review panel is working under the assumption that Question 1 refers to the provided single WQSTM documentation report that describes the 2017 model being applied for the Mid-Point Assessment of the Total Maximum Daily Load (TMDL). The review panel understands that the draft of the report documentation (dated May 2017; link in Appendix B) was preliminary and was subsequently supplemented through presentation material (see **Tables 1 and B-1**). The panel strongly believes, however, that an improved "final" documentation report should be provided and that this report should reflect a thorough description of the 2017 model. This report would be for use by the general scientific community and especially by the resource managers and policymaker's staff in assessing this tool. Therefore, that report should give a thorough explanation and justification of the changes/simplifications (including evidence that simplifications will not affect the management decisions it supports) made to the 2017 model relative to the previous model version. Note that the panel applauds simplification of model structure where appropriate; however, it will be important to document for model end users that a given simplification does not substantively reduce model skill and thereby reduce reliability of model outcomes.

Based on the above considerations, the comments below focus on how the panel believes that the May 2017 WQSTM draft report should be edited and amended to include content that was provided to the panel only verbally and/or in PowerPoint Presentation format. The objective is to thus provide a complete documentation of the 2017 model in one cohesive report.

The report should be revised to include the following suggestions:

- Please add a Table of Contents, List of Figures, and List of Tables to the document.
- The introduction should include a discussion of the stated use of the 2017 model version for management support relative to the potential research value of previous versions of the model. The Panel recognizes two broad uses for process models like the Chesapeake Bay WQSTM: 1) providing input information to support management/policy decision making (e.g., by addressing specific questions posed by system managers); and 2) serving as an important platform for data synthesis and analysis, hypothesis formulation and examination of research questions being posed by the research and management community. Some models can accomplish both, and we think the Bay model has done that reasonably well over the years. However, it seems that this last round of changes has focused more on the management use, potentially at the expense of the research use. *Given the need for a mid-term TMDL review, we understand the management focus.* Nevertheless, our comments on each of the process formulation and parameterization

changes that we are charged with reviewing will address our thoughts on both uses. It is possible that some changes may enhance or expedite (or at least not affect) the addressing of management questions, but that they may detract from the model's ability to support the research community. For example, while it appears that removing the zooplankton biomass sub-model will not impact the nutrient load allocation question, this change may prevent the model from addressing upper-food-web research questions. The report should at least provide evidence that each change/simplification, such as the removal of the zooplankton state variable, will not lead to a meaningful change in the management decisions relative to the TMDL.

- The review panel recommends that the report have a separate chapter reporting on the methods and results for testing the impacts of increased temperature, climate related changes in riverine inputs, and sea level rise (and associated tidal wetland loss) to the TMDL endpoints (dissolved oxygen-DO, chlorophyll a, and clarity). A discussion of whether the TMDL will likely need to be adjusted to account for these responses would be helpful. The review panel's thoughts on these issues are presented in the answers to the relevant review questions. The panel suggest that much of the content of this chapter can be drawn from Wang et al. (2017).
- Chapter 2 should contain a more detailed description of the G1, G2, G3 changes in the model and a graphic presentation of how the change affected the model output, especially the TMDL endpoints.
- The panel recommend that the report contains a separate section, preferably in the loading chapter, devoted to describing the analyses performed on understanding the extent and effects of sediment filling the reservoir behind the Conowingo Dam, including how this filling changes the loading from the Lower Susquehanna and how that affects or does not affect the short- and long-term responses of DO, chlorophyll a, and clarity in the Bay.
- The report should include a chapter on the transition of the oyster biomass representation in the model and its potential impact on water quality standards in the Bay. There is one paragraph in the introduction, but no analysis of how the oyster module has been updated from the 2010 to the 2017 model.
- The panel recommends inclusion of a concluding chapter that presents a summary of the improvements in the 2017 model for use in supporting the Mid-Point TMDL. This chapter should also present the plans (and/or results) for the application of the model for TMDL support.
- The panel recommends that the CBP provide the WQSTM model output online in a common data format (e.g., netCDF on a THREDDS server) so the research community has easy access to these results. Although the CBPO has an excellent history of providing model output upon request, the unusual format of the output currently makes it difficult for researchers to use.

- In the above context and also in regard to other topics not specifically noted above, the panel would advise incorporating the updated and informative information presented in PowerPoint presentations subsequent to the May 2017 report (see **Table 1**) into the final documentation.

Question #2 "Please comment on the overall appropriateness of the approach taken in the application of G1, G2, and G3 organic behavior in the water column and sediment of the WQSTM (as described in the Beta 3 WQSTM Documentation. Is the applied approach appropriate? What could be done to improve the representation of the various organic decay rates in the WQSTM?"

It is entirely scientifically appropriate and defensible to expand the classes of organic material in the water column of the CBWQSTM to include a completely refractory class (hereafter referred to as G3). For many years, the sediment flux model linked to the water column model has already treated organic matter as three distinct classes based on reactivity. The motivation behind making the water column and sediment flux models more consistent was the introduction of shoreline erosion loading. Briefly, the introduction of shoreline erosion organic matter loading exceeded 11% of the total load, which substantially changed model-observation comparisons. Model developers determined that much of the shoreline erosion loading was very refractory as it had been processed for some time before eroding into the bay.

In assessing the parameters added to the model as a result of this change, most processes affecting the production (metabolism) and consumption (hydrolysis) have been set to 0 and therefore do not have a substantive effect on organic matter cycling (only insofar as this class is a way of effectively removing organic matter from the model). Three parameters associated with G3 organic matter are non-zero: the fraction of carbon, nitrogen, and phosphorus funneled to the G3 organic matter pool after predation (consumption of phytoplankton by grazers) has been set to 5, 3, and 1%, respectively. One recommendation of the panel is to explain how these values were determined. These values do not represent a substantial fraction of the organic matter pool and the fraction of organic matter that ends up in this pool likely quickly settles to the sediment (since it cannot be hydrolyzed while in the water column). The only potential concern is that this model formulation can change the overall fraction of organic matter that is bioavailable. For example, the total nitrogen load from shoreline erosion and Conowingo infill scour will be heavily influenced by the proportion attributed to these reactivity classes. Long-term studies of organic matter decay from these various sources are only beginning to become available. The panel encourages the CBP to revisit this topic as more long-term degradation experiments shed light on the bioavailable content of these sources. Finally, assessment of this change in the model was difficult because there is no systematic comparison of the model with and without G3 reactivity in the water column. That is, even if the pool of bioavailable organic matter has not changed significantly, there is a question of whether this formulation changes the spatial variability in organic matter cycling, accumulation, and processing. This model experiment could be performed assuming shoreline erosion is minimal or only using G1 and G2 shoreline erosion loading. Long term, the CBP should also consider whether, with 30+ years of model output becoming the norm, to include a longer-term reactivity class in between G2 and G3.

Question #3 "Given the current state of modeling, research, and monitoring on the increased net transport of nutrients and sediment out of the Lower Susquehanna reservoir system, please comment on the scientific rigor of the WQSTM approach used to represent the increased nutrient and sediment loads on Chesapeake water quality standards of DO, chlorophyll, and clarity/SAV. Is the representation of nutrients and sediment under all states of flow, including moderate and extreme flow events, sufficiently well simulated for the condition of reservoir infill?

The review panel concurs with the CBP that there are multiple lines of evidence indicating that the Conowingo Reservoir is already very close to a state of "dynamic equilibrium," wherein the sediment loads entering the reservoir are balanced by the sediment loads leaving the reservoir over a decadal time frame. Consequently, while the reservoir has historically been a significant sink for sediment (and associated particulate nutrient loading), it is appropriate, for purposes of allocation modeling, to now treat it essentially as a "pass-through" for upstream loading.

The panel notes, however, that the Susquehanna at Conowingo can accumulate delivered sediments during lower flows and then deliver especially high loads (and even in excess of reservoir input) during especially high 'scour flows.' Under these circumstances loading comprises a combination of scoured sediment plus already high pass-through loads. What constitutes 'scour flows' is, however, difficult to determine and is perhaps changing over time. While prior analyses (Langland 2015; Cerco 2016) indicated that scour flow could be defined as greater than 11,300 m^3/s, there have been statistical analyses that contend that flows as low as ~5,000 m^3/s may now be causing sediment and nutrient loads higher than those observed in prior decades (Hirsch 2012; Zhang et al. 2016). Better understanding and *in situ* measurement of the scour relationship is important, because the return period for any given flow event gets significantly shorter for decreasing flow level – for example, Langland (2015) has reported a 2-3 year return period for a 9,400 m^3/s event versus 5 years for a 11,300 m^3/s event.

Interestingly, WQSTM model results from the above-described effects indicated minimal direct impact on Bay clarity from the increase in suspended sediment loading. The conclusion of the modeling team is that Submerged Aquatic Vegetation (SAV) on Susquehanna flats immediately downstream from the Conowingo Dam plays a significant role in dampening the impact of suspended sediment loading. There is a very large immediate increase in light attenuation that occurs after the scoured load enters the Bay (almost 10 m^{-1}) which quickly decreases on a timescale of days-weeks. The panel appreciates this evidence to suggest that the LSRRS sediment loading may not be a large issue in regard to long-term water clarity in the Chesapeake

Bay. Nonetheless, however, significant scour of reservoir sediments from the Susquehanna occurs for short periods of time at flows above 11,300 m^3/s (400,000 cfs), and the long-term impacts on the Susquehanna Flats are not yet well understood. This is an issue that should stay "on the radar" for future consideration.

Perhaps more importantly, the modeling results to date suggest that increased loads of organic matter and nutrients will have an impact, estimated as a 0.1-0.2 mg/L decline in bottom DO (Cerco and Noel 2016). In this regard, it is clear to the panel that large inputs of organic matter and nutrients associated with the solids are potentially detrimental to Bay health in the long term. As reasonably simulated through the 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 was shown to declines by up to 0.2 mg/L, although the computed decline was 0.1 mg/L or less when averaged over the summer season (Cerco and Noel 2016). Given this potential impact, the panel recommended that sensitivity analysis be conducted on the increased loadings of organic matter and especially nitrogen that could be associated with intra-decadal scour events. Such sensitivity analyses should be more completely documented if they have been run, and should be conducted if they have not. The results should inform a more complete understanding of the potential importance of Susquehanna loadings (from both upstream and from scour) during major storm events and can thus inform the needed changes in allocations associated with changing performance of the Conowingo reservoir.

One important question regards the model's ability to simulate short term changes in particulate loading brought about by 'scour' events. Such events can result in long-term changes in the overall loading to the bay (calculated as an approximately 1.5-1.7 million pound increase in Phosphorus loading according to a presentation to STAC at their September 2017 meeting (Linker, Bhatt, and CBP Modeling Team, September 2017). In this regard, the review panel understands that the Phase 6 Watershed Model (WSM) model has been modified based on the CBP's best current understanding of declining reservoir performance due to reservoir infilling (materials linked in Appendix B); however, it should be noted that this process of simulating infill loads is novel and that the CBP approach was changing over the course of the review – appropriately, we might add, in response to new information becoming available from other on-going work. Since the beginning of this respective review process, the CBP modeling team had the information needed to recognize that (1) all three lower Susquehanna Reservoirs are now in dynamic equilibrium, (2) historical loading trends estimated from observations by the method of Weighted Regression by Time, Discharge, and Season (WRTDS) should be included in model calibration, (3) constant delivery factors should be used for scenarios involving both increases or decreases in the sediment and phosphorus loads, and (4) a flow dependent dynamic G-series response should be used to simulate the proportion of infill scoured that is bioavailable to the downstream estuary. During the period of this review, however, an Exelon-funded study of scour dynamics titled the Lower Susquehanna River Reservoir System Model Enhancement was concluding and was being separately reviewed by another expert team on which panelist Brady also served (see Ball et al. 2017). This parallel study used a combination of results from diagenesis experiments and modeling to determine the potential impacts of scour load downstream. According to a STAC Quarterly Meeting presentation (Linker, Bhatt, and CBP Modeling Team, September 2017), the modeling team has since incorporated the dynamic G-series model in their simulations in the following way – at high flows (i.e., over 6,000 cfs), the proportion of the organic load in the refractory G3 portion begins to linearly increase as a function of flow. According to the presentation, this significantly improved representation of particulate organic material throughout the model domain.

Thus, the combination of WRTDS and Exelon-funded results are being used by the revised Phase 6 WSM to inform the simulation of extreme events and allow for direct comparison of WRTDS estimates with Phase 6 estimates, allowing an empirical adjustment of the "delivery factors" used by the model to provide loadings to the WQSTM. These changes thus fall into a category of heretofore un-reviewed WSM modifications that could affect WQSTM calibration and predictions. In this regard, details of the approach (adjustments to delivery factors) were hard for the panel to follow – i.e., the panel was unclear as to exactly how the WRTDS-Phase 6 comparisons are being used to change delivery factors. (This was largely because of the compressed timing, which did not allow sufficient time for full documentation – the panel learned of the details regarding the relationship between the WRTDS, the LSRRS Model Enhancement, and the current WSM only through presentations rather than through a comprehensive source of documentation). Therefore, and although it is beyond this panel's purview to review the WSM, the panel highly recommends that the modeling team formalize the description of how this new information is being used in the current formulation and exactly how improvements to particulate organic nutrient in the estuary are being measured. Additionally, in recognition that WQSTM calibration and results are dependent on good data from the watershed, the panel recommends that the LSRRS aspects of the WSM be reviewed more thoroughly in the future, once such documentation has been prepared.

Considering the above, however, the panel appreciates that the WQSTM does provide a valuable sensitivity tool to determine the impact of upstream nutrient loading on water quality and believes the modeling team is using these coupled tool appropriately in this regard, as a means to determine the influence of this new dynamic equilibrium on Bay water quality. As a separate but related matter, the panel also notes its general agreement with one principal conclusion of the prior Lower Susquehanna River Watershed Assessment (USACE 2015) – that is, that direct nutrient management and mitigation in the watershed is likely to be much more effective at sustainably reducing sediment and nutrient loads than sediment management options.

Regarding the Conowingo system, the panel has also identified several unresolved issues and questions that will need further investigation:

- It is not clear whether the CBP has plans for future improvements in mechanistic modeling of sediment and nutrient processing in the LSRRS (materials linked in Appendix B). The panel thinks, however, that such modeling would be useful – and may be critically needed – in order to better understand and simulate events at time scales shorter than a decade and to provide better data for future WQSTM calibration. The panel recommends that, in the long term, the CBP should place a priority on better modeling of this and other reservoir systems. This can be done through synthesis and incorporation of new knowledge being generated by the on-going Exelon-supported studies as well as through additional future efforts of model development, model sensitivity analysis, and experimental work to better simulate the shorter-term changes in discharge-related inputs and outputs of sediments and nutrients in the LSRRS and other major reservoir systems in the watershed.
- In the above regard, there is also some concern by the panel, based on results of a separately published "Independent Review of Exelon's LSRRS Model-Enhancements Efforts" (Ball et al. 2017) and the engineering reports upon which that review was based (CRC 2017), that the short-term variability of input loadings at Marietta may not have been well simulated by the WSM and that this could have affected the reservoir model calibration and simulations. This issue should also be ultimately addressed.
- The panel believes that continued use of sediment resuspension experiments with intact sediment cores (e.g., SEDFLOW) could provide additional valuable data on shear stress thresholds that could be combined with new data about sediment composition, based on sampling (coring) of sediments at different locations in the LSRRS. Some of this information is available in the LSRRS Model Enhancement study (see CRC 2017 for links to documents) and should be mined to increase process level understanding of the changes in loading associated with infill.
- The documentation provided for this review states that a series of experiments is underway to determine the composition and reactivity of nutrients in reservoir bottom sediments, toward better understanding the nature and reactivity of organic matter and nutrients in sediments – i.e., better parameterization of oxidation rates and extent and bioavailability. It is the panel's understanding that these results have been incorporated into the model, but the documentation should be expanded and completed. Moreover, continued refinement is advised, as additional results come to light.
- The panel suggest an analysis of the frequency and severity of high flow events in the Susquehanna over the past few decades would contribute to assessing if there is a potential for future climate change-related conditions to cause increased frequency of scour events.

Question #4 "Please comment on the overall appropriateness of the approach taken for estimating and representing future sea level rise (SLR). Is the approach sufficiently scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer-term consideration of the CBP, on how you believe the estimate and representation of SLR can be improved."

The approach taken for assessing the impact of future sea level rise (SLR) is appropriate for preliminary application. The results obtained are similar to those obtained in other previous studies (Irby et al. 2017); however, the review panel submits the following recommendations that should be considered when moving forward with the next generation estuarine model:

As the CBP has noted in their presentations, SLR is expected to increase salinity throughout the Bay, with the greatest increase appearing at the head of the Bay. For a SLR of 0.5 m (between the mid-1990s and 2050) the projected increase in salinity in the upper Bay is between 2 PSU in wet years and 1.5 PSU in relatively dry years (Hong and Shen 2012). This is inconsistent with the WQSTM results, which show a larger increase at the mouth of the Bay than at the head of the Bay. This inconsistency between the WQSTM and other published Chesapeake Bay SLR simulations (Hong and Shen 2012) is most likely because the outer boundary condition for the WQSTM is located directly at the Bay mouth (near CB7.4), whereas most other Chesapeake Bay models have the outer boundary for their grids located well outside the Bay mouth (Lanerolle et al. 2011; Hong and Shen 2012; Testa et al. 2014; Feng et al. 2015; Irby et al. 2016; Xia et al. 2016). Placing the outer boundary on the shelf is preferable, especially for climate change simulations, as the interior Bay dynamics are much less sensitive to a boundary that is located on the shelf, compared to one located directly at the Bay mouth. In the future, the WQSTM grid should be extended so the outer boundary is located on the shelf, similar to Hong and Shen 2012 and Feng et al. 2015. In this case, it would not be necessary to increase the salinity at the Bay mouth, as has been done in the WQSTM climate change simulations to date. In addition, it would be useful to use a nesting method to let the inner bay model couple with an outer coastal ocean model.

Currently the WQSTM climate change simulations impose an increase in salinity of 0.4 PSU at the Bay mouth, citing Saba et al. (2016). The actual increase in salinity found at the Bay mouth in this publication (for the high resolution CM2.6 model) ranges from 0.15 PSU at the surface to 0.22 PSU at depth (Saba, pers. comm.). Since the WQSTM climate change simulations demonstrate that the impact of a change of 0.4 PSU at the Bay mouth has a very minor effect on estuarine DO, the panel recommends that this potential increase in open ocean salinity is ignored in the future.

The current WQSTM does not allow for SLR to increase the surface area of the Bay, since wetting/drying is not incorporated. In the next generation estuarine model, the panel recommends that SLR be allowed to inundate the coastline through numerical wetting and drying, and thus increase the surface area of the Bay.

Question #5 "Please comment on the overall appropriateness of the approach taken for estimating and representing future temperature changes and their impact on Chesapeake water quality standards of DO, chlorophyll, and clarity/SAV and key living resources. Is the approach sufficiently scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe the estimate and representation of future estuarine temperature and effects can be improved."

The approach taken represents a good start at estimating the impacts of future temperature changes on the water level and the dissolved oxygen resources of Chesapeake Bay. While the panel contends that the climate modeling protocol is defensible and appropriate for the purposes of the Mid-Point Assessment, the panel has some reservations about the climate change modeling protocol for long-term management use. Therefore, it is suggested that a more thorough scientific analysis be conducted. Specific suggestions are listed below.

The temperature growth curves should be reexamined to more accurately quantify the impact of very high water temperatures on Chesapeake Bay phytoplankton. Although some algae exhibit a sharp drop in growth rate at elevated temperatures (Chapra et al. 2017), most phytoplankton communities tend to have higher growth rates at higher temperatures (Eppley 1972). Although individual types of algae may have temperature optima as employed in the WQSTM, warming temperatures will lead to shifts in algal composition that favors species with higher temperature optima and higher maximum growth rates. By not taking this into consideration, the current version of the WQSTM may be underestimating the impact of warming temperatures on changes in productivity and oxygen in the Bay. Another suggestion for consideration is the inclusion of an existing high temperature tolerant/optimized algal group. This could include the possibility of high-temperature tolerant tropical species in the brackish and saline waters, and the possibility of increased cyanoHABs (harmful algal blooms) in the up-estuary freshwater that could occur due to climate-induced hydrologic impacts. However, the panel is aware that too much model complexity can impair predictive capabilities (Friedrichs et al. 2006, 2007; Xiao and Friedrichs 2014), so adding algal groups should be considered carefully before enacting.

The solubility equation used in the WQSTM and provided in the documentation is currently inaccurate at temperatures greater than 30°C (equation 42 in Cerco and Noel 2017). The equation used assumes that water above 35°C holds more oxygen than it does at 35°C, which is not physically correct. The original white paper reference for this equation (Genet et al. 1974) could not be located. The review panel recommends that the CBP revise the WQSTM to use either Garcia and Gordon (1992) or the relationship recommended by the USGS (https://water.usgs.gov/software/DOTABLES/) and redo the climate change analysis with this revised relationship.

To assess the effect of future warmer temperatures on DO, the review panel recommends examination of the cumulative annual hypoxic volume (measured in hypoxic volume days) rather than average summer hypoxic volume, since it is possible that climate change may result in an earlier start to the hypoxic season (Bever et al. 2013; Irby et al. 2017). Additionally, to examine the impact of warming temperatures on Chesapeake water quality standards, the CBP needs to examine higher DO levels, and not just DO concentrations less than 1 mg L^{-1}. The DO water quality standard for the "Open Water" year-round designated use (Tango and Batiuk 2013) is: 30-day mean > 5 mg L^{-1} (for tidal habitats with salinity > 0.5 PSU). Even though warming temperatures may have a relatively small impact on anoxic volume, other modeling studies have shown that substantially larger effects are felt at higher oxygen concentrations. Thus, the panel recommends that the CBP examine cumulative hypoxic volume levels for higher DO concentrations up to 5 mg L^{-1} to better understand the full impact of warming temperatures on Water Quality Standards Attainment.

The WQSTM simulations, forced by changes in atmospheric temperature, predict a water temperature warming of ~0.6°C at the bottom of the estuary between the 1990s and 2050. This level of warming is considerably lower than that recently estimated by others (Ding and Elmore 2015; Saba et al. 2016; Muhling et al. 2017). The magnitude of bottom temperature change is critical, and may explain the smaller change in hypoxic volume estimated by the WQSTM for 2050 compared to other recent Chesapeake climate change studies (Irby et al. 2017). The review panel recommends that the CBP re-evaluates the change in temperature imposed at the open boundary, at the Bay surface, and in the water entering through the rivers. In addition, earlier data analyses have shown that bottom waters in the Bay are warming slightly faster than surface waters (Preston 2004). The WQSTM results do not appear consistent with these data. This discrepancy should be investigated further as sediment processes and organisms tend to be highly sensitive to bottom temperature.

Over the longer-term, the CBP should consider the impacts of changes in wind forcing on oxygen concentrations in the Bay, and should look at the sensitivity of their results to GCM, emission scenario and downscaling methodology.

To assist with these analyses, the WQSTM review panel recommends that the CBP take advantage of an advisory group to assist the modelers in making minor model modifications to better address climate change and in developing adequate model scenarios that go well beyond merely prescribing an assumed air temperature rise. See also the panel response to Question #9.

Question #6 "Please comment on the overall appropriateness of the approach taken for estimating and representing SLR tidal wetland loss and its impact on Chesapeake water quality standards of DO, chlorophyll, and clarity/SAV and key living resources. Is the approach sufficiently scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe estimates and model representation of future tidal wetland loss can be improved."

This relatively simplified model (i.e., largely empirical and concentrating on only the most important processes that contribute loading to the Bay) is poised to possibly improve the WQSTM simulation of DO and chlorophyll, however, this needs to be quantitatively demonstrated. While the simplified wetland model is not a full representation of all relevant processes, it does help improve the overall Chesapeake Bay modeling based on the nitrate simulation with and without the wetland module; however, this also must be quantitatively demonstrated. Similar demonstrations should be made to directly show improvements in DO and chlorophyll simulations and these should be included with the documentation.

Regarding wetland loss, the internal biogeochemical dynamics within the wetland area should change under the potential climate change/SLR. For example, the CO_2 inside the wetland area should change the Chesapeake Bay wetland ecosystem, so some discussion should be added to documentation about model limitations in these and other regards. In particular, two panel members question the extent to which new wetland area or wetland accretion will occur under the SLR (Stralberg et al. 2011), and note there is likely to be great uncertainty in these projections. Properly modeling and projecting these processes remains a very difficult challenge.

Overall, and given the complexity of wetland dynamics, the panel is concerned about the degree to which the current model can simulate major change. Nonetheless, the results do suggest improvement to the model simulation after inclusion of the wetland module. Unless there is a major error in the SLAMM (Sea Level Affecting Marshes Model) results of wetland area change, the results suggest only a minor impact to the Chesapeake Bay simulation on the basis of wetland loss scenario. If the process is indeed of minor importance, then this simple model system could continue to be used for simulating the potential climate change/SLR.

Question #7, part 1: "Is the approach taken in the estimates of shoreline erosion nutrient loads and the simulation of nutrient attenuation by tidal wetlands supportive of an improved representation of shallow water dynamics?

In general, based on the presentations to the panel, the new modeling approaches feature some improvements over the previous representations. Below are suggestions for additional improvements.

Shoreline Erosion

The shoreline erosion simulations seem mainly focused on estimating how much erosion occurs and how much nitrogen (N) and phosphorus (P) are eroded. Current estimates are that N erosion is negligible but P erosion is comparable to other non-point source (NPS) P loads. However, the fate and bioavailability of the various particulate P forms are currently not well understood. Future models will need to simulate the transformations and availability of shoreline-erosion particulate P forms if the necessary data are available. If not, measures should be taken to obtain the needed information and modeling improved when data become available.

Probably the most important sink for shoreline eroded material and other suspended solids loads is deposition and burial in estuarine sediments. Increased shoreline erosion and TSS loads probably lead to nearly equal increase in sediment accretion. Most of the eroded N and P is likely to accumulate in the sediment without affecting water quality. This may already be incorporated into the model in some form, but more data on N and P burial may be needed to improve the simulations. For an early example of the importance of considering sediment accretion, see Nixon (1987).

The fate of particulate P in estuaries depends partly on its chemical form. Most of the NPS P discharged from watersheds is particulate P. There are many different organic and inorganic particulate forms with differing availability. The Chesapeake Bay model currently assumes that only 14% of the particulate P eroded from shorelines is inorganic, based on data from Ibison (1992). This is percentage is probably too low. More recent studies suggest that most of the particulate P discharged from watersheds is inorganic P associated with iron oxides (e.g., Jordan et al. 2008). Other studies have found that most of the particulate P accumulating in oligohaline sediments of Chesapeake tributaries is inorganic P associated with iron (Hartzell et al. 2017). Release of this pool of inorganic P from the sediments is enhanced by increasing salinity (Jordan et al. 2008; Hartzell et al. 2010, 2017; Hartzell and Jordan 2012). The panel recommends that the model be updated to provide a more realistic representation of the particulate P being deposited in Chesapeake Bay sediments.

Currently the model represents particulate matter eroded from shorelines as having uniform composition. Surface soil is generally much richer in organic matter and nutrients. Therefore, the quantity and quality of particulate P from shoreline erosion may differ depending on how much of the eroded material was from surface or subsoil. Erosion from higher, steeper shores is likely to include more subsoil. The panel suggests that the Chesapeake Bay modelers investigate the importance of distinguishing erosion of soil vs. subsoil from shorelines.

Overall the panel recommends that the CBP focus on the form of P being eroded and whether it will be taken up by the phytoplankton community, or deposited in the bottom sediments.

Nutrient attenuation by tidal marshes

Adding denitrification from marshes improved WQSTM predictions of nitrate concentration in the York River. Representations of respiration and denitrification in the model seem reasonable. However, the empirical foundation for denitrification estimates is not strong. It is difficult to estimate denitrification under field conditions. Most measurements of denitrification are done on intact cores or soil slurries. Some denitrification studies rely on measuring denitrification potential with the acetylene block technique, but it is difficult to extrapolate these measurements to large spatial scales with confidence.

Marshes have a reputation for being sinks for nutrients and sediments though they have also been described as sources of organic matter. Measurements of tidal exchanges of nutrients with tidal marshes can vary among different marshes. The elevation of marshes in the intertidal zone affects the net tidal exchanges of materials. For example, Jordan and Correll (1991) used automated sampling to measure tidal exchanges from two marshes of differing elevation in the mesohaline Rhode River. They found that the low marsh imported organic N while the high marsh exported organic N. The low marsh also imported organic P, nitrate, and total suspended particles, while there were no significant net exchanges of those materials by the high marsh. The largest net flux from the high marsh was export of organic carbon. In general, the high marsh tended to export organic N and C while the low marsh imported particulate matter. Due to the export of organic N, the high marsh showed a net export of total N suggesting that nitrogen fixation in the marsh exceeds denitrification and N accretion in the sediments, resulting in the marsh being a source of fixed N to the estuary. Export of dissolved organic carbon by the high marsh is the subject of ongoing research at the Smithsonian Environmental Research Center (personal communication with Dr. Thomas Jordan, 2018).

Higher elevation marshes are submerged for shorter periods and, therefore, have less time for suspended sediments to be deposited on the marsh surface. Thus, sediment accretion in higher elevation marshes is more due to accumulation of autochthonous organic matter than accumulation of deposited inorganic sediment. By comparison, subtidal sediments are always underwater and can accrete more inorganic particles than equal areas of tidal marshes. In the upper Rhode River only 15% of the total deposition of inorganic particulate matter occurred in the tidal marshes that covered 60% of the area (Jordan et al. 1986). The shallow subtidal sediments seemed to be more of a nutrient sink than the tidal marshes, which mostly seemed to transform nutrients from particulate to dissolved forms (Jordan et al. 1991).

The panel recommends that the model incorporate changes in marsh exchanges related to the elevation of the marsh in the intertidal zone, which may change depending on the balance between marsh accretion and SLR.

Effects of sea level rise on tidal marshes

The predictions for changes in marsh area over the next 50 years show a slight increase followed by a slight decrease, with little overall change for the Chesapeake Bay as a whole. Beyond 50 years, more rapid net loss of marshes is predicted. The effects at smaller spatial scales will likely differ greatly among Chesapeake sub-estuaries; some areas might see large net losses or gains. Predicting these local differences and effects on water quality will likely be important for management decisions over the next 50 years.

Question 7, part 2: Continued: Are [the approaches taken] scientifically defensible and appropriate for preliminary application?

Yes, they are probably adequate for preliminary application.

Question 7, part 3: Please feel free (but not obligated) to also comment, for the longer-term consideration of the CBP, on how the shallow water simulation approach can be improved going forward. For example, what science is missing from our current analysis in regard to shallow water dynamics and the effective simulation of shallow water DO, chlorophyll, and clarity throughout the Chesapeake? Given the findings of the multiple model shallow water assessment, how can future representations of the water quality in small tidal embayments and tidal rivers be improved? (As examples of additional issues worthy of further consideration, one might consider the use of variable model grids, wind resuspension of phytoplankton and sediment, phytoplankton behavior to avoid self-shading, and improvements to modeling of phosphorus/pH and redox dynamics.

The Shallow Water Modeling (SWM) project has revealed that the WQSTM does not accurately simulate the upstream salinity gradient in the Chester River, whereas higher resolution models are able to reproduce this gradient (**Figure 1**). The panel therefore recommends that in the future a higher resolution model is needed in the shallows, preferably with an unstructured grid including multiple vertical levels that can adequately resolve the mainstem bathymetry of the tributaries (Ye et al. 2016).

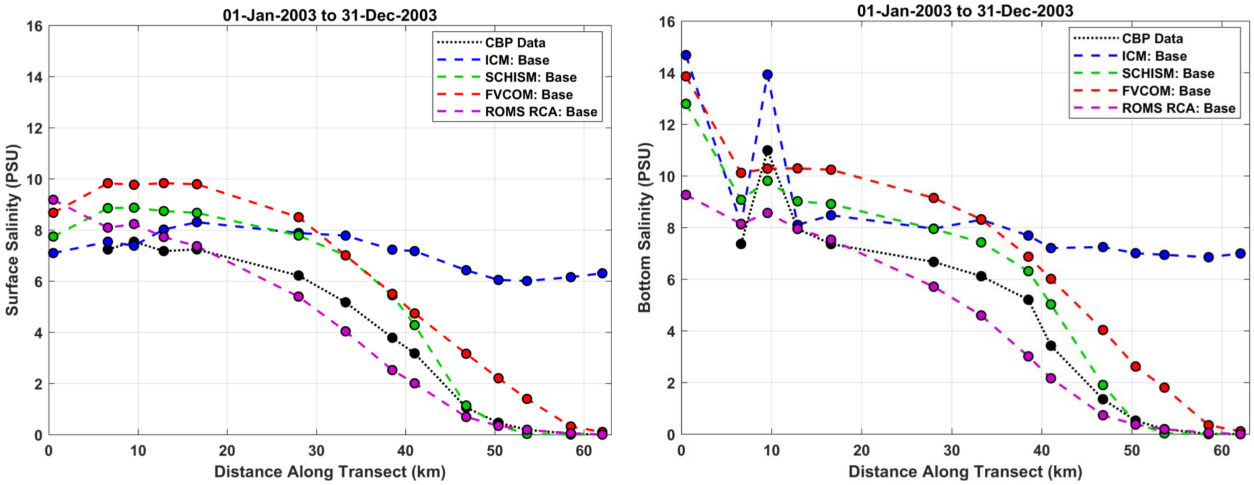

Figure 1. Model comparisons with data for surface and bottom salinity along the length of the Chester River for four different computer models (unpublished data; M. Friedrichs, Virginia Institute of Marine Science).

Since the WQSTM does not accurately simulate a conservative tracer like salinity in the upstream reaches of the Chester River, it will likely have difficulty simulating more complex non-conservative tracers such as phytoplankton, oxygen, nitrogen, phosphorus and TSS at that location and perhaps elsewhere. Before correcting the WQSTM water quality simulations that are of interest to managers, the review panel recommends that the CBP first ensures that conservative physical variables like salinity are being accurately simulated in the upstream reaches of key tributaries, and including some smaller tributaries such as the Chester River. This will help ensure that physical processes that are critical for the accurate simulation of water quality variables, e.g., advection, diffusion and mixing, are being properly simulated in the WQSTM.

While simulation of salinity remains elusive and will probably require higher resolution, statistical analyses of measured chlorophyll and nutrient concentrations can provide insights into the dominant factors affecting water quality in shallow waters. For example, a recent study (Jordan et al. 2017) compared 49 Chesapeake Bay sub-estuaries and Mid Atlantic Coastal Bays with differing local watershed land use and found that summer concentrations of total N and chlorophyll were positively correlated with the percentages of cropland and developed land in the local watersheds. Total P was positively correlated with the percentage of cropland not with the percentage of developed land (Jordan et al. 2017). Shallow water (<2m deep) inside the sub-estuaries had lower concentrations of nitrate and higher concentrations of chlorophyll than adjacent water outside the sub-estuaries (Jordan et al. 2017). Ultimately, the simulation models will need to replicate these patterns. In the meantime, statistical models can help inform management decisions.

Question 7, part 4: How critical do you consider these components for the scientific validity of future shallow-water modeling and how are they best addressed?

To calibrate and validate future models of shallow water it will be important to have more water quality data in Chesapeake sub-estuaries available to modelers, especially in shallow (<2m deep) and nearshore (within 200m) waters. To model the effects of nutrient attenuation by tidal marshes, the model should incorporate factors such as marsh elevation that account for differences among marshes in their net exchanges of nutrients. To model the impacts of particulate P loads from shoreline erosion or other sources, it will be important to incorporate the factors that affect P burial in sediments. Switching to a higher resolution model is imperative to improving shallow water simulations in the Bay.

Question #8 "Please comment on the scientific rigor of the methods used to estimate oyster biomass in sanctuaries, aquaculture, and natural bars and simulate their influence of on water quality. Is the approach to the simulation sufficiently scientifically defensible and appropriate for preliminary application?"

The oyster module appears to use the best and most freely available data for estimating the oyster populations among natural reefs, sanctuaries, and aquaculture leases. The approach for parameterizing factors in the model is certainly defensible, especially given the apparent lack of detailed information on farm sites and culture practices. The only serious concern is the estimate of aquaculture biomass, which is assumed to be equal to harvest size. This seems very conservative as there are multiple cohorts being cultured per year and it takes more than 1 year to reach market size; typical bottom culture is a 3-4 year turnaround time from seed to harvest. Regardless, conclusions of Cerco and Noel (2007) align well with several other studies that suggest oysters (e.g., sanctuaries and wild stocks) can have a meaningful impact on water quality in Chesapeake Bay but that point and non-point of nitrogen must be reduced to curb system-wide eutrophication.

Q8 Continued: Are you aware of additional scientific information that should be included? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe estimates and model representation of these issues can be improved?

The feeding responses of oysters are dynamic, responding simultaneously to multiple environmental parameters. The present module relies on mechanistic models from Cerco and Noel (2007) to estimate the dynamic feeding activity of oysters. Gray and Langdon (2017) tested the accuracy of mechanistic models on species other than *C. virginica* in Yaquina Bay, OR. It was determined that such mechanistic models may force the estimated feeding activity of oysters to respond to more environmental parameters than oysters do under natural conditions, typically resulting in underestimation of their clearance rates. Although this finding does not warrant immediate concern, the panel suggest this paper be reviewed and the CBP consider the appropriateness of mechanistic feeding models in future oyster module use.

Aquaculture in Virginia and Maryland is rapidly expanding. The current model accounts well for the current influence of bottom culturing of oysters in the Bay. If the oyster module is included in future model development, model architects should consider other gear types that this emerging industry is likely to exploit as the industry matures; gear (e.g., floating trays, rack and bag, long-lines) and practices (e.g., surface vs bottom) and crop orientation to overlying water determines how these populations will interact with the environment and their influence on the local water quality (Newell and Campbell 1998; Drapeau et al. 2006; Grant et al. 2007; Lunstrum et al. 2017). If gear and practice data becomes available, these types of details should be included for fine tuning models in the future.

As mentioned above, fine tuning for model parametrization could include collecting fine scale data on gear and practice type to quantitatively estimate the impact aquaculture is having on water quality/nutrient cycling. Other modeling platforms that explicitly look at the effect of shellfish aquaculture on environmental quality and account for biomass, gear, and practice type have been developed (ShellSIM, ShellGIS, & **F**arm **A**quaculture **R**esource **M**anagement (FARM)) and should be explored. Incorporating these platforms or adopting their approach may be helpful in future model development.

FARM models may also allow the calculation of nutrient-trading or credits as it converts estimated nitrogen removed by the oysters to human population equivalents and calculates the potential value of the ecosystem service represented, providing a substitution or ‘‘avoided’’ cost of land-based nutrient removal.

While oyster cultivation is not yet part of the nutrient-trading program in Chesapeake Bay, there is discussion and research on the use of oyster aquaculture as a best management practice (STAC 2013), and the USEPA Regional Ecosystem Services Program and NOAA are supporting research to investigate the potential removal of nitrogen through oyster harvest.

Question 9: "Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how future Chesapeake water model structures and processes can be modified to better represent the tidal water quality standards of DO, chlorophyll, and clarity/SAV in the face of challenges of climate change, growth, and other future impacts. For the longer-term consideration of the CBP, what major shortcomings you find in the overall approaches and procedures used and what alternative approaches might you recommend?"

As previously noted, a significant issue with the current WQSTM grid is the low horizontal resolution in the shallow waters of the Bay. The shallow waters are also not depth resolved: regions less than 5 feet deep have only one model layer, prohibiting any time of estuarine circulation in the upper tributaries. Many tributaries are only one cell wide, and thus the deeper central channel cannot be resolved. A more highly resolved grid is required to accurately simulate the fluxes of nutrients and oxygen through Chesapeake Bay shallow waters.

As also noted above, the outer boundary of the grid needs to be moved farther out onto the continental shelf, to assist with improving estuarine and tidal circulation within the Bay.

The review panel recommends that the CBP reexamine the model P dynamics, and no longer treat PIP as inert particulate matter. It contains bioavailable P from gradient-driven desorption in the water column as well as diagenesis of the sediments when they deposit. Bioavailability process experimentation (DCDA bioassays) performed in the Great Lakes measured the rate of release of bioavailable P (soluble reactive phosphorous or SRP) from PIP at about 10%/day (DePinto et al. 1981; DePinto et al. 1986). This finding was incorporated into a eutrophication model application to western basin of Lake Erie (Verhamme et al. 2016) by using a first-order reversible kinetic formulation, where desorption of exchangeable or "labile" PIP (LPIP) occurred at ~10%/day and adsorption of SRP onto PIP occurred very fast. Using this approach the maximum net desorption rate is 10%/day, and the net rate approaches zero as equilibrium is approached. Of course, the PIP-containing sediments are settling and depositing into the bottom sediments at the same time.

To assist with these analyses, the WQSTM review panel recommends that the CBP assemble a small advisory group to focus specifically on the estuarine component of the CBP modeling system. The advisory group can assist the modelers in making minor model modifications to better address climate change and in developing adequate model scenarios that go well beyond merely prescribing an assumed air temperature rise.

The review panel also recommends that the CBP establish a plan for the continuing development and improvement of the WQSTM over the next several years. With recent and future retirements, it is not clear how future WQSTM analyses will be conducted. The review panel further notes the importance of having the next generation WQSTM recalibrated and revised in the next few years, and that it be subjected to a follow-up technical review well in advance of

2025. The intent here is to ensure that the model is working well before it is needed again for the 2025 TMDL recalculations.

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Cerco, C.F. and M.R. Noel. 2017. The 2017 Chesapeake Bay Water Quality and Sediment Transport Model. A Report to the US Environmental Protection Agency Chesapeake Bay Program. May 2017 Draft. US Army Engineer Research and Development Center, Vicksburg MS. 108 pp. (Link in Appendix B).

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Appendix A
Peer Review Panel Charge and Questions

The 2017 version of the WQSTM is the most recent of a series of increasingly refined versions of coupled hydrodynamic and water quality models of the Chesapeake Bay developed since 1987. Different versions of the model have been operational for more than three decades guiding Chesapeake Bay Program (CBP) management decisions. New aspects of the current WQSTM are improved representation of the bioavailability of particulate organics and improved ability to simulate Conowingo infill and climate change in tidal waters. Refinements to the shallow water simulation include attenuation of nutrient and sediment loads through tidal wetlands, the representation of shoreline loads of nutrients, and the explicit representation of oyster aquaculture, sanctuaries, and wild populations.

Recognizing that the general approach and scientific basis of the currently used WQSTM model were reviewed more thoroughly by STAC previously (see "Prior WQSTM-related STAC Reports" noted below) and that a more complete review of best practices for CBP modeling approaches will be undertaken in the coming years, the CBP is currently requesting, through the Modeling Workgroup, a STAC review primarily of the newer WQSTM modeling aspects noted above, which are intended for implementation in the coming year and will likely be used through at least 2025. In this regard, the review requested here is intended primarily as a more focused consideration of the reasonableness and objectivity of the model within the context of available science and given the constraints associated with providing a stable, objective, and scientifically reasonable modeling environment for use toward regulatory and management purposes in the next eight years.

Prior WQSTM-related STAC Reports (for background):

Johnson, Z., M. Bennett, L. Linker, S. Julius, R. Najjar, M. Mitchell, D. Montali, R. Dixon. (2016). The Development of Climate Projections for Use in Chesapeake Bay Program Assessments. STAC Publication Number 16-006. http://www.chesapeake.org/pubs/360_Johnson2016.pdf

Linker, L., R. Hirsch, W. Ball, J. Testa, K. Boomer, C. Cerco, L. Sanford, J. Cornwell, L. Currey, C. Friedrichs, R. Dixon. (2016). Conowingo Reservoir Infill and Its Influence on Chesapeake Bay Water Quality. STAC Publication Number 16-004. http://www.chesapeake.org/pubs/356_Linker2016.pdf

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D. Breitburg, E. H., R. Newell, A. Butt, D. Orner, R. Magnien. (2002). Suspension Feeders: A Workshop to Assess What We Know, Don't Know, and Need to Know to Determine Their Effects on Water Quality (STAC Publication Number 02-002). http://www.chesapeake.org/pubs/fffinalreport.pdf

Reports to be reviewed by the Panel:

Beta 4 WQSTM Documentation
[Questions #1, #2, #3, #6, #7, #8, and #9]
http://www.chesapeakebay.net/documents/2017_WQSTM_Documentation_DRAFT_5-10-17.pdf

2017 WQSTM Documentation Appendix A: Time Series of 1991-2000 Observations and Simulation Results - http://www.chesapeakebay.net/documents/Appendix_A_1991-2000_time_series_DRAFT_5-10-17.pdf

2017 Water Quality and Sediment Transport Model Documentation: Appendices B, C, and D - http://www.chesapeakebay.net/documents/Appendices_B-C-D_of_WQSTM_Documentation_DRAFT_5-10-17.pdf

Resource Materials for the Panel:

- **Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science (2016) [Question #3]**
  https://dl.sciencesocieties.org/publications/jeq/abstracts/45/3/882
- Impact of Reservoir Sediment Scour on Water Quality in a Downstream Estuary (2016) **[Question #3]**
  https://dl.sciencesocieties.org/publications/jeq/abstracts/45/3/894

- Influence of Reservoir Infill on Coastal Deep Water Hypoxia (2016)
  [Question #3]
  https://dl.sciencesocieties.org/publications/jeq/abstracts/45/3/887

- Assessing Water Quality of the Chesapeake Bay by the Impact of Sea Level Rise and Warming
  [Questions #4 and #5]
  http://www.chesapeakebay.net/publications/title/assessing_water_quality_of_the_chesapeake_bay_by_the_impact_of_sea_level_ri

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- Management modeling of suspended solids in the Chesapeake Bay, USA (2013)
  [Question #7]
  http://www.chesapeakebay.net/documents/CFC_EMECS_clean.pdf

- Can Oyster Restoration Reverse Cultural Eutrophication in Chesapeake Bay? (2007)
  [Question #8]
  http://www.gesaq.org/P2Clew/documents/Cerco%20and%20Noel%20Chesapeake%20Bay%20oysters.pdf
- Monitoring, modeling, and management impacts of bivalve filter feeders in the oligohaline and tidal fresh regions of the Chesapeake Bay system (2010)
  [Question #8]
  http://www.sciencedirect.com/science/article/pii/S0304380009005249

2010 TMDL Documentation

The 2010 Chesapeake Bay Eutrophication Model (2010)
http://www.chesapeakebay.net/content/publications/cbp_55318.pdf

Development of the Chesapeake TMDL Allocation (2013)
http://www.chesapeakebay.net/documents/TMDL_Development_10-13.pdf

Evaluation of a Three-dimensional Hydrodynamic Model Applied to Chesapeake Bay through Long-Term Simulation of Transport Processes (2013)
http://www.chesapeakebay.net/documents/Hydrodynamic_Model_Transport_Processes_Evaluation_10-13.pdf

Monitored and modeled correlations of sediment and nutrients with Chesapeake Bay water clarity (2013)
http://www.chesapeakebay.net/documents/Water_Clarity_Simulation_10-13.pdf

General Documentation on Chesapeake TMDL and Models:

EPA's "Chesapeake Bay TMDL" web site (*Link Updated 1/31/17*)
https://www.epa.gov/chesapeake-bay-tmdl/chesapeake-bay-tmdl-document

The 2002 Chesapeake Bay Eutrophication Model (2004)
http://www.chesapeakebay.net/content/publications/cbp_26167.pdf

WQSTM Peer Review Questions:

General note: The questions below focus primarily on helping the CBP to identify any "fatal flaws" that you believe must be addressed before the modeling is implemented in late 2017 or early 2018. Many of these questions end by suggesting that you should please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe the estimate and representation of SLR can be improved. In particular, please feel free to identify the most important shortcomings you find in the approaches and procedures used and to recommend alternative approaches, research, and data gathering to be conducted for the longer term. Given the time constraints of the review, however, such comments are not necessarily expected at this time.

1) Please comment on the WQSTM documentation. Is it clear, well organized, and complete (Taking into account that it is largely based on the fourth Beta release of Phase 6 Watershed Model and 4 months ahead of final release)?
(Note: This is a question that can perhaps best be addressed after other review questions have been considered, but early feedback is welcome through on-going discussions with CBP personnel for purposes of clarification regarding other peer review questions.)

2) Please comment on the overall appropriateness of the approach taken in the application of G1, G2, and G3 organic behavior in the water column and sediment of the WQSTM. Is the applied approach appropriate? What could be done to improve the representation of the various organic decay rates in the WQSTM?

3) Given the current state of modeling, research, and monitoring on the increased net transport of nutrients and sediment out of the Lower Susquehanna reservoir system please comment on the scientific rigor of the WQSTM approach used to represent the increased nutrient and sediment loads on Chesapeake water quality standards of DO, chlorophyll, and clarity/SAV. Is the representation of nutrients and sediment under all states of flow, including moderate and extreme flow events, sufficiently well simulated for the condition of reservoir infill?

4) Please comment on the overall appropriateness of the approach taken for estimating and representing future sea level rise (SLR). Is the approach sufficiently scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe the estimate and representation of SLR can be improved.

5) Please comment on the overall appropriateness of the approach taken for estimating and representing future temperature changes and their impact on Chesapeake water quality standards of DO, chlorophyll, and clarity/SAV and key living resources. Is the approach sufficiently scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe the estimate and representation of future estuarine temperature and effects can be improved.

6) Please comment on the overall appropriateness of the approach taken for estimating and representing SLR tidal wetland loss and its impact on Chesapeake water quality standards of DO, chlorophyll, and clarity/SAV and key living resources. Is the approach sufficiently scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe estimates and model representation of future tidal wetland loss can be improved.

7) Is the approach taken in the estimates of shoreline erosion nutrient loads and the simulation of nutrient attenuation by tidal wetlands supportive of an improved representation of shallow water dynamics? Are they scientifically defensible and appropriate for preliminary application? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how the shallow water simulation approach can be improved going forward. For example, what science is missing from our current analysis in regard to shallow water dynamics and the effective simulation of shallow water DO, chlorophyll, and clarity throughout the Chesapeake? Given the findings of the multiple model shallow water assessment, how can future representations of the water quality in small tidal embayments and tidal rivers be improved? (As examples of additional issues worthy of further consideration, one might consider the use of variable model grids, wind resuspension of phytoplankton and sediment, phytoplankton behavior to avoid self-shading, and improvements to modeling of phosphorus/pH and redox dynamics. How critical do you consider these components for the scientific validity of future shallow-water modeling and how are they best addressed?)

8) Please comment on the scientific rigor of the methods used to estimate oyster biomass in sanctuaries, aquaculture, and natural bars and simulate their influence of on water quality. Is the approach to the simulation sufficiently scientifically defensible and appropriate for preliminary application? Are you aware of additional scientific information that should be included? Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how you believe estimates and model representation of these issues can be improved

9) Please feel free (but not obligated) to also comment, for the longer term consideration of the CBP, on how future Chesapeake water model structures and processes can be modified to better represent the tidal water quality standards of DO, chlorophyll, and clarity/SAV in the face of challenges of climate change, growth, and other future impacts. For the longer term consideration of the CBP, what major shortcomings you find in the overall approaches and procedures used and what alternative approaches might you recommend?

Appendix B
Links to Documentation and Resources Provided to the Panel

The primary documentation material provided by the CBPO includes:

1. An initial summary document by C. Cerco and M. Noel (Cerco and Noel 2017) entitled "The 2017 Chesapeake Bay Water Quality and Sediment Transport Model: A Report to the US Environmental Protection Agency Chesapeake Bay Program (May 2017 Draft)"

    - Accessible at: http://www.chesapeake.org/stac/presentations/277_20170501_CercoandNoel2017_WQSTMDraftReport.pdf

2. Appendices to Cerco and Noel 2017

    - Appendix A (1991-2000 Time Series): http://www.chesapeake.org/stac/presentations/277_CercoandNoel2017_Appendix_A_1991-2000_time_series.pdf

    - Appendices BCD: http://www.chesapeake.org/stac/presentations/277_CercoandNoel2017_Appendix_BCD.pdf

3. Four different sets of PowerPoint presentations that were given at four meetings held between June 6, 2017, and August 9, 2017 (with the addition of a fifth meeting on October 17, 2017, that was not considered to be officially within the purview of this review due to timing) – see **Table B-1**.

Table B-1. Links to presentations at information sessions held by the Chesapeake Bay Program (CBP) partnership's Modeling Workgroup between June 6, 2017, and August 9, 2017 utilized by the review panel.

Information Session	New Information Provided	Location of Materials
June 5-6. Initial WQSTM Information Session for WQSTM Review Panel	Primary documentation explained.	Agenda 1. Challenges of the 2017 Midpoint Assessment addressed by the WQSTM 2. Overview of New WQSTM Elements 3. Simulation of G1, G2, G3 Particulate Organics 4. Conowingo Infill Simulation 5. Representation of SLR and Tidal Wetlands 6. Climate Change, SLR, and Temperature 7. Representation of Tributaries and Shallow Water 8. Representation of Oyster Aquaculture
July 7. Follow-up Information Session for WQSTM Review Panel (webinar)	Explanation of model use of G1,G2, G3 organic matter fractions; Comparison of 2010 and 2017 WQSTM results using WSM Phase 5.3 inputs	Agenda 1. Follow-Up Actions for the Peer Review Panel 2. Overview of Key Scenario Progress 3. Sensitivity Scenarios – Estuarine Circulation and SLR 4. Representation of Particulate Organic Loads 5. Comparison of 2010 and 2017 WQSTM for WIP Loadings
July 25. CBP Modeling Workgroup Quarterly Review Part 1	Phase 6 watershed model application to Conowingo (Bhatt and Shenk); Conowingo Exelon-Sponsored Model Findings (Sullivan and Michael)	Meeting Webpage 1. Progress on P6 Model Application to Conowingo, Climate Change 2. Conowingo Final Reports
August 9. CBP Modeling Workgroup Quarterly Review, Part II	Interim Calibration of WQSTM to "key scenarios" w/ Phase 6 Watershed Model; Sensitivity scenarios w/ 2050 Sea Level Rise	Meeting Webpage 1. (Final) Sensitivity Scenarios – Estuarine Circulation and SLR 2. Key Scenarios on Interim WQSTM Calibration
October 17. CBP Modeling Workgroup Quarterly Review	Final WQSTM Calibration Selection based on Finalized Phase 6 Inputs (including modifications relating to Conowingo Dam; Run 223 Time series (1991-2000)	Meeting Webpage 1. Finalizing the 2017 WQSTM 2. WQSTM Run 223 Time Series 1991-2000