Watershed Modeling Workplan Options for 2025

This document is being prepared for the October 25-26, 2021, Water Quality Goal Implementation Team (WQGIT) meeting where the Chesapeake Bay Program (CBP) partnership will prioritize options for the development and application of the Phase 7 suite of modeling tools and the CBPO watershed modeling team's development time. The goal of the prioritization is to set the partnership up for decision processes in 2025 and future years to achieve the goals and outcomes under the Chesapeake Bay Watershed Agreement. Prioritization may change in the future in response to partnership need.

Partnership's Plan for the 2025 Chesapeake TMDL Assessment

There is not yet a comprehensive partnership plan for what is to occur in 2025, however, there are at least three tasks that the partnership has agreed to. 1) The PSC voted for a reassessment of climate change through 2035. 2) The partnership agreed in the TMDL to full implementation of Best Management Practices (BMPs) that meet the Phase III Watershed Implementation Plan (WIP) planning targets (planning targets). 3) 2025 is the end of the 2024-2025 milestone period and the milestone assessment will occur.

2035 Climate Change Assessment

On December 17 2020 the Principals' Staff Committee (PSC) met to discuss the decision made on addressing 2025 climate change conditions. Along with approval of the modeling and the loads for 2025, they agreed that "In 2025, the Partnership will consider results of updated methods, techniques, and studies and revisit existing estimated loads due to climate change to determine if any updates to those 2035 load estimates are needed." The specific recommendations from the WQGIT were:

- Develop a better understanding of the BMP responses, including new or other emerging BMPs, to climate change conditions.
- Compare the current 2025 climate change assumptions with measured climate conditions through 2024 to include: rainfall volume, intensity, and distribution; air temperature, hydrology, water temperature, sea level rise, and changes in Bay stratification and circulation.
- Consider the efficacy of using projections from measured trends versus downscaled global climate model data for revised 2035 estimates.
- Improve understanding and simulation of climate change impacts to open water designated use in shallow waters.

There are several responses to the above WQGIT recommendation that are underway. Virginia Tech scientists are producing a comprehensive literature survey on the effects of climate change on BMP performance. In addition, a WQGIT-funded project to produce updated intensity-duration-frequency curves for all counties in the watershed will supply necessary estimates of climate effects. Another response is an improved shallow and open water simulation and assessment being addressed through an EPA Request for Applications (RFA) for development of a new estuarine model, and through the development of a new tidal water quality interpolator that will run on finer temporal and spatial scales. Finally, assessment of the measured change in climate and the effectiveness of relying on climate models has been informed by a NOAA-funded project led by VIMS and Penn State scientists leading to an evaluation of future climate inputs that will occur in 2024 and 2025.

Planning Target Recalculation

From the 2010 Bay TMDL executive summary: "The TMDL is designed to ensure that all pollution control measures needed to fully restore the Bay and its tidal rivers are in place by 2025, with at least 60 percent of the actions completed by 2017." This is repeated in several sections dealing with the timeline for implementation and reasonable assurance that the goals will be achieved. There is no provision in the TMDL documentation for what happens in 2025 or later years other than achieving appropriate implementation levels. Section 1.2 points out that achieving implementation in this timeline was a consensus decision: "At the October 1, 2007, meeting of the PSC the seven watershed jurisdictions and EPA reached consensus that EPA would establish the Bay TMDL on behalf of the seven jurisdictions with a target date of 2025 when all necessary pollution control measures would be in place (CBP PSC 2007)."

During the July 9, 2018 PSC meeting the PSC approved the Phase 6 suite of modeling tools and the planning targets and they further agreed that "The jurisdictions' Phase III WIP nitrogen and phosphorus planning targets will remain unchanged through 2025, recognizing that the PSC reserves the right to revisit this decision if necessary." This decision indicates the possibility of planning target changes in 2025, but not the inevitability.

A recalculation of planning targets could be triggered by the approval of a new watershed model, a demonstration that the current planning targets are insufficient to meet water quality standards or excessive in their protection, or a change in the equity rules governing the planning target calculation. For example, a change in planning targets could be handled by a Phase IV WIP process or, as in the case of planning target reductions due to climate change, through the milestones process.

2025 timeline

Historically, new versions of the watershed model have taken several years to develop. Phase 5 was first conceptualized a decade prior to its use with intensive development occurring over the final seven years. Phase 6 also had a seven-year development schedule. Nominally, there are also seven years between the planning target decisions of 2018 and the year 2025, however the first several years were dedicated to the climate change analysis completed in 2020 and 2024 and 2025 will be reserved for review and decision. Development years will be limited to 2021, 2022, and 2023. This significantly reduced schedule limits the scope of change for a model that can be delivered by the end of 2023. Prioritization will be necessary, and choices should be made on the basis of anticipated partnership decisions in 2025 and beyond. Prioritization may be revisited as work and the decision process progresses.

A detailed description of the benefits and level of effort is provided in the following pages for potential areas of focus listed below, identified through past CBP discussions and documents and the availability of data or techniques. A summary is Table 1. Prioritization questions are posed at the end of this document.

Prioritization questions

Would the partnership benefit from a Phase 7 CAST running at a land-river segmentation of county/NHD100k scale rather than the current land-river segment scale?

With the scale of the Phase 7 CAST in mind. How would the following potential areas of focus be prioritized.

Table 1: Potential areas of focus for prioritization by the WQGIT

Potential Areas of Focus	**Recommend-ations**	**Impacts Estuarine Model**	**Impacts CAST**	**Level of effort**	**Benefits**
Finer-scale modeling	WQGIT, other GITs, STAC	✓	✓	High	Greater accuracy watershed modeling; Enables fine scale targeting of practices; Needed for some co-benefits
Spatially explicit CAST	Non-CB TMDL partners		✓	Medium	Enables CAST output on a fine scale
Physical process simulation	STAC, WQGIT other GITs, CBPO	✓	✓	Low-High	Greater watershed model accuracy overall
Nutrient Application calculation	CBPO		✓	Medium -High	Increases transparency of CAST scenarios; Reduces unintended consequences of model and data changes
Land use change 1985-2035	CBPO, WQGIT	✓	✓	High	Greater accuracy of land use changes through time. Allows direct use of fine-scale land use data in CAST
Improve climate change modeling	PSC, WQGIT	✓	✓	Low	Directly addresses PSC priorities; improves confidence in 2025 climate decision.
Uncertainty Quantification	WQGIT, STAC			Medium	Helps prioritize model updates; Incorporates trends in monitored data
Co-benefits and ecosystem services	WQGIT, other GITs, STAC		✓	Low-High	Helps partners develop comprehensive plans that benefit local citizens.
WQ standards Assessment	WQGIT, STAC			Low-Medium	Potential to assess all tidal oxygen standards and to delist segments

Current Phase 6 Model Structure

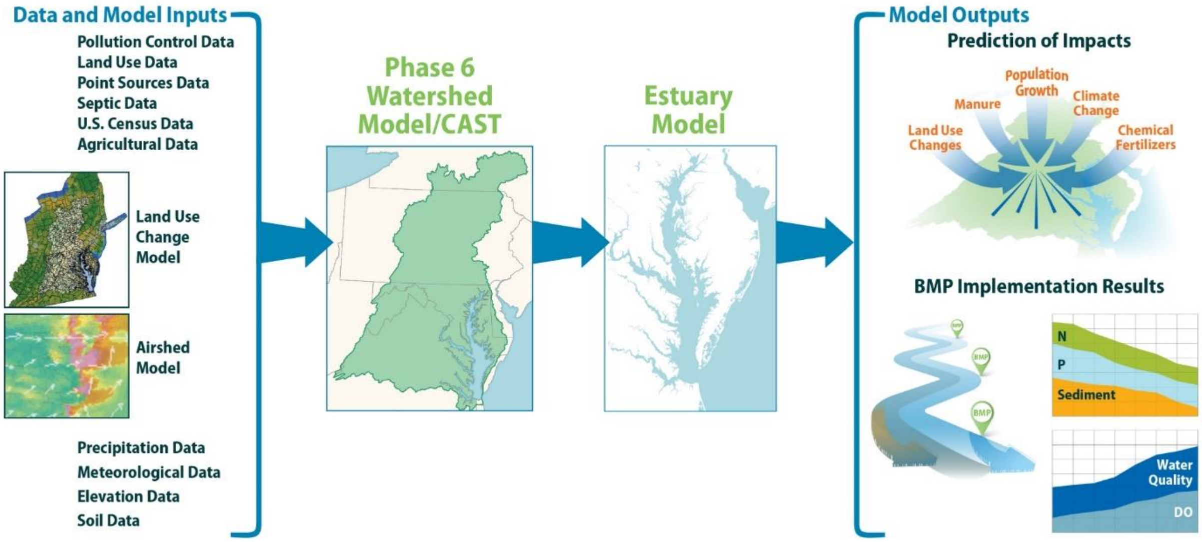

Figure 1: CBP TMDL Modeling Suite

The CBP's full TMDL modeling suite is shown in Figure 1. The modeling is driven by various types of data that help predict changes in loads of nitrogen, phosphorus, and sediment, which in turn affect dissolved oxygen in the tidal water. Land change modeling provides estimates of the extent of land uses from 1985 through the present and projects future land use change. The watershed model predicts the changes in loads due to the changes in land uses and other inputs. The estuarine model predicts the changes in dissolved oxygen resulting from changes in loads. Assessment procedures are used to determine the level of dissolved oxygen standards attainment for a given scenario. This document focusses on potential changes to the watershed model and its inputs. Estuarine model changes are discussed in a separate document.

The Phase 6 watershed model has two linked components as shown in Figure 2. The Chesapeake Assessment Scenario Tool (CAST) generates the official CBP scenario results for time-averaged hydrology. Time-averaged hydrology allows the model to estimate load changes over the long term as opposed to a wet or dry year. For any CAST scenario, the dynamic model can be used to generate hourly output from the time-averaged output of CAST, incorporating weather dependence and lag times. The dynamic model is used as input to the estuarine model, to calibrate the Phase 6 model suite against observed data, to investigate climate change effects, and to compare

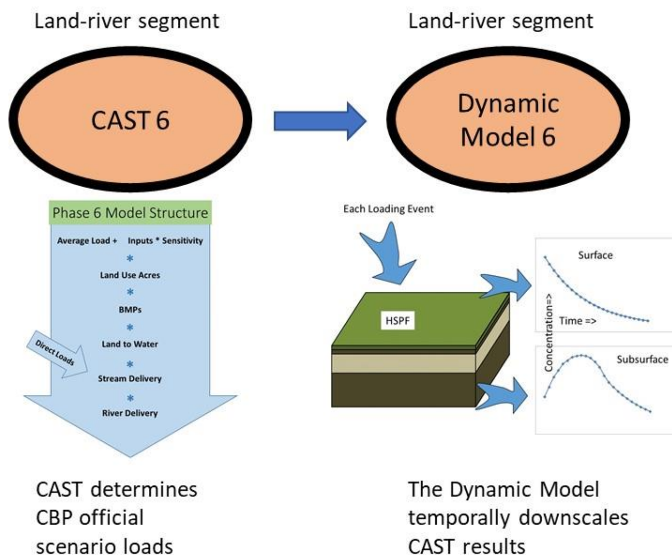

Figure 2: Relationship of Phase 6 CAST with average hydrology and Dynamic Model with time-variable hydrology

the results of the Phase 6 model against flow-normalized trends computed from observed data.

The CAST calculation for the load from a land use within a land-river segment is shown in Figure 3 and explained in section 1.3.3.1 of the CAST model documentation, reproduced here.

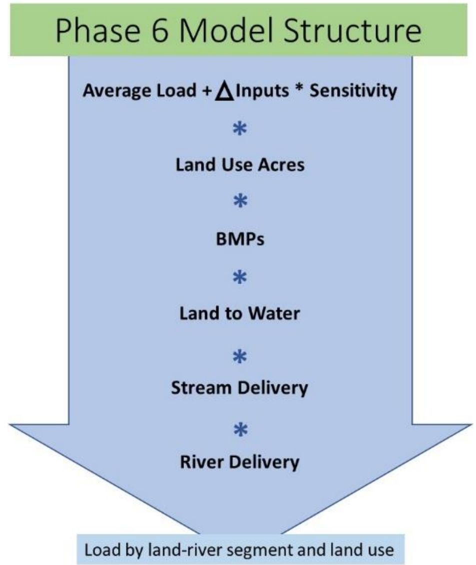

Figure 3: Phase 6 CAST structure

Average Loads are loads per acre per year for each land use averaged across the entire Chesapeake Bay watershed. Average loads are not true edge-of-field loads, but average for what would reach a small stream.

Inputs are the factors that can change through scenarios that affect nutrient export from a land use. These can include applications to the landscape of nutrients from atmospheric deposition, fertilizer, manure, and biosolids. Other examples are stormwater runoff, sediment washoff, and the storage of phosphorus in the soil. Delta inputs are the difference between the inputs to the land use in the local area and the Chesapeake Bay-wide average input.

Sensitivities are the Chesapeake Bay-wide average change in export load to a small stream for each unit change in input load. The top line in Figure 3 (average loads, inputs, and sensitivities) therefore represents the loads exported from a land use to a stream in a land segment taking into account local applications but not local watershed conditions. For sediment the entire top line is represented by a spatial application of the Revised Universal Soil Loss Estimator. Nutrient and sediment loads are then multiplied by the area of the land use in the segment (Land Use Acres) and the effect of local BMPs.

Land-to-water factors are then applied to account for spatial differences in loads due to physical watershed characteristics. Land-to-water factors do not add or subtract to the loads over the entire Chesapeake Bay watershed, but instead represent the spatial variance of nutrient transport.

The application of all the above factors (average loads, inputs, sensitivities, land use acres, BMP effects, and land-to-water factors) results in an estimate of loads delivered to a stream or waterbody in a land-river segment.

Next, **Stream Delivery factors** are applied to account for nutrient and sediment processes in streams with average flow less than 100 cubic feet per second. These are attenuation factors that act to decrease nutrient delivery in small streams as the loads move to the boundary of the larger modeled river reaches.

River Delivery factors account for nutrient attenuation processes in the larger rivers as loads move to the estuary. Streams and rivers are modeled separately because different sources of information are used to estimate their delivery coefficients."

Using the calculation described above and shown in Figure 3, CAST generates the official CBP partnership results for all tracking and planning scenarios, whether they are generated by any of the more than 2,000 individual users or by the Chesapeake Bay Program Office (CBPO).

Finer-Scale Modeling

The Finer-Scale Modeling topic is an upgrade to the scale of the underlying processes simulated in the watershed model. The Spatially Explicit CAST topic is an upgrade to the interface that would deliver the information at any scale.

The current Phase 6 CAST and dynamic watershed d inherited their spatial scale from the Phase 5 watershed model. The land-river segment scale simulates major rivers and offers output on a scale which has been appropriate for regional, state, and county-level decision-making. A Phase 7 Dynamic Model and CAST are envisioned with a land-river segments reduced in scale to the National Hydrography Dataset 1:100000 (NHD100k) level, further divided by counties. The new segmentation shown in Figure 4 would allow differentiation of load sources within counties on a roughly one square mile watershed basis.

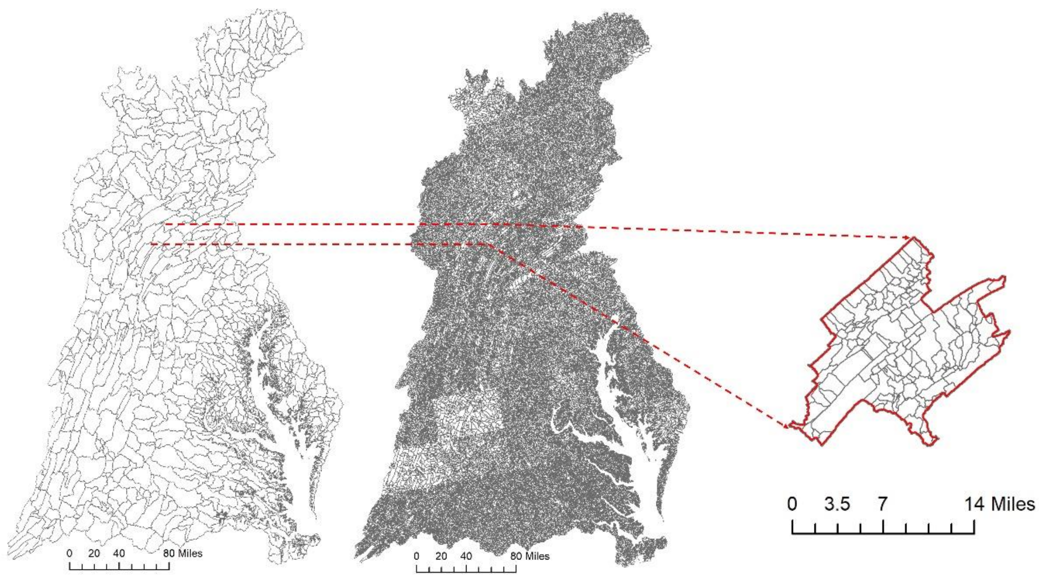

Figure 4: watershed scale in phase 6 and proposed phase 7 models.

Some of the information used to produce load estimates at the NHD100k scale will be available at a much finer resolution such as a 1-meter or 10-meter scale. For example, 10-meter information on sediment sources and transport in the landscape (Figure 5) was rolled up to a land-river segment scale in Phase 6. The inclusion of these data sets dramatically improved the accuracy of the load calculation relative to monitored data. Theoretically, predictions of sediment load at the 10-meter scale that are consistent with CAST at the land-river segment scale could be made. While other inputs are only available at the county scale, they can be downscaled to NHD100K catchments.

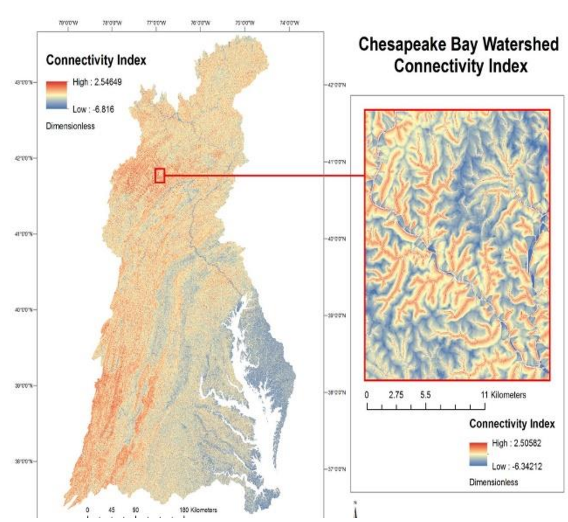

Figure 5: Sediment interconnectivity metric in Phase 6

CAST users may still choose to use CAST at broader scales if they do not need or lack confidence in the finer scales.

A potential vision for the Phase 7 suite of models is to generate 10-meter a ‘Cellular Model’ of loss potential for nitrogen, phosphorus, and sediment. A Cellular Model component is expected to improve the delivery factors used in CAST and identify source areas with greater precision. The Cellular Model could be integrated into tools such as Spatially Explicit CAST (discussed below) or [field doc](). Such predictions would need validation prior to use in management.

A proposed finer-scale Phase 7 watershed model structure is shown in Figure 6. It is similar to the Phase 6 relationship (Figure 2) with the addition of the Cellular Model and the change in scale for CAST and the Dynamic Model. A fine-scale version of the watershed model could include all models at the scales indicated in Figure 6 or have some components simulating a coarser scale. It would also be possible for hydrology and sediment, or just hydrology, to be run at a finer scale with other constituents represented at a coarser scale.

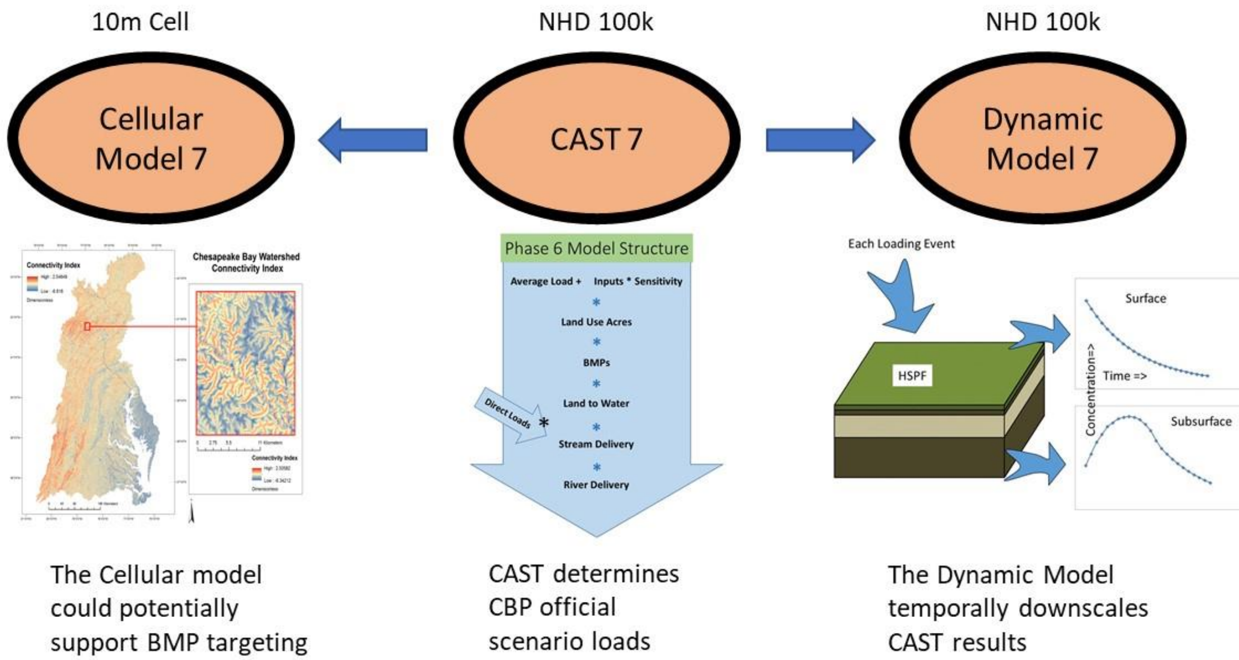

Figure 6: Relationship between the Phase 7 CAST, dynamic, and Cellular models

Components of both the NHD100k CAST and the Cellular Model exist in the Phase 6 model. Land-to-water and stream-to-river factors for nutrients were both estimated at the NHD100k scale before being aggregated to the Phase 6 land-river segments through a weighted average based on land use. Sediment edge-of-field and land-to-water factors were both estimated at a 10-meter scale prior to aggregation to the Phase 6 land-river segment scale, again through a weighted average based on land use.

Nutrient or sediment loss from a point on the landscape is dependent on both natural and anthropogenic causes. It is anticipated that natural factors and land use acreage contributing to loading would be available on a cellular or NHD100K-level, however many management variables, such as manure, crops, and fertilizer would remain at a county level. The Phase 6 CAST assumes constant delivery and land use over a land-river segment and constant management over a county. The Phase 7 CAST could follow this same pattern but create finer resolution for natural and land use factors.

Potential Benefits of Finer-Scale Modeling

Targeting

Many studies show that a small percentage of the land area generates a large majority of the nonpoint source loads, particularly for pollutants such as phosphorus and sediment. Additional work has shown significant cost savings from geographic targeting of BMPs. Many of the processes governing runoff operate at the field to small watershed scale. The current Phase 6 CAST allows users to target BMPs at a land-river segment based on current watersheds averaging 80 square miles. A Phase 7 CAST using land-river segments at the scale of the NHD100k would allow targeting and differential crediting of BMPs down to the level of approximately one square mile. A Phase 7 Cellular model would have the potential to allow for targeting on a much finer scale pending validation of the approach.

Participants at a 2019 Science and Technical Advisory Committee (STAC) workshop on targeting reviewed models, watershed science, and targeting strategies and strongly recommended the development of targeting capability in the CBP partnership's watershed model, specifically:

- Improve the spatial prediction capability of the Bay TMDL accounting system
    - Develop finer scale modeling capacity to guide and inform targeting
    - Continue to improve spatial resolution of datasets that drive the CBP models and increase sharing and development of remote sensing and high resolution data that can inform the location of NPS loads and BMP removal effectiveness
    - Allow for differential crediting of NPS BMPs

The WQGIT identified "finer scale modeling" as a science need during the Strategy Review System (SRS) process, however the details of the science need refer only to the urban sector, reasoning that fine scale will help the partnership to come up with a more robust representation of parameters that govern phosphorus simulation in urban areas and improve stream bank erosion simulation. The WQGIT also listed improving the "understanding of source sector contributions to [N,P,S] loading" as a science need, which follows from identifying the areas of the landscape contributing the most loading.

Accuracy at the Decision Scale

In general, simulation models have a much finer simulation scale than the scale of decisions for which they are used. The estuarine model is used to make Bay TMDL decisions that primarily concern a handful of main-Bay deep-water and deep-channel designated-use segments, however the model itself has 57,000 spatial simulation units. The Phase 6 model is used for CB TMDL-related decisions at the county, state-basin, and CB watershed wide scale, yet has a finer spatial scale. The STAC Phase 6 watershed model review recommended a finer scale to resolve important physical transport processes, a point that was amplified in the STAC workshop on modeling in 2025 and beyond.

Increasingly, CAST is being used for purposes other than the CB TMDL to make decisions at sub-county scales. Users will compare loading rates among areas outside the model, using CAST estimates that are available at larger scales. Many users are making decisions using CAST for townships, stormwater authorities, and HUC-12s. Moving to a finer scale would increase the accuracy for these users.

Accuracy for the Estuarine Model

It is anticipated, following multiple identified WQGIT science needs, that a new estuarine model will be developed that will inform DO, chlorophyll, and SAV/clarity criteria attainability in smaller embayments. A finer-scale watershed model would provide more accurate loading information for those embayments.

Assessment of Co-Benefits and Ecosystem Services

The partnership has prioritized the calculation of co-benefits and ecosystem services on multiple occasions. Finer-scale modeling enables assessment of management effects on environmental variables at the scale more relevant to local stakeholders. For example, brook trout habitat tends to be streams smaller than what is currently simulated in the Phase 6 dynamic model and CAST. Incorporating the finer scale into CAST, especially with the spatially explicit CAST interface described below, could allow users to evaluate the importance of reducing temperature and improving brook trout habitat with buffers, and also see the impact on TN, TP, and TSS. This makes CAST more broadly accessible beyond those solely focused on water quality while facilitating increased implementation of water quality improvements.

Jurisdictional water supply modeling

The Virginia Department of Environmental Quality (DEQ), the Interstate Commission on the Potomac River Basin (ICPRB) and the Susquehanna River Basin Commission (SRBC) all maintain water supply models for short-term operations and long-term planning. In the case of DEQ and ICPRB, the models are based on prior phases of the CBP watershed model. Initial work on the CBP's finer-scale hydrology model has been undertaken collaboratively with DEQ and with data input from SRBC. It is expected that this relationship will deliver low flow and reservoir simulation for the CBP and a more integrated and modern modeling system for the state and commission partners.

Level of Effort and Feasibility of Finer-Scale Modeling

It was anticipated that a finer scale model would be a priority of the CBP partnership, and the CBPO modeling team has been performing preliminary work on input data and hydrologic simulation. Changing the scale of the watershed model is a significant effort requiring years of work from the CBPO staff. The modeling team develops the simulation of the physical environment. The CAST team develops the inputs, designs the CAST interface and process flows, and creates and manages the scenario processor to ensure quick results from scenarios. A rough plan exists to deliver a new Phase 7 watershed model in time for potential use in 2025. It would include CAST and the Dynamic Model at the NHD100k scale, and a Cellular Model at the field scale. Since this work is essentially a research project, full success cannot be guaranteed. However, given that land-to-water and stream-to-river variables are already available at the NHD100k scale in Phase 6, it is certain that calculations can be made for a Phase 7 CAST at the NHD100k scale with upgrades that are prioritized during development.

Spatially Explicit CAST

The Finer-Scale Modeling topic is an upgrade to the scale of the underlying processes simulated in the watershed model. The Spatially Explicit CAST topic is an upgrade to the interface that would deliver the information at any scale.

The overall objective of CAST is to facilitate implementation of BMPs that improve water quality. Using the high resolution land cover data in CAST is expected to enhance CAST users' ability to improve water quality and focus estimated outcomes to smaller geographic scales. This enhancement will help CAST be understood and supported by partners and stakeholders with a wide range of technical knowledge, thereby expanding usage conservation project staff and farm advisors in rural areas. d addition, the enhancement will also negate the need for urban planners to convey their site-specific land use to the larger scale information currently available in CAST.

CAST currently uses multiple geographic scales for annual progress tracking and planning scenarios. Both tracking and planning options are at the county, state, or various sizes of watersheds; the finest scale currently available is county. Spatially explicit data (1 meter) are used to inform the tabular land use for these geographic scales. However, planning currently cannot be done on a spatially explicit basis. This limitation prevents CAST users from site-specific and project-specific planning. The lack of spatially explicit land cover data inhibits users from gaining confidence in the CAST land use and resulting load estimates. Targeting BMPs to land uses that have the highest load and areas with the highest delivery to streams and the Bay also is limited in CAST.

The land data team has impervious and land cover mapped for 1984, 1992, 2001, 2006, and 2011, at 30 meter resolution. The National Land Cover Database (NLCD) provides nationwide land cover data. The 2013 data are mapped at 1-meter and 10-meter resolution. The 2018 data soon will be available at the 1 meter and 10-meter resolutions. These data are incorporated into the tabular land use in CAST but CAST cannot be queried or at the original land use scales of 1-meter or 10-meter resolution. The intent of Spatially Explicit CAST is to allow the user to define an area of interest and CAST would calculate downscaled information, consistent with other CAST outputs, based on the land use in that area.

Using the spatially explicit land cover data also facilitates best use of all components of a Phase 7 watershed model: CAST, the Dynamic Model, and the Cellular Model.. The CBP Modeling team already has downscaled the hydrology to the National Hydrography Dataset Plus High Resolution, Version 2 (NHD+) (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution). The Modeling team also has a methodology for the stream bed and bank loads that makes better use of upland delivery to streams for the same NHD+ scale (G. Noe, USGS, presentation to the Modeling Team, 9/22/2020). USGS estimated all inputs, except BMPs, at the NHD100K catchment scale using a similar method (Data release forthcoming). Coupling the finer scale hydrologic model and stream delivery with the spatially explicit land use would allow better crediting of BMPs that have upland benefits. Currently, a proportion of all upland land uses in a sector are credited. With these finer scale data, BMPs like buffers can have upland effects credited to the actual land use that drains to the buffered stream area. This also opens the door to temporal definition of BMPs in CAST, which currently is part of NEIEN.

Potential Benefits of Spatially Explicit CAST

Incorporating the spatially explicit data would allow CAST users to refine their planning at the field and project scales while increasing their ability to target BMPs. This would be used for planning, or "what if", scenarios. Users can continue to access annual progress tracking data that does not include the spatially explicit information. The TN, TP, TSS, and cost results can continue to be provided in the current format since the data can be stored at specific geographic scales including latitude and longitude rather than land-river segments.

The co-benefits and ecosystem services can also be targeted based on data available in the Cross GIT Mapping Layers (https://gis.chesapeakebay.net/mpa/scenarioviewer/) such as priority living resource areas, brook trout, black duck focus areas, toxic contaminant impairments, and diversity layers. With the incorporation of the Optimization Tool, the targeting becomes automated. A spatially explicit version of CAST would help users gain confidence in the CAST land use and resulting load estimates, refine planning and help target BMPs, and potentially better credit BMPs with upland benefits.

Level of Effort and Feasibility of Spatially Explicit CAST

The capacity to undertake this work does not currently exist within the Chesapeake Bay Program CAST team. However, previous experience with modelers at Drexel University suggests that they would have the experience and knowledge to develop a spatially explicit version of CAST. They would provide a supplement the existing CAST team to ensure that usability and CAST user experience would be consistent across the products.

Physical Process Simulation Improvement

The accuracy of the watershed model relies on the quality of estimates for the factors that are used to calculate loads and the processes simulated in those factors. Many of these processes and factors could be improved regardless of the decision on rescaling the Dynamic Model and CAST. A few examples follow. Other potential areas for improvement could be pursued for an improved simulation of the watershed. The 2018 STAC workshop on the future of CBP modeling and the Phase 6 model review provided many opportunities for improvement.

Improve nutrient speciation calculation. Inorganic nutrient species are more readily available than organics and therefore controlling inorganics that reach the tidal water will have a more beneficial effect on dissolved oxygen in the Bay. Timing has a similar effect where nutrients delivered in the late fall and early winter have a much smaller effect than nutrients delivered in the late spring and summer. This principle is well-understood by the partnership and was used in determining that the 13 million additional pounds of nitrogen contributed by the Conowingo infill was equivalent to a 6-million-pound reduction from other sources. Similarly, it takes about 7 pounds of reduction from the James to equal a 1-pound reduction from the Susquehanna according to the TMDL nutrient exchange ratios. Participants in a 2019 STAC workshop discussed land use, stream, and BMP effects on speciation and timing of nutrient delivery and recommended that the CBP partnership move toward the consideration of speciation in the Bay TMDL and WIPs and toward giving more credit for actions that had a large effect on inorganic nutrients. Considerable knowledge gaps exist for how streams process nutrients and the effect of BMPs on nutrient speciation.

Improvement in urban phosphorus. Currently there is one entry for watershed modeling identified by the WQGIT in the SRS science needs database, which is under the heading "finer scale modeling". The explanatory text identifies the need to "1) refine urban phosphorus sensitivities & 2) investigate the impact of urban BMPs using SWAT and/or SWMM models" for the purposes of "1) to come up with a more robust representation of parameters that govern phosphorus simulation in urban areas 2) improve stream bank erosion simulation". SWAT and SWMM are commonly used model codes. This science need will require more discussion by the partnership, but partners noted during the finalization of the Phase 6 CAST and Dynamic Models that more effort was needed in urban phosphorus simulation relative to the simulation of agricultural phosphorus sources. The urban phosphorus application rates were identified as an area needing improvement.

Improve sediment processes. Phase 6 achieved a dramatic improvement in the sediment calculation over earlier models, however opportunities for continued improvement exist. The calculation of sediment delivery ratios based on an interconnectivity metric and the estimation of small stream contribution were based on new methods and are detailed in sections 2 and 6, respectively, of the Phase 6 documentation. Both important underlying data sets have been improved since the Phase 6 calibration and could be incorporated into a new model.

Temperature simulation. Temperature has always been part of the dynamic model simulation as it drives nutrient cycling processes on land and in the river. The dynamic model simulates annual and daily temperature cycles with reasonable accuracy in large rivers. The current simulation, however, is poorly matched to the **climate** change management questions the partnership now faces. The model underlying the dynamic model was not created with climate change in mind and the simulated Phase 6 long-term temperature effects on nutrient cycling and dissolved oxygen are likely underestimated.

Algorithms could be developed to modify the soil and water temperatures within the watershed to accurately predict effects of climate change on nutrient delivery and living resources.

Stream bed and bank loads. In Phase 5 and earlier watershed models, loads generated though stream and river erosion were assigned to upland sources. In Phase 6, responding to partnership requests, erosion loads in streams were assigned to the stream itself, creating the separate load source in CAST of "Stream Bed & Bank" which is assigned to the "natural" load category. Stream Bed & Bank loads have created some difficulties in interpretation of CAST output as they change through scenarios relative to upland load sources. For Phase 6 CAST, the partnership could reconsider options of categorizing the loads from erosion. Some options may require additional work by the Modeling and CAST teams.

Sensitivities to Nutrient Inputs. When inputs of fertilizer, manure, atmospheric deposition, fixation, or crop uptake are modified in scenarios, the load changes according to sensitivities as shown in Figure 3. With years of additional research available, the sensitivities to inputs could be updated with the latest published information.

Potential Benefits of Physical Process Simulation Improvement

Improvements in the simulation of physical processes will help to identify where and when loads detrimental to water quality arise in the watershed. A more accurate depiction of physical processes will improve the ability of the CAST and the Dynamic Model to predict and explain trends seen in monitoring data and as a result improve the confidence in the accuracy of CAST and Dynamic Model scenarios. With sources and geographic areas more accurately identified, the CBP partnership will be able to better develop more cost-effective implementation plans. Better process simulations of quantities like temperature and sediment will also potentially inform co-benefit calculations.

Level of Effort and Feasibility of Physical Process Simulation Improvement

As monitoring data are employed in new scientific studies, the knowledge generated from them can be incorporated into future models. Opportunities exist and will continue to be developed for the inclusion of improved process simulation in future models. Some tasks, such as incorporating new stream loading estimates can be accomplished in a few weeks' time where others will take longer. The accuracy of the CBP partnership's modeling tools will improve relative to the level of effort available from the CBPO modeling team and other scientists within the partnership.

Simplify Nutrient Application Calculation

The simple structure of the Phase 6 CAST had the intended benefit of transparency to users. Knowing the value of the eight parameters for the blue arrow calculation shown in Figure 3 as well as the methods used to derive them produced a model that was more understandable than previous versions and had greater buy-in from the CBP Partnership. As an unexpected benefit, it also proved more accurate than the previous overly complex watershed models that it replaced.

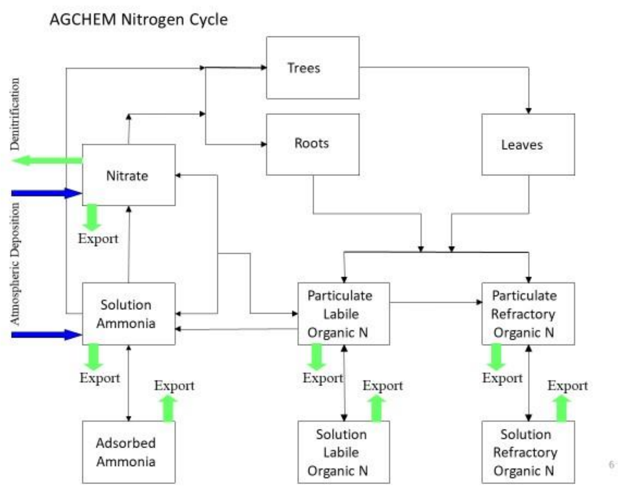

Figure 7: Phase 5 HSPF-ACHEM nitrogen cycle

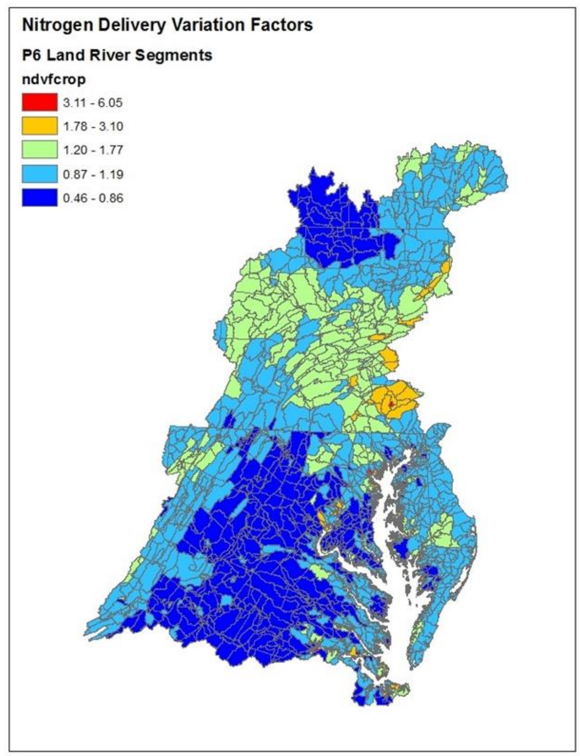

Figure 8: Phase 6 land-to-water factors

For example, in Phase 5, the nitrogen land-to-water factors were not an input, rather they were an output of the nitrogen cycling model depicted in Figure 7 that ran on an hourly time step with dozens of parameters for each land use and county. The complexity sometimes led to calculations of a load that was significantly higher or lower than what would be expected relative to neighboring counties. The uncertainly associated with those calculations lowered the confidence in the Phase 5 watershed model and led to unproductive discussions of modeling details rather than focusing on decisions and implementation guided by the models.

In contrast, the land to water delivery factors in the Phase 6 watershed model shown in Figure 8 are based on a published model based on observed data that simply considers three factors having to do the rainfall and soil properties. High and low loading rates vary smoothly across the landscape and are explainable based on well-understood processes. In Phase 6, there have been no issues raised by the partnership relative to land to water factors in the years since their adoption.

During the formulation of the Phase 6 watershed model, the WQGIT and the agricultural stakeholder community in particular articulated that they wanted the model to be understandable and transparent. The Phase 6 nutrient application algorithms were built through deliberative discussion in the Agricultural Modeling Subcommittee and approved by the WQGIT's Agriculture Workgroup. However, in the drive to include the combined knowledge of the group and to recreate processes in the model that reflected reality, a highly complex model of nutrient application was created as shown in Figure 9. Additionally, the number of agricultural land uses grew from nine in Phase 5 to seventeen in Phase 6. The additional complexity may have contributed to the length of more recent discussion by the partnership around topics such as incorporation of the Census of Agriculture data, implementation of nutrient management, nitrogen fixation calculations, and other topics. The CBPO modeling and CAST teams could be tasked with working with the Agriculture Workgroup on a process to explore simplification of the nutrient application calculation.

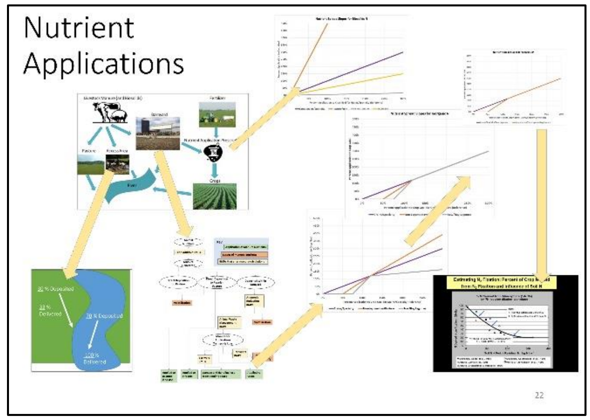

Figure 9: Phase 6 nutrient application model

Potential Benefits of Simplifying the Nutrient Application Calculation

It is a well-known principle of modeling that the point of minimum model uncertainty is not with the most complex nor the simplest model, but rather at a point of moderate complexity that can be approached through simplification of complex processes (Figure 10). A simplified process and land use representation may result in a less time-intensive process for model upgrades as the effects of changes in model inputs would be understood in advance . The suggestion to simplify process representation in Phase 7 has been voiced by a diversity of CBP partners familiar with agricultural modeling in recent years. A [July 2021 presentation] to the AgWG kicked off discussions on Phase 7 watershed model priorities and simplification was among issues to consider.

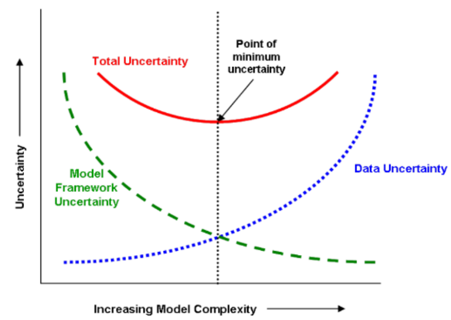

Figure 10: Conceptual relationship between complexity and uncertainty in models (from Hanna 1988 and EPA 2009)

Level of Effort and Feasibility of Simplifying the Nutrient Application Calculation

Simplification of the watershed model such that it contains only the most important data and processes, yet still is able to answer the questions the partnership poses will take the combined efforts of the CAST team, the modeling team, and a partnership group with expertise in agricultural modeling. Conversations should begin now for approved recommendation to be ready by 2023.

Improve Representation and Simulation of Land Use Change 1985-2035

High-resolution land use data with 13 classes were accepted by the WQGIT on 8/23/2021 for changes over the 2013-2017 time period in Phase 6 CAST-2021. They may also be used to represent conditions over the 2017-2021 period once those data are developed. The high-resolution land use data are more transparent and verifiable than the land use data used to characterize the 1985 – 2013 period in CAST. The data for this historic period were produced using a combination of sources such as the Census of Agriculture, National Land Cover Dataset, and Decennial Census of Population and Housing that were reconciled with each other through a “true-up” process that introduced anomalous changes in land use. Thus, the land use data for the historic period are inconsistent with the land use data for the more recent period and are difficult to verify. Resolving this issue cannot be done until Phase 7 of the watershed model.

The high-resolution land use data series under development for the 2013-2021 period has 60 land use classes. While this level of detail is not necessary for Phase 7, it allows for flexible aggregation to more general classes with greater precision and relevancy to water quality than was possible for Phase 6. For example, the current “mixed open” land use is composed of many different recently mapped classes (e.g., natural succession, suspended succession, bare construction, active mining, and timber harvest). Some of these sub-classes have significantly different pollutant loading rates.

Forest clearing is the greatest land use transition in the watershed, and it is spatially concentrated in a subset of counties and temporally episodic, properties which are not well represented in Phase 6 CAST. The majority of counties in the watershed do not report annual timber harvest data and therefore are assumed to have 1.5% of their forests harvested on an annual basis. The resultant magnitudes and spatial patterns of harvest are not supported by evidence in the CBP’s high-resolution land use change data. These data could serve to replace reported timber harvest data in Phase 7 which may likely be more accurate than reporting which, in Maryland for example, only covers activities on state lands.

The hyper-resolution hydrography data also has potential to inform Phase 7 because it represents a much higher drainage density on the landscape with shortened pathways from hillslopes to channelized flow. At a minimum, these new hydrography data could inform models of stream temperature and urban phosphorus. They also will inform updates to landscape connectivity indices affecting sediment and associated phosphorus. With additional research, hyper-resolution data are expected to inform the construction of the Cellular Model discussed under the heading “Finer-Scale Modeling”

One of STAC’s recent recommendations for improving the utility of the Chesapeake Bay Land Change Model was to include the forecasting of timber harvest activities and agricultural expansion and contraction. Implementing these improvements would enhance the consistency of future land use with the current and historic land use conditions in the watershed and improve consistency with the Census of Agriculture. Additional possible improvements include parameterizing the model using the high-resolution land use change data for the period 2013-2021 and backcasting the high-resolution land use data through 1985 at the parcel scale using recently-released annual satellite land cover data.

Potential Benefits of Improved Land Use

Developing a temporally consistent and more accurate land use change dataset for the period 1985-2035 will likely improve the calibration of the Dynamic Model and improve the transparency and accuracy of CAST. Temporal consistency and a basis in mapped, rather than tabular, data will reduce the changes introduced into CAST when new Ag Census numbers are included. Mapped land use data in CAST will also facilitate other the other proposed efforts in this document of Finer-Scale Modeling and Spatially Explicit CAST.

Level of Effort and Feasibility of Improved Land Use

The high-resolution land use data are under development and funded through 2024. Improvements to the land change model are currently supported by USGS.

Improve Simulation of Climate Change for 2035

As discussed in the introduction of this paper, the PSC has decided that climate change between 1995 and 2035 will be evaluated in 2025 and has asked for improvements in the climate simulation in the models. For the watershed model, the major points of emphasis in the WQGIT recommendations to the PSC were the method of calculating the climate effect on precipitation and temperature, and the effect of climate change on BMPs.

In the climate change modeling documentation, the Modeling Workgroup agreed with the WQGIT that BMP effectiveness change was an important consideration for the upcoming 2025 decision on 2035 climate and added that the effect on processes in small streams was not completely represented in the 2020 decision on 2025 climate.

Participants in a 2018 STAC workshop on climate change modeling recommended near term improvements that were generally included in the 2020 climate decision. For the 2025 decision on 2035 climate, they also emphasized evaluating the effects on BMP performance and recommended relying more on multiple downscaled global circulation models rather than an extrapolation of past trends. They stressed the evaluation of uncertainty associated with predictions of future climate and the use of uncertainty in the decision process.

Choice of climate change conditions can be added to the CAST interface, allowing CAST users to choose results under one or more conditions.

Potential Benefits of Improving the Climate Change Simulation

The evaluation of 2035 climate in 2025 is the only future modeling use that has been the subject of a PSC decision to date. Additional work on the climate features of Phase 6 or Phase 7 would be responding to the partnership's priorities. However, the current watershed model's climate simulation does not have a long list of necessary improvements from the WQGIT, the Modeling Workgroup, or STAC.

Level of Effort and Feasibility of Improving the Climate Change Simulation

The CBPO modeling team could begin work on addressing small stream responses to climate change and perform follow-on work from the STAC synthesis of expected BMP effectiveness changes. A limited number of current urban BMPs could be assessed against the updated intensity-duration-frequency rainfall curves. Work on precipitation and temperature inputs is premature since these inputs represent a climate scenario that will be run in 2024 or 2025, likely based on newer climate models and more recent data.

Uncertainty Quantification

Uncertainty quantification of the watershed model has been a recommendation from STAC to the CBP partnership on many occasions throughout the history of modeling at the CBP. Recommendations have come from both workshops and watershed model reviews. For example, a 2013 workshop on Multiple Models for Management in the Chesapeake Bay Watershed suggested that analyzing the output of multiple watershed models would be a way to quantify uncertainty and recommended that the CBP partnership use this method to communicate confidence in model predictions. A 2016 STAC workshop on model uncertainty was not officially written up, however, draft recommendations were presented to the WQGIT. The workshop participants recommended that the Modeling Workgroup start by identifying sources of uncertainty and that the WQGIT articulate how uncertainty analysis would be used in decision making. The 2017 STAC review of the Phase 6 model had multiple recommendations which focused on the importance of the estimation of uncertainty and the opportunities presented by the Phase 6 structure to pursue an uncertainty quantification.

Broadly speaking, there are two methods of estimating uncertainty – forward propagation and inverse quantification. Forward propagation involves starting with the uncertainty of the individual inputs and processes in a model and then running the model many times to estimate the uncertainty of the combined system. Inverse quantification involves statistical comparison of the model with observed data to see how close the model comes to the data.

Potential Benefits of Uncertainty Quantification

Uncertainty quantification by forward propagation leads to an estimate of overall model uncertainty and to an estimate of the importance of the individual model inputs and processes which can be used for prioritizing model improvements. For example, if the proportion of overall model uncertainty due to the uncertainty in land-to-water factors is very low, but the proportion of overall model uncertainty is high due to the uncertainty in stream-to-river factors, it makes sense to spend development time on stream-to-river factors. Since this method does not use observed data, there is uncertainty around the confidence limits calculated.

Uncertainty quantification by inverse methods gives a direct estimate of the success of the model's prediction through comparison with observations. Assigning uncertainty to different factors within the model is more difficult and requires much more data, however it is anticipated that the accuracy of the model in various geographic settings or time periods could be assessed through inverse methods.

Either method would help the CBP partnership to prioritize updates to model processes and data and could help the partnership understand the overall uncertainty of the predictions. To maximize effectiveness of the CBPO modeling team's work, it is necessary for the WQGIT to decide how uncertainty would be used in the Bay TMDL process. Uncertainty could be used as an explicit margin of safety, in the evaluation of WIPs by EPA or other partners, or perhaps used directly in the allocation of updated planning targets between states and sectors.

Level of Effort and Feasibility of Uncertainty Quantification

The CBPO modeling team has already started on uncertainty quantification through inverse methods. Part of the difficulty involves making appropriate comparisons between model and data. CAST predicts long-term changes in pollutant loads due to BMPs without regard to lag times. There are no comparable directly observed data for CAST predictions and so lags are added to CAST through the Dynamic Model and observed data are flow normalized to account for weather effects. Investigation is taking place in the context of the USGS/CBPO *factors affecting trends* team with initial presentations made to the Modeling Workgroup. Presentations will be made to the WQGIT at the October meeting showing progress on the inverse method and work is continuing.

The Phase 6 structure is much more amenable to uncertainty quantification by forward propagation than any previous CBP partnership watershed model due to its fast run times and the availability of uncertainty estimates for many of its parameters. No work has begun, but it is estimated that it would take 1-2 years for a full uncertainty quantification by this method.

An understanding of how the WQGIT might use uncertainty quantification and how it ranks relative to other priorities will be useful for organizing modeling team efforts.

Co-Benefits and Ecosystem Services

Within the context of the CBP partnership, ecosystem services are the value that ecosystems provide to people and co-benefits are the positive effects on non-Bay TMDL CBP outcomes that come from the implementation of management practices intended to meet the Bay TMDL goals. CAST scenarios represent change in land use and management practices over time as well as plans for future implementation. Traditionally CAST calculates the nitrogen, phosphorus, sediment loads and the cost of the BMPs, but could be modified to calculate other benefits.

If benefits could be expressed in dollars, the value of diverse sets of benefits could be compared against one another and against the cost of BMP implementation. If monetization of benefits cannot be achieved, summable quantities such as stream miles of living resource habitat restored could be given as a CAST output representing the aggregate effect of a BMP implementation plan. As a starting point, a simple listing of the ecosystem services or co-benefit categories could be an output of a CAST scenario.

The CBP partnership has expressed interest in co-benefits and ecosystem services in the SRS science needs database with a recommendation for "Ecosystem services identification, quantification and valuation" which cuts across all GITs. Two STAC workshops led by WQGIT members have called for increased effort towards quantification of ecosystem services. A 2017 workshop on "Quantifying Ecosystem Services and Co-Benefits of Nutrient and Sediment Pollutant Reducing BMPs" called for the CBP partnership to work towards quantification goals through a broad stakeholder process. The 2017 optimization workshop found that while the primary objective of CAST optimization should be to minimize cost, a secondary or alternative objective should be to maximize co-benefits. Co-benefits were also explicit recommendations of STAC workshops on contaminants of concern, BMP siting, the future of CBP modeling, and climate change.

Potential Benefits of Co-Benefits and Ecosystem Services

As expressed in the partnership documents above, quantification of ecosystem services and co-benefits provides local stakeholders with incentives for implementing BMPs that are also beneficial to the attainment of the Bay TMDL.

Quantification would allow users to explore more comprehensive solutions once the optimization functionality, currently being developed, is integrated with CAST. Constraints on achievement of various ecosystem services could be set to minimum desirable amounts and solutions could be found that minimized cost while simultaneously meeting Bay TMDL and local environmental goals. Full monetization would allow local decision-makers to find optimal solutions across many types of outcomes.

Ecosystem services and co-benefits could also be considered in implementation targeting exercises, potentially resulting in changing regional priorities. For example, BMPs that benefit the Bay are generally most effective near the tidal waters. However, if these BMPs also have a large enough benefit to local streams, the total ecosystem benefit may actually increase with distance from the Bay.

Level of Effort and Feasibility of Co-Benefits and Ecosystem Services

Work on quantifying ecosystem services with the specific goal of integrating these benefits into CAST has begun through a collaboration between EPA Office of Research and Development, and the CBPO.

Significant progress is being made in benefits related to carbon sequestration and air pollutant reduction, with the possibility of calculating habitat metrics as well.

Results from an early study that suggested important avenues of inquiry are available under the co-benefits heading on the CAST page on developing plans. Additionally, co-benefit quantifications exist that could be investigated for use in CAST. EPA's Watershed Management Optimization Support Tool contains a module on co-benefits. The Ecosystem Services Market Consortium of Federal, nongovernmental organizations (NGOs), and corporate partners is funding research on the multiple benefits of agricultural conservation practices.

Other opportunities include estuarine models of *Vibrio* and harmful algal blooms that may respond to management practices included in WIPs and recent research on the health benefits of preserved open land. What is needed is for the work to be done to take the existing research and match it up with input and output variables in CAST and to determine appropriate output metrics with the understanding and concurrence of the CBP partnership. The modeling team could work with the ecosystem services team and the CAST team at the CBPO can help coordinate this effort. Significant work is being done within the USGS Chesapeake Bay Program linking living resources to various watershed metrics which may be able to be linked to CAST input and output variables. An investment in the CAST interface is needed to fully integrate both the co-benefits and ecosystem services data as well as the optimization tool functionality.

Assessing All Bay TMDL Water Quality Standards

Water quality standards are the ultimate measure of success for the Bay TMDL. While the partnership has set an implementation goal for 2025, the Bay TMDL will remain in place until all tidal water quality standards for dissolved oxygen, water clarity or underwater grass abundance, and chlorophyll *a* are met. Figure 11 from [section 3](#) of the Bay TMDL documentation shows how the various standards are distributed through sections of the Bay and depths to protect a diverse array of living resources. The CBP partnership's water quality standards attainment [indicator](#) shows consistent progress in attainment. However, only a subset of the standards can be assessed with the CBP partnership's current monitoring and data interpolation software and so the true rate of progress is unknown. Figure 12 shows the water quality standards that cannot be assessed in gray text on the right side of the figure. None of the Bay's 92 segments has a complete assessment of water quality standards and so none can be delisted.

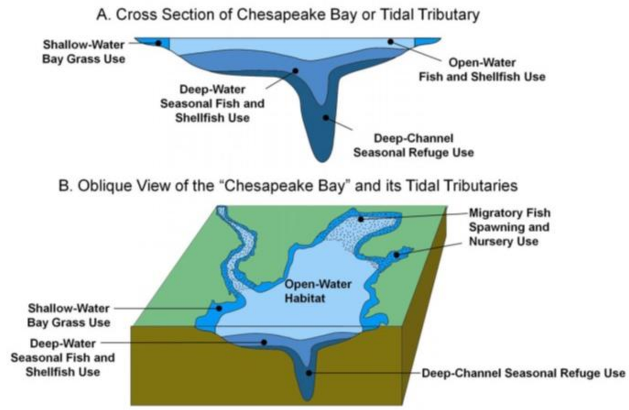

Figure 11: Designated uses for the Bay and Tidal Tributaries. Section 3 of Chesapeake Bay TMDL documentation

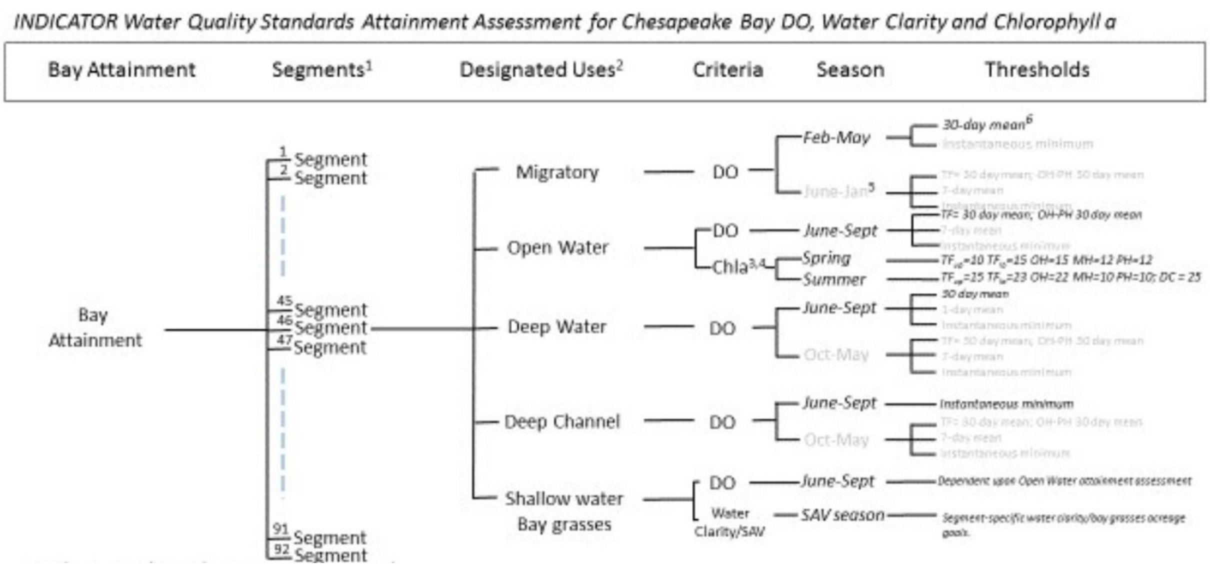

Figure 12: Assessed (normal print) and unassessed (gray print) water quality standards. From CBP's tidal water quality standards attainment indicator [methodology documentation](#).

Participants in a 2008 STAC workshop entitled "[Assessing the feasibility of developing a four-dimensional (4-D) interpolator for use in impaired waters listing assessment](#)" recognized that there were two barriers to assessment of all standards – insufficient monitoring and the lack of an established method within the CBP partnership to adequately interpolate data through three-dimensional space and through time (4-D). The participants recommended the use of multiple vertical monitoring profilers, which measure oxygen and other necessary variables hourly at multiple depths, to supply necessary data. The workshop report also contains descriptions of several candidate interpolation methodologies.

In the past decade monitoring technology has advanced and successful trials of vertical profilers have demonstrated the usefulness of the data and the robustness of the equipment. Figure 13 shows a diagram of the vertical profiler technology and data collected from a WQGIT-funded project intended as a proof of concept. Hourly data were collected, and the success of this project has led to likely deployments of similar technology by state and federal agencies in 2021.

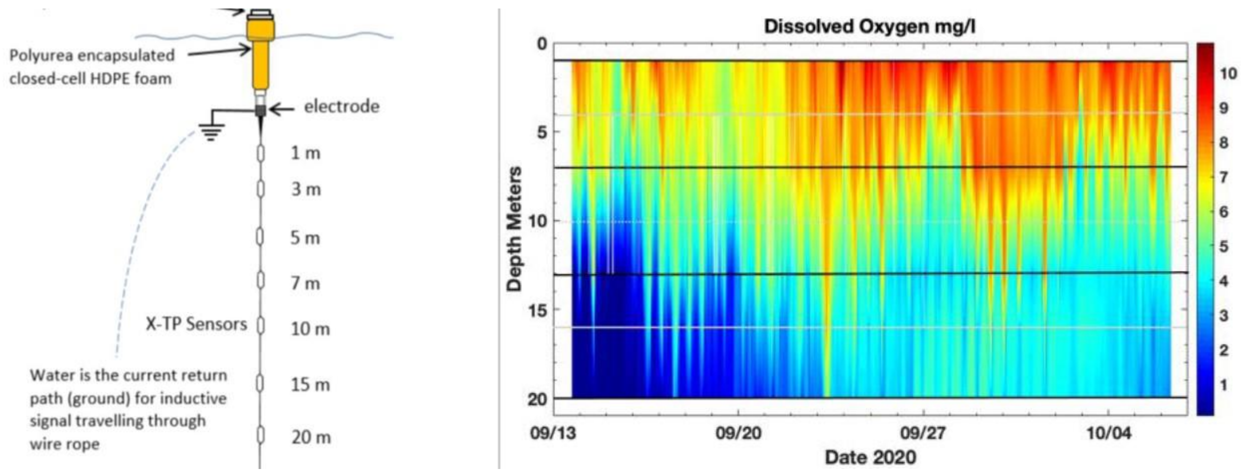

Figure 13: Diagram of vertical profiler technology and provisional data

Discussions of appropriate interpolation techniques have begun in STAR's Bay Oxygen Research Group. Progress is being made in understanding how oxygen varies in space and time. Methods already in use locally and methods developed for similar analyses in the Gulf of Mexico are being considered for implementation in a replacement for the decades-old interpolator currently used for water quality standards assessment.

Potential Benefits of Assessing All Bay TMDL Water Quality Standards

With current methods, none of the 92 Bay segments has a full assessment of all water quality standards. With the implementation of a monitoring program and an appropriate interpolation software, jurisdictions would be able to remove passing segments from the 303d list with a full assessment of water quality standards.

The CBP partnership has so far based Bay TMDL planning target and allocation decisions on deep water and deep channel designated uses. New monitoring and tools, combined with a refined estuarine model, would allow the partnership to consider local prioritization in shallower embayments.

A better assessment of dissolved oxygen will potentially allow the CBP partnership to make better connections to living resources. Historical assessments of dissolved oxygen and standards assessment, combined with living resources data, could raise the possibility of linking standards more closely to living resources and the calculation of estuarine co-benefits to Bay TMDL implementation.

Level of Effort and Feasibility of Assessing All Bay TMDL Water Quality Standards

STAR's Bay Oxygen Research Group (BORG) has begun meeting and has identified CBPO monitoring and modeling team members who are making progress in evaluating statistical methods for producing a replacement for the CBP tidal water interpolator. This work is on-going and expected to be completed for 2025. Simultaneously, federal and state efforts to improve tidal monitoring continue. Members of the CBPO modeling team are involved in both of these efforts. Knowing the WQGIT's priority level for assessment of water quality standards relative to other potential Phase 7 will help the CBPO modeling team appropriately allocate necessary resources.