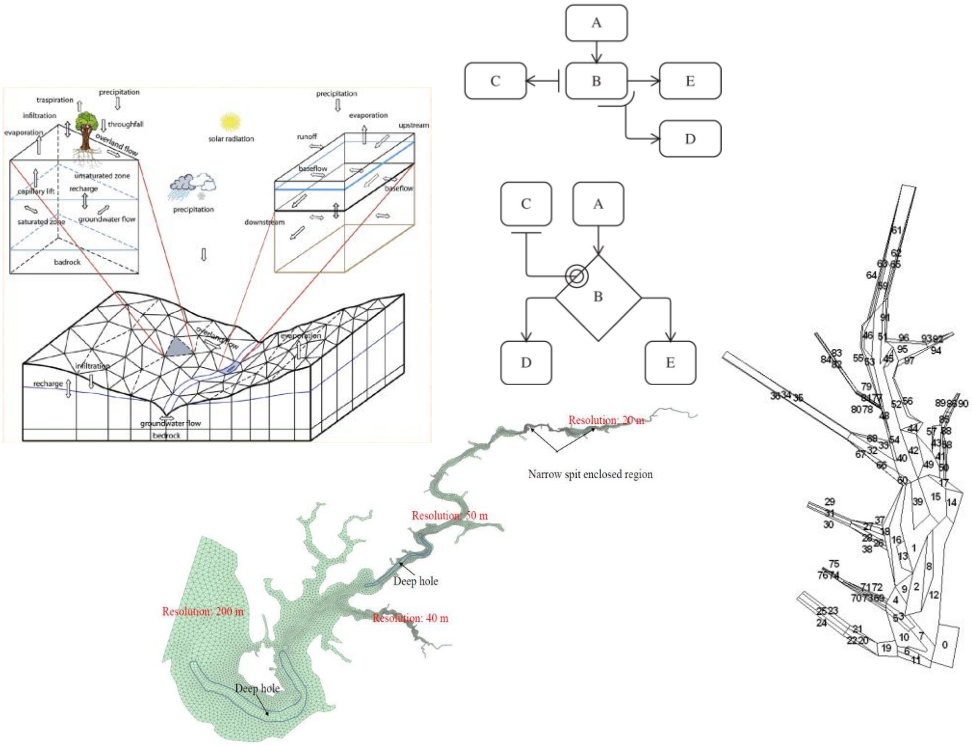
Chesapeake Bay Program Modeling in 2025 and Beyond: A Proactive Visioning Workshop



STAC Workshop Report
January 17-19, 2018
National Conservation Training Center
Shepherdstown, WV

STAC Publication 19-002

About the Scientific and Technical Advisory Committee

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

Publication Date: April 16, 2019

Publication Number: 19-002

Suggested Citation: Hood, R.R., G. Shenk, R. Dixon, W. Ball, J. Bash, C. Cerco, P. Claggett, L. Harris, T.F. Ihde, L. Linker, C. Sherwood, and L. Wainger. 2019. Chesapeake Bay Program Modeling in 2025 and Beyond: A Proactive Visioning Workshop. STAC Publication Number 19-002, Edgewater, MD. 62 pages.

Cover graphic: A composite image showing: an example of a watershed model with an unstructured grid - the Penn State Integrated Hydrologic Model (PIHM, upper left); an example of a estuarine hydrodynamic model with an unstructured grid - Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) implemented in Chester River in Chesapeake Bay (bottom left); schematic diagrams of modular model structures that allow models to plug into one another, and that allow easy swapping of alternative models and formulations (top middle); and the spatial structure of the Chesapeake Atlantis Model (CAM, far right).

The enclosed material represents the professional recommendations and expert opinion of individuals undertaking a workshop, review, forum, conference, or other activity on a topic or theme that STAC considered an important issue to the goals of the Chesapeake Bay Program. The content therefore reflects the views of the experts convened through the STAC-sponsored or co-sponsored activity.

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Executive Summary

The Chesapeake Bay Program (CBP) has used its modeling system as a planning tool to inform strategic management decisions and adaptation toward Bay restoration since the 1980s. This modeling system has been continually updated with improvements and advancements intended to keep pace with emerging science. However, it has been more than a decade since the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC) convened a dedicated workshop to discuss future directions for the suite of modeling tools used by the CBP. Given developments over the past twelve years (since the previous model visioning workshop), and the completion of the 2017 Mid-point Assessment of the EPA's Total Maximum Daily Load regulatory process, STAC agreed that 2018 was an appropriate time to convene a workshop aimed at formulating a vision for future CBP modeling to guide the partnership into the future (i.e., from 2025 and beyond).

The workshop gathered regional and national experts together to develop a vision for a post-2025 (Phase 7) modeling system. Invited speakers and participants included experts in (1) the Bay Program's modeling system, (2) alternative integrative modeling approaches, (3) multiple and ensemble modeling, (4) shallow water modeling, (5) uncertainty assessment, (6) open source and community modeling, (7) stakeholder engagement and social science, (8) modular modeling approaches, and (9) CBP management needs.

This report presents the conclusions of workshop experts on how to improve the Phase 6 modeling system for TMDL development in 2025 and beyond (Findings) and specific guidance that emerged from breakout group discussions on how to realize this vision for future CBP modeling (Recommendations).

Findings

1. There are still opportunities to improve and "evolve" the CBP modeling system so that it can be applied more effectively in the year 2025 and beyond.
2. The review and feedback of the CBP models by and from STAC-sponsored review teams, the Modeling Workgroup, and the Water Quality GIT (Goal Implementation Team) works and should continue. Continued feedback from federal, state, and local jurisdictions to improve the models is also essential.
3. Efforts to incorporate living resources should start by using living resource models that are forced using output from the CBP partnership models – e.g., water quality parameters. The CBP estuarine water quality model should define habitat quality and/or impacts on higher trophic level organisms; it should have a structure that supports direct coupling with models of higher trophic level species.
4. Management decisions guided by the CBP partnership models should reflect social and economic outcomes outlined in the 2014 Watershed Agreement.

5. The participatory modeling approach taken by the CBP should continue to be advanced, improved, and refined.
6. Modular modeling techniques should be adopted in the CBP partnership models wherever possible.
7. The CBP partnership should expand its efforts to make its models applicable to smaller "local" scales, appropriate to decision making for smaller-scale jurisdictions and watersheds.
8. The CBP should continue its efforts to work toward assessing the uncertainties in its modeling suite, with particular attention to simulated responses to management actions in the context of the TMDL.
9. The airshed (CMAQ) and the Chesapeake Bay Land Change (CBLCM) modeling efforts should continue with their currently planned near-term model developments.
10. The CBP should continue to employ and develop the Phase 6 Watershed Model that uses multiple models to determine responses to management actions.
11. Potential future development of the hydrodynamic and biogeochemical models should focus on transition to a hydrodynamic model with an unstructured grid that can provide much greater resolution in the shallow tributaries of the Bay.
12. The current living resource simulation in the CBP water quality model, which includes submerged aquatic vegetation (SAV) and oysters, should continue to be developed with the goal of improving these models.
13. The Chesapeake Bay Fisheries Ecosystem Management Model's (CBFEM's) and Chesapeake Atlantis Model's (CAM's) higher trophic level models should be moved under the development umbrella of the CBP and set up in such a way that the higher trophic level impacts of changing nutrient loads can be easily assessed.
14. The approaches, processes, and parameterizations used in the CBP models for estimating the impacts of climate change and sea level rise on the TMDL should be reexamined in detail.
15. The CBP partnership models should strive to provide outputs related to local ecosystem services and economic impacts that are of direct interest to local stakeholders.
16. The CBP should continue to work toward strengthening its ties with the scientific community and it should continue to support adaptive management.
17. Future model development should continue to be driven by management needs and future models must support time-certain management deadlines.
18. The 2025 next generation CBP suite of models should provide support of better understanding across a wide range of scales. Models that use unstructured grids are particularly well suited to cover this wide range of scales.

Recommendations

Estuarine recommendations

Hydrodynamics

The Chesapeake Bay Program partnership should:

1. Implement a next-generation unstructured-grid modeling system to replace the existing estuarine hydrodynamics/water quality/sediment transport modeling system
2. Use a single primary model that is supported by multiple models (e.g., including those developed within the academic community) for performing analyses to quantify model uncertainty and confidence levels.
3. Continue to engage the scientific community to evaluate model performance, and to engage a diversity of stakeholders to ensure that local needs are adequately met.
4. Allocate more resources to support the implementation and application of the new primary estuarine model and the activities in 1-3.

Biogeochemistry

The Chesapeake Bay Program should:

1. Use two-way coupling between hydrodynamic and biogeochemical models for setting TMDLs and one-way coupling should still be used for model development and testing.
2. Implement a modular, experimental framework that allows for testing of new/alternative biogeochemical models and formulations to inform the management model, and expand its engagement with the academic and government research communities.
3. Enhance the working relationship between biogeochemical and living resource modeling groups to help inform living resource restoration goals.
4. Provide the resources that are needed to accomplish these recommendations. These should include more human resources and funds to increase capacity for documentation, education on new modeling approaches, and online access to model outputs.

Ecosystem approaches

The Chesapeake Bay Program should establish an Ecosystem Modeling Subcommittee responsible for both tidal and non-tidal aquatic systems and empower the Subcommittee to meet the following objectives:

1. Adopt a portfolio of different approaches for modeling living resources, including those identified in the “Recommendations” section of the full report.
2. Select a formal set of criteria to help guide which living resources (including habitats) to model, and when.

3. Consider the importance, relevance, and application of all of the following elements in meeting the first two objectives:
    - non-linear responses of living resources to nutrients and sediment; new approaches for modeling primary producers;
    - re-integration of zooplankton into the biogeochemical model to facilitate coupling to higher trophic levels;
    - identification and closing of data gaps in regard to our understanding of living resource modeling;
    - articulation of mechanisms for communication and stakeholder involvement; and
    - emphasizing ways that modeling living resource responses can improve communication of co-benefits of restoration to stakeholders.

Watershed recommendations

Land use

The Chesapeake Bay Program should:

1. Better characterize agricultural dynamics in the land use model.
2. Better characterize forests and forest dynamics in the land use model.
3. Incorporate the future risk of climate change into its land use projections.
4. Enhance representations of the drivers of land use change such as population and employment distributions, and distributions of sewer service, infill, and redevelopment.
5. Better characterize stream corridors focusing on fluvial geomorphic metrics and riparian zone land uses.
6. Increase model transparency to enhance stakeholder trust with an open-source, cloud-based, modular design.
7. Develop a regional transportation model to help project potential future changes in transportation infrastructure and its impacts on land use and atmospheric emissions.

Hydrology

The Chesapeake Bay Program should:

1. Provide information for managers to justify development of finer resolution models that can resolve key features and address issues of local significance like flooding and water supply.
2. Develop these fine-scale models for small watersheds in addition to the watershed –scale Chesapeake Bay watershed model used for management.
3. Continue development and refinement of the Chesapeake Bay watershed-scale watershed model. The model should ultimately adopt an agile, modular design to facilitate investigation of additional processes and alternative formulations, and to increase transparency.

4. Develop a complementary monitoring system that can co-evolve with the modeling system.

Nitrogen

The Chesapeake Bay Program should:

1. Better quantify nitrogen sources and sinks by exploiting available high-resolution data and by process modeling.
2. Build on the Phase 6 concept by developing an ensemble approach for the steady-state management model.
3. Adapt Phase 6 by implementing a more formal modular and hierarchical modeling system.
4. Incorporate more data in model calibration and in characterizing nitrogen sources and sinks.
5. Analyze mechanistic models to better quantify (best management practice) BMP performance.
6. Develop an ensemble of dynamic watershed models.
7. Model aquatic living resource outcomes.

Phosphorus

The Chesapeake Bay Program should:

1. Distinguish between dissolved and particulate P and update fluvial biogeochemistry in riverine P delivery and tidal water P cycling.
2. Distinguish hydrologically active and connected zones to identify critical source areas to target limited restoration resources more efficiently.
3. Better account for land use change effects on P exports to capture legacy effects.
4. Use the Phase 6 watershed model as a means of extrapolating and relating local findings to larger scales. Local nutrient and phosphorus monitoring data should be used for calibration.

Sediment

The Chesapeake Bay Program should:

1. Understand the importance to management of properly representing time scale of sediment processes in the CBP watershed model.
2. Establish a sediment modeling work group with expertise from the CBP, the geomorphology community, and stakeholders to engage thinking about how to improve the representation of sediment dynamics in the CBP watershed models.
3. Implement short-term improvements to the Phase 6 Model by 2023. Examples could include development of alternative tools to evaluate upland sediment sources; improvement of estimates of sediment delivery across watershed scales; and improvement of the representation of lowland sediment production and storage.

4. Design and implement a replacement model that better represents new understanding of sediment dynamics (beta version by 2023; full implementation later).
5. Incorporate linkages between sediments and nutrient and carbon fluxes, habitat, and living resources, recognizing that transport of other constituents is of key importance for sediment at the whole-watershed scale.

1. Introduction

The Chesapeake Bay Program (CBP) has used its modeling system as a planning tool to inform strategic management decisions and adaptation toward Bay restoration since the 1980s. This modeling system has been continually updated with improvements and advancements intended to keep pace with emerging science. These improved models have been periodically locked down to set Total Maximum Daily Load (TMDL) nutrient reduction targets, most recently with the 2017 “Mid-point Assessment” that used the Phase 6 modeling system[1]. This science- and modeling-based method is a fundamental underpinning of the Chesapeake Bay Program’s approach to environmental management that will continue into the foreseeable future. The CBP’s Scientific and Technical Advisory Committee (STAC) has been actively engaged in the model development and application throughout the CBP’s history; however, prior to the workshop reported here, it had been more than a decade since STAC convened a dedicated workshop to discuss future directions for the suite of modeling tools used by the CBP (Sanford et al. 2006).

It is important to recognize that there have been rapid advances in physical and biogeochemical process understanding, computer science, and environmental systems modeling approaches and techniques in recent years. Several workshops and synthesis reports have provided recommendations for how the CBP should consider evolving the modeling system to keep up with the state-of-the-art in land use, watershed, airshed, estuarine, living resources, and socio-economic modeling for its restoration efforts. These include STAC-sponsored workshops on multiple/ensemble modeling (Weller et al. 2014), shallow water modeling (Friedrichs et al. in prep.), optimization tool design (Davis-Martin et al. 2017), and uncertainty assessment (Davis-Martin et al. in prep.). They also include an NRC-motivated report and recommendations from the Modeling Laboratory Action Team (MLAT) on how the CBP might reorganize its modeling infrastructure (Bennett et al. unpublished). In addition, the Chesapeake Community Modeling Program (CCMP) has long advocated that the CBP should continue efforts to fully adopt open-source and community modeling approaches (Hood et al. 2002). There have also been two recent projects led by academic researchers in the Chesapeake Bay region on the development of approaches for engaging stakeholder communities in the model development process, “Project FishSmart” (Miller et al. 2010; Ihde et al. 2011) and “Oyster Futures” (Oyster Futures Stakeholder Workgroup, 2018). Finally, the NSF-funded Community Surface Dynamics Modeling System (CSDMS) and its Chesapeake Focus Research Group (CFRG) brings state-of-the-art modular modeling approaches and tools to the table along with the CSDMS Interagency Working Group (IAWG), which seeks to engage federal, state, and local agencies in model development efforts. All of these new technologies, approaches, and recommendations should be considered in planning for the future.

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[1] https://www.chesapeakebay.net/what/publications/phase_6_modeling_tools

Given the developments since the previous model visioning workshop, and in particular the completion of the 2017 Mid-point Assessment of the EPA's TMDL regulatory process, STAC agreed that 2018 was an appropriate time to convene a workshop aimed at formulating a vision for CBP modeling to guide the partnership into the future, i.e., from 2025 and beyond.

This report presents the findings and recommendations of this workshop, which convened January 17-19, 2018 at the National Conservation Training Center in Shepherdstown, West Virginia. The workshop gathered 60 regional and national experts together to develop a vision for a post-2025 (Phase 7) modeling system. Invited speakers and participants included experts in (1) the CBP modeling system, (2) alternative integrative modeling approaches, (3) multiple and ensemble modeling, (4) shallow water modeling, (5) uncertainty assessment, (6) open source and community modeling, (7) stakeholder engagement and social science, (8) modular modeling approaches, and (9) CBP management needs.

The overarching goal of the workshop was to create a vision for modeling in 2025 and beyond. To prepare the workshop participants to achieve this goal, significant workshop time was invested in reviewing background material related to the status of the current CBP management modeling system and previous recommendations, and discussing likely management needs in 2025 and beyond.

The workshop planning was guided by the following overarching questions:

1. *Description of needs:* What are the mandates and the scientific, computational, and data management challenges the CBP faces in the coming years, and what critical changes and upgrades will have to be made to the CBP modeling system to meet these challenges?
2. *Review of advice:* How can information and recommendations from previous workshops and committee reports and organizations such as the STAC, National Research Council (NRC), CCMP and CSDMS be brought to bear to address these needs?
3. *Description of resources:* What human and infrastructure resources are going to be available to meet these future needs and challenges? How can resources be used more efficiently and collaboration among government, private, and academic partners be maximized? What additional resources might be needed and how might the various stakeholders and partners work most effectively to find or generate these?
4. *Visioning for 2025 and beyond:* Can a well-informed, realistic, and unified vision for future CBP modeling be created to guide us into the future?

The workshop began with a full-day plenary session, supplemented by pre-recorded video presentations that were viewed by participants prior to the workshop that addressed the first three questions above. The presentations and discussion reviewed the purpose of the CBP models, the current state of the CBP modeling system, and the goals of the workshop. In this plenary there were also presentations and discussions related to overarching considerations, such as management goals and challenges, how new technologies and modeling approaches can be used to address CBP modeling needs, and what a 2025 Phase 7 modeling system might look like. The second day of the workshop was spent in breakout sessions, organized around each of the major components of the CBP modeling system: land use, watershed hydrology, watershed nitrogen, watershed phosphorus, watershed sediment, estuarine physics and water quality, and living resources/ecosystem approaches. The breakout groups were charged to consider the needs and resources of the CBP partnership, within the context of prior advice, to develop a vision for future modeling. A final half day plenary session consisted of concise reports from the breakouts and discussion of the common elements and compatibility among proposed needs in the various component areas, with a view toward formulating a realistic and unified vision for future CBP modeling in 2025 and beyond.

The results of the workshop are organized into two sections in this report, followed by appendices. The first section on **Findings** highlights factual conclusions and the consensus of professional opinion that emerged from the workshop presentations and discussion. Those findings consider management perspectives, cross-cutting topics (e.g., the challenge of incorporating living resources and socio-economics into CBP models, the benefits of doing participatory modeling, the benefits of adopting modular approaches, the need to enable local scale decision support, and assess uncertainty and risk), the strengths and weaknesses of the current CBP modeling system, previous STAC advice, and a potential strawman for a 2025 modeling system. The second section on **Recommendations** presents specific actions that workshop participants recommended to advance CBP's modeling system for TMDL development in 2025 and beyond. Appendices include the workshop **Agenda**, a list of **Workshop Participants**, and **Links to Detailed Breakout Group Notes** from day 2 of the meeting.

2. Findings

The discussion in this section is a summary of the presentations made in plenary on the first day of the workshop. Any opinions expressed represent those of the individual making the presentation, not necessarily the outcomes of discussion at the workshop.

2.1 Management perspectives (Lee Currey and Rich Batiuk)

Introductory presentations by program managers with state agencies offered a broad overview of management goals and perspectives that provided context and guidance for subsequent breakout group discussions. The following summarizes the main points that were made:

Figure 1: Covers of federally mandated comprehensive restoration plans. These plans drive billions of dollars in environmental investments. The scientific underpinnings to these jurisdictional plans are the CBP partnership models. The plans shown here are (at the top) the 2010 *Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment established by the US Environmental Protection Agency* and (below from left to right) the 2010 C*hesapeake Bay TMDL Watershed Implementation Plan for the District of Columbia,* the 2010 *Pennsylvania Chesapeake Watershed Implementation Plan*, *Delmarva's Phase I Chesapeake Bay Watershed Implementation Plan* for 2010, the 2010 *Commonwealth of Virginia Chesapeake Bay TMDL Phase I Watershed Implementation Plan*, *Maryland's Phase I Watershed Implementation Plan for the Chesapeake Bay Total Maximum Daily Load* for 2010, *West Virginia's Chesapeake Bay TMDL Watershed Implementation Plan* for 2010, and the 2010 *Final Phase I Nutrient and Sediment Water Quality Improvement and Protection Plan for New York Susquehanna and Chemung River Basins and Chesapeake Bay Total Maximum Daily Load*.

- CBP partnership models must reflect recent scientific understanding and be relevant to current environmental issues in order to best inform significant Bay policy and funding decisions (Figure 1) that are driving billions of dollars in environmental investments. They must do so even while also providing a reasonably stable foundation upon which to base jurisdiction legislation, regulations, and investments.
- The current suite of CBP models are used to inform management decisions for nutrient and sediment pollution reduction and to evaluate progress toward those reduction goals.

- For programmatic success, Bay managers need to have strong political, financial, and scientific support. The science has to be objective, honest, defensible, and relevant while also being timely. Tools are also needed that foster collaboration and innovation, and all of the modeling and modeling support tools need to be transparent, relevant, understandable, and stable. These tools must also be able to assist managers in quantifying benefits, costs, uncertainties, and risks.
- The workshop is timely. The CBP partnership has determined that there are no "fatal flaws" in the recently approved Phase 6 models and the managers are not ready to consider implementation of major upgrades to the models at this time; however, it is understood that efforts to improve the CBP model system need to start now if they are to be available in 2025.
- The Phase 6 models are improvements over previous model versions and have more buy-in because of review and feedback from two key groups: scientists via STAC; and managers via the Water Quality Goal Implementation Team and its workgroups. The partnership review approach continues to work well.
- The recent Principals' Staff Committee (PSC) charge to assess the influence of climate change on Chesapeake water quality by the 2022 Milestone Assessment needs to be addressed. Recent STAC workshop recommendations need to be finalized, synthesized, and implemented.
- Over the next year, federal, state, and local jurisdictions will apply the Phase 6 models extensively in the development of the Phase III Watershed Implementation Plans (WIPs), which will guide water quality management implementation in the Chesapeake to 2025. Jurisdiction feedback to this visioning process is essential and should be scheduled immediately following completion of the Phase III WIPs.
- Implementation of water quality management practices has always occurred at the local level and the CBP partnership management goals and nutrient load allocations are becoming more local. Future CBP models need to be developed that are relevant to local concerns in the watershed, in addition to improving the simulation of nutrient-related hypoxia in the Bay.

Recent management successes and challenges where models played an essential role were also highlighted. The successes include achievement of the 2025 Chesapeake Bay watershed municipal and industrial wastewater treatment facilities goal a decade early, the summertime dead zone is decreasing in size (Figure 2), submerged aquatic vegetation (SAV) is recovering (Lefcheck et al. 2018; see also https://www.chesapeakeprogress.com/abundant-life/sav), and the blue crab population appears to be more stable than it was a decade ago.

The challenges include a changing human and natural environment. Climate change will influence weather patterns, which will affect sea level, hydrology, biology, biogeochemistry, and human use of the environment. The impacts of increasing population will continue to produce environmental stress. The population in 2010 was 17.4 million but the 2025 population is projected to be 19.4 million, which is an 11.5 percent increase.

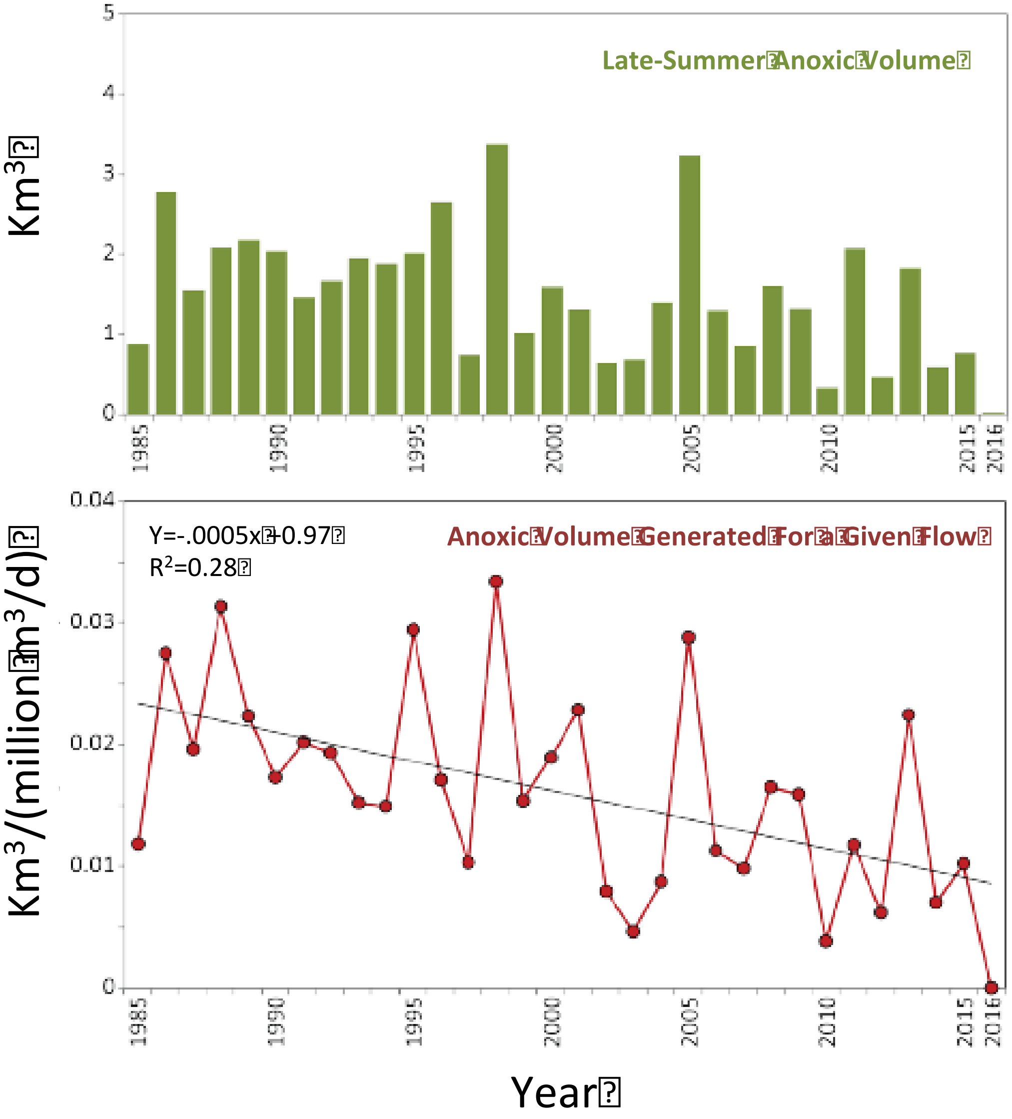

Figure 2: Late summer anoxic volume (top panel) and late summer anoxic volume normalized to flow, the latter showing a pronounced decline from 1985 to 2016.

Aside from the need to be relevant to Bay watershed agreements, additional challenges have been identified by managers that would ideally be addressed with model outputs on a local scale, such as flooding, water supply, local infrastructure protection, recreational uses, clean water for shellfish harvesting, stream restoration, flood plain re-connection, beneficial uses, and socio-economic connections. Collectively, these additional model outputs have come to be known as co-benefits or ecosystem services by the CBP.

Given past successes and rapid advances in the CBP partnership models, CBP managers are optimistic that the tools will be developed that are needed to assist managers in expanding existing programs and building new ones to restore the Chesapeake Bay and its watershed.

2.2 Cross-cutting topics (Scott Phillips, Tom Ihde, Lisa Wainger, Alexey Voinov, Eric Hutton, Lora Harris, Gary Shenk, Elizabeth North)

Several cross-cutting issues were reviewed in a panel discussion. The panel discussions were supported by summary presentations by panelists that workshop participants had been asked to review prior to the workshop. These included presentations on the need and challenge of incorporating living resources and socio-economics into CBP models, the potential benefits of doing participatory modeling to facilitate more stakeholder engagement, the benefits of adopting nimble modeling and modular approaches, and the need to enable local-scale decision support, and to assess uncertainty and risk. The following summarizes the main points that emerged.

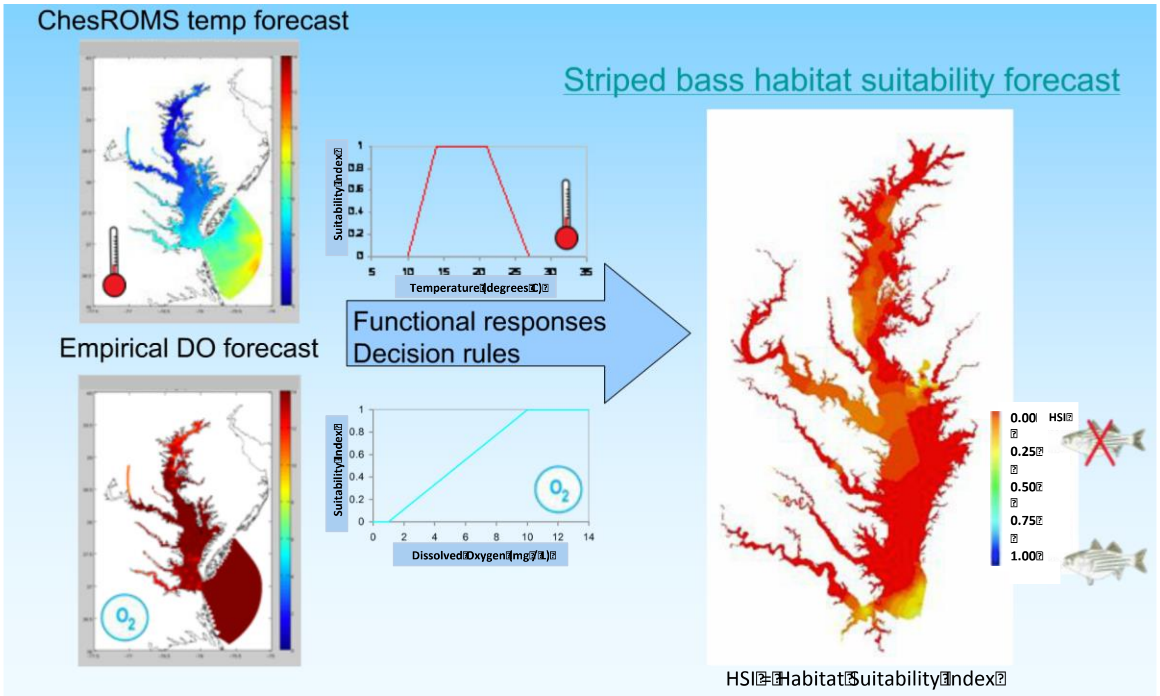

Figure 3: Schematic diagram of a striped bass habitat suitability model. This is an example of a “secondary model” that uses output from the CBP partnership models (e.g., water quality parameters) to define habitat quality and/or impacts on higher trophic level organisms (from Hood et al. 2010).

Efforts to incorporate living resources should start with further development and application of models that use output from the CBP watershed and water quality models, e.g., water quality parameters, to define habitat quality and/or impacts on higher trophic level organisms, e.g., the effects of water clarity on SAV; temperature and oxygen on striped bass (Figure 3); and oxygen on blue crabs. The CBP partnership estuarine water quality model should have a structure that enables direct coupling with models of higher trophic level species. Models of higher trophic levels should be modular so that they can be easily “swapped in and out” of the estuarine model. Over time, the incorporation of feedback from changes in numbers and activities of organisms at higher trophic levels should be integrated into water quality modeling. To accomplish this, the CBP must better engage with the higher-trophic-level modeling community.

Management decisions that are guided by the CBP partnership models should reflect social and economic outcomes, including the goals and outcomes identified in the 2014 Watershed Agreement[2] that are not directly related to water quality. These decisions should include consideration of things that humans care about such as water clarity, ecosystem resilience, sportfish abundance, sediment in shipping channels, and other environmental endpoints. They should also include the impacts of human actions that can impede or facilitate restoration efforts. The models should also have sufficient spatial and temporal resolution to support more refined management choices such as comparing the impacts of using different buffer types in a particular spot, and to enable the assessment of the impact of management decisions on human uses such as the impacts of restoration on specific recreational sites or shellfish beds.

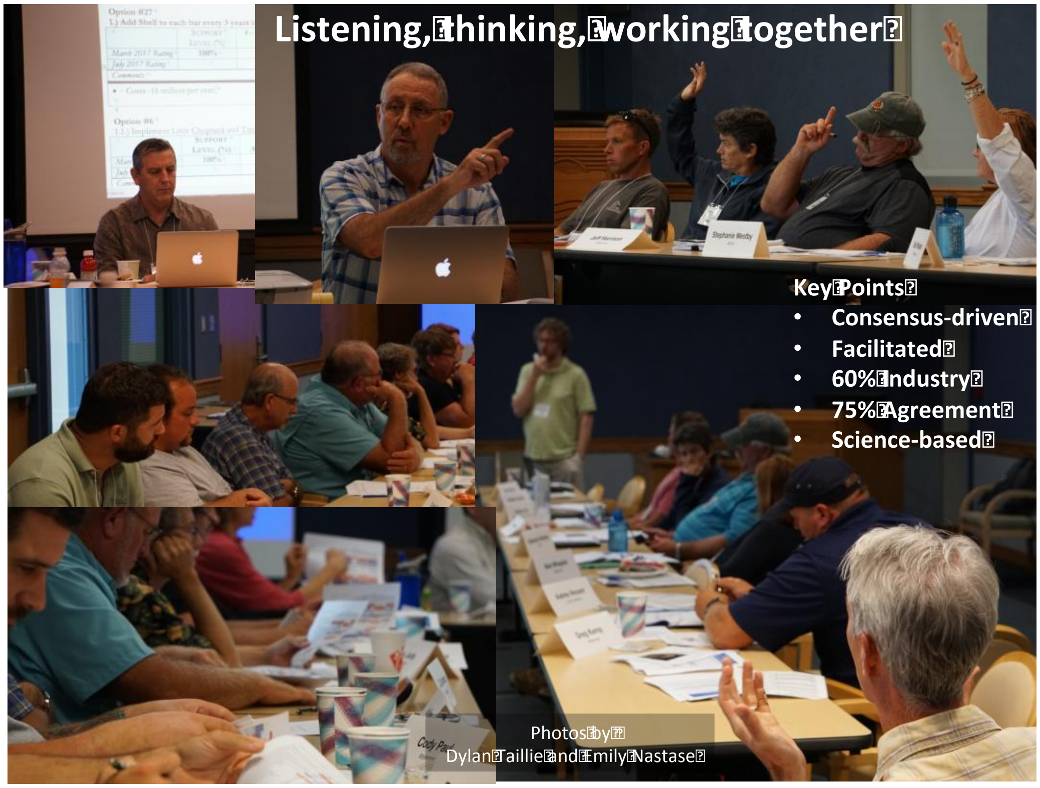

Figure 4: Photographic composite of an Oyster Futures stakeholder meeting. Oyster Futures was an NSF funded participatory modeling project that brought stakeholders together with scientists to develop and employ models that were used to help guide the development of consensus oyster management recommendations for Chesapeake Bay.

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[2] https://www.chesapeakebay.net/what/what_guides_us/watershed_agreement

Participatory modeling approaches provide a powerful means for increasing stakeholder engagement and buy-in. With such approaches, participants co-formulate the problem as well as the approach to finding solutions and can benefit from model use at all stages, i.e., in the description, solution, and decision-making actions of the group (Figure 4**).**

These approaches should be adopted by the CBP to the extent that it is possible. The CBP already elicits stakeholder input and concerns via its GITs and, as needed, adapts the partnership models appropriately in response. The models have achieved a significant level of buy-in and acceptance in that they are being used to allocate the pollution reduction effort; however, more could be done to work with stakeholders, particularly with local and ecological stakeholders, on designing solutions. Project FishSmart (Miller et al. 2010; Ihde et al. 2011) and Oyster Futures (Oyster Futures Stakeholder Workgroup, 2018; Figure 4) are examples of how participatory activities can be enhanced through approaches tailored to specific management needs.

Modular modeling refers to approaches that allow models to plug into one another thus allowing easy swapping of alternative models and formulations (Figure 5). This requires the adoption of a system of rules, protocols, and interfaces for model development. There are many advantages to modular modeling such as the promotion of openness and transparency of methods; the enabling of easier connections to the monitoring and research communities; and the facilitation of ensemble modeling. Modular modeling techniques should be adopted in the CBP partnership models wherever possible.

The CBP partnership needs to continue its efforts to make its models more directly applicable at smaller (local community) scales. Local managers want access to tools that can be used for local decision making, with the flexibility to assess multiple scenarios. Prediction of locally relevant restoration outcomes may also prove a powerful incentive to motivate investment and implementation. Some of these tools already exist in the CBP partnership models and multiple approaches for improving representation at smaller local scales (such as using unstructured or nested grids) have been proposed. Application to smaller scales requires that the models have sufficient resolution to resolve the regions and questions under consideration. However, refining spatial scale and increasing parameters have costs in

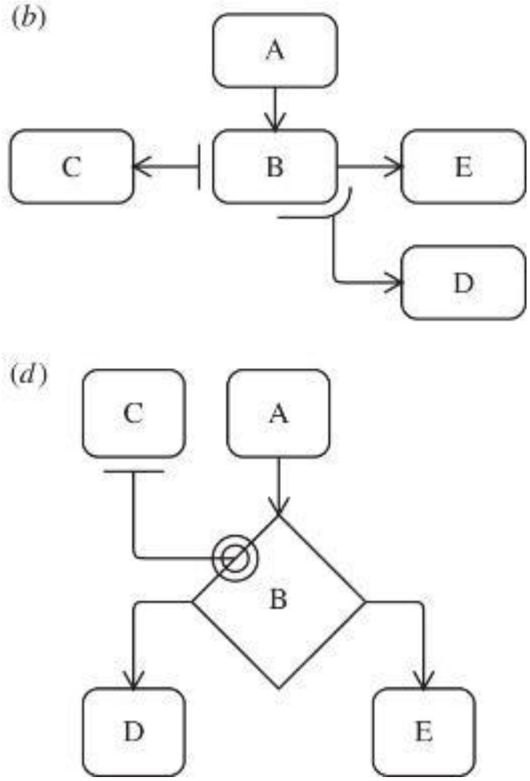

Figure 5: Schematic diagrams of modular model structures that allow models to plug into one another, and that allow easy swapping of alternative models and formulations.

computational time, development effort, data requirements, and parameter uncertainty. Some components of the CBP modeling suite may not benefit from further increases in resolution and so careful consideration should be given to which components to refine. A possible technical solution would be for the models to have adjustable spatial resolution and a modular design that would allow for a variable number of simulated processes.

Discussions have been ongoing in STAC for some time about the need to assess and address the uncertainty associated with simulated responses to management actions. Uncertainty in the predictions of the CBP TMDL decision support modeling system (Figure 6) is not yet being quantified except in the limited case of climate inputs and there has been little science yet applied to the issue of how managers can use uncertainty estimates to make the most robust decisions. Faster computer run times, increasing use of cloud-based computing systems, and ongoing efforts to increase uncertainty quantification of many input parameters through statistical means or the use of multiple models should enable much better quantification of model outputs in the future. However, these methods are not yet employed in a regulatory sense or in the generation of Bay-wide TMDLs. Historically, managers have not pushed for uncertainty quantification, perhaps related to unsettled questions regarding how to incorporate uncertainty into decision-making and the expense of performing the uncertainty analysis. To attract the attention of managers, uncertainty quantification must answer management-relevant questions. For example, managers may want to know the confidence that a certain set of management interventions will result in a particular degree of water quality standards attainment. Managers may also want to understand societal risks associated with levels of standards attainment and consider such confidence estimates as a key criterion in policy selection.

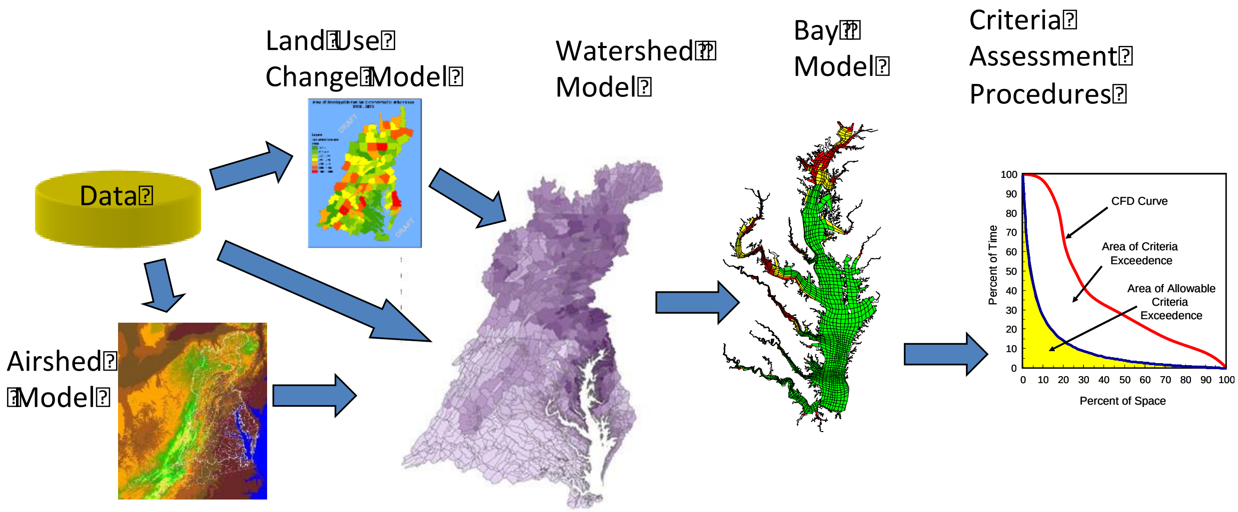

Figure 6: The CBP TMDL decision support system. Uncertainty in the predictions of the modeling system are not yet being quantified except in the limited case of climate inputs. What is the confidence that a certain set of management actions will result in a particular amount of standards attainment? Where should the CBP spend resources to increase that confidence? Note that “Bay Model” is synonymous with “Estuarine Model” referred to in the text.

2.3 The Chesapeake Bay Program models

To provide the workshop participants with the background necessary to have productive visioning breakout groups, the status of the current CBP management modeling system was reviewed in a series of plenary presentations that described the major components of the Phase 6 modeling system.

2.3.1 Airshed (Jesse Bash)

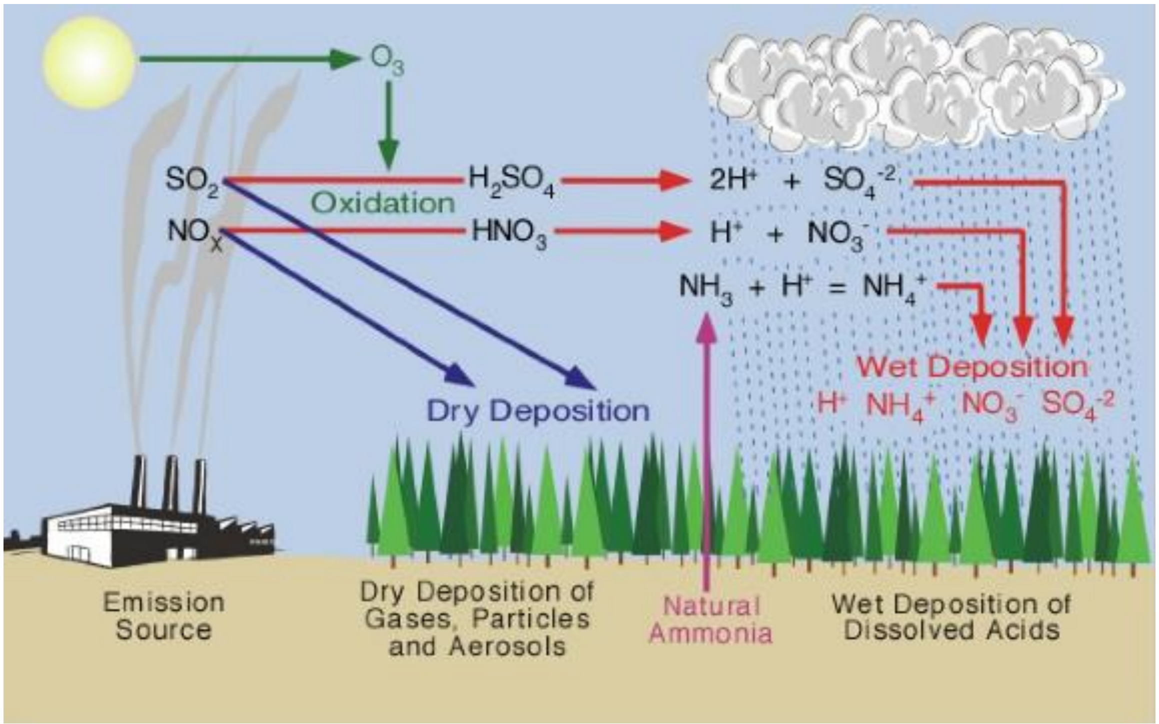

Figure 7: Schematic diagram of CMAQ airshed model that simulates transport, chemistry and deposition (gaseous and precipitation scrubbing) for ozone, particulate matter, toxics, acids, trace gases, etc., simultaneously. Transport, transformation and deposition of SO_2 and NOx depicted here.

The airshed model is the Community Multiscale Air Quality (CMAQ; Figure 7) modeling system, which is an open-source atmospheric transport and deposition model of the U.S. EPA Atmospheric Science Modeling Division (Foley et al. 2010). It consists of a suite of programs for conducting air quality simulations (Bash et al. 2013). The currently available CMAQ model has a domain that covers the North American continent at a 36 km x 36 km grid scale and is nested at a finer 12 km x 12 km grid scale over the Chesapeake watershed and Bay. It uses meteorological inputs from a weather model combined with emissions data from the EPA's National Emissions Inventory to calculate atmospheric transport, transformation, and deposition of a suite of anthropogenic pollutants, including several forms of oxidized (e.g., NOx) and reduced (e.g., NH_3) nitrogen. The predictions are augmented with results from an empirical model derived from data collected from 35 monitoring stations in the Chesapeake Bay watershed to provide daily estimates of both wet and dry deposition of NOx and NH_3 over the watershed and tidal Bay.

The airshed model was reported to do a reasonably good job at capturing the 2002-2012 trends in ambient oxidized nitrogen concentrations, which gives confidence that dry deposition is also simulated well (Zhang et al. submitted). Mid-Atlantic trends in oxidized and reduced N wet deposition are also captured well by the model. Planned near-term model developments include expanding the characterization of organic N deposition, better quantifying oxidized nitrogen concentration biases, more validation against field measurements, higher resolution simulations, and better quantification of parameterization uncertainty.

2.3.2 Land use (Peter Claggett)

The Chesapeake Bay Land Change Model (CBLCM, Figure 8) analyzes and forecasts the effects of population and employment growth on land use and wastewater in the Chesapeake Bay watershed for input into the CBP's Watershed Model and for other analyses (Claggett et al. in prep; see also output posted on the Phase 6 viewer[3]. The model forecasts change annually at a 30-meter resolution, which can be aggregated to a larger scale for a particular application. The model's forecasts are based on: 1) state-sanctioned projections of population and employment; 2) population and housing data reported by U.S. Census Bureau; 3) land-cover trends derived from satellite imagery; 4) mapped protected lands and sewer service areas; and 5) county-level zoning data. The CBLCM provides a means to address the challenge of determining how to maintain progress restoring the Chesapeake Bay in the face of continued population increase and urban development.

The CBLCM is capable of simulating future scenarios of residential and commercial development driven by exogenous projections of population and employment. For any particular scenario, e.g., "Accelerated Land Protection", the CBLCM produces 101 maps of potential future land use enabling an explicit quantification of uncertainty at the small watershed and county level. The CBLCM is being run for all states in the Mid-Atlantic region.

In 2015, the CBP partners committed to mapping land cover throughout the Chesapeake Bay watershed at 1m resolution. These data, representing 2013 conditions, form the baseline for backcasting and forecasting land use change in the Chesapeake Bay watershed. In addition, the USGS and CBP partners are analyzing these data together with high-resolution elevation data derived from LiDAR to better estimate the potential effects of riparian forest buffers, wetlands, upland runoff reduction measures, and stream restoration on nutrient and sediment loads. The analyses are also being used to help target restoration efforts and inform land development decisions.

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[3] https://chesapeake.usgs.gov/phase6/map/

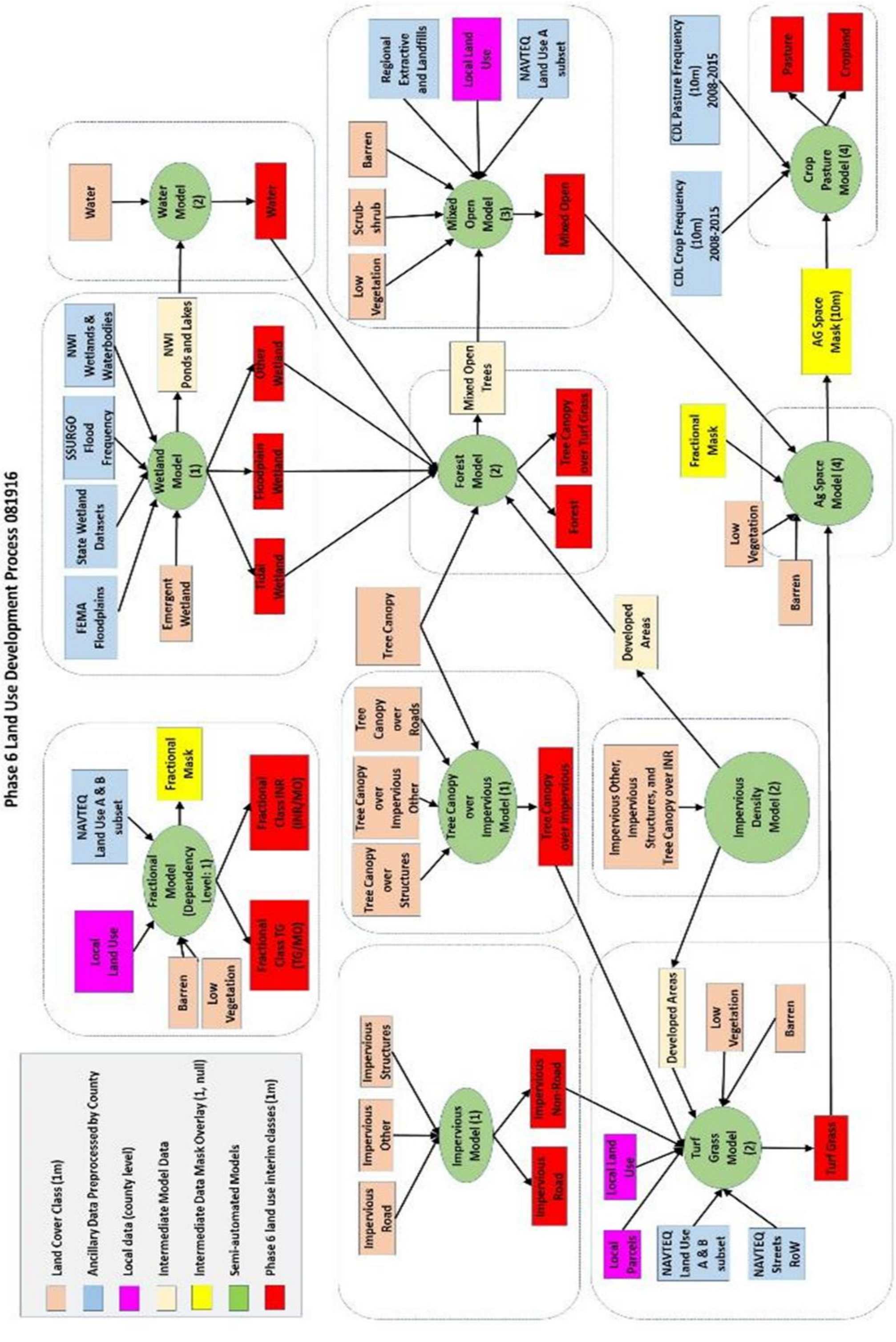


Figure 8: Schematic diagram of the Phase 6 land change model.

Potential future directions for development of this model include: repeat high-resolution characterization of land cover/use every 4-5 years, remapping past years each time; monitoring hot-spots of land use change every 2-years with Landsat satellite imagery; deconstructing current, high-resolution land use annually to 1984; mapping the locations of all animal operations and dedicated silviculture operations; tracking forest age; refining the characterization of cropland and pasture based on reported best management practices (BMPs) and other ancillary data; and using land change monitoring to verify land use and conservation BMPs.

2.3.3 Watershed (Gary Shenk)

The Phase 6 Watershed Model is used to estimate freshwater, sediment, nitrogen, and phosphorus loads to the Chesapeake Bay from multiple sources in the watershed. There are two versions of the Phase 6 Model (Figure 9), a time-averaged version widely used by the CBP partnership and a dynamic model version used to link the watershed, estuarine, and airshed models.

The CBP partnership uses the time-averaged version of the Phase 6 Model in the Chesapeake TMDL for assistance in setting planning target goals and tracking nutrient reduction progress toward the goals. The time-averaged Phase 6 Model uses simple parameterization to describe spatial differences in sediment and nutrient loading due to land use, management practices, and watershed transport. While there are few parameters in the Phase 6 Model, each parameter is supported by an extensive analysis that may include multiple models, expert elicitation, literature reviews, and statistical analysis. The time-averaged Phase 6 Model is available to users as the Chesapeake Assessment Scenario Tool (CAST) at cast.chesapeakebay.net.

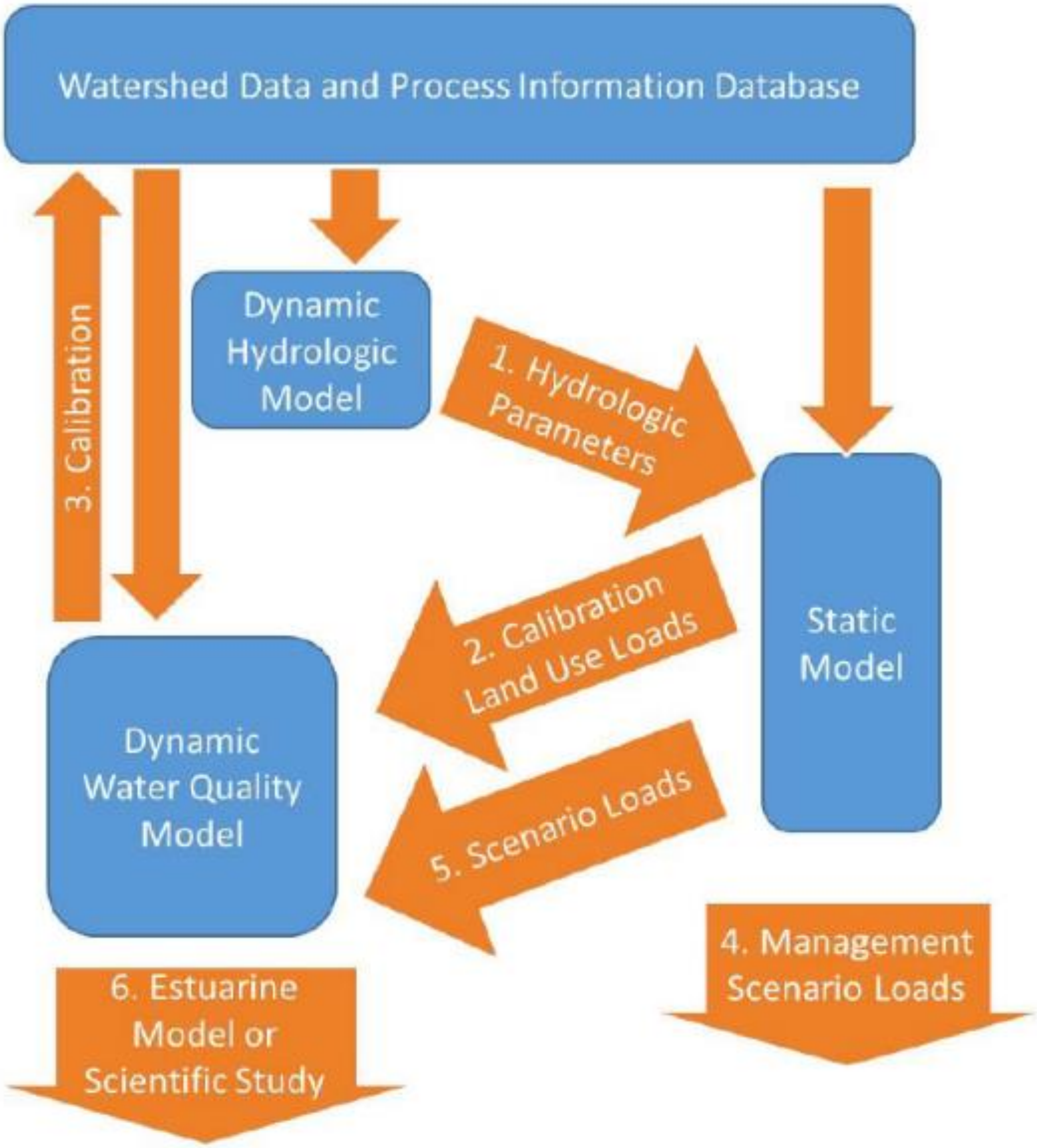


Figure 9: Relationship between the steady state and dynamic watershed models.

The CBP also maintains a dynamic Phase 6 Model to provide daily loads to the estuarine water quality model and to estimate some parameters in the time-averaged model. The dynamic model uses the Hydrological Simulation Program-Fortran (HSPF) to simulate hydrology and sediment. Nitrogen and phosphorus are simulated by a lagged temporal disaggregation of loads estimated by the time-averaged model. The dynamic and time-averaged models are calibrated together in an iterative process. The river delivery parameters in the dynamic model are calibrated to match in-stream monitoring data. Spatial biases are then used to update parameters in the time-averaged model and the dynamic model is then recalibrated. Documentation for the Phase 6 watershed model is available on the CAST web site: http://cast.chesapeakebay.net/Documentation/ModelDocumentation

Additional sources of data, models, or analyses could be used for the time-averaged model and new model structures could be considered for the dynamic model. In this regard, an outcome of the discussion was that it was reasonable for the CBP to continue for the immediate future to employ the current Phase 6 Watershed Model that uses multiple models (both dynamic and time-averaged) to determine TMDLs but to work diligently on further development for the scheduled periodic updates. One potential priority for future development of the Phase 6 dynamic model is incorporation of explicit carbon transport, transformation, and loading in addition to N, P and sediment.

2.3.4 Estuarine hydrodynamics and biogeochemistry (Carl Cerco)

Figure 10: CH3D hydrodynamic model grid.

The estuarine water quality model is a coupled hydrodynamic-biogeochemical-sediment transport model that includes coupled models for SAV and for benthic filter-feeders. This is the decision model for tidal Bay dissolved oxygen (DO), chlorophyll, and clarity water quality standards. The hydrodynamic model (Curvilinear Hydrodynamics in 3-dimensions or CH3D) is based on a model originally developed by Sheng (1986) that was subsequently modified extensively for application to Chesapeake Bay (Johnson et al. 1991; Kim 2013). The hydrodynamic model is forced by tides, wind, freshwater inflow, and heat exchange at the water surface; salinity and temperature fields are prescribed on offshore open boundaries using observations. Daily freshwater inflow from rivers, diffuse coastal plain surface flows, and groundwater flows are all prescribed using output from the Phase 6 Watershed Model. The CH3D model then calculates time-dependent variations in salinity, temperature, water-level elevation, velocity, and turbulent diffusivity in three dimensions with a 90-second time step. It provides realistic intra-tidal computations. CH3D employs a Z-grid in the vertical direction. There are up to 19 layers with a uniform layer thickness of 1.52 m, except that the top layer thickness fluctuates with sea level. The surface layer is 2.14 m thick at mean tide. Horizontally, the governing equations in the Cartesian coordinate system are recast in a boundary-fitted curvilinear coordinate system to cope with the irregular shoreline configuration and deep channel orientation. In the present Chesapeake Bay configuration there are 11,064 surface cells and 56,920 total cells with an average grid cell dimension of 1,025 x 1,025 m (Figure 10).

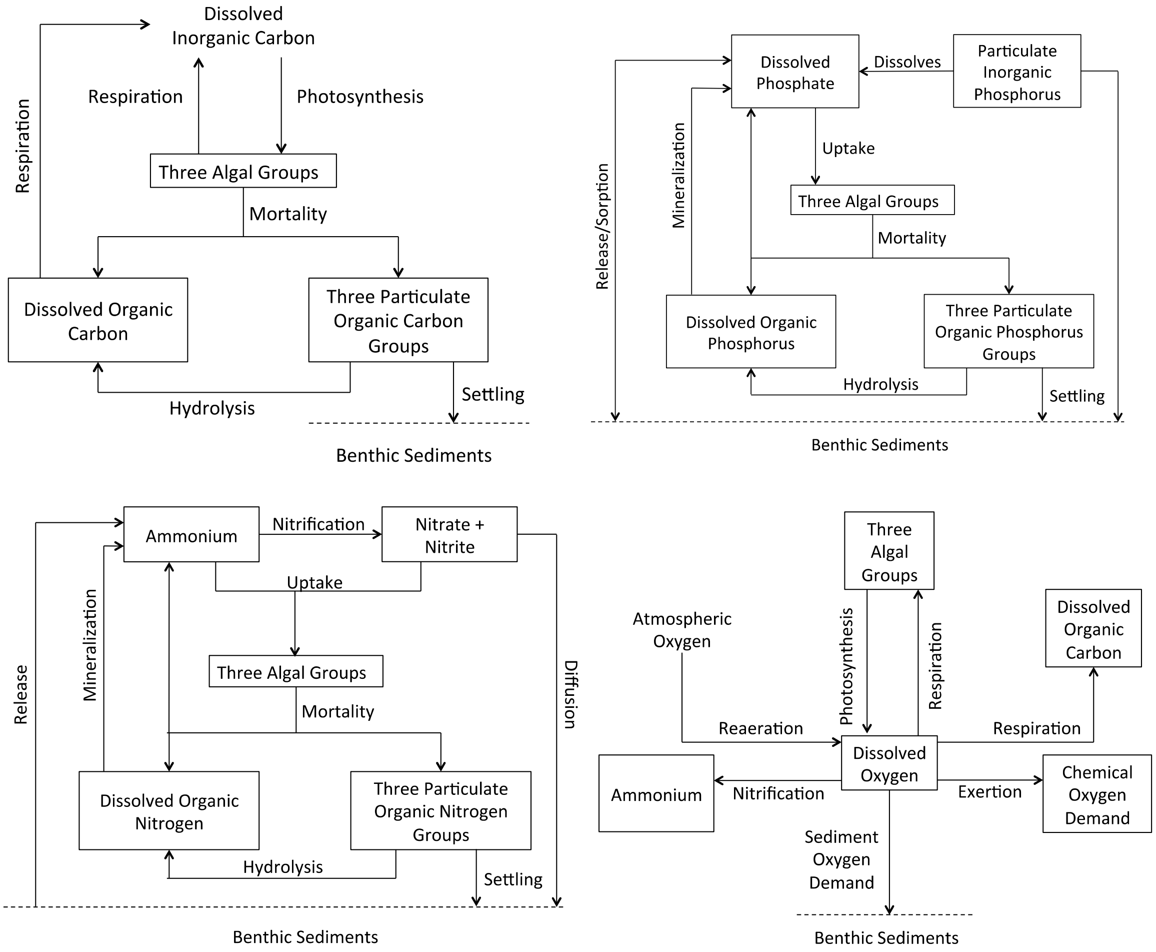


Figure 11: Schematic diagrams of the C, P, N and O_2 cycles in CE-QUAL-ICM.

The output from the CH3D hydrodynamic model, along with nutrient and sediment loads prescribed by the Phase 6 Watershed Model, are used to force an independent biogeochemical/water quality model (Corps of Engineers Integrated Compartment Water Quality Model or CE-QUAL-ICM; abbreviated ICM; Cerco and Cole 1993; Cerco and Noel 2013). The ICM Model uses the same grid as CH3D and is forced with hourly transport from CH3D, daily loads from the watershed model, and monthly boundary concentrations of nutrients at the mouth of Bay. The computational time scale is minutes. The ICM Model is a finite-volume eutrophication model that presently incorporates 24 state variables that include multiple forms of algae, carbon, nitrogen, phosphorus, silica, and dissolved oxygen (Figure 11). The model includes a benthic diagenesis submodel for calculating sediment oxygen demand and sediment-water nutrient flux (details below), and a sediment transport submodel for calculating sediment loading, deposition, erosion, and transport. A dynamic SAV model is incorporated to calculate the water clarity/SAV standard for the restoration of SAV and account for positive feedbacks that improve water clarity, e.g., SAV slows flow and reduces sediment resuspension. A dynamic oyster model is included to account for the effects of oyster filtration on water quality and clarity.

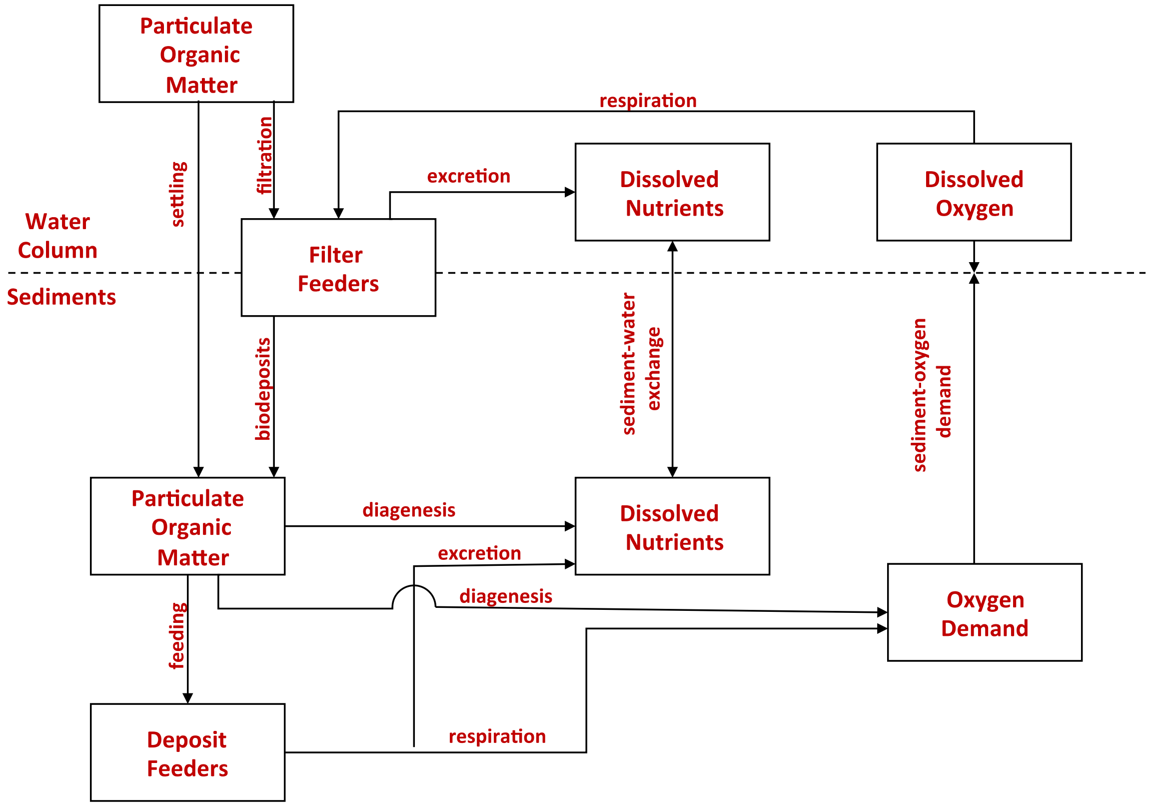


Figure 12: Schematic diagram of the sediment diagenesis submodel.

The sediment diagenesis submodel (Figure 12), based on DiToro (2001), is coupled to ICM in order to account for the response of sediment-water nutrient and oxygen exchanges to management actions in the watershed. The spatial and computational time scales of the sediment diagenesis model are the same as the water quality model. The diagenesis model considers a 10 cm thick active sediment layer. The active layer incorporates an aerobic surface layer with the remainder considered anaerobic. The thickness of the surface aerobic layer is calculated based on overlying water column oxygen concentration and model calculated sediment oxygen demand. The aerobic first layer is usually much thinner than the anoxic second layer (1-2 mm vs. 10 cm). In the anoxic layer, organic matter (N, P and C) remineralization occurs via denitrification; sulfate reduction and methanogenesis depending upon nitrate availability and salinity regime. The model responds to conditions in the water column instantaneously. Years of model spin up are required, however, to equilibrate new scenario loads with burial and refractory diagenetic processes.

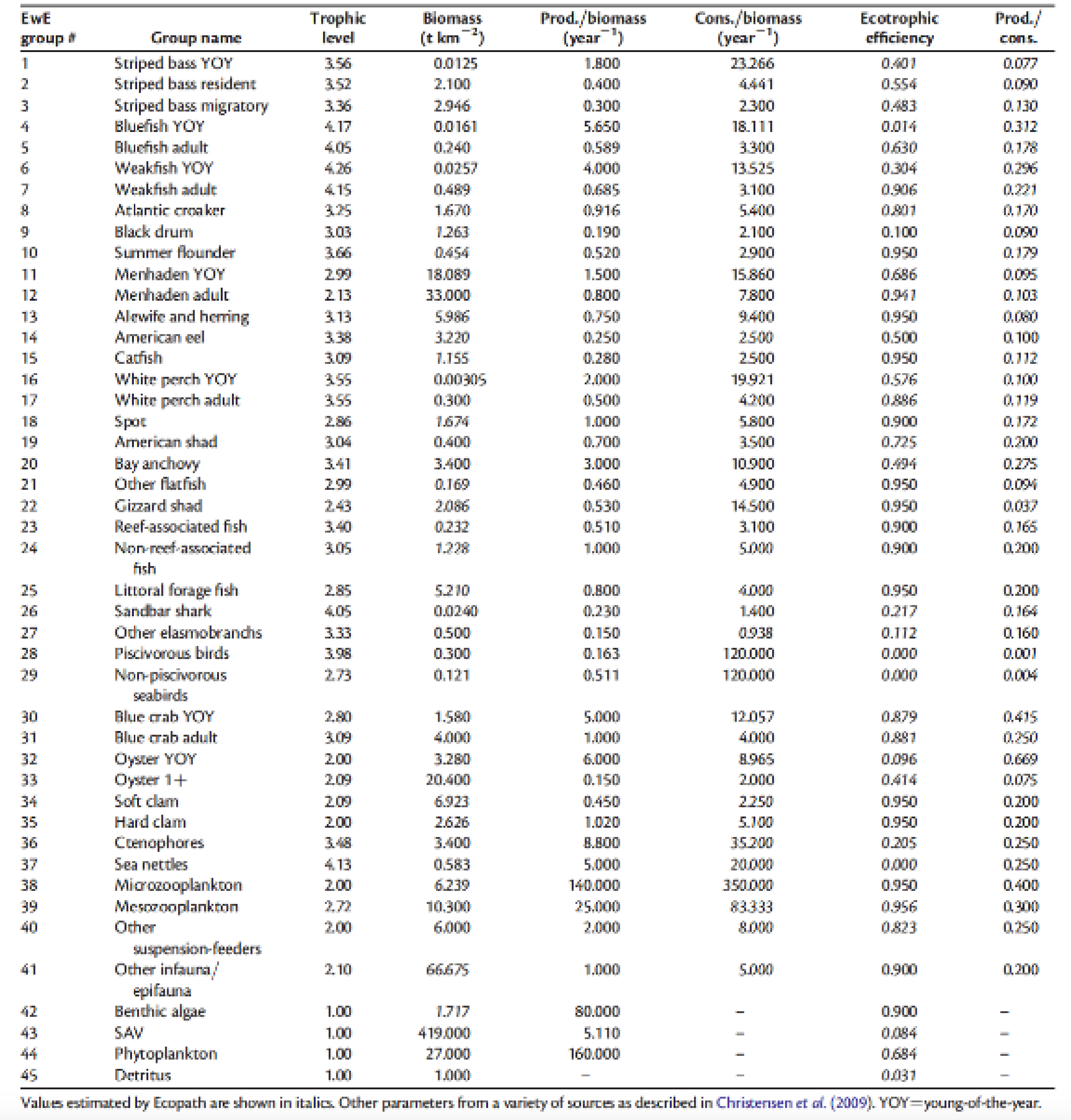
Potential future development of the hydrodynamic and biogeochemical models relates mainly to their configuration and resolution. Transitioning to a model with a fine scale unstructured grid could provide the greater resolution needed in the shallow tributaries of the Bay. At present, ICM is run “offline” from CH3D. That is, hydrodynamics from a single CH3D model run are saved and used repeatedly by ICM. This configuration is efficient in terms of computational resources, but prohibits feedbacks between ICM and CH3D. Whether or not the biogeochemical model should be run “offline” in future implementations, or “online” (fully coupled) to allow dynamic feedbacks between the hydrodynamic and biogeochemical models is an important question that needs to be considered. Future implementations would benefit from having watershed model forcing that includes carbon. At present, carbon loading to the estuary is estimated by ratio to organic nitrogen loads.

2.3.5 Estuarine living resources (Tom Ihde and Raleigh Hood)

Ecosystem modeling approaches compliment the biogeochemical and physical models discussed so far, in that they are designed to estimate living resources (i.e., animal and habitat populations) explicitly, in the context of their environments. Some approaches (e.g., Ecopath with Ecosim, EwE; Christensen and Walters 2004) are designed to incorporate the main trophic drivers that affect populations (i.e., predators and prey). Other, more complicated approaches (e.g., Atlantis, Fulton et al. 2003; Fulton et al. 2004) attempt to model populations in the context of the whole system; these are termed “end-to-end” modeling approaches, and include the bio-geophysical environment, as well as the spatial dynamics of habitat quality, availability, and phenology of each modeled group. Both EwE and Atlantis models have been developed for the Chesapeake Bay system.

Ecosystem approaches are designed to aid in policy decision analysis, and provide information on trade-offs for policy makers by simulating future environmental scenarios that may not have yet been observed in our data record (e.g., water temperatures predicted 50 years from now for this region, expected increased human populations, projected habitat loss or gain, attainment of the nutrient and sediment TMDL’s, etc.). Such models compliment the regulatory models described above, because they are designed for strategic planning for future conditions, simultaneously predicting population outcomes for multiple populations under new conditions, in contrast to regulatory models that seek to predict attainment of water quality standards (realized DO, nutrient, or turbidity) under established BMP’s.

Given the wide range of outcomes and goals of the 2014 Watershed Agreement that are not directly addressed with the regulatory models, ecosystem approaches that seek to model living resources directly are likely to be increasingly important for the CBP.



EwE group #	Group name	Trophic level	Biomass (t km^{-2})	Prod./biomass (year^{-1})	Cons./biomass (year^{-1})	Ecotrophic efficiency	Prod./cons.
1	Striped bass YOY	3.56	0.0125	1.800	*23.266*	*0.401*	0.077
2	Striped bass resident	3.52	2.100	0.400	*4.441*	*0.554*	0.090
3	Striped bass migratory	3.36	2.946	0.300	2.300	*0.483*	*0.130*
4	Bluefish YOY	4.17	0.0161	5.650	18.111	*0.014*	*0.312*
5	Bluefish adult	4.05	0.240	0.589	3.300	*0.630*	*0.178*
6	Weakfish YOY	4.26	0.0257	4.000	13.525	*0.304*	*0.296*
7	Weakfish adult	4.15	0.489	0.685	3.100	*0.906*	*0.221*
8	Atlantic croaker	3.25	1.670	0.916	5.400	*0.801*	*0.170*
9	Black drum	3.03	*1.263*	0.190	2.100	0.100	0.090
10	Summer flounder	3.66	*0.454*	0.520	2.900	0.950	*0.179*
11	Menhaden YOY	2.99	18.089	1.500	15.860	*0.686*	*0.095*
12	Menhaden adult	2.13	33.000	0.800	7.800	*0.941*	*0.103*
13	Alewife and herring	3.13	*5.986*	0.750	9.400	0.950	*0.080*
14	American eel	3.38	*3.220*	0.250	2.500	0.500	0.100
15	Catfish	3.09	*1.155*	0.280	2.500	0.950	*0.112*
16	White perch YOY	3.55	0.00305	2.000	*19.921*	*0.576*	0.100
17	White perch adult	3.55	0.300	0.500	4.200	*0.886*	*0.119*
18	Spot	2.86	*1.674*	1.000	5.800	0.900	*0.172*
19	American shad	3.04	0.400	0.700	3.500	*0.725*	0.200
20	Bay anchovy	3.41	3.400	3.000	10.900	*0.494*	*0.275*
21	Other flatfish	2.99	*0.169*	0.460	4.900	0.950	*0.094*
22	Gizzard shad	2.43	*2.086*	0.530	14.500	0.950	*0.037*
23	Reef-associated fish	3.40	*0.232*	0.510	3.100	0.900	*0.165*
24	Non-reef-associated fish	3.05	*1.228*	1.000	*5.000*	0.900	0.200
25	Littoral forage fish	2.85	*5.210*	0.800	*4.000*	0.950	0.200
26	Sandbar shark	4.05	0.0240	0.230	1.400	*0.217*	*0.164*
27	Other elasmobranchs	3.33	0.500	0.150	*0.938*	*0.112*	0.160
28	Piscivorous birds	3.98	0.300	0.163	120.000	*0.000*	*0.001*
29	Non-piscivorous seabirds	2.73	0.121	0.511	120.000	*0.000*	*0.004*
30	Blue crab YOY	2.80	1.580	5.000	*12.057*	*0.879*	*0.415*
31	Blue crab adult	3.09	4.000	1.000	*4.000*	*0.881*	0.250
32	Oyster YOY	2.00	3.280	6.000	8.965	*0.096*	*0.669*
33	Oyster 1+	2.09	20.400	0.150	2.000	*0.414*	*0.075*
34	Soft clam	2.09	*6.923*	0.450	*2.250*	0.950	0.200
35	Hard clam	2.00	*2.626*	1.020	*5.100*	0.950	0.200
36	Ctenophores	3.48	3.400	8.800	*35.200*	*0.205*	0.250
37	Sea nettles	4.13	0.583	5.000	*20.000*	*0.000*	0.250
38	Microzooplankton	2.00	*6.239*	140.000	*350.000*	0.950	0.400
39	Mesozooplankton	2.72	10.300	25.000	*83.333*	*0.956*	0.300
40	Other suspension-feeders	2.00	6.000	2.000	*8.000*	*0.823*	0.250
41	Other infauna/ epifauna	2.10	*66.675*	1.000	*5.000*	0.900	0.200
42	Benthic algae	1.00	*1.717*	80.000	–	0.900	–
43	SAV	1.00	419.000	5.110	–	*0.084*	–
44	Phytoplankton	1.00	27.000	160.000	–	*0.684*	–
45	Detritus	1.00	1.000	–	–	*0.031*	–

Values estimated by Ecopath are shown in italics. Other parameters from a variety of sources as described in Christensen *et al.* (2009). YOY=young-of-the-year.

Table 1: Basic parameters for the Chesapeake Bay Fisheries Ecosystem management Model (CBFEM).

The Chesapeake Bay implementation of Ecopath (Chesapeake Bay Fisheries Ecosystem management Model or CBFEM) uses the biomass estimations of 45 trophic groups representing the fisheries species of the Bay and their prey and predators (**Table 1**) to create a mass-balanced snapshot of the organisms and trophic linkages in the Bay as it may have been in 1950 (Townsend 2014). The snapshot provides the base model for Ecosim simulations. The 45 trophic groups represent either single stocks, substocks, or species groups that occupy similar foraging niches (**Table 1**). The model includes the representation of the key commercially important species (striped bass, bluefish, weakfish, white perch, Atlantic menhaden, blue crab, and oyster) as well as single biomass pool groups of other commercially important species (American eel, Atlantic croaker, summer flounder, spot, alewife, American shad, black drum, catfish, and bivalves). The Chesapeake Bay Ecosim module provides a 53-year (1950–2002) simulation that attempts to estimate the current status and dynamics of the Bay's fish species (Townsend 2014).

The Chesapeake Bay Ecosim simulations have been loosely coupled to the CBP water quality model by forcing it with time-dependent chlorophyll *a* output from the water quality model, which was done to assess how water quality management strategies affect upper-trophic-level organisms. Specifically, the model was used to simulate the impacts of a 40% reduction in the nutrient inputs on upper-trophic-level species (the biomass of striped bass, Atlantic menhaden, blue crabs, and eastern oysters) (Townsend et al. 2014).

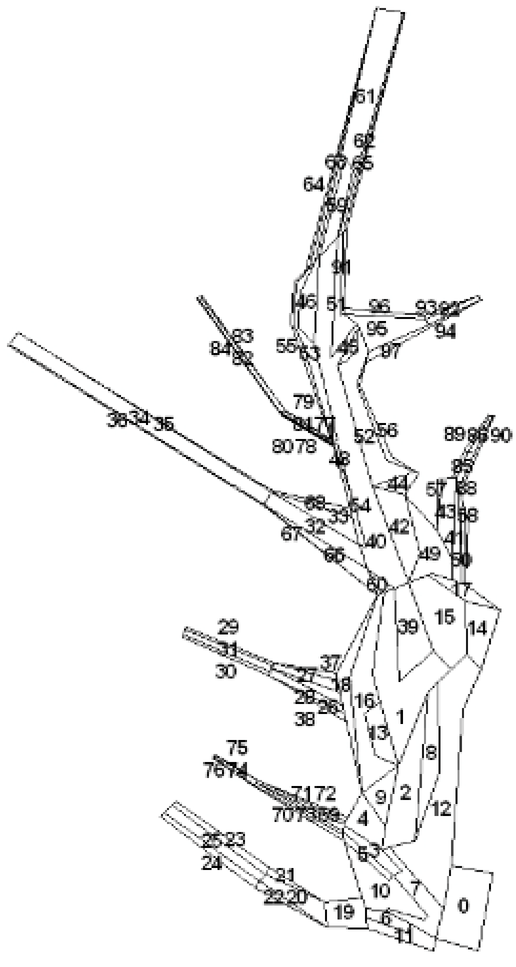


Figure 13: Spatial structure of the Chesapeake Atlantis Model (CAM). The model consists of 97 irregular polygons determined by salinity, depth, bottom type (mainstem only) and management boundaries.

The Chesapeake Atlantis Model (CAM) is, in contrast, a spatially explicit (three-dimensional), ecosystem simulation model (Ihde et al. 2016; Ihde and Townsend 2017). The CAM domain (Figure 13) includes the brackish waters and sediments of the mainstem Chesapeake Bay and eight of its largest tributaries including the James, York, Rappahannock, and Potomac Rivers in Virginia, and the lower Susquehanna, Patuxent, Choptank, and Nanticoke Rivers in Maryland. The model area is divided into 97 irregular polygons, which are aggregated areas defined by salinity, depth, and by bottom type in the mainstem Bay (Figure 13). Water movements in CAM are driven by the Navy Coastal Ocean Model (NCOM) Relocatable Model. Nutrient and sediment loads to the model are derived from the Chesapeake Bay Phase 5.3 Community Watershed Model.

CAM includes 55 functional groups to model biological processes; of these groups, 26 are invertebrates (including the primary producers and multiple bacterial groups) and 29 are vertebrates. Most invertebrates are modeled as single state variables (mg N/m^3), but two invertebrate groups (blue crab and brief squid) are modeled as linked juvenile and adult state variables. All vertebrate groups are divided into 10 age classes, each tracked by abundance and weight-at-age. CAM uses nitrogen as the currency for nutrient exchange for all groups. Metabolic waste and decaying organisms form multiple forms of detritus are cycled through bacteria to provide nutrients for both planktonic and benthic floral growth. Habitat types in CAM include both physical (mud, sand, rock and woody debris) and biogenic (marsh, SAV and oyster reef). The biogenic habitats function to provide refuge for prey from predator groups. Fish and other animal groups are assigned a “dependence” to one or more of the seven habitat types.

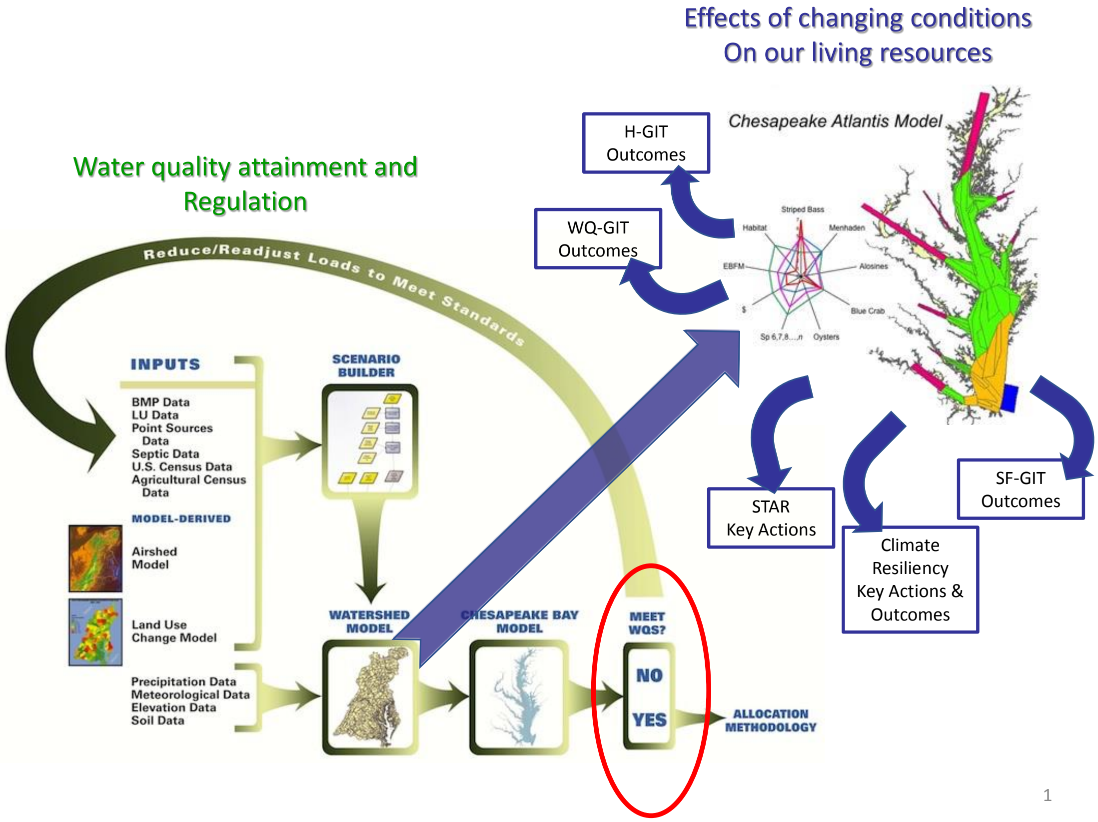


Figure 14: Relationship between the Chesapeake Bay partnership models and the Chesapeake Bay Atlantis Model (CAM) showing how the CBP Watershed Model can be used to force CAM to examine effects of restoration and changing conditions on living resources.

CAM has been used to estimate the higher trophic level impacts of fully achieving the TMDL pollutant load targets for present day climate conditions, for climate change/warming scenarios, and it has been used to predict effects of habitat loss, restoration, and cumulative effects of combinations of all these factors (Ihde et al. 2016, Ihde and Townsend 2017). These simulations were run using nutrient and sediment loads derived from the Phase 5.3 Community Watershed Model (Figure 14; Ihde et al. 2016). Neither CBFEM nor CAM (or any of the higher trophic level components of these models) have been directly coupled to the CBP estuarine hydrodynamic and biogeochemical models. The CAM model actually replaces ICM, i.e., Atlantis is built on a bio-geophysical model, and simulates the estuarine populations of both flora and fauna, including bacteria and bacterial cycling of nutrients. The feasibility of trying to extract the higher trophic level formulations from CAM and couple them to CH3D/ICM is an open question. However, CAM could potentially provide the means to compare multiple models to begin to bracket uncertainty of lower trophic level model predictions.

One role that may be important for CAM is to function as a modular replacement or alternative model to ICM in order to address many of the goals and outcomes of the most recent Watershed Agreement (2014) that relate to higher trophic level species that are not simulated by ICM

Alternatively, the CBFEM could be developed further into an Ecospace model, which would allow for (loose) coupling to ICM, as Ecospace does not contain its own bio-geophysical model. Making use of the newly developed habitat capacity model within Ecospace (Christensen et al. 2014) would allow for using ICM output as environmental drivers affecting the biomass and spatial distribution of estuarine living resources. Comparing an Ecospace version of CBFEM with CAM would then provide a higher trophic level multi-model approach. For certain species, single species models could provide good additional tools to simulate estuarine living resources, further adding to the multi-model toolbox.

2.4 Review of previous STAC advice (Lisa Wainger)

STAC provides independent scientific and technical guidance to the Chesapeake Bay Program partnership in various ways, including technical reports and position papers, reviews of CBP projects and products, in addition to coordinating and summarizing outcomes of technical workshops. The following summarizes the recommendations that have emerged from several STAC model reviews convened prior to this workshop, along with recommendations from STAC sponsored workshops, a 2011 National Academies Report, GIT meetings and discussions, and Principals' Staff Committee (PSC) meetings as they relate to six major topics.

2.4.1 Model skill, uncertainty and sensitivity

Efforts aimed at characterizing the uncertainty in the CBP partnership model projections need to continue, in addition to independent verification and sensitivity testing to understand model skill. The multiple modeling approach currently used in the watershed modeling should fully exploit the multiple model framework and work towards a true ensemble modeling approach, which will enable Bayesian approaches and more quantification of uncertainties. In addition, improved representation of the uncertainly associated with input data is needed along with characterization of uncertainty and variability in BMP performance. Efforts aimed at improving model forcing and boundary conditions also need to be undertaken to improve the skill of water quality projections, e.g., improved meteorological and ocean boundary forcing.

2.4.2 Climate and land use change

Although some elements of climate change impact on Bay processes and modeling have been addressed in the intensive set of reviews associated with the 2017 Mid-Point Assessment of

TMDL development and associated modeling, STAC-related workshops and reviews of climate change modeling had not occurred by the time of this workshop and it had been some time (approximately a decade) since STAC had reviewed land-use modeling approaches. A subsequent STAC sponsored external review of the Chesapeake Bay Program partnership's Climate Change Assessment Framework (CCAF; Herrmann et al. 2018) concluded that the Partnership's approach of using climate model projections and downscaling provides an acceptable baseline for estimating changing climate conditions for the Chesapeake Bay. However, the review also outlined several areas where more details and/or further investigations were needed (Hermann et al. 2018).

In response to this review and subsequent reports to the PSC on the CBP model-estimated impacts of climate change on the TMDL, the PSC recommended that the approaches, processes, and parameterizations that are used in the CBP watershed and estuarine models, and the CCAF for estimating the impacts of climate change and sea level rise on the TMDL should be reexamined in detail. A STAC workshop dedicated to this reexamination was convened in September 2018[4].

2.4.3 Support for impacts of local management decisions

The CBP needs to adopt more mechanistic and dynamic treatments of wetland accretion and erosion processes and their impacts on water quality, and of the impacts of the filling of the Conowingo reservoir on Susquehanna River nutrient loads. More mechanistic and dynamic models are also needed to represent urban and agricultural BMPs. In general, efforts need to be undertaken to improve the CBP models' ability to represent the impacts of management actions and ecosystem response to those actions on an appropriate geographic scale. This could mean increasing model resolution and/or implementation of more process-based mechanisms. Better representation of the geographic variability of particle transport, storage, and reworking in the Chesapeake Bay watershed is also needed, along with assessment and better representation of water residence times in the estuary that effect responsiveness of the model to management actions. Tracking of actions on the ground, like BMP implementation, and incorporating these actions into the model should also be improved.

2.4.4 Support for local benefit estimation

The CBP partnership models need to do a better job of providing outputs that are related to local ecosystem services and economic impacts that are of direct interests to local stakeholders. These include, for example, representing how management actions lead to: changes in phytoplankton community structure and the frequency of phenomena like harmful algal blooms (HABs); changes in wetland extent and the ecosystem services that are associated with them; impacts on

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[4] "Chesapeake Bay Program Climate Change Modeling 2.0" - http://www.chesapeake.org/stac/workshop.php?activity_id=289

fish and fisheries, e.g., positive impacts of reducing hypoxia, increasing benthic ecosystem health, and habitat quality in general. The models could also be used to help predict the probability of the occurrence of pathogens, e.g., *Vibrio spp.*, and their potential negative consequences such as beach closures and shellfish advisories, and the transport and negative impacts of toxic contaminants.

2.4.5 Improved integration with scientific community

The CBP should continue to work toward strengthening its ties with the scientific community. The linkages can be improved through the adoption of modular modeling approaches which, through standardization of model formats, can facilitate adoption and use of alternative research/academic codes and approaches. The linkages can also be improved by making CBP-model codes, model predictions (e.g., archived model solutions) and model forcing data, more accessible to the Chesapeake Bay modeling community. More effective interactions between the monitoring and modeling communities should also be promoted.

2.4.6 Support for adaptive management

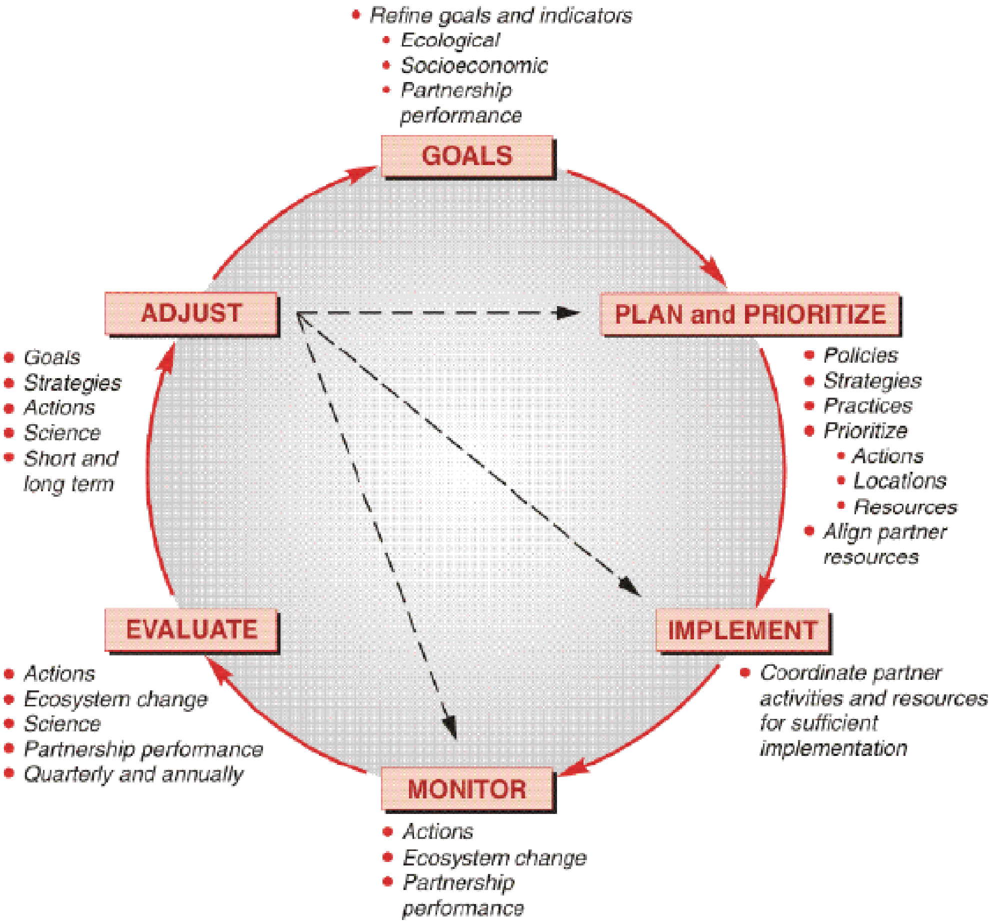

Figure 15: Schematic diagram of the adaptive management process.

Adaptive management (Figure 15), also known as adaptive resource management or adaptive environmental assessment and management, is a structured, iterative process of robust decision making in the face of uncertainty, with an aim toward reducing uncertainty over time via system monitoring. In this way, decision making simultaneously meets one or more resource management objectives and, either passively or actively, accrues information needed to improve future management. CBP managers should continue to develop and pursue adaptive management approaches to improve water quality in Chesapeake Bay.

2.5 Strawman for 2025 regulatory models (Lewis Linker)

2.5.1 Background

Trends from 1982 to 2016 in Chesapeake Bay Program's model development have included dramatic increases in spatial and temporal resolution in the core models (airshed, watershed and estuarine), and deeper integration with other key modeling efforts, such as SPARROW (Schwarz et al. 2006) in the Phase 6 Watershed Model. There has also been increased web-based distribution of open source, public domain model code, executable models, data, results, documentation, and, in general, support of community modeling. Over this time period, the Bay Program has also expanded incorporation of key living resources into its suite of models to examine the effect of water quality on a limited set of living resources (e.g., oysters and SAV, as discussed above). These trends, however, do not necessarily give us complete insight into the trajectory of model development in the future.

Both current and future CBP regulatory model development is driven by regulatory management needs. Managers want models that can help them determine: their loads; the loads of others; how much of their loads they need to control; the most efficient and cost-effective ways to achieve the needed load reductions; and how pollution management programs at different scales covering the same region fit together. Managers also need models that are available on schedule to support time-certain management deadlines such as the 2010 TMDL, 2017 Mid-point Assessment, and other major CBP decision milestones. Given these considerations, the standard operating procedures of all previous six modeling phases are likely to still be in play in the 2025 build (Phase 7) of the CBP models. That is, the CBP regulatory models and analyses will continue to be designed to assist the management community to: 1) make the nutrient reduction plans; 2) track management practice implementation; 3) make the nutrient reductions, and 4) restore the Chesapeake watershed and Bay. From this perspective, the CBP modeling tools are a means to a management end.

In addition, the CBP models encapsulate the scientific understanding needed to restore the Chesapeake Bay and its watershed. Developing this understanding involves providing support to Chesapeake Bay and coastal watershed restoration science through collaboration with academic researchers, and facilitating the establishment of connections between scientists and managers that are conducting monitoring, research and modeling in the Bay. Developing this understanding also involves providing opportunities for carrying out model-based experiments to test hypotheses and for corroborating CBP model findings. The latter is very important because it can reveal contradictions between CBP model findings and other models and/or observations, which can then be resolved.

Given these considerations, it seems likely that collaboration and cooperation between the CBP and academic and government scientists will only deepen going forward to 2025. The CBP builds models and carries out analyses, not only for setting TMDLs, but also to enable collaboration with the Chesapeake Bay scientific community and support their research to deepen a technical understanding of how to restore Chesapeake Bay and its watershed. From this perspective, the CBP modeling tools are also a means to improve collaborative, broadly supported, coastal estuarine science and restoration.

Future model development in the CBP must also build upon the triad of modeling, monitoring, and research, which considers that modeling without observations is not credible, monitoring without modeling is insufficient, and where research provides the foundation for everything (e.g., understanding of physical and biogeochemical processes and for determining model formulations, parameterizations, boundary conditions, etc.).

2.5.2 Examples of alternative models and approaches

New models that employ unstructured grids are now available for both hydrological and hydrodynamic modeling. These models can potentially solve one of the major challenges that the CBP faces, i.e., getting sufficient resolution exactly where it is needed in the watershed (e.g., representation of small streams and BMP implementations) and the estuary (e.g., representation of small tributaries to the main stem Bay) in order to support local-scale, non-tidal and tidal TMDLs.

2.5.2.1 An example of a distributed watershed model

The Penn State Integrated Hydrologic Model (PIHM) is an example of a next generation state-of-the-art, multi-process, and multi-scale hydrologic model where the major hydrological processes are simulated mechanistically using an unstructured grid and the semi-discrete finite volume method (Bhatt et al. 2014; Figure 16). Figure 17 shows an example of the domain decomposition of Mahantango Creek watershed into 2,606 triangular mesh elements and 509 linear stream elements (Bhatt et al. 2014). The model itself is "tightly-coupled" with “PIHMgis,” an open-source Geographical Information System designed for PIHM. PIHMgis provides the interface to PIHM, access to the digital data sets (terrain, forcing and parameters) and tools necessary to drive the model, as well as a collection of GIS-based pre-and post-processing tools.

Should a state-of-the-art model such as this be implemented in 2025 for all or part of the watershed? If so, should it be integrated within the existing Phase 6 structure or would it require a differently structured system? Or, is further refinement of the Phase 6 multiple modeling approach using HSPF and SPARROW that is currently employed by the CBP a more likely trajectory?

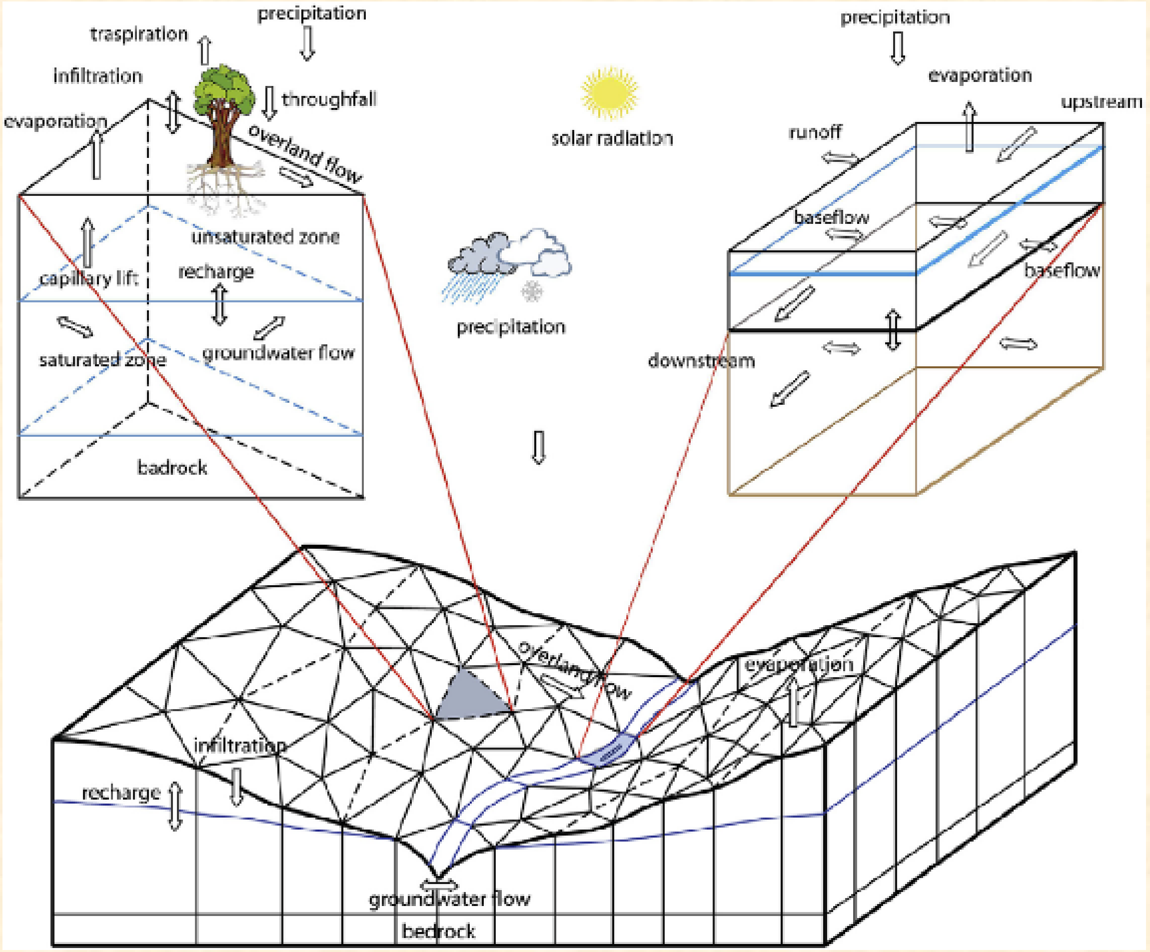

Figure 16: Example of a watershed model with an unstructured grid: The Penn State Integrated Hydrologic Model (PHIM). It is a multi-process, multi-scale hydrologic model where the major hydrological processes are fully coupled using the semi-discrete finite volume method.

Figure 17: Domain decomposition of Mahantango Creek watershed in PHIM.

2.5.2.2 An Example of an unstructured estuarine model in the Chesapeake

The Chester River hydrodynamic model based on SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model; Zhang et al. 2015; 2016) is an example of an unstructured formulation (Figure 18) that provides many advantages over the current CBP hydrodynamic model (CH3D). SCHISM is an open-source, community-supported modeling system based on unstructured grids, designed for seamless simulation of 3D baroclinic circulation across creek-lake-river-estuary-shelf-ocean scales. It uses a highly efficient and accurate semi-implicit, finite-element/finite-volume method with an Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations (in hydrostatic form), in order to address a wide range of physical processes. The numerical algorithm mixes higher-order with lower-order advection and diffusion schemes to obtain stable and accurate results in an efficient way. Mass conservation is enforced with the finite-volume transport algorithm and naturally incorporates wetting and drying of tidal flats. The number of vertical layers can also be altered spatially.

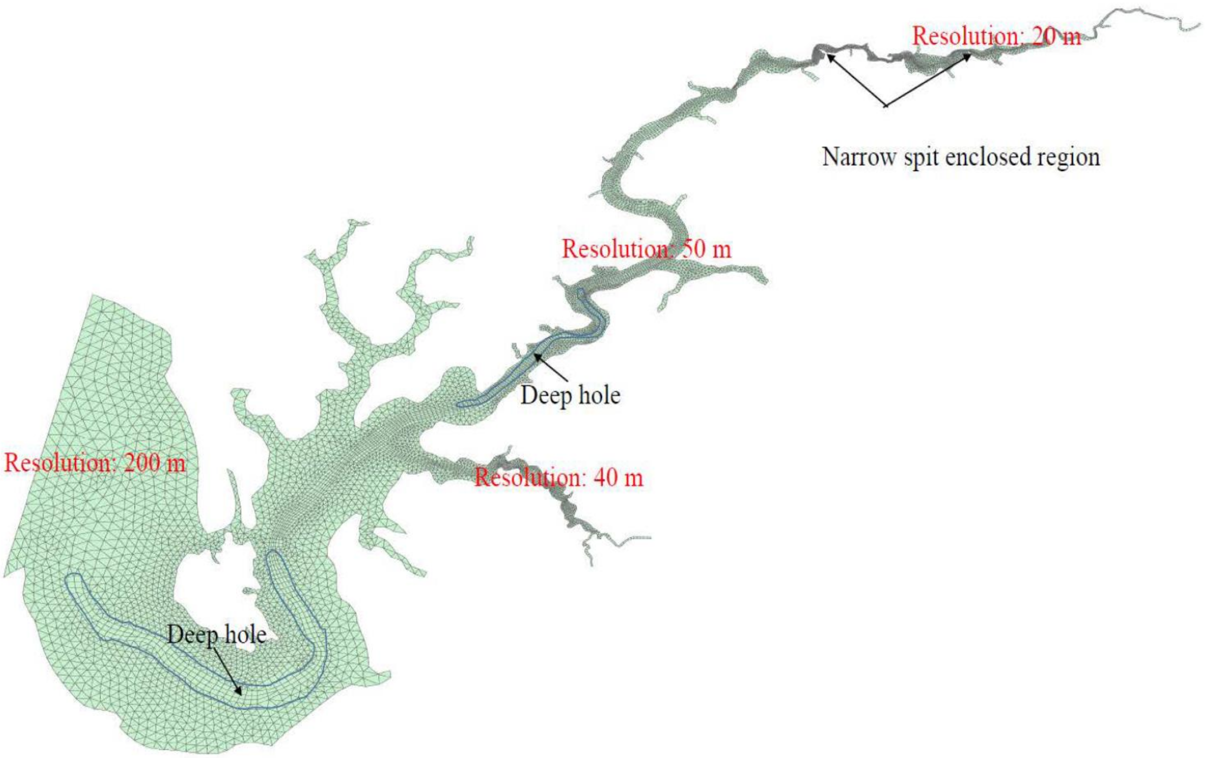

Figure 18: Example of an estuarine hydrodynamic model with an unstructured grid: Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) implemented in Chester River in Chesapeake Bay.

The SCHISM grid allows fine scale, adjustable horizontal and vertical resolution in the deep channels and flanks of the mainstem Bay and its tributaries (Figure 18). The wetting and drying allows for more accurate representation of SAV, benthic algae, and bottom light conditions, especially in the shallow tributaries. SCHISM is designed for parallel computing, which helps to satisfy the operational requirement of no more than a two-day turn-around time in management models. SCHISM's coupled wave model allows simulation of wave-induced sediment resuspension and sediment transport, which is also a required feature. SCHISM is well suited to support many other features required by the CBP, such as transport of multiple sediment particle classes and sediment diagenesis. The wetting and drying in SCHISM would also facilitate simulation of the influences of tidal wetlands on shallow water quality, and linkages to key living resources in shallow water habitat.

2.5.3 Coupled Living Resource Models

A water clarity/SAV standard has been established for the restoration of SAV. The current SAV model in ICM responds to water clarity; however, many other factors also influence SAV growth such as the physical characteristics of the bottom substrate (e.g., sandy vs. hard bottom). These additional influences need to be added to the model in order to realistically simulate the SAV growth and bed expansion observed in response to restoration efforts and improved water clarity in the Bay. Moreover, increased SAV biomass has positive feedbacks on improving water clarity because it dampens waves and slows currents, which in turn reduces sediment resuspension. The current coupled SAV model in ICM does not provide dynamic feedback to the hydrodynamics in CH3D. Future models seeking to incorporate these feedbacks should require a fully coupled hydrodynamic/biogeochemical/SAV model.

For more than a decade, oysters have been demonstrated to improve water quality, particularly in shallow water habitats where SAV grows. The current oyster model in ICM simulates oyster growth and filtration impacts on water quality and clarity, but oysters also impact rates of denitrification and provide habitat for many other species. Can some of the other ecosystem services of oysters not accounted for in the current model be incorporated in 2025?

The influence of Atlantic menhaden (*Brevoortia tyrannus*) on water clarity was examined in a study that used an individual based modeling approach with the current CBP models (Dalyander and Cerco 2010). This approach has not been used in any subsequent CBP studies. Can a more flexible and easy-to-use menhaden model be developed for examining their water quality and clarity impacts?

As described above, the Ecopath with Ecosim (CBFEM) and the Atlantis (CAM) models have been used to estimate the higher trophic level impacts that could occur by fully achieving the TMDL target pollutant loads, where both models were forced using output from CBP models (Townsend et al. 2014; Ihde et al. 2016; Ihde and Townsend 2017). Can these models somehow be more fully integrated into ICM with direct coupling (e.g., as discussed above, by further developing CBFEM into an Ecospace model, which would allow for loose coupling to ICM) or, alternatively, set up in such a way that the higher trophic level impacts of changing nutrient loads can be easily assessed? The latter can be done reasonably readily now in CAM, however, the funding to do so is currently lacking. Given that the future development of the Chesapeake Bay implementations of EwE and CAM are uncertain, can/should these models be moved under the development umbrella of the CBP?

2.5.4 Summary

The Chesapeake Bay’s TMDL regulatory process begins with good water quality standards, which includes dissolved oxygen standards for deep water, deep channel, open and shallow waters based on requirements of living resources. Chlorophyll and SAV/water clarity standards have also been established with the goal of protecting living resources. These standards, combined with CBP governance across 9 major river basins, 20 major tributary basins (by jurisdiction), and 44 state-defined tributary strategy sub-basins, provide the foundation needed to allocate the model-predicted loads to reduce hypoxia and improve water quality and habitat for living resources in the Bay.

The 2025 next-generation CBP suite of models should provide support across all of these scales, including local watershed TMDLs with fine-scale land-use and watershed modeling capability

(Maryland has > 300 non-tidal TMDLs). The 2025 suite of models should also support local tidal-water TMDLs, preferably with a hydrodynamic Bay model that employs an unstructured grid (Maryland has > 90 tidal water TMDLs). In addition, the models need to expand and better support ecological and higher trophic level (i.e., living resource) modeling. Though not discussed in this section, social scientists need to be engaged to ensure that discussions of the predictions from these finer resolution community-scale models involve the local stakeholders that will be affected by, and benefit from, the TMDLs. Finally, better economic assessments need to quantify the value and positive social outcomes of restoration, such as more fish, improved water clarity, swimmable water, etc.

Will there be a change in focus for 2025 in Chesapeake Bay management and models? The hope is that the CBP will be turning a corner in 2025 moving from determined, ongoing year-by-year nutrient reductions, despite the headwinds of growth and climate change, toward a maintenance phase of Chesapeake restoration.

2.6 Summary of Findings

The steering committee has distilled the presentations and discussion at the workshop (above) into the following key findings on how to improve the Phase 6 modeling system for TMDL development in 2025 and beyond:

1. There are no "fatal flaws" in the recently approved Phase 6 models, but there are opportunities for improvement and "evolution" by 2025 for still more effective application in the years 2025 and beyond.
2. The Phase 6 models are improved and have more buy-in than those of previous Phases because of review and feedback from STAC, the Modeling Workgroup, and the Water Quality GIT. This approach works and should continue.
3. Over the next year, federal, state, and local jurisdictions will use the Phase 6 models extensively. Their continued feedback to this visioning process is essential.
4. Efforts to incorporate living resources should start by using living resource models that are forced using output from the CBP partnership models, e.g., water quality parameters. The CBP estuarine water quality model should define habitat quality and/or impacts on higher trophic level organisms, and it should have a structure that supports direct coupling with models of higher trophic level species.
5. Management decisions guided by the CBP partnership models should reflect social and economic outcomes outlined in the 2014 Watershed Agreement. The decisions should include consideration of positive social outcomes like water clarity, ecosystem resilience, fish abundance, sediment in shipping channels, and other environmental endpoints. Models should be developed and continually improved for simulating these kinds of outcomes.
6. The participatory modeling approach taken by the CBP should continue to be advanced, improved, and refined.
7. Modular modeling techniques should be adopted in the CBP partnership models wherever possible. This requires the adoption of a system of rules and protocols for model development.
8. The CBP partnership should expand its efforts to make its models applicable to smaller "local" scales, appropriate to decision making for smaller-scale jurisdictions and watersheds. Managers want access to tools for use in local decision making, with flexibility to assess multiple scenarios.
9. The CBP should continue its efforts to work toward assessing the uncertainties in its modeling suite, with particular attention to simulated responses to management actions in the context of the TMDL. CBP managers should determine the relevant questions that need answering regarding model uncertainty and its use, so that appropriate techniques are developed both for estimation of uncertainty and obtaining guidance toward best managerial application of that knowledge.
10. The airshed (CMAQ) modeling effort should continue with its currently planned near-term model developments, which include expanding the characterization of organic N deposition,

better quantifying oxidized nitrogen concentration biases, more validation against field measurements, higher resolution simulations, and better quantification of parameterization uncertainty.

11. The Chesapeake Bay Land Change (CBLCM) modeling effort should continue with its planned near-term model developments which include, for example, repeat high-resolution land use characterization every 4-5 years, remapping past years each time; and monitoring land use change every 2-years with Landsat.
12. The CBP should continue to employ and develop the Phase 6 Watershed Model that uses multiple models to determine responses to management actions. One potential priority for future development of the Phase 6 dynamic watershed model is incorporation of explicit carbon transport, transformation, and loading in addition to the current simulation of nitrogen, phosphorus, and sediment fate and transport.
13. Potential future development of the hydrodynamic and biogeochemical models should focus on transition to a hydrodynamic model with an unstructured grid that can provide much greater resolution in the shallow tributaries of the Bay.
14. The current living resource simulation in the CBP water quality model, which includes SAV and oysters, should continue to develop with the goal of improving these models. Possible improvements include the incorporation of SAV feedbacks to hydrodynamics, and simulation of more oyster ecosystem services.
15. The CBFEM and CAM higher trophic level models should be moved under the development umbrella of the CBP and set up in such a way that the higher trophic level impacts of changing nutrient loads can be easily assessed.
16. The approaches, processes, and parameterizations used in the CBP watershed and estuarine models, and the CCAF for estimating the impacts of climate change and sea level rise on the TMDL should be reexamined in detail.
17. The CBP partnership models should strive to provide outputs related to local ecosystem services and economic impacts that are of direct interest to local stakeholders.
18. The CBP should continue to work toward strengthening its ties with the scientific community, and continue to support and pursue an adaptive management approach to improve water quality in Chesapeake Bay.
19. Future model development should continue to be driven by management needs, and future models must support time-certain management deadlines such as those that supported the 2010 TMDL and 2017 Mid-point Assessment.
20. The 2025 next generation CBP suite of models should provide support across a wide range of scales including local watershed and local tidal water TMDLs. Models that use unstructured grids are particularly well-suited to cover this wide range of scales.

3. Recommendations

Concise reports from the day 2 breakout group discussions were delivered on day 3 of the workshop. The following summarizes the major recommendations, broadly divided into two groups: estuarine and watershed.

3.1 Estuarine recommendations

3.1.1 Hydrodynamics

The Chesapeake Bay Program should:

1. Implement a next-generation unstructured-grid modeling system to replace the existing estuarine hydrodynamics/water quality/sediment transport modeling system in order to meet the anticipated 2025 needs that will require specification of local tidal water TMDLs.
2. Use a single primary model that is supported by multiple models (e.g., academic) for performing analyses to quantify model uncertainty and confidence levels.
3. Continue to engage the scientific community for evaluating performance of the new models, and the stakeholders to ensure that the Bay's nutrient reduction plans and the local needs are adequately met.
4. Allocate more resources to support the implementation and application of the new primary estuarine model and the activities in 1-3. These resources should support additional staffing at CBPO to improve the estuarine models and support improved access to outputs from these models.

3.1.2 Biogeochemistry

The Chesapeake Bay Program should:

1. Use an estuarine management-modeling framework that allows variable spatial resolution (e.g., high-resolution in shallow waters where it is needed, lower-resolution where not needed). An unstructured/hybrid grid would be a logical choice. This will facilitate inclusion of local processes that can inform management; it will help to engage with local stakeholders and use computational resources efficiently. In addition, a model with two-way coupling between hydrodynamic and biogeochemical models should be used for setting TMDLs to allow for feedbacks between physical and biological processes. One-way coupling should still be used for model development and testing because it is computationally less demanding.
2. Implement a modular, experimental framework that allows for testing of new/alternative biogeochemical models and formulations to inform the management model. This will allow for investigation of additional processes and alternative formulations to increase

certainty in the management model. The CBP should continue and expand its engagement with the academic and government research communities in order to incorporate the latest scientific advancements and knowledge.

3. Enhance the working relationship between biogeochemical and ecological modeling groups because the ultimate aim of the TMDLs is largely to inform restoration goals for living resources. The CBP should identify products from hydrodynamic and biogeochemical models that will inform living resources models/analyses and it should formalize the working relationship between the estuarine water quality and living resources modelers, perhaps via formation of a joint subcommittee.
4. Provide the resources needed to accomplish the above recommendations. These should include more human resources to replace and expand existing capacity/people, provide seed money for the recommended multiple modeling approach, and used to increase capacity for documentation, education on new modeling approaches, interoperability, data analysis, and online access to model outputs.

3.1.3 Ecosystem approaches

The Chesapeake Bay Program should:

1. Establish an Ecosystem Modeling Subcommittee responsible for both tidal and non-tidal aquatic systems. The subcommittee should adopt a portfolio of modeling approaches for living resources that includes:
    a. analyzing output from the CBP modeling system from a habitat/organism perspective;
    b. translating CBP modeling system output to develop habitat (or growth) suitability indices;
    c. using CBP modeling system output as input for ecological models, and
    d. integrating organisms into the ICM water quality model as has been done, for example, with oysters and SAV.
2. Empower the Subcommittee to select a formal set of criteria to help guide which living resources (including habitats) to model, and when.
3. Direct the Subcommittee to start with the following considerations:
    a. non-linear responses of living resources to nutrients and sediment;
    b. new approaches and purposes for modeling primary producers that include botanical processes;
    c. re-integrating consumers (i.e., zooplankton) into the biogeochemical model to facilitate coupling to higher trophic levels;
    d. identify and address data gaps for living resources, ensure accessibility to data;
    e. articulate mechanisms for communication and stakeholder involvement; and
    f. emphasize that modeling living resource responses allows communication of co-benefits of restoration to stakeholders.

3.2. Watershed recommendations

3.2.1 Land use

The Chesapeake Bay Program should:

1. Improve characterization of agricultural dynamics in the land use models. Livestock numbers and locations could be better determined, leading to better estimates of manure generation and ammonia emission. Detection of some crop types and cropping systems such as double cropping and irrigation should be improved.
2. Improve characterization of forests and forest dynamics in the land use model, focusing on states and changes such as composition, phenology, seral stage, and disturbances.
3. Incorporate the future risk of climate change into its land use projections using Representative Concentration Pathways (RCP) and sea level rise scenarios, with attendant population and employment projection trends.
4. Enhance representations of the drivers of land use change, such as population distributions, employment distributions, and emerging drivers focusing on obtaining spatially explicit distributions of sewer service, infill, and redevelopment.
5. Improve characterization of stream corridors, focusing on fluvial geomorphic metrics and riparian zone land uses.
6. Increase model transparency to enhance stakeholder trust with an open-source, cloud-based, modular design.
7. Develop a regional transportation model to help project potential future changes in transportation infrastructure and its impacts on land use and atmospheric emissions.

3.2.2 Hydrology

The Chesapeake Bay Program should:

1. Provide information for managers to justify development of finer resolution models that can resolve key features, areas of interest, source areas, and address other metrics of local significance such as flooding and water supply.
2. Develop these fine-scale models for small watersheds in addition to the watershed-scale Chesapeake Bay watershed model used for management. These fine scale models should resolve the fundamental scales of hillslope and low order streams. They should use regular or irregular mesh grids or Hydrologic Response Unit (HRU)-based, hillslope scale models and explicitly simulate delivery lags or incorporate residence time distributions. Finally, these fine scale models should be developed through partnerships between the CBP, and state or local jurisdictions.
3. Continue development and refinement of the Chesapeake Bay watershed-scale watershed model. This model should be based on a standard watershed such as the National Hydrography Dataset (NHD) or Hydrologic Unit Code (HUC). It should provide a ranking

of vulnerability or value for restoration, based on primary CBP metrics (i.e., N, P, C, sediment). This model should incorporate residence time distributions either explicitly or implicitly, co-varying with nitrogen, phosphorus, and sediment delivery. It should be consistent with fine-scale models or develop a protocol for reconciliation. Ultimately, the model should adopt an agile, modular design to facilitate investigation of additional processes and alternative formulations, and to increase transparency for scientists working on various aspects of watershed sediment, nitrogen and phosphorus transport and transformation.

4. Develop a complementary monitoring system that can co-evolve with the modeling system.

3.2.3 Nitrogen

The Chesapeake Bay Program should:

1. Improve quantification of nitrogen sources and sinks with high-resolution data and process modeling. Existing 1-m land cover data should be analyzed along with emerging high-resolution, near-stream morphology and groundwater redox layers. Riparian and wetland distributions should be quantified relative to source-stream connections. The information should be incorporated into landscape-scale models to quantify potentials to reduce nitrogen loads (Weller and Baker 2014, SPARROW). Hydrologic connectivity should be incorporated between sources and sinks (natural surface and subsurface flow and human modifications like ditches and tile drains), to identify critical source areas that contribute disproportionately to loads, and to target BMPs to those critical areas.
2. Build on the Phase 6 concept by developing an ensemble approach for the time-averaged model. This should include the development of a spatially explicit, mass-conserving, whole-Bay watershed model fit to the monitoring data (descended from SPARROW) in parallel with the CAST model. The ensemble model should estimate confidence in model predictions, test hypotheses about factors affecting sensitivities, efficiencies, delivery factors, and objectively quantify and visualize variability in sensitivities, efficiencies, delivery factors, and loads. This approach has the potential to identify patterns of poor performance that require model changes and to advance scientific understanding at the whole-watershed scale.
3. Adapt Phase 6 by implementing a more formal modular and hierarchical modeling system. This should include formalization of rules and procedures for linking among modules and across spatial and temporal scales. This will provide greater transparency and flexibility, and it will facilitate examination and testing of alternative approaches and models with higher resolution. All data, code, output, and documentation should be made openly available on-line. This will not only improve transparency, but it will also facilitate collaboration with scientists and stakeholders.
4. Incorporate more data in model calibration and in characterizing nitrogen sources and sinks, particularly in low-order streams. The efforts should include development of strategies to

use shorter time series and synoptic surveys to more effectively use the available monitoring data. New data in unmonitored areas, e.g., the Eastern Shore and Potomac River, and submarine discharges, should be collected to improve model estimates for those areas. New data should be collected in upper/small tributaries to provide load data commensurate with high resolution, fine scale map layers to better discern processes in low-order streams. Data should be collected on in-field uptake/loss relative to field conditions and landscape position to better identify and manage critical source areas.

5. Analyze mechanistic models to better quantify BMP performance. These analyses should help the CBP better: understand the mechanistic causes for poor or good BMP performance; quantify variability in performance over space and time; infer the effects of climate change; and evaluate confidence in BMP impacts.
6. Develop an ensemble of dynamic watershed models including a spatially explicit, mass balance, temporally-dynamic version of SPARROW along with the existing HSPF-CAST model. A process-based simulation model should also be implemented that can be used to better understand watershed dynamics, especially lag times, and to load the estuary model.
7. Model aquatic living resource outcomes, including stream and estuarine habitats and living resources, to connect water clarity and water quality improvements to resources of public concern and to better motivate stakeholder support for behavioral change.

3.2.4 Phosphorus

The Chesapeake Bay Program should:

1. Evaluate Phase 6 to understand the implications of the transition from Phase 5. The Phase 6 Model represents an enormous change from the previous approach. The impacts of the changes in phosphorus simulation need to be better understood. Regular reviews of the Phase 6 Model should be undertaken to insure that the model keeps pace with the state of the science.
2. Implement the ability to distinguish between dissolved and particulate phosphorus. Consider adding explicit simulation of the transport and transformation of carbon or, alternatively, an approach that involves variable C:N:P ratios dependent on conditions.
3. Identify critical source areas for phosphorus, especially those in hydrologically active and connected zones that respond differently to management actions and are most vulnerable to climate change.
4. Explore using LiDAR data to inform models and soils maps. These data might also be used to help guide application of soil phosphorus BMPs (e.g., via the BMP panel process) through characterization of subsurface/artificial drainage/fractured profiles that affect drainage export intensity.
5. Determine what happens to phosphorus when land use changes by tracking spatially explicit land use history and soil phosphorus under these changing conditions. The CBP should also understand implications for phosphorus runoff and BMPs.

6. Use the Phase 6 watershed model as a means of extrapolating and relating local findings to larger scales. Local nutrient and phosphorus monitoring data should be used for calibration. A synthesis of local-scale literature and data should be used in the further development of the Phase 6 Model. Downscaling capabilities should be developed for relating the large-scale models to local fine-scale observations and models.
7. Motivate efforts to understand the role of fluvial biogeochemical processes in riverine phosphorus delivery to the estuary. Additionally, new science to increase understanding in-stream and reservoir phosphorus transport and transformation is needed.

3.2.5 Sediment

The Chesapeake Bay Program should:

1. Understand the importance of properly representing time scale of sediment processes in the CBP watershed model to management. New science, new data, CBPO staff support and other resources are needed to fill gaps in current understanding.
2. Establish a sediment modeling workgroup with expertise from CBP, the geomorphology community, and stakeholders to engage in both long-term and short-term thinking about how to improve the representation of sediment dynamics in the CBP watershed models.
3. Implement short-term improvements to the Phase 6 Model by 2023. Examples include the development of alternative tools to evaluate upland sediment sources such as the Water Erosion Prediction Project (WEPP); the improvement of estimates of sediment delivery across watershed scales; and the improvement of the representation of lowland sediment production and storage.
4. Design and implement a replacement model that better represents new understanding of sediment dynamics. This process should start with the development of a conceptual model to rank governing processes (and how they change across time and space) in the watershed. This would provide guidance for the development of a new computational model that would represent sediment processes and time scales. The beta version should be developed by 2023 with a full implementation later.
5. Incorporate linkages between sediments and nutrient and carbon fluxes, habitat, and living resources, recognizing that transport of other constituents is of key importance for sediment at the whole-watershed scale. The physical behavior of sediment and its effects on habitat and living resources are most important for local watersheds and stakeholders.

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Workshop Program and Agenda

Chesapeake Bay Program Modeling in 2025 and Beyond:
A Proactive Visioning Workshop

A Scientific and Technical Advisory Committee (STAC) Workshop
Dates: January 17-19, 2018
Location: National Conservation Training Center (NCTC), 698 Conservation Way,
Shepherdstown WV 25443

Workshop Webpage: http://www.chesapeake.org/stac/workshop.php?activity_id=278

The Chesapeake Research Consortium (CRC), the Chesapeake Bay Program (CBP), along with the Chesapeake Community Modeling Program (CCMP) and CSDMS/CFRG, will convene a three-day workshop to understand the status of the current CBP management modeling system and discuss future directions for management modeling, with a view toward developing a roadmap for future CBP modeling in 2025 and beyond. This workshop will be guided by the following overarching questions:

1. Description of needs:
    a. What are the likely management needs of the CBP partnership over the next decade?
    b. What are the scientific, computational, and data management challenges the CBP faces in the coming years?
2. Review of advice:
    a. How can information and recommendations from previous workshops and committee reports and organizations like the STAC, National Research Council (NRC), CCMP and CSDMS be brought to bear to address these needs?
3. Description of resources:
    a. What human and infrastructure resources are going to be available to meet these future needs and challenges?
    b. How can resources be used more efficiently and collaboration among government, private, and academic partners be maximized?
4. Visioning for 2025 and beyond:
    a. What well-informed, realistic, and unified vision for future CBP modeling will guide the CBP into the future?
    b. What critical changes and upgrades will have to be made to the CBP modeling system to meet these challenges?
    c. What additional resources might be needed and how might the various stakeholders and partners work most effectively to find these?

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To prepare for the workshop, the following materials will be provided in advance:

(A) Bios of all Attendees

(B) Packet of brief reading materials:
1. Workshop proposal
2. Description of needs
    a. Management context
    b. Overview of current models
    c. Model governance
    d. Description of resources within the CBPO
2. Overview of modeling needs for Chesapeake Watershed Agreement goals and outcomes
3. Review of modeling advice
    a. Prior STAC recommendations
    b. National Research Council (NRC)
    c. Modeling Lab Action Team (MLAT)

(C) 5 Pre-recorded videos (~1 hour, 20 mins total)
https://www.youtube.com/playlist?list=PLwTknLjlLdA5xXGk7t7v6lGxUClLikKTi

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Workshop Agenda

Wednesday January 17: Day 1 – Setting the Stage

Discuss CBP's current management needs and existing modeling suite. Raleigh Hood – moderator
To make the most of our time as we listen to today's presentations to set the stage for our important work together this week, reflect on the five questions set out below to help prompt discussion and progress in the breakout sessions you will participate in on Days 2 and 3. As you listen to presentations today, please write your thoughts on a sticky note (1 thought per sticky note) and bring to Happy Hour to go over with the leads of your breakout session.

1. Given the long history of modeling in the Chesapeake Bay, where are the most urgent needs of the model ***in terms of management goals***?
2. How do these management goals intersect with ***scientific modeling challenges*** that must be overcome in order to build a successful modeling suite?
3. What barriers exist to a successful modeling suite beyond scientific challenges (e.g., institutional, resource-related, disconnects between modeling management goals and capabilities)?
4. What modeling fixes are the true "low hanging fruit" that can come to fruition on short order and also be useful in meeting our goals?
5. What outside-the-box strategies from your own field might be useful to consider or incorporate into this model visioning exercise?

For guests staying onsite, breakfast is served in the Commons from 6:30 – 8:30 am

8:00 am	**Registration/Check-In –** ***Entry Auditorium***
9:00 am	**Welcome and Introductions –** ***Instructional West*** The steering committee will introduce themselves, and provide a quick review of today's activities.
9:10 am	**Management Keynote – Lee Currey (MDE)** Currey will provide a short history of TMDL and Partnership models. Goal is to make non-CBP regulars aware of the long history of direct connection to management and the likely timelines and uses for future modeling
9:30 am	**Management Questions – Rich Batiuk (EPA/CBPO)** Batiuk will discuss the management challenges that the CBP will likely face in 2025 or further into the future. He will give his perspective on the historical requirements of these management models that will likely carry into the future.
9:50 am	**Workshop Charge – Raleigh Hood (UMCES) and Gary Shenk (USGS/CBPO)** Workshop co-chairs will review the structure and goals of the workshop

10:00 am **Break (30 min)**

10:30 am **Panel Discussion: Cross-cutting Topics - Lew Linker (EPA/CBPO) facilitate**
Participants will engage in facilitated discussion to reflect on a series of pre-recorded presentations viewed prior to the workshop

- How do we address potential modeling needs of goals and selected outcomes of the 2014 Bay Agreement? – Scott Phillips (*Tom Ihde sitting in*)
- Modeling Socio-Economics – Lisa Wainger (UMCES)
- Participatory Modeling/Stakeholder engagement – Alexey Voinov (*Elizabeth North sitting in*)
- Nimble modeling: modularity/linkages – Eric Hutton (CSDMS)
- Issue of Scale – Lora Harris (UMCES)
- Uncertainty/Risk (in a mgmt. framework) – Gary Shenk

12:00 pm **Lunch – *Commons***

1:15 pm **Existing Chesapeake Bay Models (15 mins each)**
Current state of the modeling framework: strict 10 min presentation, 5 min discussion.

Instructions to presenters: pitch the talk to everyone in the room except your small breakout. Discuss scale and discretization for temporal, spatial, and constituent dimensions. Example: estuarine models would want to know that the watershed model can deliver hourly loads at about a huc12 scale for several species of N and P. Last 2 slides – where are the models going, where should they go from here?

1:15 pm Airshed – Jesse Bash (EPA)
1:30 pm Land use – Peter Claggett (USGS/CBPO)
1:45 pm Watershed – Gary Shenk
2:00 pm Estuarine hydrodynamics and biogeochemistry – Carl Cerco (USACE, ret)
2:15 pm Estuarine Living Resources – Tom Ihde (Morgan State University)

2:30 pm **Previous Modeling Advice – Lisa Wainger (UMCES)**
Building from the document prepared in advance, Wainger will broadly cover global recommendations from NAS, STAC reviews, and STAC workshops.

3:00 pm **Break (30 mins)**

3:30 pm **Strawman 2025 models – Lew Linker (EPA/CBPO)**
Linker will discuss his vision for CBP models that may be in place by 2025. This should be seen as a starting point for discussion.

4:00 pm **Science Keynote – Kenny Rose (UMCES)**
Inspiring Model presentation
Strategic research program

4:40 pm **Instructions for the rest of the workshop – Raleigh Hood and Gary Shenk**

- Identify break-out leads and recorders
- Discuss the goals of the breakouts:
  1. A set of 2-4 draft recommendations to come from STAC to the CBP Partnership
  2. A more detailed write-up of the ideas that came out of the breakout

5:00 pm **Breakout Groups meet for Informal Happy Hour**

5:30 pm **Recess;** ***Dinner is served from 5:30 – 7:30 pm in the Commons***

Thursday January 18: Day 2 – Small Breakout Workshops

These will be mini-workshops based around the small breakout groups. Each breakout will have a leader/facilitator, and a recorder.
The goal of day 2 is for each breakout to produce 2 items:

1. *List of draft recommendations. These should be only the top consensus priorities - descriptions should fit on a single page*
2. *Longer list of thoughts from discussion, likely captured on easel pads*

For guests staying onsite, breakfast is served in the Commons from 6:30 – 8:30 am

9:00 am **Breakout Round-Robins**
Informal; each member should come prepared to share with their thoughts and ideas on new or different ways to model in regard to their breakout topic

10:00 am **Break (30 mins)**

10:30 am **Expansive Breakout Discussion**
Building from the ideas expressed in the Round Robin discussion come up with multiple development paths. Describe resource and data needs, advantages, and disadvantages for each.

11:30 pm **Lunch -** ***Commons***

1:00 pm **Focused Breakout Discussion**
Discuss alternate development strategies in detail. Narrow the list of strategies based on criteria from the plenary session (feasibility, applicability to management questions, nimbleness, ability to estimate uncertainty, and opportunity for stakeholder interaction)

3:00 pm **Break (30 mins)**

3:30 pm **Prioritizing Breakout Recommendations**

Breakout groups reach consensus on draft recommendations that can be communicated to the plenary group on a single presentation slide. Also begin work on longer descriptions of the draft recommendations.

5:00 pm **Recess;** ***Dinner is served from 5:30 – 7:30 pm in the Commons***

Friday January 19: Day 3 – Plenary Discussion

For guests staying onsite, breakfast is served in the Commons from 6:30 – 8:30 am
****Please Note: Check-out time is until 12:00 pm***

8:30 am **Large Breakout Groups: Watershed and Estuarine**
Each small-group leader or recorder will present the single page/slide of recommendations from the previous day followed by larger breakout group discussion. Recommendations may be modified during this period

10:00 am **Break (15 min)**

10:15 am **Plenary Presentation of Breakout Proposals**
All participants will reconvene and each small-group leader will briefly present the single page of recommendations, with any changes from the morning's large breakout discussion

- Dot Voting: Importance, Practicality, and Urgency
- What have we missed?

11:30 am **Lunch** - ***Commons***

1:30 pm **Compiling Recommendations & Cross-Cutters Response – Raleigh Hood and Gary Shenk**
Facilitated discussion of final recommendations presented before lunch focused on compatibility between proposed components with a view toward formulating a realistic and unified vision for future CBP modeling. 'Cross-cutters' will present their perspectives on the consensus recommendations and their major takeaways.

2:45 pm **Discuss Next Steps and Plan Forward**

3:00 pm **Adjourn**

3:15 pm **Steering Committee Meeting**

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Link to detailed breakout group reports and notes

As of April 16, 2019:

- Workshop presentations and background materials are accessible on the STAC workshop webpage

- Additional, more detailed breakout group reports and notes are accessible through a repository of Google Drive: Modeling Beyond 2025 Detailed Breakout Notes