A Path Forward in Considering Future Environmental Scenarios in Chesapeake Bay Restoration Efforts

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About the Scientific and Technical Advisory Committee

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

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Executive Summary

STAC's Climate Change 3.0 (CC 3.0) Workshop, held from May 7–9, 2024, in Arlington, VA, was convened to refine and expand existing climate modeling efforts for the Chesapeake Bay ecosystem. This workshop, the third in a series over the past eight years, aimed to advance modeling frameworks to better assess climate change impacts, in preparation for the reconsideration of the Chesapeake Bay Total Maximum Daily Load (TMDL) Planning Targets in 2027.

Unlike previous workshops that introduced major structural changes, CC 3.0 focused on incremental improvements, refining model evaluation, expanding living resource modeling, and supporting the TMDL accountability framework. Participants engaged in science presentations and breakout sessions to develop cross-sector and within-sector recommendations addressing climate-driven changes in watershed processes, estuarine hydrodynamics, biogeochemical cycles, and living resources.

Key Recommendations

1. Based on previous work, the existing modeling system connecting climate change to water quality does not need an extensive overhaul. A limited number of prioritized improvements could efficiently produce useful results for the Chesapeake Bay Program (CBP).
    - Long, continuous runs of the modeling suite could reveal tipping points and the effects of extreme events and be important for linkages to living resources.
    - Focusing development on shallow tidal waters would provide output more relevant to managers and the community.
    - Concentration on climate-related variables such as pH and acidification in the estuary and better representation of seasonal changes in the watershed may reveal insights not previously included in CBP climate work.
2. The CBP should prioritize the development and use of new and existing living resource models.
    - Creating greater accessibility of existing outputs from the estuarine model through Open Science and FAIR (Findable, Accessible, Interoperable, Reusable) data practices would expand the usefulness of the CBP models beyond the TMDL.
    - Because a full ecosystem model is not feasible in the near term, a strategic approach is needed to identify areas where management-relevant models can be developed. Initial development should focus on selected individual species and life stages at broad spatial scales.
    - Linkages should be sequential rather than coupled, to simplify the work and lower computing time.
    - Living resource or habitat models linked to spatially explicit water quality and loading models would help the CBP identify areas of the watershed where restoration would deliver the most benefit.

3. Rather than focusing on uncertainty per se, model evaluation more generally should be tailored to answer questions relevant to management. The response gap framing of the Comprehensive Evaluation of System Response (CESR) is a useful example.
    - Improved understanding of watershed responses to climate forcing functions of increased temperature and precipitation would increase confidence.
    - Expand the estuarine model evaluation data in the areas of shallow water observations, application of remotely sensed data, and ecosystem studies of the influence of increases in temperature using comparable lower-latitude East Coast and Gulf Coast estuaries

4. Consider updating the rules and procedures governing the calculation of load reduction targets in the accountability framework of the TMDL.
    - Tiered or interim targets could focus efforts in areas where positive changes may first appear.
    - An updated base hydrology and critical period would reflect more recent climate conditions and increase confidence by lessening the difference between base, current, and projected loading rates.

The CC 3.0 Workshop reaffirmed the CBP's commitment to integrating climate science into decision-making. By refining modeling frameworks and incorporating ecosystem-based management approaches, stakeholders aim to enhance the Bay's resilience to climate change and ensure the effectiveness of ongoing restoration efforts. The workshop's recommendations serve as a roadmap for scientific advancements leading up to 2027 and beyond.

Introduction

The Chesapeake Bay Program's (CBP's) Midpoint Assessment process resulted in CBP's adoption of updated nutrient and sediment planning targets in 2018, consistent with the 2010 Chesapeake Bay TMDL allocations and based on updates to the CBP's suite of models. Consideration of the effects of climate change on the CBP partnership's ability to reach Bay water quality goals was intended to be part of the 2017 Midpoint Assessment process, but the partnership decided to delay decisions until additional climate effects modeling could be completed.

Guided by the STAC products described below, the CBP's Modeling Workgroup revised the CBP's TMDL models and climate change application of the models to arrive at estimates of additional reductions necessary to defend Bay water quality standards against climate change through 2025 (Shenk, et al., 2021b). In October 2020, the Management Board (MB) reached consensus on approval of the revised models and additional loads resulting from climate change. Notably, the partnership acknowledged limitations in the science and modeling: for example, shallow open water was excluded from the climate change allocation; questions arose around model-predicted versus observed climate change; and the impact of climate change on management practice effectiveness remained largely unquantified.

On December 17, 2020, the Principals' Staff Committee (PSC) approved the MB climate decisions and further agreed to revisit climate change in 2025 to consider new science and modeling in an estimate of climate change effects on the TMDL for 2035. On March 2, 2022, the PSC decided to extend the model development period by two years based on input from the partnership. Draft models will be due for partnership review by the end of 2025, with decisions on new planning targets to be made in 2027. The STAC Climate Change 3.0 Workshop was held on May 7–9, 2024, in Arlington, VA, to develop recommendations to guide the CBP's Modeling Workgroup in producing and using the CBP's suite of models.

The Climate Change (CC) 3.0 Workshop was the third major STAC workshop on CBP climate change modeling in the last eight years. The first two workshops (Johnson et al., 2016, Shenk et al., 2021a) could be generally described as revolutionary, as they recommended fundamental changes in approaches to CBP climate change modeling compared to plans prior to those workshops. The guidance and recommendations of the previous workshops were generally adopted, either specifically or broadly, by the CBP Modeling Workgroup and Chesapeake Bay Program Office (CBPO) Modeling Team. In contrast, the STAC CC 3.0 Workshop developed recommendations that were more evolutionary in nature, with guidance for incremental extensions and refinements of many current modeling efforts.

Other STAC products that influenced the 2020 climate modeling include: *Monitoring and Assessing Impacts of Changes in Weather Patterns and Extreme Events on BMP Siting and Design* (Johnson et al., 2018)); *CBP Modeling in 2025 and Beyond* (Hood et al., 2019); and reviews of the Phase 6 Watershed Model (Easton, et al., 2017) and the Water Quality Sediment Transport Model (Brady et al., 2018). Going forward, the results of this workshop will be considered alongside other STAC products related to modeling of climate change effects. Primary among these is the Comprehensive Evaluation of System Response (CESR) (STAC 2023). A STAC review of BMP effectiveness under climate change (Hanson et al., 2022) and a workshop on rising temperatures in the watershed and the Bay (Batiuk et al., 2023) provide guidance for future climate analysis.

The workshop began with presentations of the existing policy and modeling structures and continued with presentations on emerging science of climate change and its effects. Participants were formed into breakout groups to (1) develop recommendations for new or refined methods and modeling techniques to be completed and fully operational by 2025 and (2) propose methods for longer-term development. Cross-sector breakouts considered the policy context, the modeling system as a whole, and the interactions between individual models. Within-sector breakouts used the knowledge gained from participation in cross-sector breakouts to develop specific recommendations for individual modeling packages. The prompting questions used in breakout sessions are listed in Appendix D and participants were encouraged to allow broader conversations and recommendations.

Presentation Summaries

A series of presentations provided the scientific and management background for participants prior to the breakout sessions. Links to all presentations can be found on the STAC workshop page and in the presentation titles in this document.

Management Motivation and Model Overview – *Lee McDonnell (EPA)*

The Chesapeake Bay Total Maximum Daily Load (TMDL) and the associated accountability framework is a system for setting nutrient reduction goals and developing plans to meet the goals (US EPA 2010). The nutrient reduction will improve Bay dissolved oxygen (DO), clarity, and chlorophyll to levels supportive of living resources. The CBP supports a system of atmospheric, land use, watershed, and estuarine models for use in the TMDL that can evaluate the effects on oxygen caused by climate change. The balance of positive and negative effects can be uncertain. In 2017, the CBP calculated that an additional 9 million pounds of nitrogen reduction was necessary to offset climate change, but because the number varied throughout the year as models and inputs were finalized resulted in low confidence by decision makers. In 2018, the CBP's Principals' Staff Committee (PSC) decided to reevaluate climate change effects in 2021 based on updates to models. The 2021 STAC climate change modeling 2.0 workshop (Shenk et al., 2021a) spurred re-consideration of 21 different climate effects within the 2019 CBP models, which in turn led to a decision by the PSC to adjust the TMDL planning targets downward by 5 million pounds of nitrogen and 0.6 million pounds of phosphorus (Shenk et al., 2021b). The PSC also directed the CBP to perform a reassessment in 2025, later extended to 2027, of climate change through 2035.

The CBP partnership has added challenges to the 2035 climate reassessment. The PSC directed the partnership to develop new models and methods for shallow water. STAC expanded on the shallow water theme in their Comprehensive Evaluation of System Response (CESR) report (STAC 2023), adding a living resource focus as well. The CBP's Management Board (MB) directed the Criteria Assessment Workgroup to evaluate risks to water quality standards and designated uses. The MB also asked for a better understanding of best management practice (BMP) response and to re-evaluate the use of observation and climate model output. The CBP is developing a comprehensive update to the models under the direction of the Water Quality Goal Implementation Team and the Modeling Workgroup.

Application of Climate Data and Global Climate Models to the Chesapeake Bay Program's Phase 6 Models – *Gopal Bhatt (PSU)*

Gopal Bhatt discussed the use of observed trends and downscaled climate model outputs in the CBP's previous assessment of climate change effects for the Bay TMDL.
Assessment of 2025 climate change effects was made as compared to the 1993–1995 Chesapeake Bay TMDL critical period and 1991–2000 average hydrology period. The Phase 6 Watershed Model was calibrated to the precipitation and meteorological data obtained from NLDAS-2 (Xia et al., 2013). Precipitation and meteorological inputs for 2025, 2035, 2045, and 2055, representing a change of 30, 40, 50, and 60-years as compared to the 1993–1995 critical period and 1991–2000 average hydrology period were developed to examine the expected effects of climate change. As per Scientific and Technical Advisory Committee (STAC, Johnson et al., 2016) and Chesapeake Bay Program (CBP) Climate Resiliency Workgroup recommendations, expected change in 2025 precipitation was developed based on long-term trends in historical observations, and an ensemble of global climate models (GCMs) for the 2050 and beyond. The CBP Modeling Workgroup in September 2018 recommended combining the two approaches for the periods between 2025 and 2050 (i.e., 2035 and 2045).

Long-term precipitation trends for each land segment (county) in the Chesapeake Bay watershed were estimated by performing a linear trend analysis on the Parameter-elevation Relationship on Independent Slope Model (PRISM; Daly et al., 2008) annual precipitation data. The annual PRISM dataset for the years 1927–2014 (i.e., 88 years) were used in the linear trend analysis. The period of 88-years was selected because of overlaps in the availability of historical precipitation data, nearly complete streamflow data at long-term monitoring stations, and the model calibration period. Statistically downscaled GCMs included in then recently completed Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) were used for the precipitation and temperature projections. Data for climate models and corresponding realizations of potential future socio-economic and natural scenarios defined as Representative Concentration Pathways (RCPs) were retrieved from an online archive accessed through the Geo Data Portal (Bureau of Reclamation 2013). The decision to use an existing downscaled dataset rather than either developing or applying a tailored statistical climate downscaling process was based upon the recommendations of the STAC (Johnson et al., 2016). Ensemble medians of monthly change for 31 GCMs were computed. Estimates of changes in rainfall intensity classes from published analyses, such as Karl and Knight (1998) and Groisman et al., (2004), of long-term observation-based precipitation data were used in preferential allocation of monthly change in precipitation volume into hourly data that is used for forcing the watershed model simulations. Due to the similarities between estimated changes produced by the Hargreaves-Samani (1985) and Penman-Monteith (Allen et al., 1998) methods, along with guidance provided by STAC and the recommendation of the CBP Modeling Workgroup, the Hargreaves-Samani method was used for estimating change in potential evapotranspiration.

Chesapeake Bay Program Watershed Model – *Isabella Bertani (UMCES)*

Isabella Bertani discussed the CBP Watershed model, including the current model structure, the 2019 climate application, and the next generation structure.

This presentation provided an overview of the Phase 6 CBP watershed modeling suite and how it was previously used to assess the impact of climate change on loads delivered to the Bay in the context of the Bay TMDL (Shenk et al., 2021b). The presentation also described a newly developed modeling tool (CalCAST) that is part of the Phase 7 watershed modeling suite.

The Phase 6 version of the watershed model included two distinct models, the Chesapeake Assessment and Scenario Tool (CAST) and a dynamic watershed model (DM). Revised and improved versions of both models are also part of the Phase 7 modeling suite. CAST is the official CBP watershed model used to assess management scenarios and make decisions. It is a time-averaged model that provides estimates of average annual loads delivered to the Bay under hydrologic conditions observed in 1991-2000. It is a deterministic model where watershed processes are largely represented by coefficients that in Phase 6 were obtained through a combination of literature review, results from other watershed models, and expert judgment. The DM is a largely process-based model that runs at an hourly time step and is constrained to match CAST load predictions at the average annual scale. The main purposes of the DM are to calibrate the watershed model to observed river streamflow and water quality data and to temporally disaggregate CAST average annual loads to hourly to load the estuarine model.

In 2019, CAST and the DM were used to develop an assessment of the impact of climate change on watershed loads and to quantify nutrient reductions necessary to offset the estimated impacts of climate change conditions on the Bay water quality standards (Shenk et al., 2021b). This presentation provided an overview of how model inputs and watershed processes represented in CAST and the DM were modified to develop watershed load predictions under climate change scenarios. Broadly, the major climate change modifications included (a) simulating hydrology and sediment transport on land by running the DM with climate change-modified meteorological inputs; (b) adjusting baseline atmospheric nitrogen (N) deposition loads to account for future rainfall conditions by adopting empirically-derived sensitivities to rainfall; (c) using the CBP Land Change Model to project land use in future years; (d) performing short-term (2022) projections of agricultural inputs; (e) adjusting baseline combined sewer overflow (CSO) loads to account for the expected impact of future increases in rainfall volume and intensity; and (f) developing and applying expected sensitivities of N and phosphorus (P) loads to future changes in hydrology (N, P), sediment transport (P), and soil concentrations (P) (Bertani et al., 2022, Bhatt et al., 2023, Claggett et al., 2023, Linker et al., 2023). Overall, the watershed model predicted an increase in delivery of freshwater and constituent loads for all considered climate change scenarios. Examples of model inputs and watershed processes for which the impact of climate change was not evaluated included potential changes in the frequency and severity of extreme weather events, BMP removal efficiency, groundwater temperature and groundwater lag times, reservoir operation rules, water diversions, phenology/timing of nutrient loads, length of the growing season, farmer behavior, cropping practices, rotation cycles, and phosphorus transport processes in small streams.

The presentation concluded by introducing a new watershed modeling tool called CalCAST that was developed as part of the Phase 7 version of the watershed modeling suite. CalCAST is a relatively parsimonious, spatially explicit regression-based watershed model that is calibrated within a Bayesian framework to average annual streamflow and constituent loads estimated at riverine monitoring stations across the watershed. The model is envisioned to serve as a flexible, largely data-driven tool to probabilistically test hypotheses on factors related to spatio-temporal variation in streamflow and constituent load delivery and to estimate parameters that can be then used in the Phase 7 versions of CAST and the DM.

Chesapeake Bay Program Estuarine Model – *Lew Linker (EPA), Richard Tian (UMCES), Joseph Zhang (VIMS), Carl Cerco (ATS), Jian Shen (VIMS)*

A key motivation for development of the Phase 7 Main Bay Model (MBM) was to address limitations of the previous Phase 6 estuarine model. The Phase 6 estuarine model represented a surface cell layer with a depth of two meters with subsequent cell depths of one meter. As a consequence, shallow water, often represented as one meter in depth, was unexamined. In the water quality assessment, emphasis was placed on examining the water quality DO criteria of 3 mg/l in the Deep Water and the 1 mg/l DO in the Deep Channel. However, the shallow water habitat, represented by the Open Water DO criteria of 5 mg/l, is important to living resources, such as juvenile and forage fish, that are dependent upon shallow water habitat conditions.

In addition to scale limitations, limitations within the overall Phase 6 suite of models include limited investigation into phenological or seasonal biological phenomena, correlated to climatic conditions such as longer growing seasons, different crop types, or a deceased spring freshet. Also, the effectiveness of BMPs was unchanged under climate change conditions.

To address the Phase 6 limitations in the estuarine model, the Phase 7 SCHISM MBM has either a sigma or orthogonal grid option and other fine-scale features that can fully support all 92 Chesapeake TMDL segments. The Integrated Compartment Model (IMC) water quality model code that was refined in over 30 years of CBP estuarine model development was retained, but applied at a finer scale. This has given CBP an improved capability to effectively simulate shallow water processes. Other Phase 6 limitations described above are also being addressed during the Phase 7 model development.

The primary impetus for the Phase 7 suite of models is the CBP's Executive Council's directive on climate change**,** *Directive No. 21-1*, which directed the CBP to "…advance our response to climate change impacts on water quality and living resources by applying the best scientific, modeling, monitoring and planning capabilities of the Chesapeake Bay Program [to assess 2035 climate change conditions]." In addition, the Directive "emphasized the continued need to update best management practice design standards to account for the impacts of climate change, using leading predictive models and tools, to ensure investments made today continue to yield benefits even as the climate changes."

Guidance for Phase 7 MBM development was from the 2019 STAC Workshop *CBP Modeling in 2025 and Beyond*. The Phase 7 MBM and Multiple Tributary Models (MTMs) will provide understanding across a wide range of scales using unstructured grids which are particularly well suited to allow greater resolution in the shallow tributaries of the Bay. The MTMs of the Patapsco-Back, Rappahannock, and Choptank rivers provide the CBP with localized models each with its own modeling team, which expands the partnership's efforts to make models applicable to smaller "local" scales that are appropriate to decision making for jurisdictions and watershed groups at the smaller scale.

The CBP MBM and MTMs will have improved simulation of habitat quality and impacts on higher trophic level organisms, with a structure that more directly supports coupling with models of higher trophic level species. In addition, the current living resource simulation in the CBP water quality model, which includes submersed aquatic vegetation (SAV) and oysters, will continue to be developed with the goal of improving these models.

2019-2020 Climate Management Application of the Chesapeake Bay Program Models – *Gary Shenk (USGS)*

The CBP partnership developed rules for calculating needed reductions of nitrogen, phosphorus, and sediment to meet water quality standards in the 2010 Chesapeake TMDL (USEPA 2010). Average loads are always expressed for weather in 1991-2000 to meet water quality standards in the 1993-1995 period. The incorporation of climate change means that additional reductions need to be taken such that the 1993-1995 period, projected 30 or 40 years into the future, would still meet standards. Modeling suggested that watershed loads increased and the attainment of DO standards decreased due to climate change effects. The CBP partnership decided that additional reductions would be made by the states and basins where loads increased. Additional reductions totaled 5 million pounds of nitrogen and 0.6 million pounds of phosphorus, representing a moderate increase effort relative to the 140 million pounds of nitrogen and 9 million pounds of phosphorus in the pre-existing targets (Zhang et al., 2024). Participants in the climate workshop were challenged with three concepts: (1) climate effects increased loads from the watershed and also decreased the assimilative capacity of the Bay, yet modeling indicated that climate effects could be offset just by reducing watershed loads by the total amount of increase; (2) uncertainty quantification is now possible, but the challenge of how to incorporate it in management remains; and (3) various types of models may be used for academic inquiry, but translating knowledge or function into CBP's management-focused suite of models may be challenging.

Overview of Recommendations from Prior STAC Workshops and Reviews – *Zach Easton (VT) and Jeni Keisman (USGS)*

Steering committee members Zach Easton and Jeni Keisman gave an overview on previous STAC-led workshops and reviews related to climate change effects modeling.

Climate change related recommendations from three previous STAC workshops and two STAC reports were discussed. The three STAC workshops include a 2016 STAC workshop on climate projection, which assessed available climate data for use in the Bay Program model (Johnson et al., 2016); the 2018 STAC Climate Change 2.0 workshop (Shenk et al., 2018) which provided guidance and expert advice on the models and the assessment framework used to assess the effect of climate change on the TMDL; and the Modeling in 2025 and Beyond workshop in 2018, which identified new or expanded capacity needed to address climate change, as well as collaborative opportunities to further Bay-related science (Hood et al., 2019). The two reports included a 2022 STAC review of BMP effectiveness under climate change and the 2023 Comprehensive Evaluation of System Response (CESR) report by STAC. The 2022 STAC report reviewed climate change impacts on nutrient/sediment cycling in the watershed and by what mechanisms climate change is expected to alter BMP performance (Hanson et al., 2022). The CESR report evaluated progress towards meeting the TMDL and, acknowledging the pending shortfall, suggested how progress could be accelerated (STAC 2023). The presentation evaluated CBP progress towards meeting workshop and report recommendations. The CBP has addressed many of the recommendations, in particular those related to the selection of earth system models of the climate and use of consistent climate scenarios from these models. The CBP has likewise embraced recommendations to update the estuarine model to allow better climate forcing integration. Recommendations dealing with uncertainty, both in terms of quantification in the decision process and with respect to climate impacts on BMPs, remain areas where the CBP could devote additional resources.

Chesapeake Hypoxia Analysis and Modeling Program (CHAMP): Predicting impacts of climate change on the success of management actions in reducing Chesapeake Bay hypoxia.
– Marjy Friedrichs (VIMS), Kyle Hinson (PNNL)

Marjy Friedrichs and Kyle Hinson reviewed results from the Chesapeake Hypoxia Analysis and Modeling Program (CHAMP), a project that used multiple models in a Chesapeake Bay scenario-forecast modeling system to predict the impacts of future climate change and anthropogenic nutrient inputs on hypoxia. Specifically, the goal of the project was to isolate future impacts on Chesapeake Bay hypoxia due to climate change from those due to anthropogenic inputs.

One of the first studies to examine the competing impacts of climate change and nutrient reductions in Chesapeake Bay (Irby et al., 2018) examined model scenarios with and without climate change (including temperature increases, sea level rise, and changes in watershed inputs), as well as scenarios with and without nutrient (TMDL) reductions. Results demonstrated that by 2050, sea level rise slightly increased summer bottom oxygen concentrations, whereas changes in watershed inputs slightly decreased summer bottom oxygen concentrations. Although these effects nearly offset one another, warming waters were shown to cause large decreases in future summer bottom oxygen concentrations, leading to significantly more hypoxia by 2050. On a more positive note, further scenarios demonstrated that if TMDLs were met by 2050, the increase in hypoxia due to climate change would be substantially less than the decrease in hypoxia due to achieving the TMDL reductions (Irby et al., 2018).

Pierre St-Laurent (St-Laurent et al., 2019) conducted an investigation into the cause of the increase in bottom oxygen concentrations due to sea level rise. The resulting multi-model intercomparison (including the CBP model, SCHISM, ROMS-RCA and ROMS-ECB) led to the discovery that sea level rise was being projected to cause higher temperatures in fall and winter, and lower temperatures in spring and summer, simply due to the fact that the deeper waters would take longer to warm up in summer and cool down in winter. The resulting cooler summer waters were shown in the ROMS models to decrease bottom oxygen utilization, ultimately leading to higher summer bottom oxygen concentrations. This effect, however, was largely limited to a small volume of near-bottom water. As a result, the decreases in oxygen concentration due to warming were shown to be only very slightly mitigated by sea level rise (Irby et al., 2018.)

Another CHAMP study focused on identifying and quantifying the causes of Bay warming over the past three decades. Increased marine heat waves and warmer Bay temperatures in general are well documented (Hinson et al., 2022; Mazzini and Pianca, 2022), but prior to this study their causes had not previously been rigorously investigated. Hinson et al. (2022) used a combination of historical atmospheric and in-situ estuarine temperatures, together with model simulations, to demonstrate that the Bay has warmed roughly 0.7 °C over the past 30 years, with a relatively equal degree of warming in surface and bottom waters, but substantially greater warming (nearly 1 °C) in the southern Bay near the Bay mouth. Interestingly, the study showed that Bay waters have also warmed three times more in the summer months, compared with other times of year. As a result, studies focusing on annual average temperature increases have been missing much of the impact of warming waters on ecosystem services in the Bay. In general, atmospheric warming has caused most increases in observed Bay temperatures, with rivers and sea level rise providing almost negligible changes in Bay water temperature. In Virginia waters, there is a substantial influence from the continental shelf, where changes in coastal currents along the US eastern continental shelf have caused water temperatures to increase to a much greater degree than atmospheric temperatures (Hinson et al., 2022).

To determine the efficacy of management efforts in decreasing hypoxia in the Chesapeake Bay, Frankel et al. (2022) used a combination of statistical and machine learning tools together with 3D mechanistic model results. This study aimed to address the question: How bad would Chesapeake Bay hypoxia be if nutrient reductions had not occurred over the past 30 years? Results indicated that without the nutrient reductions that occurred over the past 30-40 years, hypoxic volume would be 20-120% greater, with greater absolute increases in dryer years. Additional simulations, including changes due to increased temperatures and more frequent marine heat waves, demonstrated that climate change has currently offset 10-30% of the improvements due to nutrient reductions. Frankel et al. (2022) was thus one of the first studies to document that nutrient reductions have decreased hypoxia in the Bay, despite the counteracting effects of climate change.

At the previous STAC Climate Change Workshop 2.0 (Shenk et al., 2021a), recommendations were made to investigate (1) the impact of changes in other variables such as wind, and (2) the use of multiple Earth System Models (ESMs) to provide estimates of uncertainty for future projections. The change in total hypoxic volume days (hypoxia integrated over the year and the full Bay) in the future was shown to be almost entirely due to changes in air temperatures and watershed inputs, regardless of the definition of hypoxia used (oxygen < 3 mg/L, 2 mg/L or 1 mg/L). Changes in radiation, sea level, and continental shelf temperatures had small impacts on future hypoxia, but changes in future winds had almost no impact; this is not to say that winds do not impact hypoxia, but rather indicates that current ESMs are not predicting large enough changes in wind patterns to significantly impact future hypoxia. In addition, Hawes (2024) demonstrated that regardless of whether an extreme (cool-wet or hot-dry) or more "middle-of-the-road" ESM is selected for the future hypoxia projections, almost all scenarios typically show increases in future hypoxia. Although the magnitude of total hypoxic volume changes by more than a factor of two between dry and wet years (both now and in the future), the absolute increase in hypoxic volume is similar in both dry and wet years, leading to a much greater percent increase in dry years. Hawes (2024) also showed that year-to-year differences in hypoxia were typically much greater than the magnitude of hypoxia increases due to future climate change.

Another recommendation from the STAC Climate Change Workshop 2.0 (Shenk et al., 2021a) was to examine the uncertainties associated with future climate projections. In response, two additional recent case studies of climate change impacts on Chesapeake Bay hypoxia were presented that analyzed different aspects of uncertainty related to the methodology of climate scenarios applied to the watershed and estuary. Results from Hinson et al. (2023) showed that in a multi-model ensemble of climate inputs to the watershed, the choice of ESM, downscaling methodology, and watershed model all contributed to the relative uncertainty in changes to estuarine DO. When excluding land use changes and nutrient reductions to isolate the impacts of climate change, the multi-model ensemble increased future hypoxia due to watershed changes alone by 4±7%. However, simulations that incorporated the effect of the TMDL universally decreased levels of hypoxia by ~50% relative to the baseline, despite climate change pressures of increasing watershed air temperatures and precipitation (Hinson et al., 2023).

An additional set of results was also presented (Hinson et al., 2024) that demonstrated the impact of climate scenario methodology on Bay hypoxia. A 10-year Delta climate simulation (as is used by the CBP), wherein the baseline climatology is shifted in one direction by climate impacts on temperature, precipitation, and other variables, was compared to both a Continuous 86–year simulation and a 10–year Time Slice simulation, both of which are directly forced by downscaled climate model inputs and do not retain the same baseline climatology in the future. The choice of methodology had little to no impact on mean changes to estuarine hydrodynamics (temperature, salinity, sea surface height), but the Delta simulation was found to increase hypoxia by nearly 20%, nearly double the estimated increase found in the Continuous and Time Slice simulations. This discrepancy is related to the long-term ecosystem memory of the watershed model utilized (DLEM, Yang et al., 2015), which decreased soil nitrate and increased organic N over time. Using the same climate scenarios, the Delta methodology also increased soil moisture levels because the frequency and duration of future precipitation remained unchanged relative to baseline precipitation patterns, further contributing to greater levels of estuarine nitrate loadings. This result is an unavoidable consequence of using the Delta methodology, but the Time Slice simulation showed promise for accounting for this effect while using fewer computational resources than the Continuous simulation (Hinson et al., 2024).

Focus on Ecosystem Management – *Kenny Rose (UMCES), Bruce Vogt (NOAA)*

Kenny Rose and Bruce Vogt co-presented on ecosystem management: Rose covered relevant findings from the STAC 2023 CESR report as well as presented examples of relevant analyses of living resource responses to climate change for the Bay, and Vogt projected into the future – discussing potential winners and losers, and the process and logic towards making marine resource decisions informed by climate change.

A key finding of the CESR report is that even without meeting all TMDL and water quality goals, opportunities exist to prioritize management actions that would improve conditions for living resources. The report lays out a useful framework for addressing living resource restoration goals. For example, prioritizing water quality improvements in shallow waters may have more benefit to living resources than improvements elsewhere. It is also important to acknowledge that there are factors in addition to water quality that affect living resource sustainability. Assessing and properly capturing living resource conditions is more complicated than doing the same for water quality, because many aquatic communities of interest are mobile, are affected by multiple factors throughout complex life cycles, and respond to conditions on longer and varying timescales. Furthermore, living resource-relevant metrics may not align with those traditionally used for water quality prediction. For example, the distribution and variance of a water quality parameter (e.g., temperature, salinity) are often more informative than the mean with respect to living resource impacts. These complexities lead to greater uncertainties, which should not deter managers from using any information available.

Water temperatures throughout the tidal portion of the Chesapeake Bay are increasing and will continue to rise. This increase is driven primarily by atmospheric warming. Warming waters have variable impacts on living marine resources. Some Chesapeake Bay species are adapted to higher water temperatures, while other species are more sensitive. Blue crab and oysters are two species that thrive south of the Chesapeake Bay and can tolerate higher temperatures. Striped bass and summer flounder habitat suitability declines with rising water temperature. Some species such as cobia are showing a northward shift in distribution to cooler waters, while other species such as red drum and white shrimp are moving into the Bay in greater numbers. Warmer winters and more rapidly warming or earlier springs can also impact the timing of migrations and spawning. Understanding the vulnerability of species to these changes and communicating the impacts are key steps to ecosystem-based fishery management. More research and tools, such as the Mid Atlantic State of the Ecosystem report, can inform adaptive management approaches. Additionally, habitat restoration and conservation (marshes, oyster reefs, natural shorelines) can help build resilience for some species to these changing conditions.

Climate Effects on Biogeochemical and Hydrologic Processes in the Watershed

– Robert Sabo (EPA) and Andrew Elmore (UMCES)

Climate change will alter the processing and transport of nitrogen (N), phosphorus (P), and sediment in the Chesapeake Bay watershed. In many respects, warming temperatures may enhance biogeochemical sinks and emission loss pathways. This enhanced removal (sinks + emissions) may be offset, however, by increases in gross mineralization rates and acute, episodic losses of nutrients and sediment to waterways due to more intense precipitation events and general increases in riverine discharge at annual time scales. The net effect of these interplaying drivers is still being explored across agricultural, natural, and urban domains, but studies investigating various water quality, agronomic, and biological records offer insight on what the future may hold.

Over the last century, the Chesapeake Bay region has warmed by 1-2 °F and precipitation, while generally increasing, has become more variable. During this time, atmospheric CO_2 concentration has continued to increase. Increased CO_2, in combination with longer growing seasons, has resulted in increased carbon (C) inputs into forested/natural areas across the globe and in the Chesapeake Bay—leading to greater nutrient sinks, higher plant C:N ratios, and declines in N availability relative to biotic demand. Coinciding with this global development, atmospheric N deposition also declined in the Chesapeake Bay, likely enhancing declines in N availability. Consistent with these observations, many forested parts of the Bay displayed declines in watershed total N and nitrate export; thus, despite the increased variability and overall general increase in precipitation, N loss to waterways declined. N export from forest is now so low that additional declines will likely be minimal, and future trajectories for N export, and nutrients more generally, will likely be variable with climate change and other evolving environmental conditions (e.g., "deacidification" of forest, pests).

Similar effects of CO_2 enhancement and longer growing season mechanisms are likely at play in cropland and pasture. Indeed, despite the aforementioned temperature and precipitation trends, crop yields have continued to increase. Much of this increase in production is largely attributed to improved crop genetics and cultivation practices, but it's clear that past climate change has not offset increasing crop yield trends. This increasing crop yield trend, combined with better use of manure and fertilizer nutrient applications, has led to an overall increase in nutrient use efficiency and declines in agricultural nutrient surplus in many major agricultural regions of the

Bay since the 1980s—corresponding to observed water quality improvements. However, it's worth emphasizing that variability in precipitation has led to sometimes dramatic deviations in the crop yield trend and these deviations can result in highly depressed crop yields and large pulses of nutrients into watersheds. For example, crop yields in 2023 deviated -10 to >-20% in southeast Pennsylvania and the Shenandoah Valley due to drought. Similar drought conditions may lead to similar crop yield trend deviations again in 2024. The water quality implications of an increasingly efficient high input-output agricultural production, punctuated by large nutrient pulses driven by drought, is still to be determined, as crop cultivation and genetics are continuing to evolve into the future.

On a net basis, its likely future warming effects will contribute to declines in nutrient loads to waterways due to enhanced denitrification, longer growing, and increased biotic uptake. This warming enhancement will be offset, at least partially, by increased precipitation intensity from episodic to annual time scales. In addition, the increased variability in precipitation, particularly drought years, could result in diminished biotic update in forest, lawns, and agricultural lands that may result in particularly large pollution pulses in watersheds that may lead to water quality degradation. Overall, past climate change has likely enhanced biogeochemical removal pathways in many respects, and this enhancement, in combination with other factors, seems to be exceeding the degrading effects of increasing precipitation intensity.

The State of Decision-Relevant Regional Climate Projections – *Paul Ullrich (UC Davis)*

Climate data are essential for environmental planning across a variety of regions and sectors. To be decision-relevant, data need to be salient, credible, and authoritative. Credible and authoritative data are validated for accuracy and processes by independent experts. Relevant data are the right variables at the right spatial and temporal scales and extents. Downscaling improves salience by providing data at scales that resolve local effects. Four types of downscaling techniques can be used: statistical, dynamic, regionally refined, and machine learning. Only statistical and dynamic data sets are currently available for use. Statistical methods are the most mature, but may underestimate future precipitation extremes and have limits in their ability to downscale accurately.

Users of climate data typically use heuristic criteria for choosing data products since comprehensive evaluations of model skill have been rare or nonexistent for salient metrics, which may be different for each application. There is a recognized need for this information among funders, data producers, and practitioners, which has led to several productive workshops. A community of practice is developing that will likely lead to better systems for producing and selecting downscaled data products. Resources are now becoming available to help users select appropriate data sets. A recent earth system model evaluation project provides an evaluation of LOCA2 and STAR-ESDM products (Ullrich, 2023), which are summarized in The Atlas of the 5th National Climate Assessment (https://atlas.globalchange.gov/). Both data products are good choices and are largely in agreement.

Revisiting climate-change impacts on the Chesapeake Bay – Raymond Najjar (PSU), Marjorie A. M. Friedrichs (VIMS), Fei Da (NOAA), Mary C. Fabrizio (VIMS), Kyle E. Hinson (PNNL), Maria Herrmann (PSU), Dante M. L. Horemans (VIMS), Matthew L. Kirwan (VIMS), Thomas J. Miller (UMCES), Molly Mitchell (VIMS), Christopher J. Patrick (VIMS), Troy D. Tuckey (VIMS), and Ryan J. Woodland (UMCES)

Because the key components of estuaries are highly interconnected, a system-wide approach is required to understand how estuaries will respond to climate change. The last such study of the Chesapeake Bay was published 14 years ago and since then much research has been conducted about the impacts of climate change on this estuary. This presentation reviewed that research and identified common themes and suggestions for further research. The review included an analysis of observed trends and future projections for atmospheric conditions (including tropical cyclones), sea level, fluxes from the watershed, Bay temperature and salinity, hypoxia, the carbonate system, harmful algae and *Vibrio*, SAV, tidal marshes, fishes, shellfish, and other biota.

Atmospheric conditions. Air temperature and precipitation have increased, in agreement with global climate model simulations run under greenhouse gas increases. Extreme temperature index trends around the Bay are consistent with warming, whereas those for extreme precipitation are equivocal, even though large-scale regional trends in the Northeast and Southeast US are clearly increasing. Climate modes (i.e., persistent or recurrent climate patterns) play an important role in interannual variability (e.g., North Atlantic Oscillation). Over the 21st century, the climate zone of the Chesapeake Bay watershed is projected to shift from continental–warm summer to temperate–hot summer, though the degree of future warming is highly sensitive to emissions scenario, particularly by the end of the century. Future precipitation change is more uncertain, but the average is consistently increasing across many GCMs, with winter and spring more certain and wetter than summer and fall. Projections of temperature extreme indices are all consistent with warming. Precipitation is projected to get more extreme.

Tropical cyclones. Tropical cyclones (TCs) track through the Chesapeake Bay region about annually and can have impacts that are much greater than the short period of time (days) that their presence in the region would suggest. North Atlantic TCs have changed over the past several decades: they are more frequent and more intense, translate more slowly (increasing precipitation totals), intensify faster over the ocean, decay more slowly over land, are shifting landfall towards the US east coast, and more frequently undergo extratropical transition. There are multiple causes for these changes, including increased greenhouse gasses, reduced anthropogenic aerosols, and natural variability. North Atlantic TCs are expected to become more intense and produce more precipitation, though there is very low consensus on changes in TC frequency and the fraction of TCs that will become major. For the Chesapeake Bay and Mid-Atlantic Region, statistical–dynamical approaches generally show an increasing TC threat, while TC frequency projections using dynamical approaches show mixed results.

Sea level. Sea level is rising and accelerating throughout the Bay and rise rates are projected to double by mid-century. Emissions are important in sea level projections, particularly by late century. The tidal range is also generally increasing, in part due to sea-level rise.

Fluxes from the watershed. All water fluxes of the Chesapeake Bay watershed (precipitation, estimated evapotranspiration, and streamflow) are increasing. Climate is already increasing the total nitrogen (TN) load via increases in precipitation that are modestly offset by warming. However, flow-normalized TN sources and loads are decreasing. Susquehanna River sediment input to the Bay has decreased during low flows due to management and increased during high flows due to dam infilling. Future projections of annual streamflow are highly uncertain, due in part to the offsetting impacts of projected precipitation and temperature increases as well as the uncertainty in evapotranspiration formulae. However, winter streamflow is consistently projected to increase. In general, fractional changes in TN loads due to climate change are expected to track fractional changes in streamflow. Climate change is expected to increase suspended sediment loads due to increased precipitation intensity.

Bay temperature and salinity. Climate change has influenced Bay temperature and salinity. The Bay is warming and experiencing more heat waves. Salinity responds to increasing streamflow and sea level, which have offsetting influences. Stratification has mostly been unchanged. Bay waters are projected to continue to warm, but future salinity change due to streamflow change is highly uncertain. Sea-level rise increases salinity and stratification and has a greater impact than streamflow and tidal range in future projections. Sea level is expected to increase salinity by 1.2 to 2.5 g/kg per m of sea level rise. Spring salinity should decline due to projected increases in winter streamflow. Changes in tidal fresh and oligohaline regions are highly uncertain, particularly in summer. Stratification changes are uncertain, though sea-level rise alone is likely to increase it.

Hypoxia. Climate has already influenced hypoxia, primarily through warming. Warming is expected to be the dominant climate change factor directly affecting future hypoxia. The positive impact of planned nutrient reductions could offset negative impacts of warming on hypoxia.

Carbonate system. The carbonate system of the Bay and its watershed are changing, with documented increases in alkalinity in both environments. pH is increasing in the upper Bay and decreasing in the lower Bay. Carbonate system variables are changing due to changes in atmospheric CO_2, temperature, and riverine input of carbon, alkalinity, and nutrients. Elevated atmospheric CO_2 and temperature, along with changes in streamflow and continental shelf conditions, are projected to decrease Chesapeake Bay pH by 0.1 to 0.3 units and nearly double atmospheric CO_2 uptake by mid-century.

Harmful algae and Vibrio. Warming partly explains the increase in reported *Vibrio* human infections and *K. veneficum* and *M. polykrikoides* blooms in the Chesapeake Bay. Warming may have contributed to the emergence in the Bay of new cyanobacteria, *Lyngbya*, and its associated saxitoxin. A variety of modeling studies indicate that climate change will result in shifts of harmful algae and *Vibrio* abundance in time and space, and changes in community composition. In general, warming and eutrophication tend to increase harmful algal blooms.

Submersed aquatic vegetation. The areas of different types of submersed aquatic vegetation (SAV) in the Bay have varied considerably over the past several decades. SAV area responds to environmental variables. For example, the eelgrass decline over the past several decades has resulted from a decrease in water clarity and an increase in temperature. Total SAV projections show a large impact of nutrient management, but the results are community specific: widgeon grass is very responsive to nutrient reduction and less affected by warming while eelgrass is very responsive to warming and less affected by nutrient reduction.

Tidal wetlands. Tidal wetlands of the Chesapeake Bay are being lost to sea-level rise. Inland migration typically compensates for those losses in areas where migration is not constrained by topography. There is land available for marsh migration across the Chesapeake Bay that is similar to the current total marsh area. Projections of tidal marshes in Maryland and Virginia are highly sensitive to the particular sea-level rise scenario. While CO_2 and temperature are important drivers of marsh processes, there are numerous compensating effects, leaving sea level as the dominant driver.

Fishes. Climate change-related increases in water temperature (high confidence) and salinity (low confidence) and decreases in DO (without nutrient reductions) forecasted for mid-century and end of century for the Chesapeake Bay will affect fish through a variety of species and life-stage (egg, larva, juvenile, and adult) dependent mechanisms. Some examples of climate-related responses noted from the Chesapeake Bay in recent years include alterations in the spatial distribution of individuals, fluctuations in abundance that mirror the availability of suitable habitats, changes in the phenology of key life-history processes such as spawning migrations, and facilitation of the spread of invasive species.

Shellfish. The principal climate drivers of shellfish are changes in thermal regime and changes in the carbonate system. Changes in thermal regime alter ecological roles; for example, the extension of the growing season increases trophic demand by consumers. For blue crab, winter warming will greatly reduce overwintering, which will extend periods of crab predation in the benthos, potentially shifting community composition and productivity. The reduction in the calcium carbonate saturation state leads to corrosion of shells, which diverts energy to shell replacement from other ecological processes. Increased acidity and temperature interact to reduce calcification rates of Eastern Oyster, leading to thinning shells and increased mortality.

Other biota. A diverse community of birds, mammals, reptiles, insects, and other invertebrates inhabit or use Chesapeake Bay habitats. Evolving land use, water quality, harvest pressure, and climate over past decades have all led to population changes for many of these species. Erosion and armoring of fringing marsh and low beach nesting habitats have led to declines or extirpation of some birds. Relative to the mid-20th century, 14 seabird species now arrive earlier during their northward migration, arrive later during their southward migration, or both. Benthic biodiversity is related to many environmental factors influenced by climate change, including temperature, streamflow, DO, and phytoplankton. Over the 21st century, we can expect climate change to increasingly impact the ecology of the Chesapeake Bay.

The overall finding thus far from this review is that climate impacts on the Chesapeake Bay are no longer potential—climate is already expressing itself in nearly every aspect of the Bay for which we have long-term data. We expect climate change to emerge as a first-order driver of Bay health. However, the CBP has agency locally to mitigate the negative impacts of climate change, as this review provides clear examples of for hypoxia and SAV. There is also agency at the global scale to make a difference in outcomes for the Chesapeake Bay and, by extension, to all estuarine environments: emissions really matter. A clear example from this review is the high sensitivity of tidal marsh loss to sea-level rise scenario.

This review highlights some areas of greatest need for future research. Streamflow is one of the most important drivers of Bay processes and yet streamflow projections are highly uncertain, with even the direction of change unknown. Improvements are thus needed in understanding the drivers of long-term streamflow change. The modeling of living resources needs to be improved beyond the qualitative and empirical approaches that currently dominate applications to long-term change. Such models need to be informed by monitoring and process-based field and laboratory studies.

Breakout Group Discussions

Two types of breakouts generated initial recommendations that were later discussed and refined in plenary sessions. Four cross-sector breakouts contained a relatively even number of managers and scientists interested in watershed processes, estuarine hydrodynamics and biogeochemical processes, and living resource research and modeling. The cross-sector breakouts were all provided the same questions and were encouraged to develop recommendations for the overall modeling, scientific, and management systems. Draft recommendations from the cross-sector breakouts were presented in plenary and combined with predetermined questions to motivate discussion in within-sector breakouts. Participants were organized into four within-sector breakout groups: management, watershed processes, estuarine hydrodynamics and biogeochemistry, and living resources. A final discussion was held in plenary following the presentation of recommendations from the within-sector breakout groups. Each breakout group was required to summarize their discussion in four or fewer main points.

Predetermined questions for the breakout groups, developed by the workshop steering committee, are provided in Appendix D. Breakout leaders and participants were instructed to use the questions as a guide, but that it was not necessary to answer all questions. Breakout groups could also answer questions that arose from conversations in the groups. Discussions in the breakout groups were to determine the priority of the recommendations.

Recommendations

Cross-Sector Breakouts

The first two STAC workshops on climate change modeling (Johnson et al., 2016, Shenk et al., 2021a) resulted in specific recommendations on needed changes to the CBP's modeling system to adequately account for climate change effects on the TMDL. Model development following these workshops, including planned development for the Phase 7 models, has resulted in a system that sufficiently captures the major components of climate change effects on the TMDL, although improvements, including unimplemented recommendations from earlier workshops (e.g., evaluations of climate effects on BMP efficiencies, more mechanistic assessments of BMP performance) would enhance the CBP's understanding of climate effects and ultimately the modeling systems ability to capture relevant impacts. Workshop participants recommended analyzing the modeling system for remaining tasks and allocating new modeling efforts wisely by **prioritizing a limited number of important drivers relevant to TMDL goals**. This approach will allow resources for some of the following recommendations to move forward.

Cross-sector breakout groups developed priority recommendations that were further discussed in plenary, resulting in the emergence of a limited number of key overarching themes: model evaluation, development of living resource models, and examination of the TMDL accountability framework.

Model evaluation

Model uncertainty was a frequent theme in workshop conversations; however, the topic was broadened into a general finding that **model evaluation should be tailored to answer questions relevant to management.** Uncertainty quantification was discussed and encouraged, with a recommendation to concentrate on reducing uncertainty with respect to critical processes, drivers, and management relevant effects. The CESR report (STAC 2023) encouraged the analysis and understanding of response gaps. Participants agreed that the response gap framework was a useful method of prioritizing change. One suggestion that arose during the discussion was that rather than emphasize uncertainty in a way that might undermine confidence in our ability to make predictions, we instead propose a risk assessment framework that quantifies the potential risks and associated costs of not responding to an issue that threatens resources or human well-being, particularly in terms of the propagation of uncertainty that may mask the exceedance of critical tipping points.

Long, **continuous runs** of the modeling suite would help the partnership understand response gaps and evaluate the ability to suitably capture tipping points. Simulations of the historical record could show whether benthic-pelagic shifts and changes in SAV spatial distribution could be captured in the estuary. Long watershed model runs illuminate the ability to capture trends that are influenced by climate, weather, anthropogenic effects and time lags. The analysis should include variables that may be changing slowly over time, such as groundwater lag times and legacy nutrients, but may eventually have a large impact. Continuous runs into the future driven by climate models allow the use of climate change evaluation methods other than the delta method. Even if the effect of climate on management is constrained to use the delta method in calculating load reduction targets, more could be learned about the modeling system using continuous and time slice methods in conjunction with the delta method. The CBP should consider adding more variability to the central tendency ensemble GCM approach for long term climate scenarios, such as 2075 and 2100.

Assessing variability of water quality variables may be a more critical use of the estuarine model than assessing mean water quality predictions, as connections are made to living resources. The use of higher frequency data and the development of the CBP's new interpolation scheme will be important components of this effort.

Development of living resource models

The CBP should prioritize the development and use of new and existing living resource models. The CBP TMDL models already produce water quality and hydrodynamic output that is relevant to existing and future living resource models. Creating greater accessibility of outputs would expand the usefulness of the CBP models beyond the TMDL. The existence of the water quality outputs and living resource models provides the CBP partnership with an easy path to make quick progress in this area. Development should start with existing living resource models at broad spatial scales and work toward location-specific responses and goals. Initial development should focus on selected individual species and life stages. Linkages should be sequential rather than coupled to simplify the work and lower computing time.

Examination of the accountability framework of the TMDL

As we get further in time from the initial 2010 TMDL and as we consider recommendations from STAC's CESR report (STAC 2023), the partnership may benefit from **updating the rules and procedures governing the calculation of load reduction targets** in the accountability framework of the TMDL.

The TMDL hydrologic averaging period is 1991-2000, and the baseline for water quality, known as the critical period, is 1993-1995. When future managers are making decisions in 2050, it will likely increase uncertainty and lower confidence in the modeling results if the CBP is constrained to model the change in load necessary given 1993-1995 conditions. Workshop participants also suggested developing reduction goals that were targeted toward finer-scale restoration relevant to living resources, rather than focusing calculations and efforts on DO in the mesohaline region of the mainstem Bay and Potomac River. For example, developing or applying local fine-scale nutrient and sediment loading models with explicit linkages to living resource or habitat responses could support tiered TMDL implementation that prioritizes segments where living resource responses could be seen more quickly. Model development and application should take these considerations into account.

Additional issues

Important research questions remain. Some that were emphasized at the workshop are particularly important to the priorities of the cross-sector breakout groups. In some instances, estuarine chlorophyll concentrations may be more related to temperature and clarity than strictly nutrient-limited. Invasive species and their potential expansion of habitat under climate change are important considerations. Anthropogenic changes in phosphorus load from the watershed, particularly under climate change, is not well-understood. Nitrogen limitation may be increasing in the watershed, with effects on the transport of nitrogen and phosphorus.

Within-Sector Breakouts

The four within-sector discussions were informed by the cross-sector results. Where appropriate, some results from cross-sector breakouts are included below.

Management Breakout Group

The Management Breakout Group had a broad, wide ranging discussion of outputs and applications of the Phase 7 suite of models that would be useful for CBP decision making, particularly for achieving water quality standards under estimated 2035 climate conditions, as well as for emerging living resource habitat goals. The discussion covered eight major topics:

1. Recognize in shallow water simulation the important shallow water processes of shoreline erosion loads, sediment resuspension, oyster and other filter feeders, tidal wetlands, benthic algae, SAV, and pore water.

The understanding of shallow water processes is an active area of research. Shallow water is the interface between nutrient and sediment loading from land and tidal water processes in tidal wetlands, Submersed Aquatic Vegetation (SAV) beds, benthos, and the close association of water column and sediment processes. As a result, shallow water is a difficult region to model. We need continued research to get a better understanding of shallow water processes and their simulation.

For successful shallow water modeling, we need good estimates of sediment resuspension and shoreline erosion dynamics. An improved simulation of wave and shoreline erosion is now included in the Main Bay Model (MBM) and Multiple Tributary Models (MTMs). The inclusion of benthic algae in shallow water is also important. Benthic algae compete with phytoplankton for nutrients, so the simulation of benthic algae is necessary for the chlorophyll simulation and for estimates of light attenuation by chlorophyll influencing the SAV/clarity water quality standard. SAV can also shade benthic algae, perhaps providing an advantage to phytoplankton and SAV epiphyte biomass.

In Phase 7 we are essentially using the Phase 6 ICM model of SAV in the MBM but with some modifications. Overall, the SAV modeling is sufficient to represent the SAV response to increases or decreases in water column light attenuation, but Phase 6 failed to sufficiently represent interannual variability of SAV due to other factors controlling SAV density and area as described below. Therefore, we need to refine estimates of SAV going forward, particularly in climate change assessments. Historically, the CBP SAV model has had difficulty representing SAV distribution because in the field it is controlled by more than just light; variables like sediment composition, SAV community dynamics, and the amount of spring freshet flow and other factors affect interannual SAV biomass. We currently have a light-based simulation of SAV with SAV light at the leaf affected by light attenuation from phytoplankton, inert suspended solids, and epiphytes. These are all currently included in the ICM simulation.

An approach to refine the SAV simulation and scenarios could incorporate the recently developed VIMS SAV model (Hensel et al., 2023) with the ICM light model. We would likely need these two models together to predict future responses to climate change such as *Zostera* decline in polyhaline waters and *Ruppia* expansion in mesohaline waters. Currently the plan is to grow shallow water SAV based on observed conditions for the calibration, but ultimately we will need to incorporate a dynamic response of SAV to future climate conditions of clarity and temperature to be successful.

Simulating oysters is another important shallow water modeling component. The Phase 6 ICM simulated oysters in natural bars, sanctuaries, and aquaculture with a bioenergetics model. For aquaculture oysters, we imposed a general county average location based on harvested biomass provided by counties. One refinement would be to use remote sensing to better locate aquaculture within a county's shoreline.

The resolution of shallow water input loads will be improved in Phase 7. The CBP plans to map the Phase 7 Watershed Model loads to estuarine model grid cells at the NHDPlus scale for shallow water. Shallow water continuous monitoring data could be used to quantify the improvements made in the Phase 7 loading scale. The importance of NHDPlus fine-scale Phase 7 watershed model loads may best be demonstrated in small tributaries and embayments because of their high residence times.

There was an in-depth discussion of shallow water outputs that would ultimately be passed from the Phase 7 MBM and MTMs to living resource and habitat models. It's likely that model parameters of temperature, salinity, DO, clarity, total suspended solids, and phytoplankton could be used for shallow water habitat modeling. Temperature, salinity, and DO are likely to be master variables in most habitat simulations. The MBM/MTM outputs passed to living resource and habitat models could include outputs simulating present conditions, climate change conditions, Watershed Implementation Plan 3 (WIP3) conditions, and No Action conditions.

2. Consider examining ICM temperature-corrected rates, particularly for scenarios beyond 2050. Also, consider looking at lower latitude coastal water systems for insights into future Chesapeake ecosystem changes such as species composition.

Particular attention should be paid to temperature-corrected model process rates in assessments of estimated CBP temperatures beyond 2050, in part because the ICM model fundamentally assumes that the population of phytoplankton species composition won't change. However, as temperatures increase there are other algal species that can outgrow and compete in a 30-40 ºC Chesapeake Bay.

Currently the phytoplankton groups in the Phase 7 MBM are flexible, with different user-defined algal temperature growth curves that can be applied. Going forward, the CBP should continue to survey coastal water ecosystem science in estuaries south of the Chesapeake Bay for insights into how the ecosystem in the Chesapeake Bay could change.

3. Recommend tiered or interim targets, inclusive of the effects of climate change, for beyond 2025. Consideration of only DO in Deep Water and Deep Channel is insufficient. Interim targets until 2050 could include the shallow water environments, living resource response to climate change, and development of co-benefits.

A tiered approach to TMDL implementation acknowledges the need to achieve water quality standards while establishing staggered timelines, with interim goals that prioritize pollutant load reductions to local (segment/habitat) regions of the Bay to provide the greatest anticipated benefit to living resources. The approach needs to be developed but could be a useful expansion of Chesapeake Bay restoration approaches as we move beyond Deep Water and Deep Channel DO in the Phase 7 application.

Going forward, we recommend inclusion of tiered or interim targets. The sole consideration of DO in Deep Water and Deep Channel for water quality standards by the Phase 7 suite of models is insufficient. Interim targets until 2050 could include the representation of the shallow water environments, how they respond to climate change and management, and the development of living resource/habitat co-benefits to augment the TMDL living resource-based water quality standards.

4. Based on the best climate science, consider developing after Phase 7 a Chesapeake Bay 10-year base hydrology that has more precipitation events, more extremes of drought and high-flow events, and more recent trends to better represent future climate change hydrology.

Hydrology in the Chesapeake Bay watershed determines the relative nutrient and sediment loads from the Chesapeake state-basins. The 1991-2000 CBP base hydrology has been agreed to by the CBP partners to be equitably poised between flood and drought loads. We don't want to disrupt management decisions during Phase 7, but at some point after Phase 7, a 1991-2000 CBP average hydrology will be seen to be less relevant and more disconnected from future hydrology in the Chesapeake Bay region.

It takes a long time to find and approve an agreed-to CBP base hydrology approach. Looking forward, a potential next phase of CBP modeling could be aimed at an assessment of climate change beyond 2035. At that time, our 1991-2000 CBP 10-year base hydrology may not pass muster. Starting now to update the 10-year average hydrology for the next phase of CBP modeling makes sense. This would provide a long runway for analysis and agreement and an opportunity to examine alternate CBP base hydrologies without immediate management consequences. In addition, another Phase 7 output that will give us insight into improved CBP base hydrologies would be the long run times planned for the Phase 7 model, simulating the 35 year period from 1985 to 2020. Additional suggestions for a future CBP base hydrology include: (1) add more variability to the ensemble climate change model approach; (2) use several individual climate change models; (3) develop additional downscaled products to help bound estimates for precipitation changes; (4) pick a GCM median model based on the best match to recent historical observations. Future temperature estimates are less of a problem than precipitation and seem to be well estimated by current climate change models.

For Phase 7, the CBP plans to use the delta method with an ensemble of CMIP6 (Coupled Model Intercomparison Project 6) GCMs; finding another method agreed upon by the CBP to represent the ten-year average and three-year critical period is unlikely in the twelve months available before Phase 7 model review and application. As in Phase 6, GCMs may be unnecessary for close timeframes like 2035. If the CBP partnership is assessing 2035 climate conditions with application of the Phase 7 models during the 2027-2029 period (after the 2026 year of review), we may want to extrapolate observed temperatures and precipitation for 2035 conditions, reserving the GCMs for years beyond 2035. Alternatively, the Phase 7 models could also look beyond 2035 to climate change conditions of 2050, 2075, and 2100 to prevent surprises for CBP managers, which would require the application of GCMs.

5. More important than an uncertainty-based range of outcomes, managers would prefer efforts to get the best available central tendency impact of decadal climate change to incorporate new climate science into CBP policy.

From a CBP manager's perspective, knowing the quantitative uncertainty of pollutant behavior may change the TMDL decision rules, because the implicit margin of safety (MOS) now being applied could change to an explicit MOS, which could decrease nutrient allocation limits. An explicit MOS buffer is built into TMDL allocations to account for this quantified uncertainty. Therefore, there is the sense among some CBP managers that carefully quantified uncertainty creates a problem because it could lead to having stricter, more difficult to achieve TMDL nutrient targets. From their perspective, they are having a hard enough time hitting their current nutrient targets and see downsides in explicit TMDL uncertainty values.

There was recognition in the manager breakout that the CBP models have yet to propose a nutrient target that was subsequently seen to have gone too far in nutrient and sediment reductions. If that did happen, we'd see it in achievement of observed tidal water quality standards, which are the ultimate determination of achieving water quality standards in a

Chesapeake Bay segment. Likewise, continued nonachievement of observed tidal water quality standards ultimately leads to tighter nutrient targets.

Therefore, to CBP decision makers it's less important to generate an uncertainty-based range of outcomes than to get the best available central tendency impact of climate change to address Chesapeake TMDL water quality standards, despite the challenges of future climate conditions. This is not to say that uncertainty should be disregarded, but managers put relatively less weight on the issue than does the scientific community, given the limited time and resources available. The CBP largely addresses uncertainty in all the Phase 7 models and their climate change assessment by an implementation approach that affords opportunities for adjustments. CBP's implementation approach with the Phase 7 models and previous model phases is through a process of implementing, monitoring, and adjusting through iterative model phases to be resilient and effective across a broad range of future climate and watershed conditions.

Ultimately the Phase 7 model practitioners work to ensure that their model is well calibrated and provides a reasonable estimate within minimum and maximum bounds. If the Phase 7 model simulation represents well the 35-year record of the extensive CBP observation records, as we are trying to achieve, it is likely to be sound.

6. Consider approaches to extending the Phase 7 growing season in land uses like crops, pasture, and forests in climate scenarios. Extending the crop growing season with current Phase 7 crops or with new climate adapted crop rotations should also be considered.

Agriculture is dynamic and will respond to future climates by adopting cropping practices more suited to the warmer, longer growing seasons. This could be important to consider, but we also need to recognize that things also could get really complicated with double cropping and other processes that could uptake or sequester more nutrients within crops under climate change conditions. Also likely are changed timing of field operations, such as earlier planting and later harvest dates. With greater precipitation volume and intensity under climate change, higher sediment loads are likely. Modeling these changes may have to be done in the dynamic model rather than CalCAST.

Extending the growing season across other land uses like forest and pasture in Phase 7 should also be considered. Changes in the hydrology and loads from simulated climate change conditions should be simulated by the MBM and MTMs. In particular, anticipated reductions in snowpack and spring freshet flows and loads under climate change conditions should be examined with respect to conditions governing the onset of hypoxia in the Bay as well as impacts on living resources and habitat.

7. Consider inundation modeling of low-lying tidal areas to help in long-term planning for tidal Bay communities.

Tidal water inundation of lands from high tide events or storm surge flooding impacts water quality by introducing nutrients, sediment, bacteria, and chemicals to tidal waters. Additionally, frequent flooding can alter vegetation patterns in woodlands, agricultural areas, and wetlands, leading to issues such as ghost forests, greater nutrient leaching from agricultural lands, and loss or modification of tidal wetlands. In the CBP model examination of sea level rise, natural and human infrastructure of low-lying areas should be an area of investigation in the Phase7 MBM and MTMs.

8. Managers need flexibility in how to implement climate change responses based on the various priorities they have in different regions, communities, or agencies.

A reminder and a caution that should always be applied to CBP model development and application is the recognition that CBP managers and decision makers need flexibility in how to implement climate change responses based on the priorities of different regions, communities, or agencies. Likewise, the Phase 7 modeling work is entirely at the service of the CBP decision makers and the management problems they are trying to resolve.

In practice, this means that in model development Phase 7 practitioners should ensure that flexibility in scales of model application support CBP decision maker's regional, state, and community needs. In addition, CBP model development should lean toward flexibility in terms of the ability to apply the model in a modular fashion to CBP decision making applications in hydrodynamics, water quality, and living resources as well as for more general research applications and collaborations requested by PIs in the CBP scientific community.

Watershed Breakout Group

The watershed breakout group had a wide-ranging discussion that coalesced around three interrelated themes: the exploration of climate effects on nutrient transport, storage, and loss, Evaluate predictions relevant to climate for flow, N, P, and S, and the development of ability to identify hot spots, moments, and actors and how they change for a given climate. The group also had a separate discussion of recommendations for an upcoming research modeling project on climate change effects on BMPs.

1. Incorporate climate-related change in transport, storage, and loss

The CBP spends significant resources in the form of staff time and partnership meetings focusing on anthropogenic inputs of nutrients, land use changes, and BMP effectiveness and implementation extent. Hydrologic changes due to climate are also thoroughly considered in the CBP's watershed model. However, climate change likely has significant effects on physical processes of sediment and nutrient storage, loss, processing, and transport. For example, rising temperatures will likely increase denitrification rates and modify plant and tree species distributions, with resulting effects on nutrient transport. However, these effects can be counteracted or exacerbated by changes in soil moisture and interactions with carbon cycling (e.g., CO_2 enhancement of tree or crop growth). The structure of the CBP watershed model is flexible, allowing estimates of climate effects on transport from literature, including both empirical studies and process modeling efforts, to be incorporated directly into model estimates of climate effects. Additionally, CalCAST, the statistical version of the CBP watershed model, could directly use climate-related variables like temperature and precipitation as predictor variables, leading to the inclusion of temperature and moisture-related effects in watershed model predictions. However, integration of CO_2 enhancement for plant growth in the model is more difficult to statistically integrate, given the coarse spatial scale of the model. Cross-sector breakouts urged the consideration of approaches to evaluating the growing season length in the model for crop, forest, and pastureland uses.

2. Evaluate predictions relevant to climate for flow, N, P, and sediment

Echoing discussions in the cross-sector groups, the watershed breakout emphasized the importance of evaluating predictions of the CBP's watershed model. Such evaluations increase managers' confidence in model output, which is critical for convincing stakeholders to embrace management changes. Informed in part by CESR (STAC, 2023), the CBP has recently produced tools and indicators (Zhang et al., 2024) that present a comparison of CBP model predictions of long-term changes in nutrients and sediment relative to flow-normalized loads. However, the specific questions related to load changes caused by climate are even harder to parse using only analyses of nutrient and sediment monitoring data, considering management level effects are still being debated. The CBP would benefit from evaluating observed trends in flow at annual and seasonal time scales relative to model predictions. Performing seasonal analyses would improve the confidence in phenological predictions that may be relevant for estuarine conditions. Model experiments that isolate climate-related causes in nutrient and sediment export could be evaluated with literature estimates of trends in these processes.

3. Identify hot spots, moments, and actors and how they change with climate

The related concepts of critical source areas, control points, hot spots, and hot moments (e.g. Sharpley et al., 2011; Zhu et al., 2012; Arora et al., 2022) are important for watershed management to prioritize restoration efforts of specific areas under limited budgets. The watershed group discussed the concept that hot moments and actors—that is, critical hydrologic conditions or human actions—should inform the prioritization of restoration actions. Hot spots are a useful framework at multiple spatial and temporal scales, ranging from sub-field to watershed, and hourly to annually, to inform management actions and implement effective, stacked conservation strategies. A local BMP implementor may benefit from sub-field scale information and a funder may be able to target based on NHD catchment level information, while the CBP partnership benefits from understanding the relative influence of the various major basins draining to the Chesapeake Bay. Climate change, through alteration of transport, storage, and loss, could make the prioritization of hot spots dynamic.

The watershed group discussed two methods of developing this information. Outputs of process-based models that incorporate the necessary hydrologic and biogeochemical processes could be generalized for broad application. The models may need to be applied at fine resolution to resolve hot spots, and then scaled to CBW NHD+ catchment scales. A method was also discussed using targeted synoptic sampling, coupled with theory-guided empirical models, driven by a mass balance approach and implemented management practice data, to predict hot spots at a fine spatial scale. Using either method, a combination of both, or an alternative, the watershed group felt strongly that application at an appropriate spatial scale was an important part of building confidence in the results for use in management.

4. Advice for analysis of climate effects on BMP performance

The watershed group was given the additional task of developing recommendations for an EPA-funded effort to model climate-related effectiveness changes of BMPs. The group suggested that a high-level typology be created for categories of BMPs and that the same climate effect be assigned across the group. As a first cut, BMPs could be separated into hydrologic (e.g., stormwater ponds), structural (e.g., animal waste storage), or biochemical transformation (e.g,, cover crops), with stream buffers and stream restoration as additional, separate categories due to their complex interactions with streams.

For hydrologic and structural BMPs, the most important climate effect might be thresholds of failure. Biochemical transformation BMPs may have more complex interactions with climate. Buffers and restoration may have both. Emphasis would be given to BMP types that are both most used and most impacted by climate. The group saw significant hurdles to the applicability of models for BMP evaluation. Empirical approaches are not likely to be able to draw on enough data to evaluate effects. Process-based models such as the Soil and Water Assessment Tool (SWAT) and Hydrologic Simulation Program FORTRAN (HSPF) models are able to simulate management type BMPs, such as cover crops, conservation tillage, or nutrient management. However, they generally do not have the processes available to capture more complex BMP interactions. The Storm Water Management Model (SWMM), used for stormwater BMP evaluation, only considers hydraulic impacts; it does not have biogeochemical routines needed to assess changes to nutrient cycling and transport. Buffers and stream restoration effects may be too complex for lower resolution models to accurately simulate. While the use of a relatively simple biogeochemical model may be an appropriate approach, some attention may be given to more comprehensive, fine resolution ecohydrologic models for selected BMPs in representative, well-studied landscapes and catchments. More broadly at the workshop, there was some disagreement among and within groups over whether the most pressing need for understanding BMP performance under climate change was calculating a climate change effect or reducing uncertainty in the base assumption of BMP performance.

Estuarine Breakout Group

The estuarine breakout group had a very productive discussion that began with a general consensus that the CBP has made tremendous progress with implementation of the new physical model, and that the focus should now turn to improving the ICM:

Six major themes emerged related to the ICM:

1. Make use of new data and new techniques for model development and evaluation

There was a consensus among the estuarine breakout participants that the CBP needs to make better use of additional sources of data, beyond those collected by the monitoring program, to help formulate and evaluate the water quality model (ICM). For example, in the context of warming Bay waters, data from lower latitude ecosystems should be used to help formulate the phytoplankton and zooplankton growth/grazing rate temperature control functions in ICM (see next section). It was also noted that data from the shallow water monitoring program are consistently underutilized in water quality model evaluation validation efforts, and that, with the new higher resolution physical model, they will become increasingly important for model evaluation in the shallow waters and tributaries of the Bay. There are also many other non-CBP data sources that are not currently being used for model development and evaluation, including those collected by individual projects funded by federal agencies like NSF, NOAA, and NASA. Satellite-derived products have historically been underutilized in the CBP's water quality model evaluation Going forward, information collected by the high-resolution Copernicus Sentinal-3

Ocean and Land Color Instrument (OLCI) and hyperspectral data emerging from the new NASA PACE (Plankton Aerosol, Cloud, ocean Ecosystem) mission should be utilized.
There was also agreement in the group that the CBP needs to explore new analysis and model development techniques, including various machine learning techniques and Artificial Intelligence for formulating new or alternative statistical water quality models and "model emulators," to support the existing mechanistic 3-D water quality model (ICM) currently being used by the CBP to generate scenario runs.

2. There is still concern about several aspects of the ICM water quality model formulations

Some of the estuarine breakout participants expressed concern about several of the functions in the ICM water quality model that are being used to predict how autotrophic processes (phytoplankton growth) and heterotrophic processes (remineralization) respond to changes in temperature. Current ICM functions assume an optimal temperature for growth for each of the phytoplankton functional groups. These functions predict that, as Bay temperatures increase (e.g., due to global warming), growth rates will plateau and eventually decline. In contrast, formulations like the "Eppley Curve,", which are widely used in academia, assume that as temperatures warm, new phytoplankton communities will emerge that can take advantage of higher temperatures, resulting in phytoplankton growth rates that will continue to increase with increasing temperatures. Obviously, these two different approaches to modeling phytoplankton growth rate responses to changes in temperature will give very different predictions for how primary production in Chesapeake Bay will respond to climate change. Some participants felt the "Eppley" parameterizations should be used, but others defended the current phytoplankton growth rate temperature control functions, arguing that the optimal temperatures currently used are consistent with the data and published literature, and that they already take into account some level of adaptation. A consensus recommendation emerged that the CBP needs to look at phytoplankton growth rate temperature responses from low latitude, southern systems (the Carolinas, Florida) to get a better handle on how to specify these functions in ICM to ensure that the model responds appropriately as water temperatures rise.

Some participants in the estuarine breakout group also expressed concern about the fact that the current version of ICM does not include any explicit representation of zooplankton and argued that this was necessary to facilitate potential linkages to higher trophic level models. In the current CBP version of ICM, phytoplankton blooms are not the result of predator-prey dynamics, even though it is widely accepted in the academic research community that phytoplankton blooms in marine systems result from a mismatch between growth rates of phytoplankton (faster) and zooplankton (slower). This mismatch allows phytoplankton to break free from grazing control under optimal temperature, light, and nutrient conditions; ultimately, phytoplankton blooms are terminated through some combination of nutrient depletion or limitation and grazing losses. Participants also stressed the importance of carefully examining temperature control functions not only for phytoplankton growth (see discussion above) but also for zooplankton, to ensure that the predator–prey interaction is correctly represented both now and in the future. There was, however, some disagreement related to the incorporation of zooplankton into the water quality model. For example, one participant argued that in a past formulation of ICM that included two zooplankton size classes, the seasonal timing of those components was difficult to reproduce and it was therefore hard to justify including them.

Some members of the estuarine breakout group also argued that the current SAV model in ICM was not adequate for scenario simulations because the current formulation does not take into account crucial factors, like substrate composition, that are needed to predict where SAV will grow when water column conditions are optimal for its growth. As a result, the current ICM-predicted SAV distributions in Chesapeake Bay are unrealistic, and any efforts to predict future changes in SAV distributions in response to restoration and climate change will not be correct.

3. The water quality model needs to be able to address extreme events and tipping points

A consensus emerged among the estuarine breakout participants that the water quality model needs to be able to account for extreme events and tipping points (i.e., sudden, disproportionate changes or reorganizations of the marine ecosystem that could happen in Chesapeake Bay in response to forcing by restoration, climate change and/or extreme events). A classic Chesapeake Bay example of a marine ecosystem tipping point was the disappearance of SAV in Susquehanna flats due to the passage of Hurricane Agnes in 1972 and its sudden reappearance due to restoration and a dry period from 1997–2002. Another example is the switch from a benthic- to pelagic-dominated ecosystem that occurred in the Bay due to eutrophication in the 1970s. Can ICM simulate what happened to the SAV in Susquehanna flats? Can it properly simulate the switch back to a benthic-dominated ecosystem that will presumably happen at some point in the future due to restoration efforts? Studies need to be undertaken to determine if ICM is capable of simulating historical tipping points and the impacts of extreme events (e.g., storms and droughts), especially given that observations and current projections show that the frequency and intensity of extreme events is increasing in the Chesapeake Bay watershed. In the likely event that these studies reveal that the water quality model cannot reproduce these kinds of phenomena, then new models and model formulations will need to be identified and incorporated into ICM to allow their simulation.

4. The water quality model needs to have the ability to simulate pH and acidification

Several workshop participants expressed concern over the fact that ICM cannot currently simulate pH and acidification, which will likely be key for predicting climate change impacts on living resources in the future. Prime examples of organisms likely to be negatively impacted by acidification are the eastern oyster and the blue crab, both of which are important commercial fisheries in Chesapeake Bay and the subject of intensive and expensive management and restoration efforts. How will acidification, which is already happening in the Bay, and is expected to be exacerbated in the future due to rising atmospheric CO_2 levels, impact these efforts?

We must not only incorporate carbonate chemistry formulations into ICM that are needed to simulate pH and aragonite/calcite saturation states, but also accurately represent the carbonate chemistry boundary conditions (atmosphere, rivers and continental shelf). Given the current emphasis in the CBP on development of models that can simulate the impacts of restoration on living resources in Chesapeake Bay, and the need to make sure that ICM is capable of generating the forcing for these living resource models, this must be a high priority for the CBP.

5. Quantifying uncertainty is still important

The estuarine breakout group reiterated the need to quantify uncertainty in the outputs of the CBP models. This has been a topic of discussion for over a decade in the Chesapeake Bay research and management communities, with a previous STAC workshop dedicated to the topic and considerable emphasis on this topic at the previous Climate Change 2.0 STAC Workshop. There is a clear consensus in the academic research community that the uncertainty associated with the TMDL needs to be estimated and communicated, but there has also been pushback from the management community about the value of doing so. An obvious challenge that would emerge from producing a TMDL with error bars would be determining how to allocate the load reductions to the seven jurisdictions in the Chesapeake Bay watershed when dealing with a range of values rather than a specific target.

Breakout group participants discussed some ways that the uncertainty in the CBP models can be quantified, including ensemble approaches and "extreme value analysis." Ensemble methods involve using multiple models that provide a range of TMDL targets, thus providing an estimate of uncertainty. This approach has, for example, been used to estimate uncertainties of climate-induced changes in watershed inputs on estuarine hypoxia, using multiple combinations of models (five Earth System Models, two downscaling methods, and two watershed models that are used to force one estuarine water quality model, as in Hinson et al. (2023)). This study provides a clear road map for how the CBP should estimate the uncertainty in the TMDL using an ensemble method. In contrast, extreme value theory deals with the stochasticity of natural variability by describing extreme events in terms of a probability distribution function. This information can be used to analyze trends and the likelihood that extreme events will occur (e.g., the likelihood that future loads will be much larger or much smaller than the mean targets predicted by the CBP models).

6. Consideration of outputs needed from the water quality model to support/force living resource models

The estuarine breakout group participants spent some time discussing the kinds of outputs that might be needed from the water quality model to force living resource models (e.g., for fish, crabs, SAV, oysters). The water quality model should be used to predict how climate change will impact living resource habitat suitability. For example, model-simulated temperature and oxygen can be used to force mechanistic models that predict habitat suitability for striped bass. In this way, CBP model scenario runs can be used to predict how restoration and climate change will alter the temporal and spatial distributions of optimal (and suboptimal) habitats for certain fish in the Bay, such as striped bass, sandbar sharks and cobia (Crear et al., 2020a,b). Similarly, empirical models have been developed that can be used to predict how restoration and climate change will alter the probability of occurrence of harmful algal blooms (Horemans et al. 2023, 2024) and bacterial pathogens (Groner et al., 2018) in the Bay. As discussed above, the question of whether explicit zooplankton state variables need to again be included in ICM was raised, so that the water quality model outputs can be used to force higher trophic level models.

Living Resources Breakout Group

This breakout convened experts to discuss critical recommendations for improving living resource modeling with respect to climate adaptation. Four key recommendations were outlined to advance living resource modeling relative to climate change considerations in ways that enhance strategic responses, address data and modeling needs, and ensure that practices remain accessible, transparent, and sustainable.

1. Develop a strategic approach to living resource modeling

A strategic approach to living resource modeling emphasizes using a comprehensive framework to assess system responses under climate change. Adapting STAC's CESR report, this approach begins with a table of living resource sensitivities to climate drivers, identifying key tradeoffs and involving stakeholders to explore what can be feasibly managed. Recognizing and mapping the full range of sensitivities in living resources enables managers to identify areas where interventions may be most effective and minimizes potential conflicts among various ecosystem stakeholders. Additionally, explicitly including tradeoffs supports transparency and helps create pathways for adaptive management in a changing climate.

2. Incorporate correlated fields of drivers for key living resource responses

Understanding the responses of living resources to climate change requires modeling drivers at the appropriate spatial and temporal scales. This recommendation highlights the need for models to capture temporal correlations of drivers, as simplistic climate change effects methods (e.g., delta method) often fail to capture the nuances of climate-driven effects on habitats. Living resource models should focus on habitat capacity rather than the more difficult to model population counts, to provide a more stable metric for evaluating ecosystem changes. Adding a carbon module for acidification, along with metrics like minimum and maximum values, variance, and marine heat waves, will offer a richer picture of changing ecosystems. Moreover, specifying species and habitat distributions that may be impacted by these factors will improve predictive accuracy and relevance for resource management.

3. Enhance methods for identifying geographic sources of water quality changes

Recognizing the impacts of water quality on living resources is crucial for directing effective restoration activities. The workshop participants recommended developing or refining methods to identify the geographic sources of water quality changes at scales relevant to these activities. Such methods would allow managers to pinpoint where water quality changes originate and how these changes impact living resources that help define a sense of place within communities. Additionally, by mapping these sources, managers can prioritize areas for climate mitigation efforts that yield co-benefits for ecosystem resilience and community well-being.

4. Adopt Open Science and FAIR data practices

To promote collaboration and transparency, the workshop underscored the importance of following Open Science and FAIR (Findable, Accessible, Interoperable, Reusable) data practices. This includes providing users with access to model forcings, such as atmospheric and watershed model variables, as well as state variables and rates. By establishing these practices, model developers can create a more accessible knowledge base that encourages reproducibility, fosters collaborative innovation, and enables users to understand model limitations and build on existing work. Furthermore, requiring users to adhere to these standards ensures that data remain useful and accurate over time, supporting more robust, science-based decision-making in climate adaptation.

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Appendix A: Workshop Agenda

Chesapeake Bay Program's (CBP)
Scientific and Technical Advisory Committee (STAC) Workshop

CBP Climate Change Modeling III: Post-2025 decisions
May 7-9, 2024
Workshop Webpage
Virginia Tech Executive Briefing Center | Arlington, VA

Objectives:
- Decision in 2020 and upcoming 2027 decision
- CBP in 2020 to predict 1995-2025 climate effects, both model and application
- What models will be available for 2027 decision
    - What has been decided about these models and what has not.
- What research has been done that is relevant to the discussion

Tuesday, May 7th, 2024

9:00 am **Coffee & Light Breakfast (Provided)**

9:45 am **Welcome and Introductions –** *Mark Bennett (USGS)*
Mark Bennett will outline the workshop goals, outcomes, and agenda.

10:00 am **Management Motivation and Model Overview –** *Lee McDonnell (EPA)*
Lee McDonnell will provide an overview on the Bay TMDL and the Chesapeake Bay Program (CBP's) decisions on climate, and outline the current and planned modeling systems.

10:25 am **Application of Climate Data and Earth System Models (ESMs) to the Chesapeake Bay Program (CBP) System P6 Use of Climate Variables** – *Gopal Bhatt (PSU)*
Gopal Bhatt will discuss the use of observed trends and downscaled climate model output in the CBP's previous assessment of climate change effects for the Bay TMDL.

10:50 am **Chesapeake Bay Program Watershed Model** – *Isabella Bertani (UMCES)*
Isabella Bertani (UMCES) will discuss the CBP Watershed model, including the current model structure, the 2019 climate application, and the Next Generation structure.

11:25 am **Chesapeake Bay Program Estuarine Model**
– Lew Linker (EPA), Richard Tian (UMCES), Joseph Zhang (VIMS), Carl Cerco (ATS), Jian Shen (VIMS)
Invited researchers will review the various CBP Estuarine models, including the current model structure, the 2019 application, and the Next Generation structure.

12:00 pm **Lunch (provided)**

1:00 pm **2019-2020 Climate Management Application of the Chesapeake Bay Program Models**
– Gary Shenk (USGS)
Gary Shenk will discuss the effect of climate change from 1995-2025 on necessary reduction of nitrogen and phosphorus in the Bay TMDL.

1:15 pm **Overview of Recommendations from Prior STAC Workshops and Reviews**
– Jeni Keisman (USGS), Zach Easton (VT)
Steering committee members Jeni Keisman (USGS) and Zach Easton (USGS) will give an

overview on previous STAC-led workshops and reviews related to climate change effects modeling:

- 2016 STAC workshop on climate projections assessed available climate data for use in the CBP decision process (Johnson et al., 2016);
- 2018 STAC workshop (Shenk et al., 2021a) generated specific near-term and long-term recommendations for watershed and estuarine modeling, and methods of model application;
- CBP Modeling in 2025 and Beyond (Hood et al., 2019);
- STAC review of BMP effectiveness under climate change (Hanson et al., 2022); and
- Comprehensive Evaluation of System Response (CESR): report webpage.

1:45 pm **Chesapeake Hypoxia Analysis and Modeling Program (CHAMP): Whole system analysis** *– Marjy Friedrichs (VIMS), Kyle Hinson (PNNL)*
Marjy Friedrichs and Kyle Hinson will review results from the Chesapeake Hypoxia Analysis and Modeling Program (CHAMP), a project that used multiple models in a Chesapeake scenario-forecast modeling system in order to predict the impacts of future climate change and future anthropogenic nutrient inputs on hypoxia.

2:45 pm **Break**

3:15 pm **Introduce Breakout Exercise and Structure –** *Gary Shenk (USGS), STAC Staff*
Gary Shenk (USGS) and STAC Staff will introduce the breakout structure (cross-sector and within-sector), topics, and resulting workshop products. STAC Staff will provide an overview on how participant conversation and input are distilled into the eventual workshop report and the timeline for report completion post-workshop.

3:30 pm **Cross-sector Breakouts (expansive)**
In-person participants meet in breakout groups containing a broad cross-section of participants to discuss the overall needs for the system of models. Discussions should be expansive rather than restrictive to maximize potential topics.

4:50 pm **Wrap-Up and Objectives of Day 2**

5:00 pm **Recess**

Wednesday, May 8th, 2024

8:15 am **Coffee & Light Breakfast (Provided)**

8:45 am **Review of Day 1; Objectives for Day 2 –** *Gary Shenk (USGS)*

9:00 am **Focus on Ecosystem Management –** *Kenny Rose (UMCES), Bruce Vogt (NOAA)*
Kenny Rose (UMCES) and Bruce Vogt (NOAA) will co-present on ecosystem management: Rose will cover relevant findings from the STAC-led 2023 CESR report as well as synthesis living resource information occurring in the Bay, and Vogt will project into the future – discussing potential winners and losers and the processes to climate-informed marine resource decisions in the Chesapeake Bay.

10:15 am **Break**

10:45 am **Climate Effects on Biogeochemical and Hydrologic Processes in the Watershed** *– Robert Sabo (EPA) and Andrew Elmore (UMCES)*
Robert Sabo and Andrew Elmore will describe the climate effects on seasonal processes in the watershed.

11:25 am **The State of Decision-Relevant Regional Climate Projections** – *Paul Ullrich (UC Davis)*

Paul Ullrich will give an overview of available climate models, downscaling methods, and considerations when applying climate information to effects models.

12:00 pm **Lunch (provided)**

1:00 pm **Revisiting climate-change impacts on the Chesapeake Bay** – *Raymond (Ray) Najjar (Penn State)*

Raymond (Ray) Najjar will provide an update to a 2010 review article about the impacts of climate change on the Chesapeake Bay.

2:00 pm **Cross-sector Breakouts (prioritize)**
In-person participants meet in cross-sector breakout groups to prioritize recommendations based on Day 1 and Day 2 presentations.

3:00 pm **Break**

3:30 pm **Plenary - Cross-Sector Breakout Group Reports**
Cross-sector breakout groups facilitators will present out on their group's prioritized recommendations. One slide with four bullets will be allowed per group.

4:00 pm **Within-sector Breakouts (expansive)**
In-person participants meet in breakout groups separate for each model domain for expansive discussions. Time may be reduced if plenary discussion ongoing.

5:00 pm **Recess**

Thursday, May 9th, 2024

8:15 am **Coffee & Light Breakfast (Provided)**

8:45 am **Welcome and Structure for Day 3** – *Gary Shenk (USGS)*

9:00 am **Within-Sector Breakouts (expansive)**
Thoughts from the evening of Day 2 and continuation of expansive discussion.

10:00 am **Within-Sector Breakouts (prioritize)**
In-person participants meet in within-sector breakout groups to prioritize based on Day 1 and Day 2 presentations.

10:30 am **Break**

11:00 am **Plenary - Within-Sector Breakout Group Reports**
Within-sector breakout groups facilitators will present out on their group's prioritized recommendations. One slide with four bullets will be allowed per group.

11:30 am **Plenary – Within-Sector and Cross-Sector themes**
The workshop participants will have a facilitated discussion on the recommendations from all breakout groups. An overall prioritization will be discussed.

12:30 pm **Lunch (provided)**

1:30 pm **Plenary – Final Prioritization of High-level Recommendations**
The workshop participants will continue a facilitated discussion on the recommendations from all breakout groups, incorporating lunch conversations. An overall prioritization will be discussed.

2:00 pm **Workshop Adjourns**

Appendix B: Workshop Participants

Name	Affiliation	Name	Affiliation
Larry Band	UVa	Molly Mitchell	VIMS
Clifton Bell	Brown and Caldwell	Dave Montali	West Virginia
Mark Bennett	USGS	Ray Najjar (virtual)	PSU
Isabella Bertani	UMCES	George Onyullo (virtual)	DOEE
Gopal Bhatt	PSU	Julie Reichert-Nguyen	NOAA
Nicole Cai	ORISE	Tish Robertson	VA DEQ
Carl Cerco	Attain	Kenny Rose	UMCES
Victoria Coles	UMCES	Robert Sabo	EPA
Fei Da	NOAA/GFDL	Greg Sandi	MDE
Joseph Delesantro	EPA	Larry Sanford	UMCES
Zachary Easton	VT	Amir Sharifi	DOEE
Andrew Elmore	UMCES	Jian Shen	VIMS
KC Filippino (virtual)	HRPDC	Gary Shenk	USGS
Kendrick Flowers	USDA-NRCS	Pierre St-Laurent	VIMS
Carl Friedrichs	VIMS	Charlie Stock	NOAA/GFDL
Marjy Friedrichs	VIMS	Olivia Szot	VIMS
Normand Goulet (virtual)	NVRC	Richard Tian	UMCES
Jeremy Hanson	CRC	Paul Ullrich (virtual)	UC Davic
Colin Hawes	VIMS	Bruce Vogt	NOAA
Kyle Hinson	PNNL	Harry Wang	VIMS
Raleigh Hood	UMCES	Ryan Woodland (virtual)	UMCES
Jeni Keisman	USGS	Guido Yactayo	MDE
Lew Linker	EPA	Joseph Zhang	VIMS
Piero Mazzini	VIMS	Qian Zhang (virtual)	VIMS
Lee McDonnell	EPA		
Andy Miller	UMBC		
Thomas Miller	UMCES		

Appendix C: Breakout group questions

Questions for Cross-sector Breakouts

For the following questions, please consider:

- Are the quality and types of inputs sufficient?
- Are the relevant processes modeled and are they modeled well?
- Are the correct outputs modeled in each component?

Does the modeling system support the main Bay TMDL metrics of nutrients, sediment, oxygen, clarity, and chlorophyll?

- Is the currently planned Phase 7 modeling system sufficient to assess the influence of climate change from 1995 to 2035 on the CBP TMDL-related goals?
    - What about 2050, 2075, and 2100?
- Are there aspects of the Phase 7 modeling system that need to be expanded or added?
    - How well is temperature integrated throughout the analysis system? Do we have the proper processes simulated?
- What information needs to be passed between models?
    - How do we preserve the change in timing of flow, heat, and nutrient and sediment delivery through the handoff from Earth System Model to watershed and watershed to estuarine models?
    - How are these effects mediated by BMPs, land use, and PET?
- What are the best methods to evaluate model responses relative to climate change effects?
- What model scenarios or experiments would be helpful in understanding climate change effects?
- Does Phase 7 need to account for changes in reservoir operating rules representing increased demands of water supply under climate change conditions as well as the potential for greater reservoir spill or controlled releases in response to higher precipitation volumes and flow
- Agriculture is dynamic and will respond to future climates by cropping practices more suited to the warmer, longer growing seasons. Is this an important aspect to consider?

How could we expand the scope of the modeling beyond prior TMDL metrics?

- Living resources
    - What types of living resource effects could realistically be modeled?
    - What types are most important for management?
- Shallow water
    - What are the outcomes that we would like to model?
    - What would need to be passed between models to better understand shallow tidal water?

How do we incorporate uncertainty in all models and the *decision-making* process?

What level of accessibility is appropriate for each component? - outputs, model code, inputs?

What can be done in phase 8?

Questions for Within-sector Breakouts

Watershed

Will the Phase 7 modeling system be sufficient to understand the effect of climate on management action effectiveness and implementation in the CBP?

What are the most important climate-induced changes in the watershed?

- What are we missing?
- What can be improved?

How does the watershed model work within the model suite?

- Are we getting the right information from the ESMs?
- Are we giving the right information to downstream models?

Other issues:

- What types of uncertainty are important to management?
- How can we represent resilience?
- The CBP will be estimating the effects of climate change on BMPs through process-based modeling. Is this the appropriate approach?

With hydrology, flooding, and stream temperature potentially becoming larger issues, should there be a process-based simulation of these outputs?

Is the proposed method of using a process-based model for estimating climate effects on BMPs optimal?

Estuarine (WQ and hydrodynamics)

What are the most important climate-induced changes in the estuary?

Are there specific issues we need to consider when projecting future climate change in shallow water?

How can we best represent the temperature dependence of algal growth?

Are we getting the necessary information from the Earth System Models and watershed models?

What acidification effects are important and can they be modeled?

What information do we need from estuarine models to assess future climate impacts on living resources?

What are we missing in our projections of future estuarine conditions, and what can be improved?

How do we balance uncertainty quantification versus operational concerns?

Living Resources

What are the most important climate-induced changes in the watershed?

What are we missing?

What can be improved?

Are we getting the right information from the ESMs?

Are we giving the right information to downstream models?

Can the WQM give the right information to assess impacts on living resources?

How important is the accurate simulation of temperature? In what environments?

How can we best categorize the habitat needs?

Management

Given that the models will answer the TMDL questions as required, what additional management outcomes can be modeled? How can those additional outcomes be modeled so that the outputs are useful for decision making?

How can modeled climate change effects best inform a decision process? Is the conversion of oxygen effect to load reduction done in an optimal way?

Are the modeling aims from the plenaries and the cross-sector breakouts asking the right questions?

Are the models giving appropriate estimates of uncertainty?

Breakout Leads

Watershed	Gary Shenk	Cross-sector 1	Robert Sabo
Estuarine	Marjy Friedrichs Raleigh Hood	Cross-sector 2	Lewis Linker
Living Resources	Jeni Keisman	Cross-sector 3	Zach Easton
Management	Lewis Linker	Cross-sector 4	Gary Shenk