Synthesis Element 6: Understanding the Factors and Geographies Most Influencing Water Temperatures in Local Waters Throughout the Watershed and Across all the Bay's Tidal Waters

At-a-Glance Summary

- Development of a Phase 7 Chesapeake Bay Watershed Model at a much finer geographic scale is necessary to make predictions in changes in the watershed's water temperature for streams and rivers directly relevant to watershed living resource managers.
- Assessment of climate change's impact on the ability to achieve the states' Chesapeake Bay open-water dissolved oxygen water quality standards in shallow waters will require a new Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model.
- There is a need to understand just how feasible and what are the costs for developing Phase 7 versions of both the existing Bay watershed and Bay water quality models at these respective smaller scales are going to be.

A. Contributors

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B. Resources

Published papers cited as references; Maryland Department of the Environment Stream Temperature Model calibration results generated by Guido Yactayo; and Chesapeake Bay Water Quality Model scenario results generated by Richard Tian.

C. Approach

Engaged expert modelers to provide the latest insights into the stream/river and tidal water temperature simulation capabilities of the suite of models being used by the Chesapeake Bay Program partnership and its partners in ongoing climate change, stream and tidal water temperature change evaluations.

D. Synthesis

Existing Watershed Stream and River Water Temperature Simulation Capabilities

CBP Phase 6 Chesapeake Bay Watershed Model

The Chesapeake Bay Program's (CBP) Phase 6 Chesapeake Bay Watershed Model (Chesapeake Bay Program 2020) has two linked components. The Chesapeake Assessment Scenario Tool or CAST is the time-averaged watershed model used interactively by the CBP partnership and others to estimate long-term changes in nitrogen, phosphorus, and sediment loads based on changes in management. However, CAST has no temperature simulation capability.

On the other hand, the dynamic model component of the Phase 6 Chesapeake Bay Watershed Model (Phase 6 dynamic model) runs on an hourly time step and simulates river reach temperature. The long-term outputs for nitrogen, phosphorus, and sediment, often with temperature corrected reaction rates, in the Phase 6 dynamic model are constrained to equal the predictions from CAST. The Phase 6 dynamic model simulates temperature to inform the biological reaction rates of the dynamic nutrient simulation within the rivers. Flow and temperature in the Phase 6 dynamic model are simulated using Hydrologic Simulation Program – FORTRAN.

Hourly air temperature from a reanalysis product is used as in input to the Phase 6 dynamic model river reach simulation and also to calculate potential evapotranspiration (Chesapeake Bay Program 2020 section 10.2). Annual average temperature is used to calculate parameters controlling soil and groundwater temperature. The groundwater temperature is a set spatially varying constant for each month of the year, but monthly constants were not adjusted in the climate change scenarios as the hourly air temperature was. Upper layer soil and stormflow temperatures are parameterized such that they are essentially a damped version of the air temperature time series (Chesapeake Bay Program 2020 section 10.6.2.1). Temperature simulation in rivers is a heat balance from the constituents of advection, atmospheric interaction, radiation and bed heat transfer.

Seasonal simulation of temperature in the Chesapeake Bay watershed's rivers is generally good, however, there are several areas for potential improvement in the temperature simulation.

- Surface flow and stormwater temperature will respond to climate change in the current dynamic model, however, the parameterization of dynamic model surface flow from the land should ideally respond to climate change as well.

- Groundwater temperatures should be made to respond to climate change in the Phase 7 dynamic model.

- The current scale of the Phase 6 dynamic model river simulation is for larger streams and rivers with greater than 100 cubic feet per second average flow rates. But the most temperature-sensitive species in freshwater areas are generally found in streams smaller than the Phase 6 dynamic model river-reach scale for segments which average 70 square miles in area. A Phase 7 scale of river reaches for model segments of about one square mile are more appropriate for assessment of river and stream living resources.

MDE Gwynns Falls Model

The Maryland Department of the Environment has calibrated and applied a version of the deterministic and dynamic watershed model called Soil Water Assessment Tool or SWAT to the Gwynns Falls watershed. The SWAT model was used because it also contains a physically based and spatially semi-distributed stream temperature module (Maryland Department of the Environment 2020). The Gwynns Falls watershed model delineation was performed utilizing Baltimore County's 1:2400 scale hydrography network information and a 30-meter digital elevation model (DEM). This resulted in about 100 river segments within the study area. Figures VI-1 and VI-2, respectively, show the study area and the model segmentation.

Model accuracy is reported for all calibration stations, and for both hydrology and stream temperature in Table A4 and A6, respectively, in Maryland Department of the Environment 2020. There are also graphs that show observed and simulated results. Overall calibration statistics indicate the model was able to produce a good hydrology and stream temperature calibration (Figure VI-3).

Current Model Simulation Findings

Chesapeake Bay water temperature increases due to climate change during the period 1995-2025 are estimated to be approximately 1^{o} C, mirroring the observed and projected changes in air temperature. An extensive analysis of the effect of climate change on dissolved oxygen in the Bay has been performed by the CBP (Shenk et al., 2021), however, detailed estimates of the modeled effects on the Chesapeake Bay watershed's river temperatures were not part of the analysis.

Existing Tidal Tributaries, Embayments and Mainstem Water Temperature Simulation Capabilities

The CBP's tidal Water Quality and Sediment Transport Model computes temperature through a conservation of heat equation. Only advection and exchange with the atmosphere are considered. Temperature is generally well-simulated and is calculated in both the hydrodynamic model and the water quality model to verify the calculations of each.

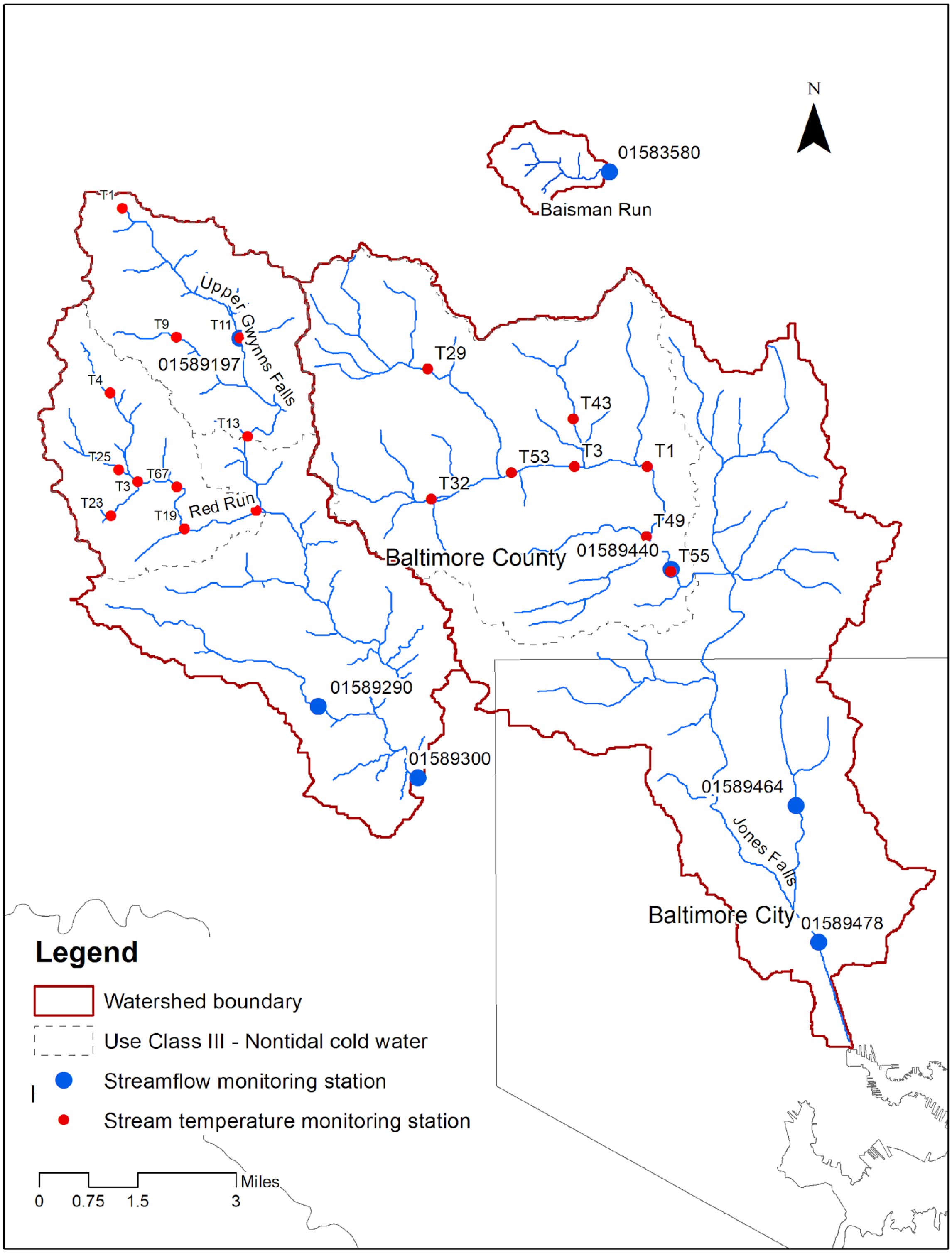


Figure VI-1. Gwynns Falls, Jones Falls, and Baisman Run streamflow and stream temperature monitoring stations.

Source: Maryland Department of the Environment.

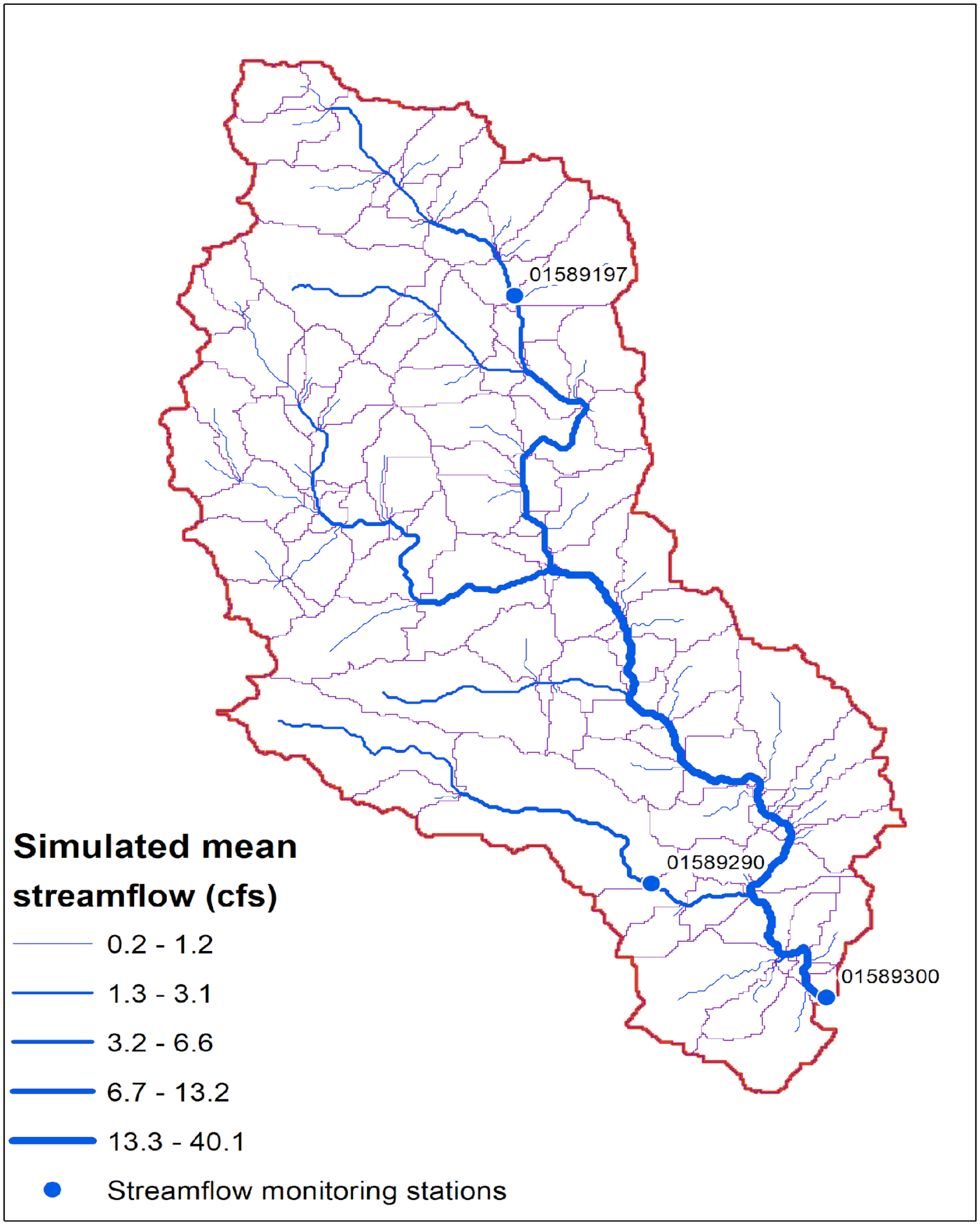


Figure VI-2. Map showing the distribution of summer streamflow for all river segments, as represented in the SWAT model.

Source: Maryland Department of the Environment 2020.

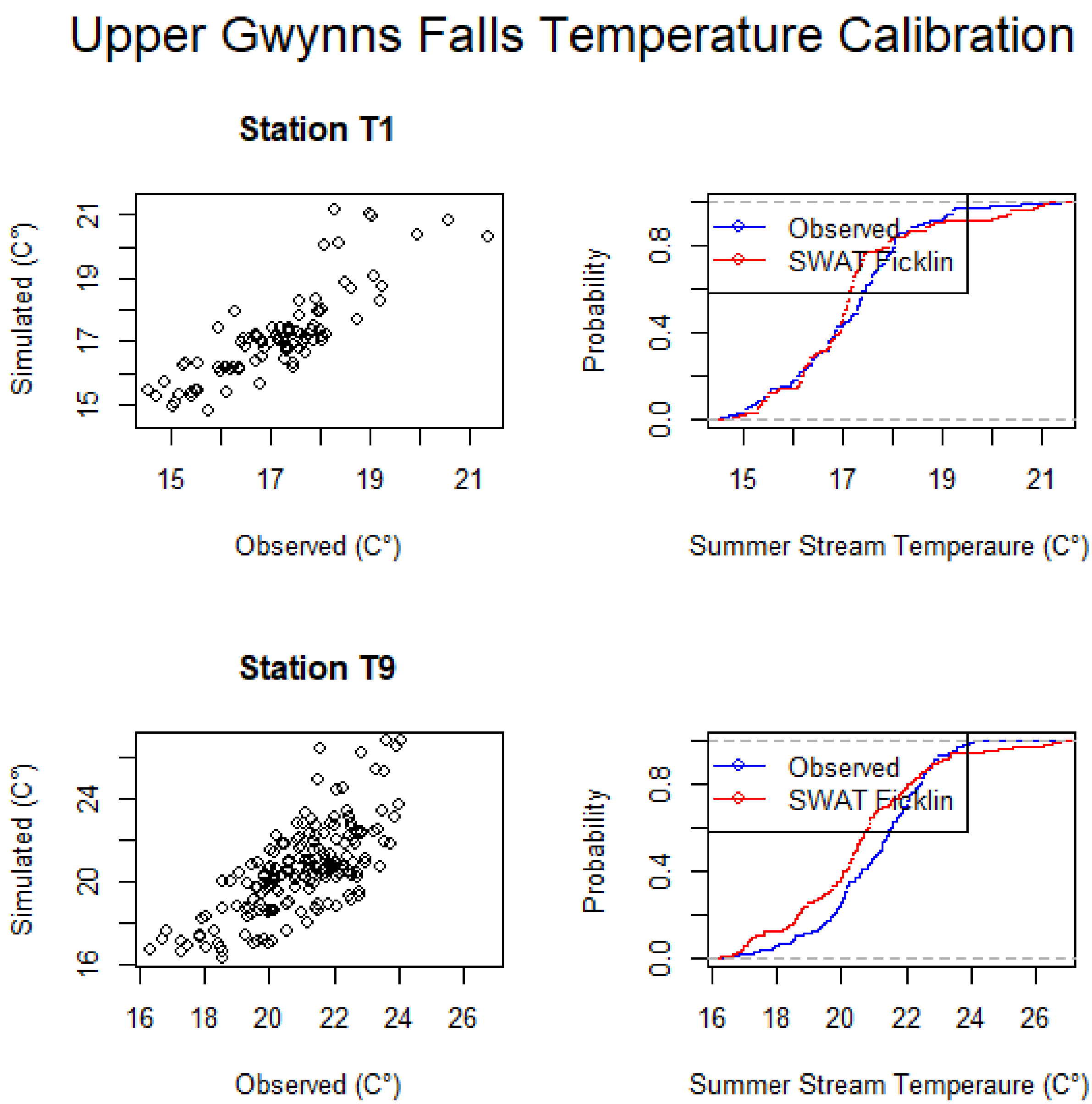
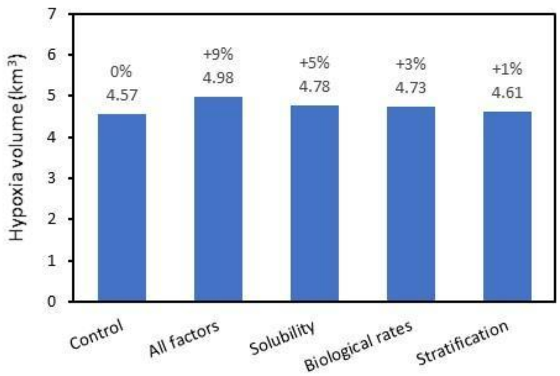


Figure VI-3. Observed and Simulated Daily In-Stream Summer Temperature in Upper Gwynns Falls Cold Water Streams.

Source: Maryland Department of the Environment 2020.

Current Model Simulation Findings

Temperature increases decrease tidal dissolved oxygen through three primary mechanisms: lower oxygen solubility, increased stratification and increased biological rates. A recent analysis by Tian et al., 2021, found that solubility was the primary effect with 55% of the total, followed by biological rates (33%), and stratification 11%) (Figure VI-4).



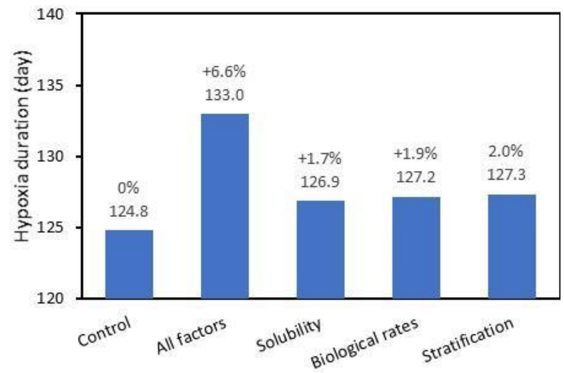


Figure VI-4. (a) Hypoxic volume (km3) in the whole Bay averaged in summer from June through September over 10 years (b) Hypoxic duration(days) at the monitoring station CB4.3C for the entire year, averaged over 10 years of simulation. Control: The control run; All factors: All warming effects; Solubility: The same as the control run but DO solubility computed under CWC; Biological rates: The same as the control run but the biological rates were calculated under CWC; Stratification: The same as the control run but with turbulence diffusivity under CWC. Percentages are the relative changes compared to the control run.

Source: Tian et al. 2021

How the Phase 7 Models Will Improve Our understanding of Water Temperature in the Chesapeake Bay Watershed and Tidal Waters

Chesapeake Bay Watershed Model

The CBP partnership is expected to give formal direction to the CBP Modeling Workgroup on the prioritization of improvements in the Phase 7 Chesapeake Bay Watershed Model during an October 2021 meeting. Therefore, the expectations provided below are provisional.

The Phase 7 Chesapeake Bay Watershed Model is currently being developed on a National Hydrologic Database 100,000 scale, which has an average watershed size of approximately one square mile, compared to the 70 square mile average in the Phase 6 Chesapeake Bay Watershed Model (Figure VI-5). This change in scale will allow the CBP to make predictions at a scale more relevant to living resource managers in the watershed. River reach-scale processes controlling temperature are important for living resources, however, they will be difficult to validate everywhere given the lack of temperature observations at the fine scale.

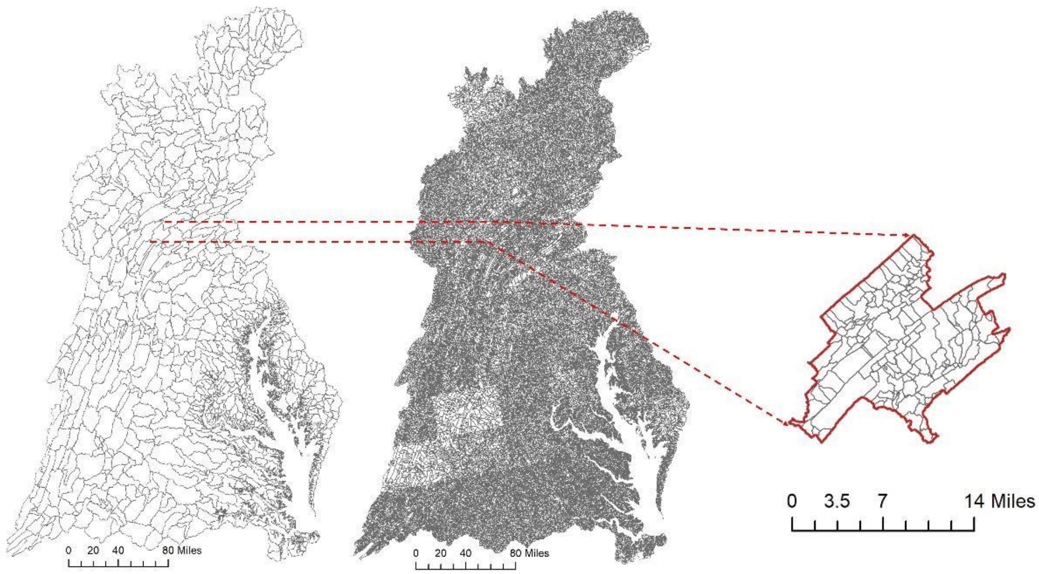


Figure VI-5. River simulation scale in Phase 6 and proposed Phase 7 Chesapeake Bay Watershed Models.

Chesapeake Bay Water Quality and Sediment Transport Model

In the tidal waters of Chesapeake Bay, Delaware, District of Columbia, Maryland and Virginia's open-water dissolved oxygen state water quality standards are based on protection of living resource habitat. The 2010 Chesapeake Bay TMDL was based on attainment of the summer open water monthly mean criteria of 5 mg/l (5.5 mg/l in tidal fresh waters), which was established to protect the growth of larval, juvenile, and adult fish and shellfish (U.S. Environmental Protection Agency 2010).

Under climate change conditions, the average annual tidal water temperatures are estimated to increase by 1° C over the three-decade period between the hydrology used for the Chesapeake TMDL (1991-2000) and the year 2025 (Shenk et al., 2021). By 2055 the average tidal water temperature is estimated to increase by 2° C for the 60 years between 2055 and 1995. Climate change temperature increases in Chesapeake tidal waters are inevitable over the next half-century, are global in origin, and are largely beyond CBP management and control.

Consequently, challenges in maintaining achievement of an open-water dissolved oxygen water quality criteria of 5 mg/l in all open-water designated uses at all times will inevitably increase throughout the next half-century. This is particularly true in the shallow water portions of the open-water dissolved oxygen designated uses of Chesapeake Bay, which are generally defined as those areas less than 2 meters in depth (U.S. Environmental Protection Agency 2010).

However, the minimum depth represented in the 2017 Chesapeake Bay Water Quality and Sediment Transport Model, used for the current assessment of climate change risk to tidal water quality standards, is 2 meters. Consequently, the depth of the nearshore areas is inaccurately represented. Until now, the Chesapeake Bay Water Quality and Sediment Transport Model was sufficient for open-water dissolved oxygen assessment, but in a changing climate with increasing shallow water temperatures the current model's simulation is unsuitable for shallow water open-water dissolved oxygen water quality standards attainment assessment.

Nevertheless, assessment of open-water dissolved oxygen climate risk is needed in shallow waters. Going forward, a new Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model is required which can:

1) Simulate shallow water at a finer scale;
2) Allow for an unstructured model grid to fit complicated shorelines;
3) Simulate wetting and drying of the intertidal region;
4) Project tidal wetland and SAV migration with sea level rise;
5) Estimate SAV responses to climate change;
6) Assess living resource co-benefits; and
7) Provide a state-of-the-art assessment of the important interface between land and water in the Chesapeake Bay estuary.

The estuarine model approach for simulation of shallow water habitats described in the CBP Scientific and Technical Advisory Committee's report on the *Chesapeake Bay Program Modeling in 2025 and Beyond: A Proactive Visioning Workshop* outlines the direction needed for a sufficient simulation of open-water dissolved oxygen in shallow Chesapeake Bay waters under climate change conditions (Hood et al. 2019).

E. Evaluation

Key Findings

- The Phase 6 Chesapeake Bay Watershed Model is sufficient for predicting climate change effects on river temperatures reaching the tidal waters, however, the simulation of climate change would be improved by adjusting ground water temperatures to future climate conditions.

- Development of the Phase 7 Chesapeake Bay Watershed Model at a much finer geographic scale would increase the ability to make predictions in changes in the watershed's water temperature for streams and rivers directly relevant to watershed living resource managers such as cool- and coldwater fisheries in headwater streams.

- Maryland Department of the Environment's development of the SWAT model for simulating stream temperatures will help understand the feasibility and accuracy of temperature simulations at a very local scale prior to development of the next phase of the Chesapeake Bay Watershed Model.

- Climate change-driven Chesapeake Bay tidal water temperature increases will continue to have a significant influence on the ability to attain the states' Chesapeake Bay dissolved oxygen water quality standards.

- Assessment of climate change's impact on the ability to achieve the states' Chesapeake Bay open-water dissolved oxygen water quality standards in shallow waters will require a new estuarine model system.

Management Implications

Chesapeake Bay Watershed's Streams and Rivers

In the watershed, the proposed finer scale of the Phase 7 Chesapeake Bay Watershed Model is expected to provide an quantifiable improvement in simulated hydrology and sediment fate and transport. The improvement in simulated flow and sediment loads will further improve the nutrient simulation beyond the Phase 6 Chesapeake Bay Watershed Model simulation. Also, the number of calibration stations for river and stream flow will almost double, which will further increase confidence in the Phase 7 model assessment. Finally, the finer scale of Phase 7 Chesapeake Bay Watershed Model throughout the watershed will allow an improved assessment of impacts on coldwater and warmwater fisheries.

Given a Phase 7 Chesapeake Bay Watershed Model scale of river reaches of about one square mile is essential to accurately simulating stream water temperatures, there is a need to understand just how feasible and cost-effective developing a model at this scale is going to be. The amount of time involved and cost of building the capability to model at this fine scale of resolution are questions which need to be answered and put in content for the timing of the management decisions depending on this next version of the watershed model.

Chesapeake Bay Tidal Waters

A Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model should be used to assess the risk to attainment of the states' Chesapeake water quality standards under 2035 climate change conditions. The finer scale of an unstructured grid model would allow the assessment of the shallow open-water dissolved oxygen concentrations under climate change conditions for the first time.

The 2010 Chesapeake Total Maximum Daily Load (TMDL) requires all of the states' Chesapeake Bay dissolved oxygen, SAV/water clarity, and chlorophyll *a* water quality standards to be fully assessed and attained. With the fine-scale unstructured grid of the Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model, the ability to do this assessment under climate change conditions of increased temperatures and sea level rise will be substantially improved.

The proposed Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model would: 1) simulate shallow water at a finer scale and depth increments; 2) use an unstructured model grid to fit complicated shorelines; 3) simulate wetting and drying of wetlands and the intertidal region; 4) project tidal wetland and SAV migration with sea level rise; 5) estimate SAV response to climate change; 6) assess living resource co-benefits; and 7) provide a state-of-the-art assessment of the important interface between land and water in the Chesapeake estuary.

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