1 Section 1: Overview and Modeling Strategy

1.1 Notes on the draft documentation

The June 1, 2017 version of the Phase 6 Watershed Model documentation is the final draft documentation for the Phase 6 Watershed Model. This draft documentation is provided to the partnership for the fatal flaw review which is to take place during the months of June and July, 2017.

The Chesapeake Bay Program's Phase 6 Watershed Model is a participatory creation of the CBP Partnership. The broad partnership participation in Phase 6 development has grown to include many workgroups. This documentation provides the partnership with a written record of the results of the many partnership decisions that have been made in the Management Board, the Modeling Workgroup, the Water Quality Goal Implementation Team (WQGIT), and the WQGIT's many workgroups.

1.2 Management Context

The Chesapeake Bay Program (CBP) Partnership is revising the Chesapeake Bay Program's Watershed Model (CBWM) used to assist in Partnership decisions. The latest version known as Phase 6 will be released upon successful completion of the fatal flaw review and will be used in the 2017 Midpoint Assessment for the Chesapeake Bay TMDL. The documentation was first released in early 2016 and was continually updated with the draft final release on June 1st 2017.

Phase 6 continues a long history of improvements to the modeling tools used to simulate the Chesapeake Watershed. Major releases of the watershed model are shown in Table 1-1 below. For a more detailed description of the history see the Chapter 1 of the Phase 5.3 Watershed Model documentation USEPA 2010a-01 and Linker, et al. 2002.

Table 1-1: Watershed Model Versions

Phase	Year	Purpose
0	1983	Split point source and nonpoint source
1	1990	Refine nonpoint source simulation
2	1994	40% reduction agreement
4.1[1]	1997	Confirmation of 40% goals
4.3	2003	Allocation to avoid a Total Maximum Daily Load
5.3	2010	Total Maximum Daily Load and Phase I Watershed Implementation Plans
5.3.2	2011	Phase II Watershed Implementation Plans
6.0	2017	Midpoint Assessment and Phase III Watershed Implementation Plans

1.2.1 Total Maximum Daily Load (TMDL)

The 2010 Chesapeake Bay TMDL sets limits on nitrogen, phosphorus, and sediment pollution necessary to meet water quality standards in the Bay and its tidal rivers. It is the largest and most comprehensive TMDL that the EPA has established to date. The Phase 5.3 Watershed Model was used extensively throughout the TMDL process to estimate loads to the estuarine model and as part of the allocation process. Initial load allocations by State and major basin were calculated according to a set of rules that

[1] The Phase 3 watershed model was a development-only version to add additional detail to the crop and forest simulation.

was based in large part on Watershed Model predictions of effectiveness of delivery of loads and the ability of each region to reduce those loads based on land use and other physical characteristics.

For more information on the TMDL and the watershed model use in the TMDL, refer to the TMDL documentation (USEPA 2010c), particularly Section 4 for the modeling of the inputs, Section 5 for the modeling of the physical setting, and Section 6 for the specifics on how they were used to set the TMDL.

Watershed Implementation Plans (WIPs) are plans for how the Bay jurisdictions, in partnership with federal and local governments, will achieve the Chesapeake Bay TMDL allocations and planning targets. Phase I WIPs were developed in 2010 to inform the TMDL allocations. Phase II WIPs were developed in 2012 to meet nitrogen, phosphorus, and sediment planning targets based on updated information in the Phase 5.3.2 Watershed Model.

1.2.2 2017 Midpoint Assessment

The goal of the WIP process is for all pollution control measures needed to fully restore the Bay and its tidal rivers to be in place by 2025. EPA expects practices in place by 2017 to meet 60 percent of the necessary reductions. The Chesapeake Bay Program (CBP) partnership is reviewing the latest science, data, modeling, and decision support tools used to estimate progress in nutrient reduction effort. Phase III WIPs will be developed by jurisdictions based on the 2017 Midpoint Assessment of progress, new information provided by the Phase 6 Watershed Model, and a related update of the estuarine Water Quality and Sediment Transport Model (WQSTM). Phase III WIPs will provide information on actions the Bay jurisdictions intend to implement between 2018 and 2025 to meet the Bay restoration goals.

1.2.3 Governance

The Phase 6 watershed model was developed with extensive partnership input and direction. The figure below illustrates the modeling governance structure with in the CBP. These groups are part of the larger CBP organizational chart.

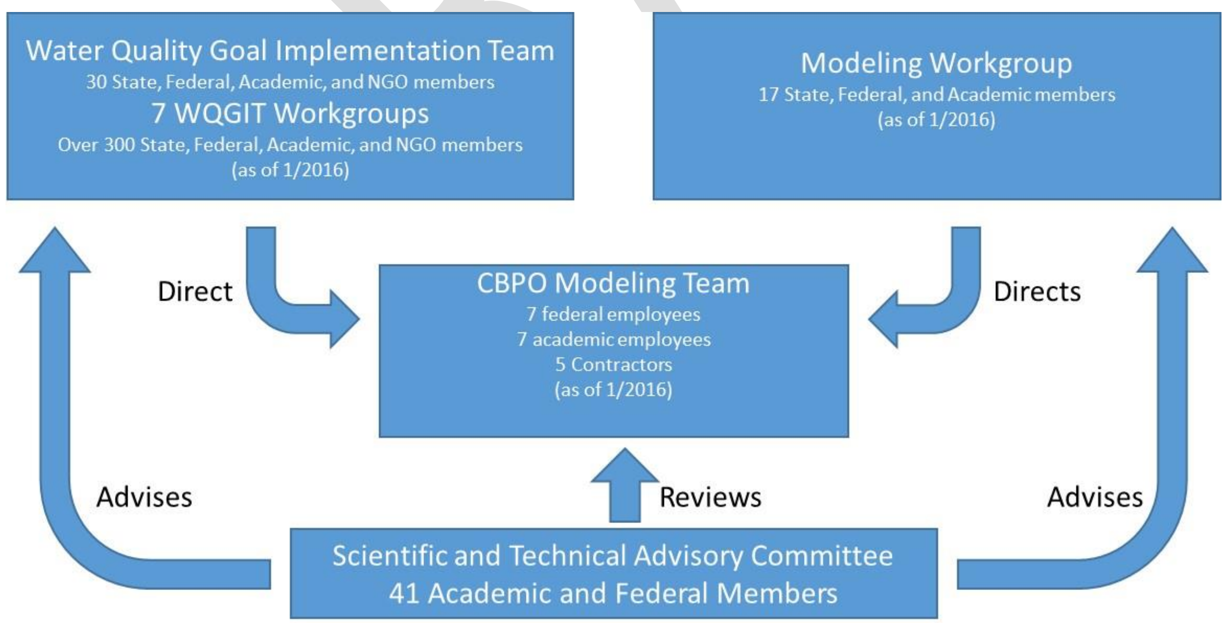

Figure 1-1: CBP Modeling Governance Structure

The Modeling Team is a cross-disciplinary group at the Chesapeake Bay Program Office (CBPO) working on development, analysis, research, calibration, and operation of the CBP modeling suite including the Land Cover Model, Scenario Builder, Watershed Model, and Estuarine Water Quality and Sediment Transport Model (WQSTM). The team takes direction from decisions of the CBP Partnership, particularly the Modeling Workgroup (MWG), and Water Quality Goal Implementation Team (WQGIT), as well as expert guidance from the Workgroups of the WQGIT. The independent Scientific and Technical Advisory Committee (STAC) advises the partnership through recommendations from workshops and reviews, and through direct communication. The MWG and WQGIT also receive considerable input from stakeholders and other interested parties that participate in regular meetings. The MWG reports to the Scientific and Technical Analysis and Reporting (STAR) group. The WQGIT reports to the Management Board and the Principals' Staff Committee.

The WQGIT directs the Modeling Team on issues related to how the models are used to inform policy. The WQGIT has seven workgroups that are directly involved in direction of Scenario Builder and the Watershed Model efforts, generally in the areas of model inputs and the extent of BMP implementation. Additionally, panels determining the effectiveness of BMPs report to the WQGIT and its workgroups. The current list of panels is available on the CBP website. The Agriculture, Forestry, Urban Stormwater, and Wastewater Treatment Workgroups direct the CBPO Modeling Team on issues related to inputs for their respective areas of interest. Some of these groups have formed subgroups to facilitate discussion. For example, many agricultural simulation decisions are first made in the Agricultural Modeling Subcommittee. The Land Use Workgroup oversees the CBPO Modeling Team in developing the land use dataset for modeling and other purposes. The Watershed Technical Workgroup works on cross sector BMP issues and facilitates BMP integration into the Watershed Model.

The MWG directs the Modeling Team on issues related to scientific integrity, modeling of the physical environment, model calibration, and issues that cross sectors such as average sector land use loading rates. The modeling workgroup adopted the following core values on 1/20/16.

- Integration - Integration of most recent science and knowledge in air, watershed, and coastal waters to support ecosystem modeling for restoration decision making
- Innovation - Embracing creativity and encouraging improvement in the development and support of transparent and robust modeling tools.
- Independence – Making modeling decisions on the basis of best available evidence and using the most appropriate methods to produce, run, and interpret models, independent of policy considerations.
- Inclusiveness - Commitment to an open and transparent process and the engagement of relevant partners, that results in strengthening the Partnership's decision making tools.

Table 1-4 near the end of this section shows the relationship between the workgroups, major parts of the watershed model, and the documentation.

1.3 Modeling Philosophy

A major version release of the CBP Watershed Model presents an opportunity to examine the structure of the model to ensure that it best meets the needs of the management community while incorporating the sound advice from the scientific community. Phase 6 is built on the structure of Phase 5.3.2 but the load estimation methods have changed significantly to better serve the community.

1.3.1 Purposes of the CBP Watershed Model

As discussed above, the CBP community has used the CBWM in much the same way throughout its history and so purposes and uses of the CBWM are well understood.

1.3.1.1 Estimate Change in Load from Management Actions

The primary water quality management decisions of the CBP are based on long-term flow-averaged estimates of nutrient and sediment load to the estuary. The management questions involve assessing the long-term loads from land uses and other sources from different geographic and political boundaries under various management scenarios. The information forms the basis of management decisions about where to implement BMPs and other control measures. The watershed model must be built to most effectively estimate load changes from changes in land use, nutrient inputs, BMP and conservation practice implementation, and waste water treatment.

In a typical year, hundreds of scenarios are run on the CBWM at different spatial scales and different levels of management. These runs are used to develop WIPs, to develop 2-year implementation goals known as Milestones, to assess progress toward WIPs and Milestones, and for special projects. Note that these scenarios are time-averaged. The temporal component is not normally considered for this management need.

1.3.1.2 Deliver Loads to the Estuarine Model

A small subset of the scenarios generated for management are also run on the estuarine model. For management purposes, these are typically run during major CBP decision periods such as the 2010 TMDL and the 2017 Midpoint Assessment. At other times, scenarios may be run for scientific inquiry. For this purpose, it is necessary to have a watershed model that is capable of loading the estuarine model at a daily time step.

1.3.1.3 Calibration and Validation

During the model development, it is essential that the model be judged against observation and other lines of evidence to ensure that it is matching the spatial and temporal patterns of loads as closely as possible. This is accomplished through a weight of evidence approach using multiple data sources. This task is only performed during the initial model development and requires a daily or hourly time step to take advantage of daily flow and instantaneous concentration measurements.

1.3.1.4 Scientific study

From time to time, the CBP managers need estimates of the effects of various physical processes on outputs of interest. For the Phase 6 model in the Midpoint Assessment, these processes include climate change and lag times. Valid scientific inquiry requires a model that incorporates the relevant processes.

1.3.2 Motivations for Change

Given the role of the Phase 5 Watershed Model in the TMDL and Phase I and II WIPs the CBP partnership and many additional stakeholders have brought additional scrutiny to the model development process. As a result, many changes have been suggested to enhance the ability of the Watershed Model to be used as the primary accounting tool for designing implementation plans and tracking progress in BMP implementation. These suggestions most often affect the first purpose listed above — change in load from management actions

1.3.2.1 STAC

The Scientific and Technical Advisory Committee has conducted a number of workshops and reviews that were influential in the priorities set by the CBP Partnership. In addition to comprehensive reviews of the CBP Phase 5 Watershed Model carried out in 2005 (STAC, 2005) and 2008 (STAC, 2008), and the Land Use and Land Cover Model in 2010, (STAC, 2010) STAC produced a more targeted review of phosphorus dynamics in 2014 that influenced the development of watershed input and processing simulation. The workshop report on multiple models in 2014 and the factsheet accompanying the report were pivotal in the development of the model structure described in Section 1.5 below and in the partnership acceptance of that new structure. The 2013 workshop report on lag times motivated the explicit inclusion of lag times in the CBP watershed model for the first time. A 2012 report on natural landscape features initiated a focus on understanding the spatial distribution of factors affecting the watershed delivery of nutrients described in Sections 7 and 8 of the documentation. In 2016, two STAC workshops directly addressed important management questions for the 2017 Midpoint Assessment. The Conowingo workshop made specific recommendations on modeling the effect of the changing bathymetry in the Conowingo and the Climate Change workshop recommended methods of incorporating climate change effects into the watershed model. Also in 2016, STAC held two workshops directly related to the use of the Phase 6 model. A workshop on optimization laid out methods and requirements for a system that would find least cost or maximum benefits for a given load reduction. The uncertainty workshop made recommendations for how to begin the process of estimating the uncertainty of the CBP modeling suite. As of this writing, the results of these workshops have not been published.

1.3.2.2 CBP Input

The WQGIT met in October of 2012 to discuss priorities for the 2017 Midpoint Assessment. A major focus of that meeting was the generation of modeling priorities. The initial list was reworked a number of times by the partnership for better organization and as additional opportunities presented themselves. The Modeling Workgroup, the Management Board, and the Principles' Staff Committee have all contributed to the list of refinements. Stakeholder meetings were also carried out. Primary among these was the 'Building a Better Bay Model' workshop planned by the Agricultural Workgroup and co-sponsored by the USDA-NIFA and Mid-Atlantic Water Program held in May of 2013. The 2017 Midpoint Assessment webpage has a list that includes modeling priorities which is kept current. From the standpoint of the CBPO Modeling Team, these can be grouped in to the following major areas, which are dealt with in the documentation as indicated in Table 1-2 below.

Table 1-2: CBP Priorities

BMP Effectiveness	7.3
BMP Implementation Accounting	7.5
Fertilizer and Manure Applications	4.2
Land Use Types and Acreage	6
Land Use Loading Rates	3
Climate Change	11
Modeling Tools Code Development	1.4
Calibration Methodology	10
Sensitivities to Inputs	4
Fine Scale Processes	7 and 9

Atmospheric Deposition Data	3.3
Lag Times	10.5
Better Representation of Reservoirs	10.6
Time Series Data	10.2

1.3.2.3 Major Themes

Taken together, three major themes arise from the advice of the groups previously mentioned in Section 1.3. These themes are multiple lines of evidence, improved data sources, and understandability.

STAC and others (for example Boomer and others, 2013) have urged the CBP to use a ***multiple modeling approach*** on numerous occasions. The benefits of the approach are discussed in STAC's report from the Multiple Models Workshop. Multiple modeling approaches, and more generally, multiple lines of evidence approaches are valuable for limiting uncertainty and also for incorporating important physical processes. The development of the Phase 6 watershed model includes various technical approaches that incorporate multiple models and multiple lines of evidence

The second major theme is ***better data***. The CBP partnership will be incorporating many new and improved data sets from climatic variables to land use to nutrient inputs as described in the sections to follow. These improved data sets have been a major focus for the WQGIT and its workgroups between the release of the Phase 5.3.2 model in 2011 and the current time.

Understandability is the third major theme of Phase 6 development. Phase 5 was developed and calibrated by a transparent process involving the CBP partnership similar to the Phase 6 process and fully documented (USEPA 2010a). Although the process and the model were transparent, the end result was not a model that was easily understandable to stakeholders due to the complexity built into the data handling, BMP, and physical simulation methods.

1.3.3 Conceptual Model

Referring to the themes and purposes in the section above, it is clear that there is a tension between the simplicity implied in a model that is more *understandable* to the community and the complexity of a *multiple model* approach that includes additional important process. There is also a tension between the primary purpose of the watershed model which is a time-averaged assessment of scenarios and the time-variable functions of loading the estuarine model and calibration.

In previous versions of the watershed model, time-averaged output was generated by running an hourly time-step mechanistic simulation model over an extended period and summarizing the output into average annual loads. Phase 6 *reverses this concept* such that the **primary model structure for management scenarios is steady-state** which the dynamic hourly time-step model driving estuarine loading is forced to match. The steady-state model is also known as CAST – the Chesapeake Assessment and Scenario Tool.

The tradeoffs between complex and simplified models are well documented in the literature. See Hanna 1988 and Beven 1993 for foundational discussions of these issues. Garcia and others 2016 and Van Liew and others 2017 are examinations of the ability of complex models to appropriately predict the water quality of streams. Taken together, these studies do not support complexity beyond the ability to constrain model parameters with data.

The Phase 6 model uses a simplified structure with parameters that are well-supported by multiple lines of evidence rather than complex models. This structure is chosen specifically to avoid problems with over-parameterization and over-calibration.

1.3.3.1 Steady State Model Structure

Figure 1-2 shows the structure of the steady-state model for nutrients. The processes represented correspond to separable scales and physical domains.

Average Loads are loads per acre 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 applications to the landscape of nutrients from atmospheric deposition, fertilizer, manure, and biosolids. ***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 1-2 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. Those loads are then multiplied by the area of the land use in the segment (L***and Use Acres***), the effect of local ***BMPs*** which act to decrease the loads, and local ***Land to Water*** factors.

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 add spatial variance for nutrient transmission.

The application of all of the above 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 100cfs. These are attenuation factors that act to attenuate nutrient delivery in the small, non-modeled 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, modeled rivers as loads move to the estuary.

Direct Loads are loads that do not come from the land surface or subsurface. Point sources and livestock deposition are in this category. Depending upon their location, direct loads may enter the conceptual model either before or after application of Stream or River Delivery Factors.

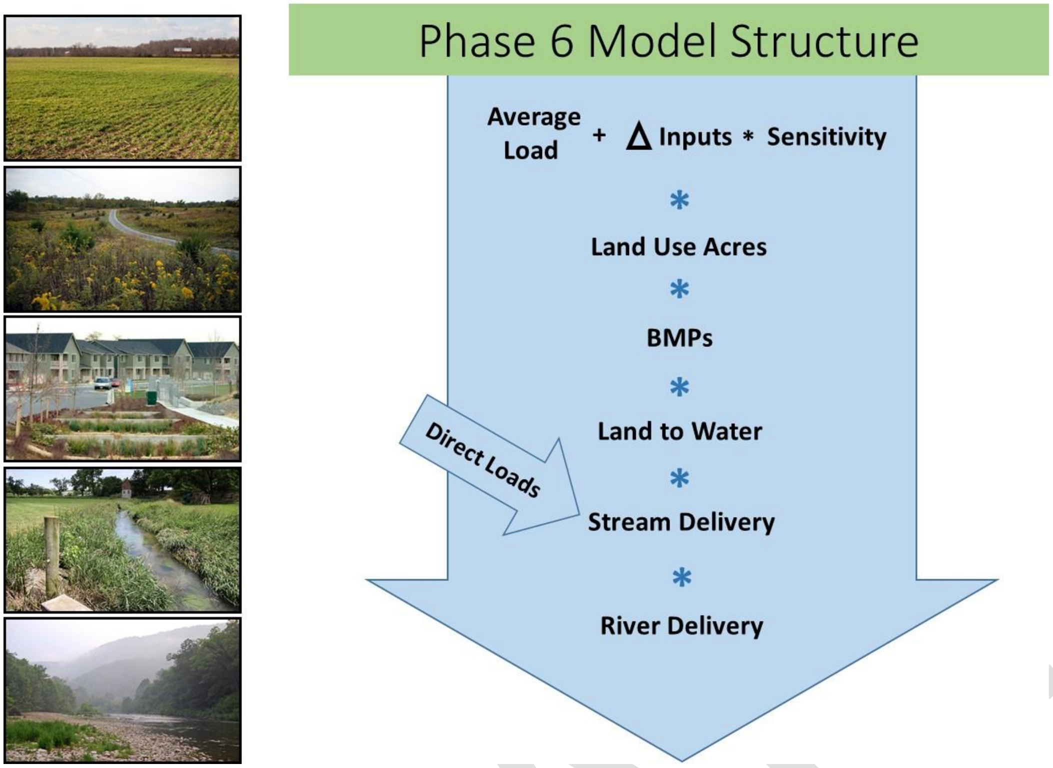

Figure 1-2: Phase 6 Watershed Model Structure

The steady-state model structure is easily understood at the level of detail depicted in Figure 1-2. Each process is a coefficient determined using the available information. The factors are publicly available and calculated according to work done by CBP workgroups. Stakeholders may choose to remain at a coarse level of detail or may increase their understanding of the individual factors by reviewing subsequent sections of this documentation.

The Phase 6 structure accommodates the scientific community's recommendations by allowing for deliberate use of multiple models and multiple line of evidence in each of the processes. The CBP has used multiple models and multiple lines of evidence wherever possible in the Phase 6 model. Table 1-3 shows some of the models that are used directly in the calculation of the coefficients for Phase 6.

Table 1-3: Models Incorporated in the Phase 6 Watershed Model

Model	Use in P6
P532	Global land simulation targets Global sector targets Sensitivity of nitrogen export to changes in nitrogen loading rates
SPARROW	Global sector targets Sensitivity of nitrogen export to changes in nitrogen loading rates Land-to-water delivery factors Stream-to-river delivery factors
CEAP/APEX	Global sector targets Sensitivity of nitrogen export to changes in nitrogen loading rates
APLE	Sensitivity of phosphorus export to changes in phosphorus loading rates
RUSLE 2	Distribution of Land Sediment Erosion
rSAS	Lag time
UNEC	Lag time
Modflow	Lag Time
Regression Models	Stream sediment mass balances

1.3.3.2 Role of the dynamic model

A steady-state watershed model is a departure from previous versions of the CBWM where time-averaged results were calculated from a dynamic model. In Phase 6, the steady-state model is used for accounting and the dynamic model that loads the estuarine model is made to equal the predictions of the steady-state model. The dynamic model is also used for calibration and to estimate the effects of physical processes to the extent that these are built in to the model.

Figure 1-3 shows the functional relationship between the steady-state and dynamic models. Both pull watershed data and process information from the same database. The software structure is discussed in Section 1-11 below. Initially, the dynamic hydrologic model is run to establish storm and baseflow quantities for each land use and land segment. These values are then used (Arrow 1 in Figure 1-3) as one of the predictors of load in the steady-state model. The steady-state model makes initial calibration predictions of loads from each land use and land segment and passes (2) these to the dynamic model. The dynamic model is run in calibration mode with a direct calibration of the river delivery factors, however many assumptions in the *steady-state model* are also examined during the calibration process. For example,

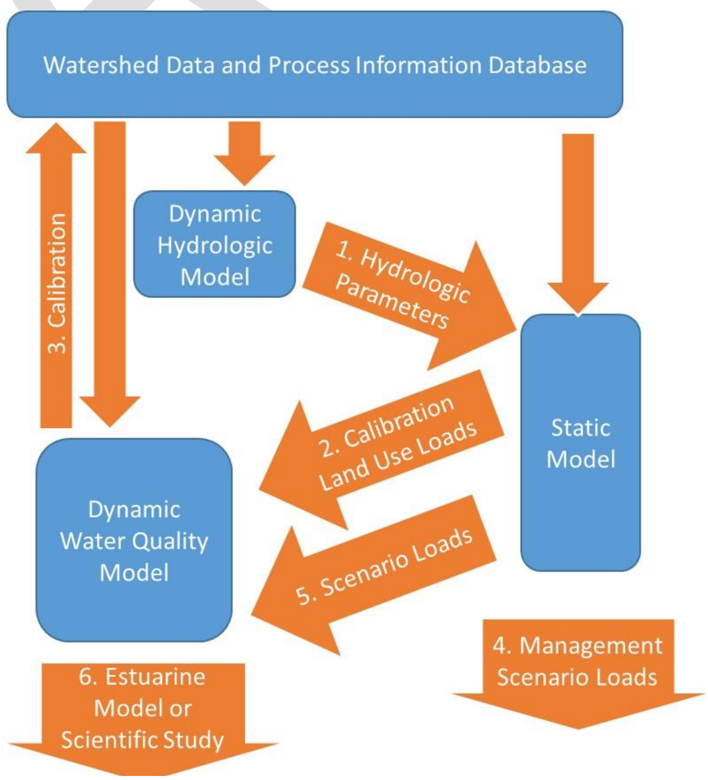

Figure 1-3: Relationship between the Steady State and dynamic models

consistent spatial bias in the long-term loads may suggest alternative approaches to Land-to-Water factors. Any changes in process coefficients are fed back (3) to the database. The process of calibration is iteration between predictions of the steady-state model (2) and updating of the process coefficients (3). After calibration, management scenarios are run (4) using the steady-state model. A small subset of the scenarios run through the steady-state model are also run (5) through the dynamic model. The results of these runs are used (6) as inputs to the estuarine model. The dynamic model can also be used to (6) investigate aspects of climate change or lag times.

1.4 Documentation

The structure of the documentation follows the structure of the model (Figure 1-4). Each major process is documented separately in sections 2 through 10. Calibration of the dynamic model is covered in section 10. Section 1 is this overview document. Section 11 is the physical setting. Section 12 details the results of some of the early scenarios and applications. This will not be kept up to date as the Phase 6 model is used. Official scenarios will be available online using a tool that will be developed for that purpose. All references are in section 14.

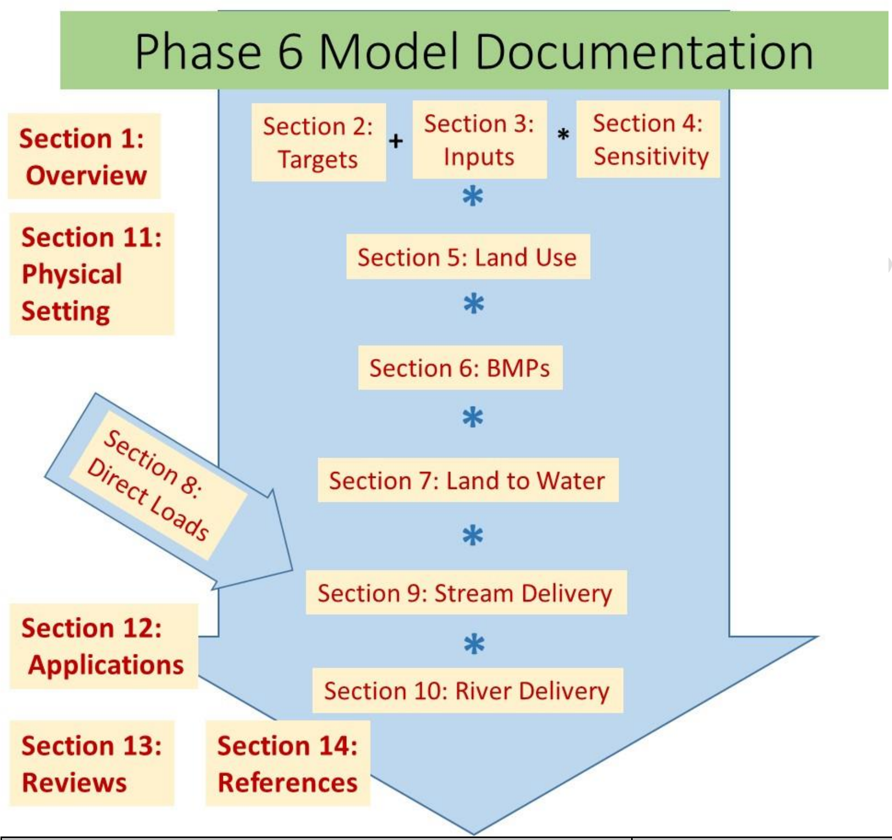

Figure 1-4 :Phase 6 Watershed model documentation structure

The structure of the documentation is for ease of finding the work behind each coefficient in the steady-state model. The documentation also reflects the various responsibilities of groups within the CBP structure. Table 1-4 shows the CBP groups with responsibility for each section of the Phase 6 model.

Table 1-4: Responsibility for Documentation and Decisions

Documentation Section	Workgroup with Primary Responsiblity	Workgroup with Secondary Responsibility
Section 1: Overview	MWG	WQGIT
Section 2: Targets	MWG	AgWG, USWG, FWG
Section 3: Inputs	WQGIT	AMS, AgWG, USWG, MWG
Section 4: Sensitivity	MWG	AgWG

Documentation Section	Workgroup with Primary Responsiblity	Workgroup with Secondary Responsibility
Section 5: Land use	LUWG	USWG, AgWG, WQGIT
Section 6: BMPs	WQGIT	AgWG, USWG, FWG, MWG
Section 7: Land to Water	MWG	
Section 8: Direct Loads	WWWG	AgWG, MWG, PSG
Section 9: Stream to River	MWG	
Section 10: River to Bay	MWG	
Section 11: Physical Setting	MWG	
Section 12: Applications	WQGIT	

1.5 Overall Software Structure

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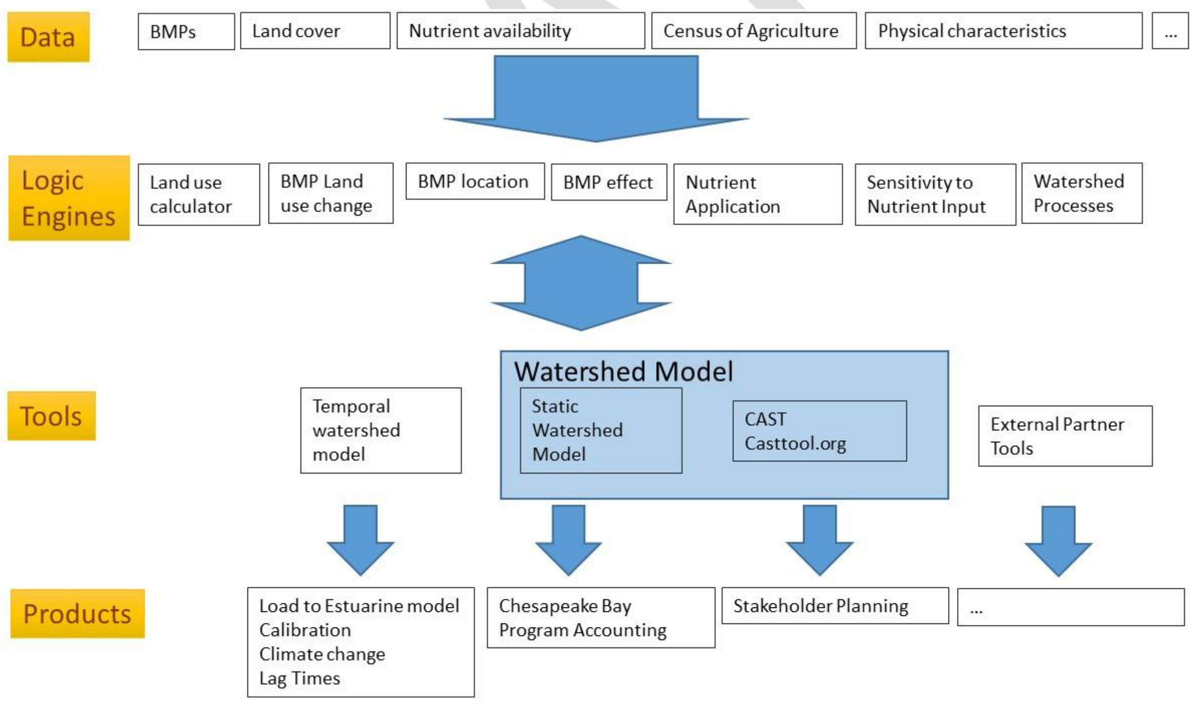

Figure 1-5: Phase 6 software structure

Figure 1-5 depicts the general structure software developed by the CBPO to run the CBWM. The top line depicts the data base that stores information about the watershed, land use, physical parameters, animal populations, and other parameters and coefficients needed in the calculations. Logic engines common to all tools are called to process the data. A user operating the tools selects the data sets to run and the tools are programmed to organize the process of calling the logic engines to make the calculations. Note that the 'Watershed Model' as understood by the CBP partnership incorporates both the steady-state Watershed Model to be used by the CBPO to run official Bay-wide scenarios, and CAST to be run by the partnership for WIPs, milestones, and other planning activities. These are in fact the same software with different interfaces for web use and internal CBPO use. The Temporal Watershed Model is only necessary for scenarios that will load the estuarine WQSTM, for calibration of the overall system, and for scientific investigation of processes such as climate change and lag times. The CBPO recognizes that other groups that are part of the CBP partnership may also want to develop tools that use the same logic. The logic engines will be available as web services that could be integrated tools in addition to the CBP watershed models and CAST.

1.5.1 Comparison of model structure to previous CBWM phases

In all previous phases of the CBWM, the dynamic model was used as both the accounting model for management scenarios and the loading model for the estuarine model. The CBWM was fed by various databases, most notably scenario builder, which was used to estimate manure and fertilizer applications and to spatially distribute BMPs, among other functions. CAST and its location-specific versions MAST and VAST were introduced in Phase 5 as a tool that would approximate both Scenario Builder and the average output of the dynamic CBWM.

For Phase 6, the terms CAST and steady-state watershed model are synonymous and encompass all of the functions previously performed in scenario builder. The web interface for stakeholders and the public will be known as CAST, available at http://casttool.org. CBPO staff will have a separate interface with more functionality that will require more expertise to run.

1.6 Release Schedule

Beta 1 — The first public version of the Phase 6 watershed model was released in the form of a presentation at the Modeling Workgroup Quarterly Review and posting of nutrient loads and calibration plots on 1/4/2016. Limited documentation followed several weeks later. Beta 1 was the first working version of Phase 6, but still had a significant number of inputs set at Phase 5.3.2 values. A webinar was given to the partnership on 3/10/2016 to explain the model and the schedule. This webinar is recorded and available:
https://epawebconferencing.acms.com/p5gqg3teldg/?launcher=false&fcsContent=true&pbMode=normal

Beta 2 — Beta 2 was released and the Modeling Workgroup Quarterly Review on 4/19/2016 with documentation in the following weeks. The CBPO modeling team replaced most Phase 5.3.2 data with Phase 6 data in the Beta 2 release and the documentation was made more complete. A webinar for the Beta 2 release can be viewed here: http://epawebconferencing.acms.com/p7pjy0ohedk/

Beta 3 —The Beta 3 model was the first concerted attempt by the CBPO modeling team to calibrate the overall modeling system. This calibration included tuning of parameters in the river simulation in the classic water quality modeling sense but, more meaningfully, involved examining the datasets and processes that make up the Phase 6 modeling system. There were few changes in the input data and so section 4 of this documentation, Terrestrial Inputs, was not updated.

Beta 4 — The Phase 6 Beta 4 model was released at the Modeling Workgroup's Quarterly Review meeting on 12/13/2016. This model had very significant changes in nutrient inputs and BMPs based on the CBP Partnership's decisions and data as of 9/30/2016.

Draft Phase 6 — The final draft version will include updates from the CBP Partnership as allowed by the WQGIT and, most notably, will include the fine-scale land use for 2013 and a new backcast methodology for the remaining years. The Draft Phase 6 was released with this documentation on June 1 2017.

Phase 6 — After a final fatal flaw review by the CBP Partnership, the Draft Phase 6 version along with any approved changes will become the Phase 6 model in August 2017.